- •Goals,
- •Opportunities, and
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USGS Earthquake Hazards Reduction Program

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Goals, Opportunities, and Priorities for the USGS Earthquake Hazards Reduction Program

By ROBERT A. PAGE, DAVID M. BOORE,
ROBERT C. BUCKNAM, and WAYNE R. THATCHER

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Cover. Damage scenes from the 1989 Loma Prieta, California, earthquake.
Photographs by Charles E. Meyer, U.S. Geological Survey

PREFACE

This report presents a new strategic plan for the U.S. Geological Survey's Earthquake Hazards Reduction Program (EHRP), which is directed at understanding the causes and effects of earthquakes, evaluating potential earthquake hazards, and predicting earthquakes and their geologic effects. The program is a principal component of the National Earthquake Hazards Reduction Program, established by the Earthquake Hazards Reduction Act of 1977 for the purpose of reducing risks to life and property from earthquakes. The initial plan for the EHRP was defined in U.S. Geological Survey Circular 780, published in 1978, and the program was modified somewhat during the 1980's. This report represents the first wholesale reformulation of the program strategy.

As a strategic plan, this document provides the scientific framework and rationale for the EHRP. It defines the goals and objectives of the program and the types of activities by which the goals should be pursued. Further, it suggests priorities for program activities in the context of two annual funding options—$50 and $100 million. This document is not an itemized workplan and thus does not define how, when, and where specific activities should be undertaken. The intended audience of this report is primarily the earth-science and earthquake-hazard-reduction community.

The reformulated strategy for the EHRP emphasizes an integrated multidisciplinary approach to earthquake problems, a logical sequencing of program goals, and the effective transfer of research results to those charged with implementing hazard-reduction measures. Emphasis is placed on filling critical gaps in knowledge, continuing and intensifying productive research activities, and incorporating promising new avenues of research and new technology.

The Loma Prieta, California, earthquake disaster of October 1989 prompted a reexamination of ongoing efforts to reduce earthquake risks. Between May and October 1990, the U.S. Geological Survey sponsored an intensive, broad-based review of the goals and priorities of its EHRP, which involved earth scientists, engineers, planners, social scientists, and emergency-management experts drawn from academia, government, and industry. The ideas and recommendations of this diverse community are reflected in the plan presented here.

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Goals, Opportunities, and Priorities for the USGS Earthquake Hazards Reduction Program

By Robert A. Page, David M. Boore, Robert C. Bucknam, *and* Wayne R. Thatcher

EXECUTIVE SUMMARY

This report redefines the goals and objectives of the Earthquake Hazards Reduction Program, identifies promising directions for future research, defines priorities for activities under annual funding options of $50 million and $100 million, and discusses the transfer of program results to the planning and engineering communities charged with reducing losses from future earthquakes.

The magnitude 6.9 Loma Prieta, California, earthquake of October 18, 1989 demonstrated the serious vulnerability of a major urban area to a large, nearby earthquake. Although not uncommonly large in terms of previous U.S. earthquakes, this shock caused more than $6 billion of property damage in the San Francisco Bay-Monterey Bay region, left over 12,000 homeless, and killed 62 people. As a result of increasing urbanization in earthquake-prone regions throughout the Nation, seismic risk to people and property continues to grow. Furthermore, the probability is high that larger and more destructive earthquakes will strike this or other major urban areas in the United States during the next 30 years.

Although earthquakes cannot be prevented, their effects are controllable to a large degree, so that loss to life and property can be reduced. To this end, the U.S. Geological Survey (USGS) conducts its Earthquake Hazards Reduction Program (EHRP) to understand the causes and geologic effects of earthquakes. Over the past decade, the EHRP has produced significant new insights into the nature and severity of the earthquake threat in regions throughout the country, including California, the Pacific Northwest, Utah, and the central Mississippi Valley. Also, advances in the understanding of seismic shaking and its effects on structures have lead to improvements in design codes and building practices. With respect to the Loma Prieta earthquake, the EHRP contributed not only to the technical knowledge of what happened during the earthquake but also to the preparedness level of the communities affected by the shock.

The EHRP is one of the four major elements of the National Earthquake Hazard Reduction Program (NEHRP); it is that part of the national program carried out by the USGS. Activities complementary to the USGS efforts are conducted by the National Science Foundation, the National Institute for Standards and Technology, and the Federal Emergency Management Agency, which also provides overall coordination for the NEHRP. These agencies have important roles in using and communicating information generated by the EHRP.

Mindful of the increasing earthquake threat to the Nation, as underscored by the Loma Prieta earthquake, the USGS in mid-1990 initiated within the earth-science research and earthquake-hazard-reduction community a review of the scientific goals and strategies of the EHRP and a discussion of the opportunities and priorities of the program for the 5-year interval 1991-1995. This review and discussion culminated in the new strategic plan presented here. Shaping the plan are four goals, sequenced progressively from directed research to practical application:

•**Understanding what happens at the earthquake source**—Why and how does a segment of a geologic fault suddenly slip and produce an earthquake? What physical conditions within the Earth control where and when an earthquake occurs?

•**Determining the potential for future earthquakes**—Where are future earthquakes likely and unlikely to occur? How large will they be? How often will they occur? When will they occur?

•**Predicting the effects of earthquakes**—During an earthquake of a certain magnitude, how severely and for how long will the ground shake? Where will hillsides slide, and flatlands fissure and crack? On what types of ground will earthquake damage be concentrated? Which faults will offset the Earth's surface? By how much? Which coastlines will be elevated or submerged? Where will destructive sea waves be generated? What losses to structures are expected?

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•**Using research results**—What new hazard-reduction strategies become possible as understanding of earthquake phenomena advances? What scientific information is needed and can be furnished to practitioners in the engineering, land-use-planning, and emergency-management communities? How can such information be most effectively communicated to these practitioners?

Recent program accomplishments and scientific advances together with new technologies show highly promising opportunities and directions for the program that would significantly accelerate progress on program goals:

•Intensive studies of the role of local geologic conditions in governing the severity of seismic shaking and the failure of foundation materials and of structures and lifeline facilities

•Modernization of seismograph networks with high-fidelity digital recording

•Application of satellite-based geodesy to measure rates of earthquake-generating deformation processes within the Earth

•Geologic investigations of prehistoric earthquakes to determine how frequently potentially damaging earthquakes occur

•Intensive studies of stresses and fluid pressures deep within active fault zones and their role in controlling earthquake faulting

To continue progress on the broad research frontier that has characterized the EHRP since its birth, two program options are presented. A $50 million per year option would restore health to a program whose vitality was being sapped during the 1980's by the cumulative effects of inflation; however, this option does not even equal the constant-dollar budget of the EHRP at its inception in 1978. A $100 million per year option would allow the pace of progress to accelerate; the new opportunities and directions highlighted above would be aggressively pursued at the same time that productive ongoing studies were being enhanced. In addition, new talent and expertise would be attracted into the field.

Program priorities under the two options are defined in terms of increments of efforts referenced to the fiscal year 1990 program, the focus of the program review that lead to this report:

$50 Million Per Year Option

•Triple support to document, study, and predict damaging levels of seismic shaking in the ground and in structures and lifeline facilities

•Reinstitute research on earthquake-triggered landslides and other failures of natural and artificial earth-foundation materials

•Intensify cooperative efforts with State and local governments to map earthquake hazards and assess potential earthquake losses in local demonstration areas within urban centers in northern and southern California, the Pacific Northwest, and the central Mississippi Valley

•Complete installation of the national digital seismograph network

•Increase studies of the origins of earthquakes, especially in the Central and Eastern U.S.

•Expand geodetic surveys of broad-scale earth deformation that causes earthquakes

•Augment communication of earthquake-hazard information and hazard-assessment methods to users

•Strengthen other ongoing program activities, and repair and replace broken and outdated equipment

$100 Million Per Year Option

•Extend cooperative efforts with State and local governments to map earthquake hazards to several other high-risk urban regions throughout the Nation

•Intensify studies of damaging levels of seismic shaking both in the ground and in structures and lifeline facilities

•Augment studies of shaking-induced landsliding and other failures in earth-foundation materials

•Extend geodetic and geologic studies of rates of earth deformation to all the principal seismic zones in the U.S.

•Conduct focused geologic and geophysical surveys to relate earthquake activity to buried geologic structures

•Modernize regional seismic networks with high-fidelity digital recording

•Expand intensive geophysical monitoring of localities where large earthquakes are most likely to occur within the next two or three decades from two localities to five

•Initiate detailed investigations of rock types and physical properties within an active fault zone and of stresses and fluid pressures at depths at which earthquakes occur

•Facilitate and augment the communication of hazard information and assessment methods

Successful pursuit of program goals and objectives requires, first, close collaboration among researchers in different disciplines and vigorous involvement of academia, State and local government, and the private sector, and, second, effective communication between researchers and those charged with implementing earthquake-hazard-reduction measures. National, regional, and topical working groups will be essential elements to integrating efforts and addressing problems within the diverse components of the EHRP.

INTRODUCTION

A mere 10 seconds of strong seismic shaking in the 1989 Loma Prieta, California, earthquake (magnitude 6.9) resulted in 62 deaths, 12,000 homeless, and over $6 billion in property damage in the San Francisco Bay-Monterey Bay region. This loss serves as an urgent warning of the great vulnerability of modern urban areas to the destructive effects of a large earthquake and emphasizes the enormous technical, political, and social efforts required to effectively cope with the problem. Recently published forecasts show that shocks as large or larger than the Loma Prieta event and much closer to heavily populated areas are highly likely to occur elsewhere on the San Andreas fault system in California within the next 30 years. The consequences of those earthquakes will be catastrophic and felt nationwide; they highlight the critical need for a vigorous program of hazard mitigation.

The potential for destructive and costly earthquakes, however, is not just a California problem, for significant seismic hazards have been identified in 39 States. Large historical earthquakes with magnitudes comparable to or greater than that of the Loma Prieta earthquake have occurred not only in the Western U.S.—Alaska, California, Hawaii, Idaho, Montana, Nevada, and Washington—but also in the central Mississippi Valley (New Madrid, Missouri, region, 1811–1812) and in the Eastern U.S. near Charleston, South Carolina (1886). Significant earthquakes have also occurred in the Northeast: recurrence of the magnitude $6^1/_4$ earthquake (1755) off Cape Ann, Massachusetts, would possibly cause $2 to $10 billion in damage and hundreds of deaths in the Boston area alone, even with the shock located offshore. In the mid-continent, a magnitude $7^1/_2$ earthquake, somewhat smaller than the largest earthquake in the 1811–1812 New Madrid series of earthquakes, might cause 300 fatalities and produce $3 billion in damage in the City and County of Saint Louis alone, which together represent only a small fraction of the potentially affected area. In Utah, detailed investigations of fault displacements have identified the occurrence of prehistoric earthquakes of about magnitude $7^1/_2$ on the Wasatch fault as recently as 300–400 years ago. The repeat of such an event today in the Salt Lake City area could cause estimated losses of $5 billion and thousands of fatalities.

The National Earthquake Hazards Reduction Program (NEHRP) was established by Congress in 1977 and implemented in 1978 to develop information and strategies needed to reduce seismic risk to people and property. The program involves four principal agencies including the U.S. Geological Survey (USGS), whose program mission is to develop a base of earth-science data and knowledge for the effective reduction of earthquake hazards. In pursuing its mission, the USGS involves the talents and expertise of universities, State geological surveys, regional and local governments, and private organizations. Since 1978 the capacity for reducing earthquake hazards has grown markedly, in large part because of improved understanding provided by the EHRP of the earthquake threat. The Loma Prieta earthquake, however, caused the USGS in consultation with a broad cross-section of the earthquake-research and hazard-reduction community (appendix 1) to reexamine its component of the national program (hereinafter referred to as the USGS Earthquake Hazards Reduction Program, or simply the EHRP) with the intention of increasing its effectiveness in contributing to the reduction of hazards in many areas of the country now known to be threatened by large earthquakes.

This document presents a revised strategy for the EHRP. Program goals and objectives are redefined, important topics for accelerated research and promising new technological capabilities are highlighted, activities for addressing the program goals are recommended, and two funding options are discussed: one at $50 million and a second at $100 million.

Primary Federal Agencies Participating in the National Earthquake Hazards Reduction Program

National Earthquake Hazards Reduction Program (NEHRP) activities are conducted primarily by four principal agencies: U.S. Geological Survey (USGS), National Science Foundation (NSF), National Institute for Standards and Technology (NIST), and Federal Emergency Management Agency (FEMA). USGS and NSF conduct earth-science and engineering research on the causes and effects of earthquakes and disseminate that knowledge to the user community. NIST undertakes engineering studies to determine appropriate building-code requirements for earthquake resistance. FEMA is responsible for overall program co-ordination and for providing assistance to State and local governments, private organizations, and individuals in the implementation of hazard-reduction measures.

The risks associated with earthquakes can be reduced in several ways, each requiring information and knowledge from earth science and engineering research:

•Appropriate land use in earthquake-prone regions demands knowledge of the hazards posed by strong shaking, ground failure, and surface faulting

•Earthquake-resistant design of structures necessitates understanding how the ground will shake and respond in future earthquakes

•Preparedness for future earthquakes requires that the magnitude, extent, and imminence of damaging earthquakes be specified on national, regional, and local scales

•Recovery from earthquake disasters is aided by rapid availability of reliable information on the mainshock location and magnitude, probable damage distribution, and likelihood of potentially damaging aftershocks

Such information can only be obtained from a research program that includes a broad range of integrated seismic, geophysical, geologic, and geodetic investigations. Since its inception, the EHRP has proceeded on the thesis that (1) earthquake effects cannot be understood and accurately predicted without knowing the nature of the sources that generate strong ground motions; (2) mapping earthquake hazards for land-use decisions requires knowledge of local geology and how different geologic materials respond to and modify the character of seismic waves; and (3) reliable long-term earthquake forecasts derive from knowledge of the location of the faults capable of generating earthquakes, the mechanics of earthquake recurrence, and the geologic record of prehistoric earthquakes.

Progress on these subjects has been substantial during the EHRP, and the technical advances that have been realized provide a solid framework for an even stronger program of earthquake-hazard reduction. In addition to the technical accomplishments, the development of a talented and experienced earthquake-research and hazard-reduction community over the same timespan provides a strong personnel capability to pursue an aggressive program.

RESEARCH AND IMPLEMENTATION: TWO PARTS OF A WHOLE

The EHRP is an earth-science program directed first at expanding and strengthening the base of scientific knowledge usable for effective reduction of earthquake hazards. Equally important, however, is the effective and timely flow of scientific information to the myriad of potential users, ranging from the general public to engineers, planners, government officials, business leaders, and many others. Implementation—the process of applying research results to reduce future earthquake losses—is a responsibility broadly shared by agencies and institutions within and beyond the NEHRP. This chapter discusses the implementation process as it pertains to the EHRP, defines the role of the EHRP in the transfer of hazard information and hazard-assessment methods to those charged with taking actions to reduce hazards, and illustrates how information developed under the EHRP supports specific hazard-reduction strategies.

For research results to be used in the reduction of hazards, technical information must not only be understandable to the would-be user, but also relevant and usable to the practicing professional. The initial responsibility for transferring research results of the EHRP lies with the program itself. The program must inform engineers, planners, and emergency managers about new opportunities for hazard reduction arising from improved understanding of the earthquake threat or the availability of new earth-science information. At the same time, the program must learn from practitioners in the hazard-reduction arena of their needs for specific types of information and products. Within a problem-focused program like the EHRP, researchers must be heavily engaged in this dialog with the user community. But researchers alone cannot carry the burden of implementation; the program must also engage those trained and skilled in communicating and applying research results.

The other principal NEHRP agencies—National Science Foundation (NSF), Federal Emergency Management Agency (FEMA), and National Institute for Standards and Technology (NIST)—have roles in the transfer and use of information and knowledge generated by the EHRP. Earthquake, strong-motion, and structural-response data collected by the EHRP are heavily used by researchers within the NSF earth-sciences and earthquake-engineering programs, and the strong-motion and structural-response data provide the basis for improving earthquake-resistant design and construction, a goal shared by NIST and NSF. National shaking-hazard maps produced by the EHRP support the development of improved seismic-design provisions in building codes and standards, a principal concern of NIST. Finally, FEMA utilizes and transfers earth-science information from the EHRP in assisting State and local governments to implement comprehensive earthquake-hazard-reduction programs and in supporting public education and awareness programs.

The EHRP contributes directly to four hazard-reduction measures: land use, engineering, preparation, and recovery. *Prudent use of the land* to avoid or minimize exposure to hazards is one line of defense against earthquakes. In many instances, structures and facilities can be located on stable ground where they are not exposed to severe shaking; to surface faulting; to complete or partial failure of the underlying foundation material; to landslides, rock falls, debris flows; or to tsunamis. The EHRP develops methods for assessing earthquake hazards on both site-specific and regional bases and demonstrates the use of these methods in pilot hazard-mapping projects within earthquake-prone urban regions. No budget option discussed in this plan is sufficient to map earthquake hazards throughout all the high-risk urban regions of the United States. Thus, the program policy is to engage in cooperative projects with State or local government agencies to map hazards in urban or urbanizing localities—parts of large metropolitan regions—where the earthquake risk is perceived to be large and where there is a commitment to incorporate such maps in land-use practices to reduce earthquake hazards. A fundamental purpose of such projects is the transfer of research

Examples of Significant Accomplishments of the USGS Earthquake Hazards Reduction Program (1978-1990)

- Prehistoric earthquake chronologies determined from the recent geologic record for the Wasatch fault, Utah, and the San Andreas fault, California
- Association of the New Madrid seismic zone in the central Mississippi Valley with a buried 500-million-year-old continental rift
- Realization of the potential for great coastal earthquakes in the Pacific Northwest
- Recognition of blind (buried) thrust faults as sources of potentially very damaging earthquakes (for example, the 1983 magnitude 6.7 Coalinga and 1987 magnitude 5.9 Whittier Narrows, California, earthquakes)
- Capability to instantaneously determine earthquake locations and magnitudes
- Accurate locations and reliable focal mechanisms for felt earthquakes throughout most of the U.S. derived from data recorded by regional seismograph networks funded by the USGS and the Nuclear Regulatory Commission
- Routine determination of source characteristics (for example, seismic moment, focal mechanism, source complexity) of large earthquakes worldwide from the global digital seismograph network
- Geodetic mapping of contemporary deformation in the Western U.S.
- Development of continuously recording surface (long-baseline) and borehole strainmeters of very high sensitivity
- Definition of state of stress along the San Andreas fault in California and how it differs from that in surrounding stronger regions
- Recognition of the role of fault geometry in starting and stopping earthquake rupture
- A physical model for earthquake faulting—the velocity-weakening/velocity-strengthening hypothesis
- Successful long-term forecasting of large earthquakes in areas of seismic quiescence on plate-boundary faults on a worldwide basis
- Long-term, probabilistic forecasts of earthquakes for the San Andreas fault system
- Initiation of a focused earthquake-prediction experiment at Parkfield, California, with an integrated plan for issuing and responding to an earthquake prediction
- Determination of the characteristics of near-source strong ground motion in moderate-sized earthquakes
- Instrumental recordings of dramatic amplification of ground motion on soft soil sites
- Instrumental recordings of pressure increases in shallow ground water and the onset of liquefaction during strong ground shaking
- Development and demonstration of methods for mapping earthquake hazards (faulting, shaking, liquefaction, landsliding) in the Salt Lake City, Los Angeles, and San Francisco Bay areas
- More than 50 workshops on reducing earthquake hazards, involving 5,000 people and including every earthquake-prone region of the Nation
- First mass distribution (3 million copies) of an educational pamphlet discussing the earthquake hazard in a metropolitan area (San Francisco Bay region) and how to prepare for future earthquakes

information to local earth scientists, engineers, and planners so that hazard mapping can be extended with State and local resources.

Hazards cannot be avoided entirely by site selection; in urban regions, scarcity of land pushes development into more hazard-prone areas. Also, lifeline facilities, because of their distributive nature, must traverse hazardous areas. Thus, because hazardous areas cannot be avoided entirely, structures must be designed and built to resist the effects of earthquakes. In the United States, *engineering* has been and is today the most widely practiced earthquake-hazard-reduction strategy. By world standards, life loss in U.S. earthquakes has been admirably low; however, the country can ill afford the billions of dollars of damage that attend large earthquakes in or near urban regions, such as the recent Loma Prieta earthquake. The role of the EHRP with respect to engineering is to provide to the engineering community technical information about how the Earth will behave in future earthquakes. National maps depicting the ground-shaking hazard are prepared under the program and provide the basis for seismic design criteria in national building codes; the maps must be revised periodically to incorporate new information about earthquake potential and how shaking decreases with distance from the source. The EHRP collects data to document ground shaking, ground failure, and structural response for the benefit of the earth-science and engineering communities and develops more accurate methods for predicting the character and severity of shaking and ground failure at sites underlain by various geologic materials and geotechnical conditions.

The consequences of an earthquake can be reduced through *preparation* for its occurrence. Over the past decade, this loss-reduction strategy has gained prominence largely because of the greatly increased awareness of the seriousness of the earthquake threat and improved understanding of the nature, magnitude, and likelihood of the threat in different regions of the country. The EHRP, with its national focus on understanding the origins and geological effects of earthquakes, deserves credit for much of this progress. In support of this strategy, the role of the program is to furnish accurate earth-science information for the education of the public and those responsible for mitigating earthquake risk. Most significant is the capability being developed under the EHRP to identify regions where damaging earthquakes are likely to occur and to predict their consequences in terms of damage patterns and aggregate losses. This capability provides a basis for effective preparatory actions. For example, probabilistic estimates of earthquake occurrence on the San Andreas fault system provide a rational framework for deciding priorities for allocating scarce resources to strengthen or replace unsafe structures. Since the start of the NEHRP, awareness of the earthquake threat has increased dramatically among local governments, businesses, and the public, particularly in those areas where the EHRP has been most active—San Francisco Bay region, southern California, Utah, Washington, Oregon, and the central Mississippi Valley region.

The fourth hazard-reduction measure—*recovery*—seeks to moderate the economic and social impacts of an earthquake disaster. In support of this strategy, the role of the EHRP in the immediate aftermath of a destructive earthquake is to provide (1) rapid and reliable scientific information on the size and location of the earthquake and on the likelihood of potentially damaging aftershocks and (2) where possible, maps depicting probable areas of severe ground shaking and extensive ground failure. Techniques for assessing earthquake hazards developed under the EHRP are useful in evaluating the suitability of sites for postearthquake reconstruction. Finally, progress in quantitatively assessing and mapping earthquake hazards and relating hazards to earthquake losses is establishing a sound technical basis for implementing insurance as a vehicle both to spread the economic risk of disasters and to encourage actions to reduce exposure to earthquake risk.

NEW DIRECTIONS

New scientific insights and greatly enhanced technological capabilities provide strong justification for an expanded program aimed at reducing earthquake hazards. In particular, the significant successes of the EHRP point to specific opportunities where focused studies can yield major advances in knowledge and hazard mitigation. Here we highlight five topics that are especially exciting opportunities:

- Site-specific prediction of earthquake effects
- Modern technology for seismograph networks
- Contemporary deformation rates with Global Positioning System technology
- Prehistoric earthquakes and long-term probabilistic forecasting
- The physics of faulting

Site-Specific Prediction of Earthquake Effects

The amount of damage to a structure depends on the character of ground shaking, the interaction between the structure and its earth foundation, and the dynamic response of the structure; consequently, knowledge of all these factors is required to predict damage and thus losses. Ground shaking beneath a structure, in turn, depends on many factors: the duration and amplitude of motion at the earthquake source, the distance of the structure from the source, the modulation of seismic waves as they propagate from the source to the site, the geologic structure beneath the site, and the geotechnical properties of earth foundation materials.

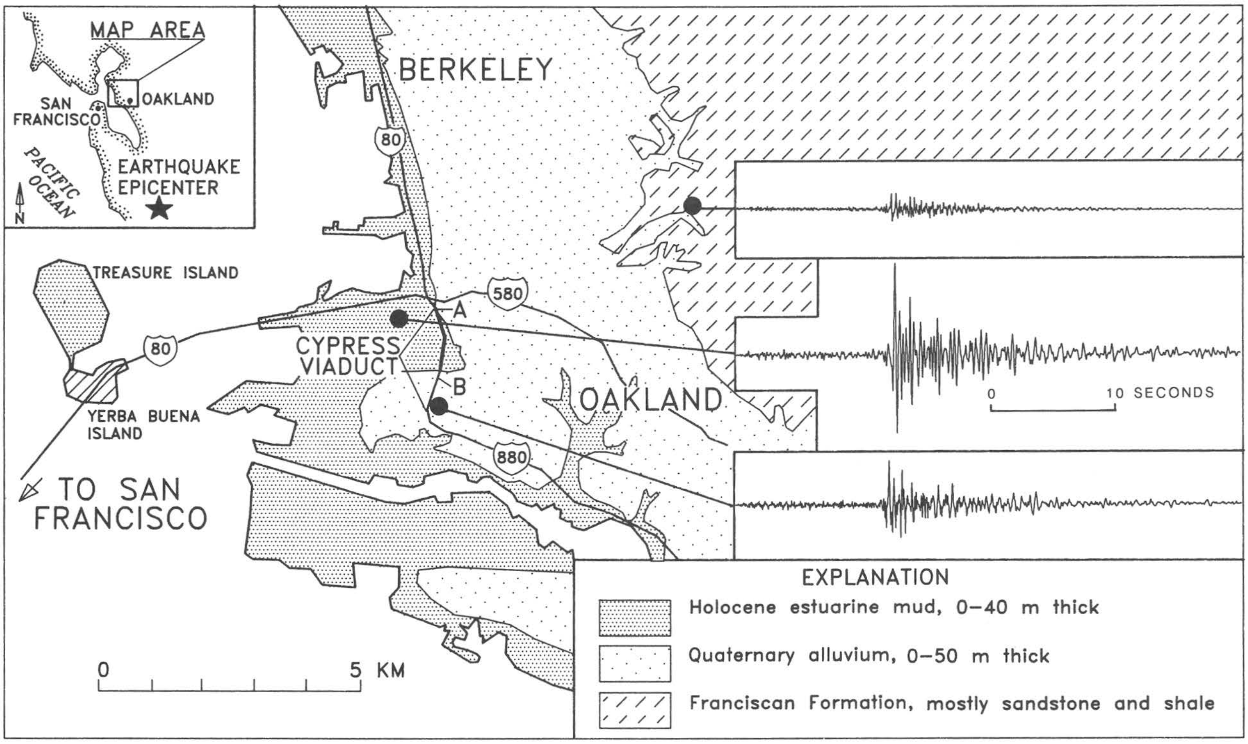


Figure 1. Intensified shaking on weak ground contributed to catastrophic collapse of freeway viaduct in 1989 Loma Prieta, California, earthquake. Two-thirds of the 62 deaths in the magnitude 6.9 Loma Prieta earthquake resulted from collapse of the upper deck of a mile-long segment of the Cypress Viaduct (photograph) of Interstate 880 in Oakland, about 80 km from the earthquake source region. The soils underlying the collapsed segment (between points A and B, *bottom*) are soft, young mud beneath about 2 m of artificial fill, whereas those under the adjacent sections, which did not collapse, are older, stiffer alluvium. Although there are no records of the mainshock from the immediate vicinity of the viaduct, recordings of horizontal ground velocity from an aftershock clearly document stronger shaking on the mud than on nearby alluvium and rock (*bottom*). The aftershock recordings implicate local amplification of shaking on the mud as a factor contributing to the failure of the viaduct.

The 1989 Loma Prieta earthquake and before it the disastrous 1985 Mexico City shock graphically demonstrate that most of the damage from major events typically occurs in areas of young, poorly consolidated geologic units, sites where ground motions are amplified and soil failure or liquefaction may occur. Recent studies strongly suggest that major progress toward reliable, quantitative prediction of ground shaking in future earthquakes can be achieved through concentrated, comprehensive investigations of earthquake shaking in a few regions possessing a variety of geologic site conditions, including young unstable deposits. Such investigations should be focused in regions where the likelihood for a large earthquake within the next decade or two is high and also where it is certain that scientifically valuable smaller events would be recorded. The San Francisco Bay area is one region that fills these criteria.

A comprehensive investigation of ground shaking directed at improving methods and reliabilities of site-specific predictions should involve:

•Source modeling to predict the range of expected motions for events of specific magnitude on particular fault segments

•Geologic mapping to determine the distribution of young geologic units capable of locally amplifying shaking or susceptible to failure during strong shaking

•Geologic mapping and seismic and geophysical surveys to determine the seismic velocity structure between source and site

•Development of computational methods to model three-dimensional wave propagation for examining the modulation of seismic waves along the source-site path

•In situ and laboratory measurements of physical properties of site-foundation materials and their behavior at high strain levels

•Operation of strong-motion seismograph arrays to record ground motion near the source during major earthquakes

•Installation of special-purpose surface and borehole instrumental arrays at selected sites to measure ground-motion amplification, nonlinear soil response, liquefaction, and ground failure during major earthquake shaking

•Deployment of special-purpose instrumental arrays, encompassing strong-motion sensors in boreholes and structures, to study soil-structure interaction and the seismic response of engineered structures.

To ensure that these activities focus effectively on matters of concern to both the earth-science and engineering professions, the earthquake-engineering community should be involved in planning the investigations.

These investigations would lead to an ability for routinely predicting earthquake effects at specific sites with a degree of precision and reliability not currently available. Such a capability has wide application in providing a quantitative basis for refining national building codes, developing local building codes, land-use planning, and siting and design of vulnerable lifelines and critical facilities in seismically active regions.

Modern Technology for Seismograph Networks

Regional seismograph networks supported by the EHRP and the Nuclear Regulatory Commission have supplied detailed knowledge of seismicity in many of the most seismically active parts of the Nation. These networks have provided the framework measurements necessary to better define the earthquake potential, to relate seismicity to geologic structures and tectonic processes, to promote understanding of the physics of the earthquake source, and to guide other program activities. Regional seismic networks have also made it possible to monitor changes in activity with time and, in a few regions, to begin issuing near-term hazard advisories for potential future activity. All of these achievements have come using technological capabilities developed in the 1960's and not significantly upgraded since that time.

Despite limited implementation during the late 1980's of fully digital systems for recording, transmitting, and analyzing seismic data, results clearly illustrate the revolutionary impact that this new technology can have on seismic monitoring. The new digital seismograph systems can provide on-scale recordings over a broad range of frequencies of both small events and nearby shocks as large as magnitude 5, while the conventional narrow-band, short-period analog systems commonly saturate for shocks as small as magnitude 3 and in such cases supply information only on the arrival time and direction of the initial motion and on the duration of the seismic waves. In addition, the increasing availability of both microwave and high-data-rate satellite telemetry provides an efficient means for transmitting digital signals from remote locations. High-speed digital computers can analyze such data instantaneously, and sophisticated analyses can extract unprecedented detail about earthquakes sources and Earth structure. Even the present limited and widely spaced deployment of digital stations around the globe illustrates the great benefits of digital technology. Source properties are now routinely obtained for an order of magnitude more earthquakes worldwide than previously analyzed, and the resolution with which the gross features of Earth structure can be determined has greatly improved.

Extension of these technical capabilities to regional seismic networks as well as the National Seismograph Network would complement and markedly enhance the results achievable with the existing analog seismograph networks. Better determinations of earthquake source properties would facilitate understanding both the geologic forces responsible for earthquakes and the physical processes governing seismic slip on faults. Improved three-dimensional models of seismic velocity could be related to both regional and local geologic structure and could be applied to improve earthquake locations and predictions of earthquake site effects. Instantaneous determination of earthquake parameters has several important applications to hazard mitigation. Faster and more accurate determinations of the magnitude, location, and spatial extent of slippage in large local earthquakes would permit the prompt issuance of earthquake and aftershock advisories to disaster management organizations. Also, instantaneous high-quality digital seismic data from major offshore and sea-floor earthquakes could be used to improve the speed, reliability, and precision of warnings of large, potentially destructive tsunamis; more timely and effective warnings could then be issued to vulnerable regions distant from the epicentral region.

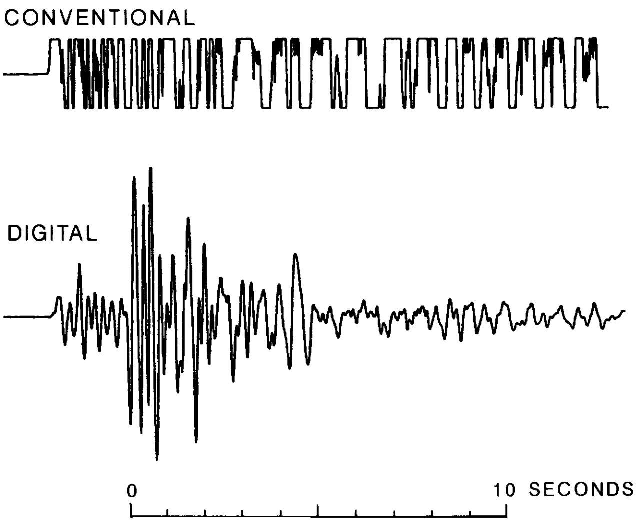


Figure 2. New digital technology offers high-fidelity recording of earthquakes. Most seismographs in operation today faithfully record ground motion over only a limited range of amplitude; seismographs capable of recording frequent small earthquakes clip the peaks and troughs of the infrequent, but more damaging, larger shocks (*upper trace*). In marked contrast to these conventional instruments are new digital seismographs that are capable of providing on-scale records of earthquakes over a wide range of magnitude and distance and over a broad range of frequencies (*lower trace*). This comparison of records from Pasadena, California, of a magnitude 4.9 earthquake obtained at a distance of only 16 km illustrates the great superiority of the digital seismograph in providing an accurate, full-scale record of the ground motion. The widespread deployment of digital seismographs would provide unprecedented detail on fault movements at the earthquake source, modification of seismic waves as they propagate through the Earth, and ground motion at the recording site. Such detailed knowledge is fundamental to improved earthquake-resistant design of structures and prudent land-use decisions in active seismic regions.

Contemporary Deformation Rates with Global Positioning System (GPS) Technology

High-precision geodetic surveying carried out since 1970 has been very successful in determining present-day crustal movements along the San Andreas fault system in California and a few regions of the Western U.S., including Alaska and Hawaii. However, this measurement program, employing ground-based laser-ranging methods and airborne measurements of atmospheric parameters along the laser-beam path is logistically complex, is carried out only by Federal agencies, and does not encompass all of the seismically active regions of the U.S.

Over the last several years, a new surveying method using measured time differences in radio signals from Earth-orbiting satellites has revolutionized geodesy and inaugurated a new era for crustal deformation measurement. This new method, the Global Positioning System (GPS), has many advantages. From an operational viewpoint, the method is logistically simpler, and the GPS instrumentation is widely available and used by scientists both inside and outside the government. The technical advantages of the GPS method include the simultaneous determination of vertical and horizontal position and a useful interstation range of hundreds of kilometers to less than one kilometer; moreover, there need not be line of sight between instrument stations. Five years of testing, field deployment, precision evaluation, and analysis software development, along with a new generation of improved and easier-to-use GPS receivers, make this field ready for rapid expansion.

The most urgent needs for GPS surveys within the EHRP are both dense local coverage in selected regions and broad regional mapping of crustal deformation throughout the seismically active parts of the U.S. Deformation rate is a factor in determining earthquake potential, and its measurement complements the geologic and historic earthquake information used to quantify the earthquake risk throughout the Nation and to provide deeper understanding of seismic potential and earthquake-generating processes. Dense areal surveys around active faults can yield estimates of fault slip rate needed for long-term probabilistic earthquake forecasting. Detection of the rates and patterns of crustal movements in active fold-thrust belts (for example, Los Angeles Basin and southern Alaska) can be applied to assess the earthquake hazard of faults that do not reach the Earth's surface.

Prehistoric Earthquakes and Long-Term Probabilistic Forecasting

Geologic studies offer a means for extending the seismic history of a region much farther back in time than recorded history, which for many parts of the

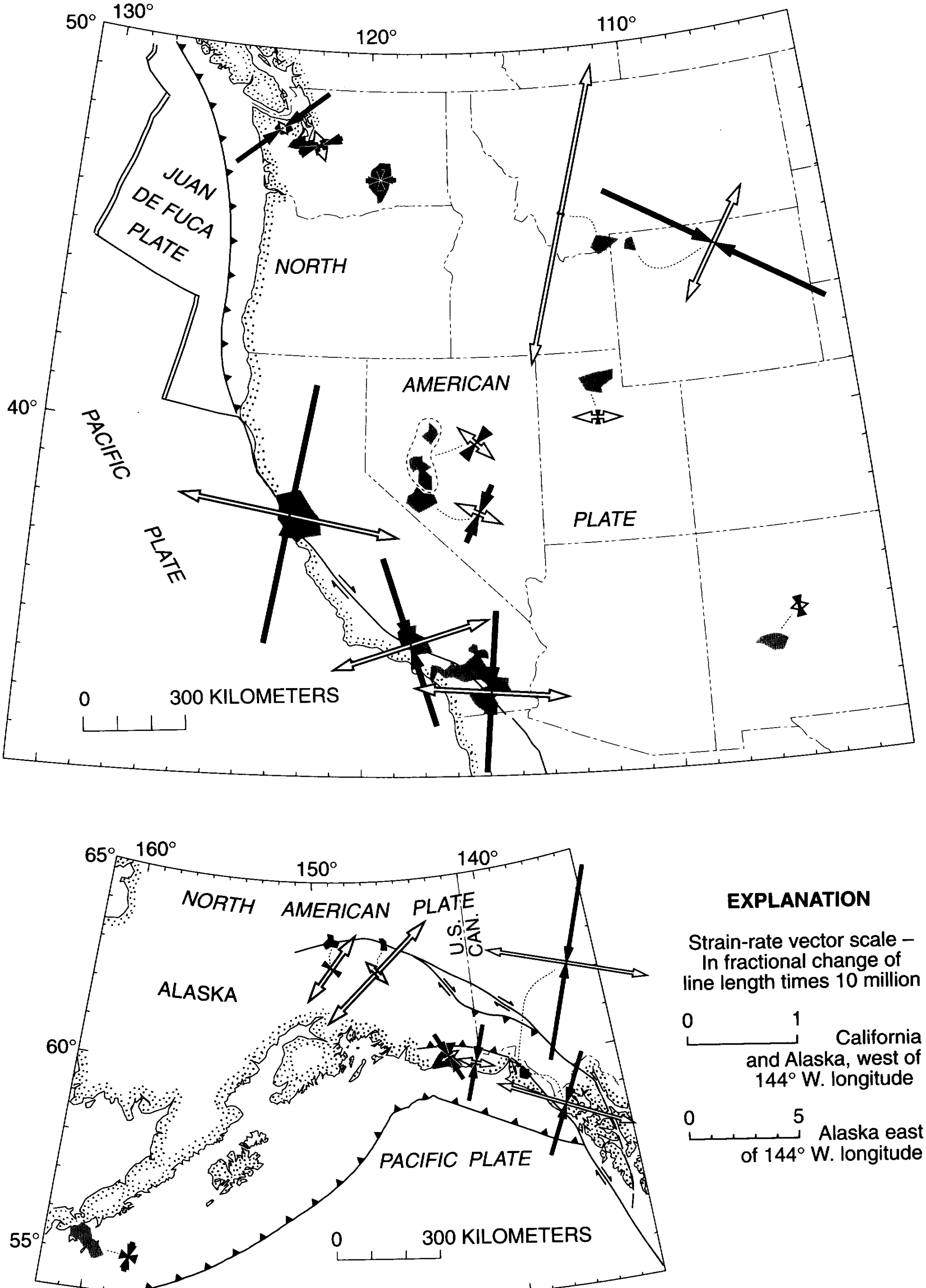


Figure 3. Repeated surveys of geodetic networks document the slow straining of the Earth that results in earthquakes. High-precision surveying in selected seismic zones throughout the Western U.S. over the past two decades documents slow deformation of the Earth associated with the accumulation of potential earthquake energy. Such energy will eventually be released in large, possibly destructive earthquakes. The arrows and their lengths indicate directions and magnitudes of principal strain rates measured for each geodetic network (*shaded polygons*). (Solid arrow, compression; open arrow, extension. Note lengths of vectors for Alaska east of 144°W. longtitude are reduced by a factor of five.) The rate of deformation determines the rate of seismic activity; more rapid deformation correlates with more frequent large events. The patterns of deformation are related to the fault slip expected in future earthquakes.

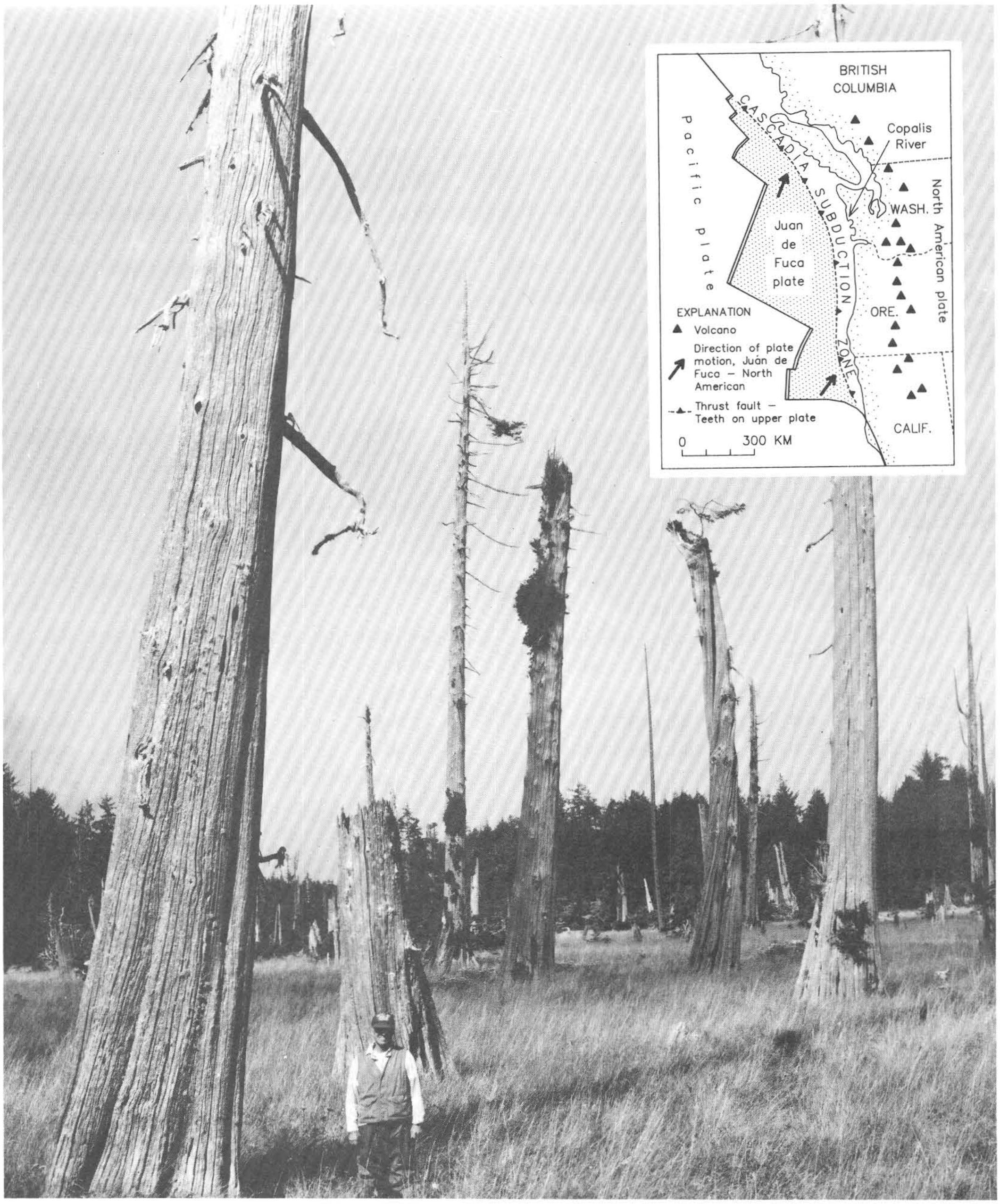


Figure 4. Ghost forest testifies to sudden subsidence in coastal Washington about 1700 A.D., probably from a great offshore earthquake. Dead trunks of western red cedar protrude through a tidal marsh along the Copalis River, western Washington. The floor of the cedar forest lies a meter below the man's feet, buried by intertidal mud. The mud indicates that the trees died when the forest floor was submerged in brackish water, most likely as a result of a few meters of coastal subsidence during a great earthquake on the shallow, mostly offshore part of the Cascadia subduction zone, where the Juan de Fuca plate is being thrust beneath the coast giving rise to the Cascade chain of volcanoes. At least two submergence episodes, recorded by buried soils here and elsewhere on the Washington coast, have occurred in the past 2,000 years. The submergence provides strong evidence for prehistoric great earthquakes in the Pacific Northwest. Ten years ago, earth scientists did not regard the Washington and Oregon coast as a likely site for a magnitude 8 class earthquake because no known shock of that size had ever occurred. However, evidence recently uncovered by studies funded by the EHRP has convinced most scientists that great coastal earthquakes have indeed occurred and that they pose a grave, previously unrecognized threat to the region.

Nation is much shorter than the recurrence interval of large earthquakes. Detailed studies of active faults and of earthquake-generated features preserved in the geologic record alone can provide information on the occurrence, timing, and size of ancient earthquakes. For example, fault studies can yield the long-term average rate of slip and, in some cases, information as specific as the date, length of fault rupture, and amount of fault offset for individual prehistoric shocks. These studies are critical data for fault-specific, long-term earthquake forecasts, such as those that are having a broad impact on hazard mitigation along the San Andreas fault system in California. With a comparable knowledge base, such assessments could be made for well-defined active fault zones elsewhere, such as the Wasatch fault zone in Utah.

Also, detailed geologic studies of tectonically raised and submerged shorelines and of shaking-induced depositional and deformational features in unconsolidated sedimentary deposits can provide information critical for deciphering the size and recurrence rate of large earthquakes. During the last decade, substantial progress has been made in defining earthquake chronologies for the past several thousand years in the Pacific Northwest, southern Alaska, and South Carolina.

Intensified geologic studies have high potential for yielding information critical to forecasting, on a probabilistic basis, future earthquake activity in several yet-unstudied regions and to refining forecasts in areas where they have been made. In the Central and Eastern U.S., dating of prehistoric earthquakes from liquefaction-induced deformational structures in unconsolidated geologic deposits (Charleston, South Carolina), identifying and dating movements related to Holocene fault scarps (Meers fault, Oklahoma), and dating prehistoric faulting events (New Madrid seismic zone, central Mississippi Valley region) have illustrated the capabilities of geologic methods for spatially defining and quantifying earthquake potential in regions of moderate or low seismic activity where surface faulting is rare or absent. In seismically active regions where prehistoric chronologies are incomplete or absent, new studies can be crucial in providing firmer constraints on the long-term hazard; for example, the Hayward fault in the eastern San Francisco Bay region ruptured in two magnitude 7 events during the 19th century, but no information is available for earlier events. Recent studies landward of plate-collision zones in the Pacific Northwest and southern Alaska have shown how deciphering the prehistoric record of episodic coastal subsidence or uplift can demonstrate seismic hazard and provide bounds on recurrence intervals for great earthquakes.

Fault-specific earthquake forecasts derived from geologic investigations, supplemented by information from historical earthquakes and constraints supplied by seismicity, fault mapping, and geodetic measurements, are highly valuable. Within the EHRP, they are useful in identifying specific regions for program focus and intensified monitoring, where additional efforts can yield high returns. More importantly, in a broader perspective, pinpointing fault segments with high earthquake probability heightens public awareness of seismic hazard, provides a rationale for allocating resources for preparedness and response activities, and permits the construction of explicit scenarios for expected earthquake effects.

The Physics of Faulting

Recent studies of fault behavior highlight a longstanding dilemma of fault mechanics but also suggest new research activities that could shed new light on the conditions controlling earthquake fault slip and resolve the dilemma. It has been recognized since the late 1950's that translation of crustal blocks on low-angle faults over large distances requires the presence of seemingly extraordinary conditions on the fault itself. The great pressure exerted on the surface of a buried, low-angle fault by the weight of the overlying rock mass acts to resist slip on the fault. For slip to occur, either the stress causing slippage must be extremely high (perhaps unrealistically so) or some mechanism is required to weaken the fault and thereby permit slippage with a smaller driving stress.

With vertical strike-slip faults the same difficulty arises, and other data emphasize the dilemma. If the stress resisting fault slip were high, then substantial frictional heat should be generated by fault slippage and appear as a conspicuous excess flux of heat near major faults. However, more than two decades of measurements of near-surface heat flow across the San Andreas fault have failed to uncover any evidence for a heat flow anomaly, apparently suggesting low resisting stresses. At the same time, laboratory experiments on simulated faults, in situ stress measurements in the upper few kilometers of the crust, and theoretical models of fault failure all suggest that high stresses are required to move major faults and these studies have supplied no compelling mechanism for fault weakening. Such is the paradox!

New data from studies in California provide further evidence bearing on this major unresolved issue. Borehole geophysical data and earthquake fault-plane solutions suggest that maximum compressive stresses are oriented nearly perpendicular to the San Andreas fault, implying that resistive stress on the fault is quite low. Furthermore, borehole measurements of stress and heat flow to depths of 3.7 km beneath Cajon Pass near the San Andreas fault in southern California (see figure 5) indicate low stress and normal heat flow at near-seismogenic depths. Thus, two further independent lines

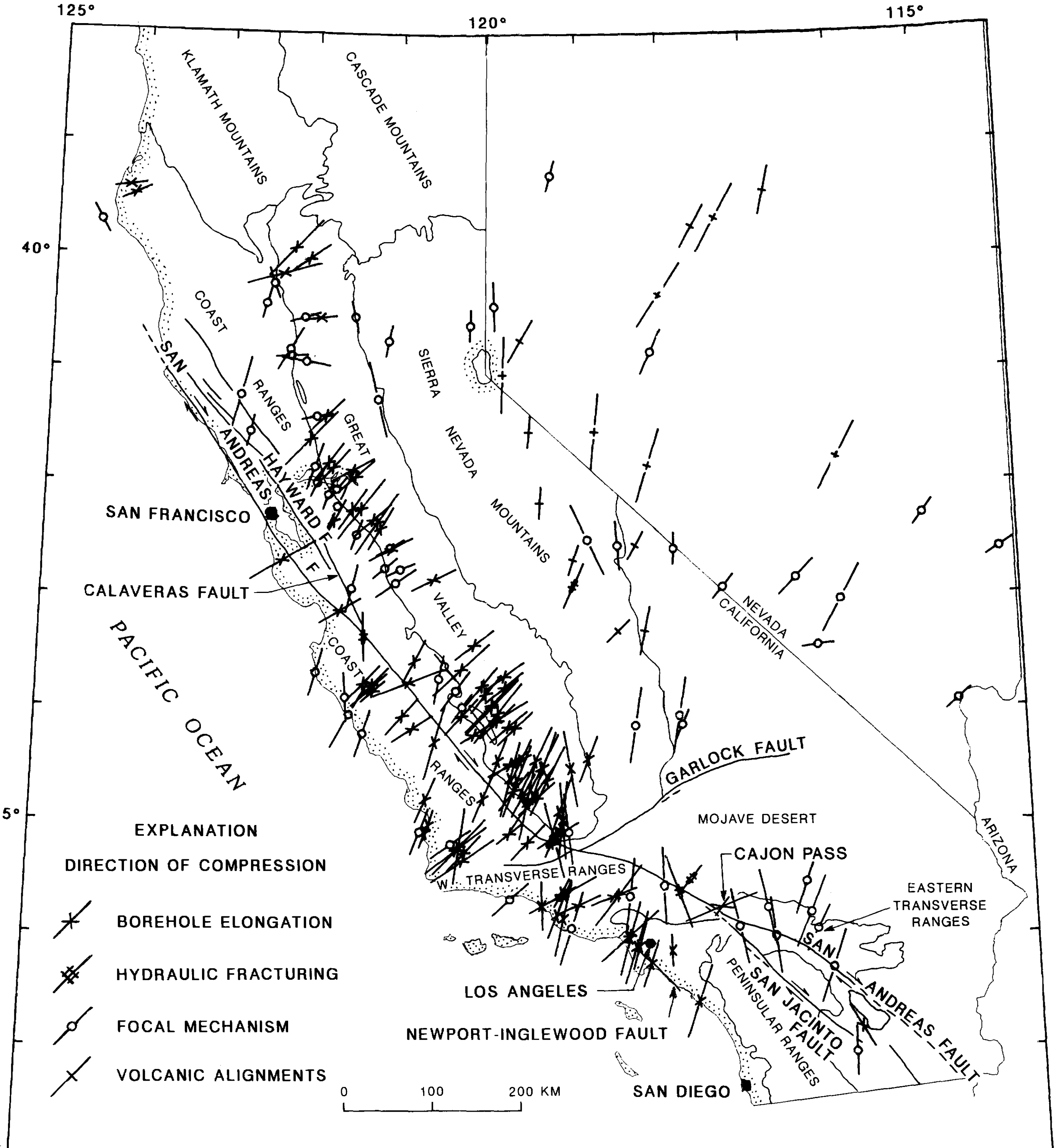


Figure 5. Direction of crustal compression in California suggests San Andreas fault system is very weak. When the inferred direction of maximum horizontal compression in the shallow crust tends to be nearly perpendicular to the trace of a vertical fault, slip on the fault is inhibited unless it is very weak and thus able to slip under low applied shear stress. This seems to be the case for the San Andreas fault system in central California. The directions of compression are inferred from measurements of borehole deformation and hydraulic fracturing of boreholes, from focal mechanisms of numerous small and moderate earthquakes adjacent to the fault system, and from alignments of young volcanoes (eastern California and Nevada).

of evidence support the low-stress alternative, suggesting the importance of investigating the little-studied matter of fault weakening and determining conclusively the stress-slip behavior of seismogenic faults.

Such investigations require laboratory and theoretical studies of fault behavior and field investigations of seismogenic fault zones. High fluid pressures confined within a narrow fault zone or low friction on the fault surface could reduce shear resistance to fault slippage. Further laboratory rock-mechanics studies are needed to establish the mechanical behavior of rocks and minerals that slip under low driving stresses. The implications of fluid pressures that approach the confining pressures exerted by overlying rock need to be explored theoretically, in the laboratory, and in situ. Finally, resolution must be sought by direct observation in active fault zones, by studying exhumed faults, by indirect probing of fault zone properties using seismic and electrical methods, and by carefully planned scientific drilling in a few well-studied areas.

PROGRAM GOALS AND OBJECTIVES

Although the mission of the EHRP is unchanged from previous years, its goals and objectives are reformulated to reflect current ideas about promising avenues of research, the critical need for integrated and coordinated multidisciplinary research, and the important role of researchers in transferring technical knowledge to those charged with hazard mitigation. The redefined goals and objectives are listed not in order of importance or priority but in a logical context, starting with the goal of improved physical understanding of earthquake origins and progressing to determining earthquake potential, predicting geologic effects of earthquakes, and finally transferring hazard information and hazard-assessment methods to would-be users.

Goal I. Understanding the Earthquake Source

Why and how earthquake faulting occurs are fundamental questions for the EHRP to address. Answers to these questions would provide a firm base of scientific understanding for developing effective and reliable hazard-reduction measures. Without such knowledge, approaches to earthquake hazard assessment must be empirical and phenomenological. These approaches are useful when they are firmly tied to reliable observational data sets. When data are lacking or unreliable, however, the value of these approaches is limited. In such situations, hazard assessments necessarily rely on imperfect, idealized models of the earthquake source to evaluate the potential effects of future shocks.

Progress toward understanding the earthquake source is measured through the formulation and validation of conceptual and quantitative models. The process of model building and testing draws heavily on seismological, geodetic, and geological data, whose acquisition is justified under other program goals and incorporates field, laboratory, and theoretical studies specifically focused on earthquake source processes, which are justified under this goal. For example, stress-induced slip on fault surfaces in frictional contact can be studied using the methods of laboratory rock mechanics, simulating the properties of active crustal fault zones; the effects of pressure, temperature, rock type, and fluid pressure and flow can also be explored in these experiments, and the bulk properties (elastic moduli, strength, permeability, porosity) of the surrounding rock mass can be determined as well. In addition, in situ measurements of stress, temperature, fluid state, and rock type can be applied to test and constrain both laboratory and theoretical modeling of fault failure. Realistic earthquake-source models must also incorporate the effects of geometrical complexity of fault surfaces, heterogeneity in material properties, and interaction among the elements of the network of faults that characterizes most seismically active regions.

The results of such syntheses of field, laboratory, and theoretical studies have widespread applicability to a range of issues within the EHRP. For example, the character of strong ground motion depends on properties of the fault surface, material and geometrical heterogeneities within fault zones, and the physics of rupture propagation. Also, long-term earthquake forecasting depends on the mechanics of recurrence and the factors influencing recurrent behavior. In addition, understanding of fault failure helps define appropriate monitoring strategies for intermediate- and short-term earthquake prediction in intensively instrumented areas.

Objective I-1: Determine the Physical Properties and Mechanical Behavior of Active Fault Zones and Their Surroundings

The composition and constitutive properties of fault-zone materials as well as the surrounding medium and the pressure, temperature, and fluid-state conditions at seismogenic depths must be known in order to constrain laboratory and theoretical analogs of faulting. Studies of exhumed faults can provide clues to mechanics and material properties, and indirect methods for probing fault-zone properties with surface measurements can be used to determine structure and thermomechanical behavior. However, direct measurements of in situ properties are ultimately required to resolve outstanding ambiguities (see section "The Physics of Faulting") and provide the constraints required to define relevant parameters for laboratory experiments and fault modeling.

Tasks:

- •Undertake geologic studies of exhumed fault zones to infer structure, composition, pressure/temperature conditions, and mechanical behavior.
- •Carry out seismic and other geophysical surveys (for example, thermal, electrical, magnetic, gravity) to remotely determine fault-zone properties, including rheological, frictional, and hydrologic properties.
- •Undertake scientific drilling to directly sample and measure in situ properties.
- •Conduct laboratory rock mechanics experiments on simulated faults using field constraints on relevant fault-zone properties.
- •Undertake induced-seismicity studies as a means of determining effects of loading and fluid pressure on fault failure.

Objective I-2: Develop Quantitative Models of the Physics of the Earthquake Process

Understanding of the earthquake process is codified in quantitative models from which the occurrence and source characteristics of future earthquakes can be predicted. Because of their predictive capabilities, quantitative models of the earthquake process are fundamental to fully reliable hazard-reduction strategies. The earthquake process needs to be modelled on two time scales: a long-term scale commensurate with the slow buildup of crustal strain, and a short-term scale commensurate with the sudden release of stored crustal strain in a seismic faulting episode.

The process of strain energy buildup and seismic energy release, inclusively termed "the earthquake cycle," consists of a long interval of slow elastic deformation and stress increase in the Earth's crust adjacent to an active fault and the abrupt release of this accumulated stress by sudden fault slip in an earthquake. Understanding of the long-term stress buildup and the governing criteria for fault failure bears importantly on estimating earthquake potential of specific faults, and fundamental knowledge of the processes that lead up to and immediately precede fault failure is central to developing methods and defining monitoring strategies for short-term earthquake prediction. Because earthquake-prone regions usually contain not just a single fault but rather a complex system of parallel and intersecting faults, the physical and dynamic interactions among the elements within a fault system is a complexity in the earthquake process that begs understanding.

The dynamic features of sudden fault slip determine the character of strong ground motion, which is the principal destructive effect of earthquakes. The amplitude, duration, and frequency content of this motion depend on earthquake source dynamics and in turn determine the response of manmade structures. Hence, estimation of strong ground motion requires knowledge of slip on a fault as a function both of position on the buried fault surface and of time. Slip information is derived from the analysis of both local (strong motion) and distant (regional and teleseismic) seismograms after the observed waveforms are corrected for the modulating effects of propagation between source and receiver. Such analyses help constrain generalized models of rupture

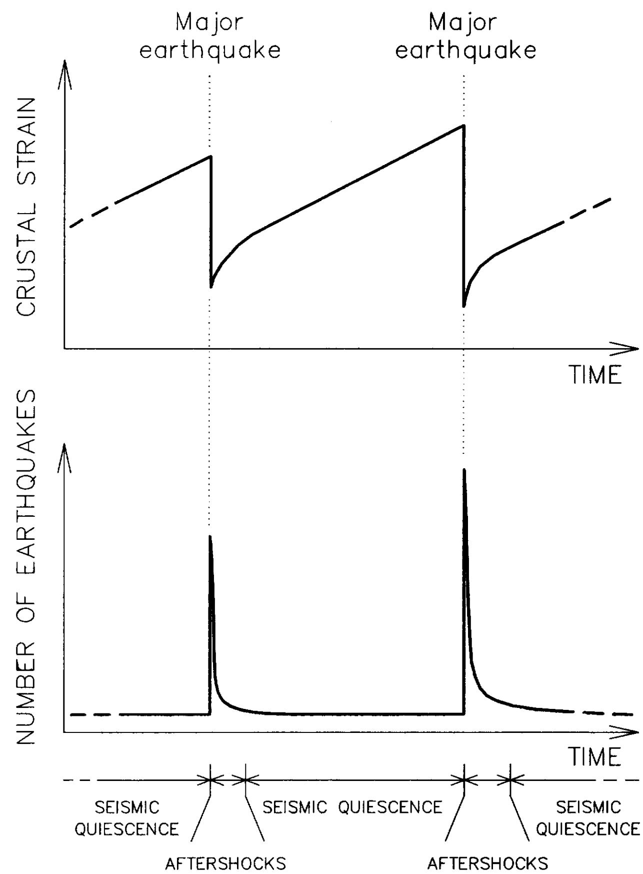


Figure 6. Earthquakes are a repetitive process involving slow straining and sudden failure of the Earth. Earthquakes result from the slow elastic straining of the Earth's crust followed by sudden failure of the crust manifested in slip on a fault. This sequence of events repeats many times over millennia. The concept of the *earthquake cycle*, schematically illustrated here, refers to the repetitious accumulation and release of strain in crustal rocks. On an individual fault segment, there is little or no earthquake activity during most of the interval of slow strain accumulation between major earthquakes. In some cases, significant earthquake activity precedes the major shock. Practically all the stored elastic strain energy is released by fault slip during the major earthquake. A rapidly diminishing flurry of earthquakes, known as aftershocks, follows the main earthquake and reflects the readjustment of stresses in the crust following the major episode of fault slip. A short-term phase of rapid straining that persists for a period of years also follows the main earthquake.

propagation, as well as specific models for individual faults or fault segments. Generalized models, in turn, can be applied to predict the source characteristics of earthquakes on faults or fault systems for which such information is lacking.

Model formulation depends on observational data, and the laws of physics determine details of mechanical behavior of a single fault and of interactions between faults. Predicted effects can be compared with observations of crustal deformation, seismicity, earthquake-recurrence patterns, and seismic waveforms to test models and suggest iterative improvements. New measurements can be geared to both increase the inventory of empirical observations and to provide critical tests of candidate physical models.

The development of physical models will contribute directly to the design of long-term earthquake forecasting and focused monitoring experiments, and data from these activities will in turn feed back into model building and evaluation. Typically, long-term forecasts depend critically on idealized earthquake recurrence models, and the fundamental basis of these models requires investigation and testing against seismic, geologic, and geodetic observations. The intermediate- and short-term fault behavior prior to rupture predicted by earthquake-instability models will contribute to defining focused monitoring strategies, and data from dense instrumental networks will provide further model tests.

Tasks:

- Develop generic physical models of the complete earthquake cycle and of fault interactions and test against relevant seismic, geodetic, and geologic observations.
- Develop methods for deriving slip information from seismic waveforms, accounting for wave propagation effects, and apply to existing seismic data sets.
- Determine general features of rupture for generic and fault-specific dynamic models.

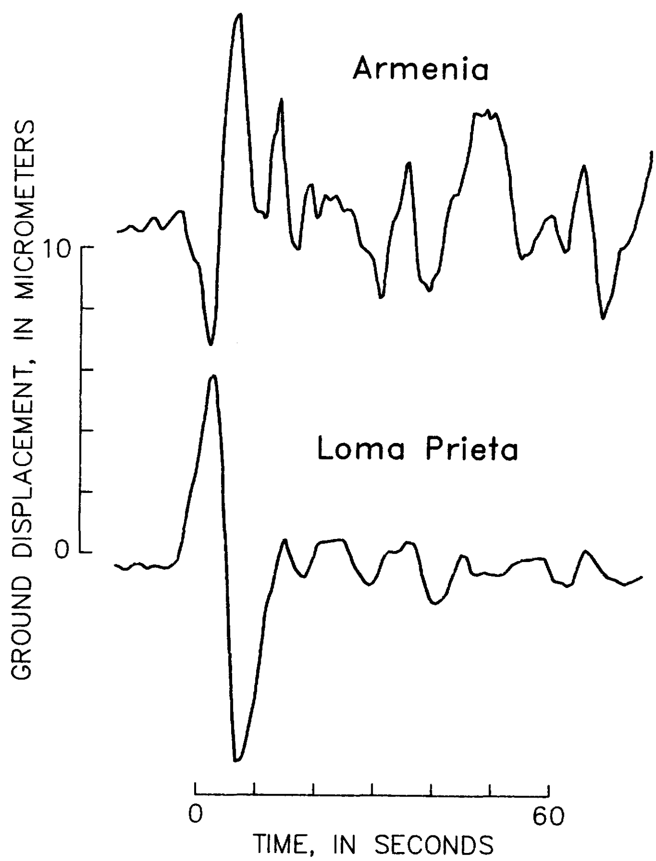
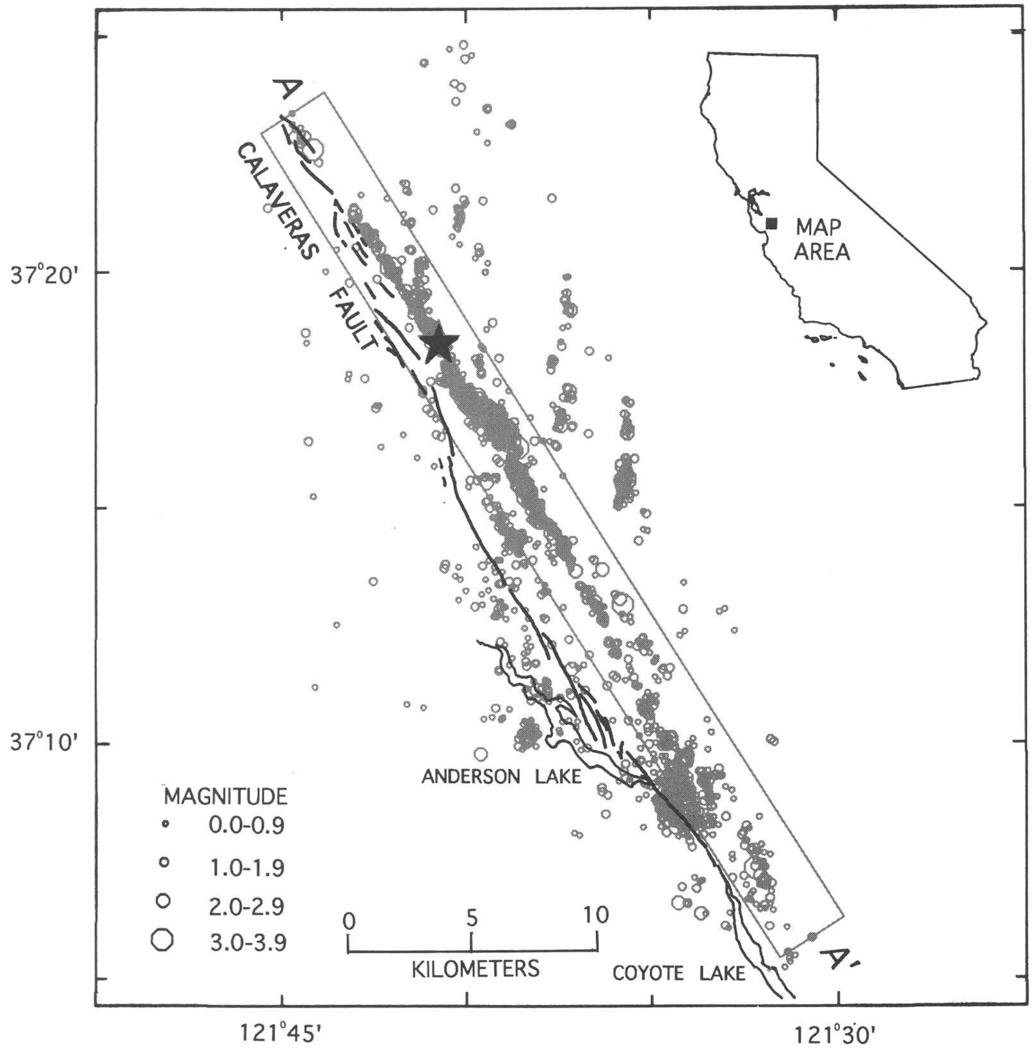


Figure 7. High-fidelity seismograph records yield detailed information on fault motion at the earthquake source. Seismic waves convey considerable information about fault slip, even those waves recorded at great distances. These digital records of *P*-waves from the 1989 Loma Prieta, California (magnitude 6.9), and 1988 Armenian (magnitude 6.7) earthquakes, both written at Harvard, Massachusetts, exhibit marked differences although the events are about the same magnitude. The simple, short-duration waveform for the Loma Prieta event contrasts markedly with the complex, extended motions for the Armenian shock, which continued for more than a minute. The duration of strong ground motion near the source influences the amount of ground failure and structural damage. Had near-source ground motion in the Loma Prieta earthquake persisted as long as it did in the Armenian shock, losses in the San Francisco Bay area would have been considerably greater.

Figure 8. Better understanding of the earthquake process promises more reliable assessment of earthquake hazards. ▶ Recent research suggests that patterns of small frequent earthquakes can be used to pinpoint patches on individual faults where maximum slip will occur during future large earthquakes, and hence where maximum seismic energy will be released. This figure compares the distribution of slip on the Calaveras fault during the magnitude 6.2 Morgan Hill, California, earthquake of 1984 (whose focus, or origin, is shown as a star) to the pattern of seismicity for the 6 months following the earthquake. As seen in map view (*upper*), the aftershock foci (circles) form a complex pattern, dominated by a north-northwest-trending linear belt of epicenters, which defines the primary fault. In the vertical section oriented along the fault (*lower*), the slip in the mainshock (contoured in 20-cm intervals) is superposed on the pattern of aftershocks originating within the 3-km-wide box shown in the map. Few aftershocks occurred where the slip was greatest; rather the aftershock activity tends to surround patches of high slip. The seismicity of the preceding 15 years reveals a similar pattern. These results suggest that stuck fault patches, which are likely to slip only in larger earthquakes, can be defined from detailed patterns of background seismicity; such patches are likely to generate particularly damaging levels of ground motion. The information in this example derives from various seismograph networks: fault slip was calculated from strong-motion seismograms recorded close to the fault and from distant seismograms recorded by stations of the Global Digital Seismograph Network, whereas earthquake foci were determined from data recorded by the regional Northern California Seismograph Network.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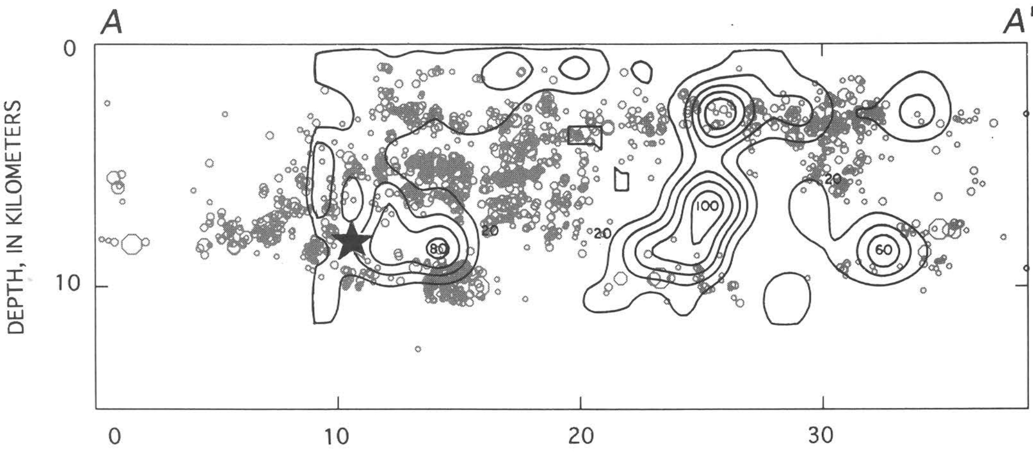
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Goal II. Determining Earthquake Potential

Determining the likelihood and characteristics of future earthquakes is a basic component of the EHRP and involves defining and characterizing potential earthquake sources and source regions, determining rates of seismic activity, and establishing the state of each source within its earthquake cycle. These broad objectives determine the kinds of investigations outlined under this goal. Many of these activities utilize concepts of the nature of the earthquake source developed under goal I, and the results obtained under this goal provide information needed for predicting earthquake effects (goal III).

The objectives and activities outlined here concern a broad range of area and time. At one end they include regions as large as several States and time measured in hundreds of thousands of years; at the other extreme they relate to features as small as a single fault and a time scale as short as a few minutes, as in the case of a short-term earthquake prediction. The objectives under this goal are organized into three general categories that reflect the primary emphasis of each group of objectives: geologic-framework studies and regional earthquake potential, local earthquake potential and fault-specific earthquake forecasting, and earthquake prediction and focused monitoring experiments.

Geologic-Framework Studies and Regional Earthquake Potential

To improve estimates of the earthquake threat throughout the U.S., this group of objectives focuses on improving understanding of the factors that determine when and where earthquakes occur. These objectives are directed at characterizing entire tectonic domains or regions encompassing complex systems of actively deforming geologic structures.

Estimating regional earthquake potential incorporates geological and geophysical information portraying the structural and tectonic setting, historical and instrumental records of seismicity, and geologic and geodetic data describing the patterns and rates of deformation of the lithosphere. Integration of these data provides a basis for defining regions of similar seismic potential within the U.S. and for estimating the likelihood and maximum magnitudes of earthquakes within those regions. The data and concepts derived from these studies of regional geologic framework also provide a foundation for preparing national and regional maps of ground-shaking hazard and a context for forecasting earthquakes on individual faults.

Objective II-1: Determine the Geological and Geophysical Setting and Characteristics of Seismically Active Regions

The relationship between seismicity and geologic structures is clear in some areas with high rates of localized deformation, such as along parts of the San Andreas fault in California and in some areas of the Western U.S. where large historical earthquakes have produced surface faulting. However, throughout vast regions of the U.S., and particularly in the Central and Eastern U.S., there commonly is no clear association between surface geologic structure and earthquake epicenters. Integrated analysis of geological mapping and geophysical and geodetic surveys is needed to develop an understanding of factors responsible for localizing the seismicity in such areas. Increased emphasis should be placed on regional studies of the geomorphic and stratigraphic evidence of Quaternary deformation to expand the data base on types of tectonic settings that have been active in the recent geologic past and on rates of deformation on various types of structures in different tectonic regimes.

Because seismicity may migrate and cluster with time, use of the relatively short historical and instrumental record of seismicity may give an incomplete picture of the long-term earthquake potential of a region. More certain estimates require both an understanding of geological processes and factors that control patterns of seismicity in space and time as well as knowledge of the nature of temporal variations in seismicity. Geological studies to characterize and date prehistoric earthquakes (commonly referred to as paleoseismology) provide a means of extending the record of earthquakes beyond that provided by instrumental or historical records and should be a major component of regional framework studies.

Earthquake-prone regions typically comprise complex patterns of fault-bounded crustal blocks that move with respect to each other and in some cases deform internally. Sudden slip between blocks results in an earthquake. Over the last decade, there has been considerable progress in defining crustal blocks in several active seismic regions from accumulating geologic, geodetic, and seismological data. However, little is known about the forces acting on individual crustal blocks and, in particular, about the importance of stresses acting on their edges relative to basal stresses arising from deformation or movement of the substrate on which they rest.

The information acquired and evaluated under this objective should be compiled in a digital data base that would also support other components of the EHRP. For example, information collected to study the geological factors responsible for localizing seismicity would also aid evaluation of regional and local earthquake hazards. Data are most likely to be compiled under focused regional and local geological framework studies; however, the need for integrated data compiled on a national scale requires a comprehensive, readily transferrable data base that can be utilized and updated by scientists

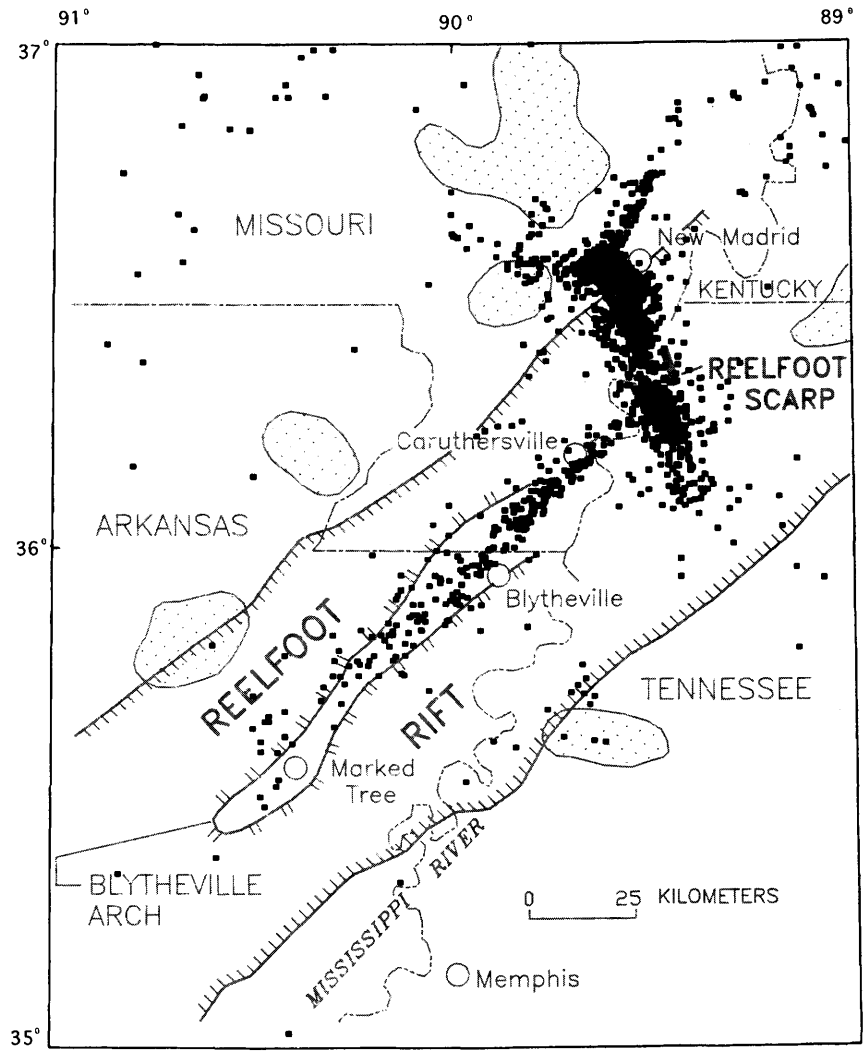


Figure 9. Discovery of buried rift under the Mississippi Valley helps explain origin of great earthquakes. The New Madrid seismic zone in the central Mississippi Valley was the site of a series of major earthquakes in 1811–1812, perhaps the largest known to have occurred in a stable continental interior. Until recently, the earthquakes were not linked to any recognized geologic structure. Aeromagnetic and seismic-reflection data now show that the recent earthquakes (solid squares) concentrate along a buried rift, 60-km wide by 300-km long. The rift formed at least 500 m.y. ago, and the downdropped block of crust in the rift is now deeply buried by younger rocks and sediment. The fault-bounded, downdropped block lies between the single-hachured lines on the map, which shows major geologic structures and recent earthquakes in the most active part of the New Madrid seismic zone. The linear trend of earthquakes between Marked Tree and Caruthersville coincides with the Blytheville arch (double-hachured line), a buried, uplifted belt of sedimentary rocks that were deposited in an ancient basin along the rift axis. Detailed geologic investigation in a trench excavated across the Reelfoot fault scarp, within the margins of the rift, found evidence of two prehistoric earthquakes at that site in addition to the 1811–12 earthquakes. These results indicate that three earthquakes have ruptured this fault within the past 2,000 years, which yields a recurrence interval estimate of 600 to 900 years for this particular fault. High-resolution geophysical surveys and detailed geological studies are still needed to refine the history of prehistoric earthquakes in the New Madrid seismic zone and to define relationships between seismicity and such features as buried igneous plutons (patterned areas), deep basins, fault zones, and rift boundaries.

from diverse and largely independent research projects. Such an integrated data base, using Geographic Information System (GIS) technology, will also provide readily accessible information for regional earthquake-hazard assessment and will expedite production of a variety of maps at different scales and with various types of information.

Tasks:

- •Collect and synthesize geological and geophysical data in seismically active regions and in regions that show geological evidence of earthquakes in Holocene or late Quaternary time to define the three-dimensional geological structure and properties of the crust and lithosphere and the nature of late Quaternary deformation.
- •Investigate the mechanisms by which crustal blocks within active seismic regions move and deform.
- •Assemble and maintain an integrated national digital data base of geological and geophysical information at a regional scale.

Objective II-2: Determine the Occurrence, Distribution, and Source Properties of Earthquakes and Relate Seismicity to Geologic Structures and Tectonic Processes

Monitoring seismicity provides fundamental data for all aspects of the EHRP, ranging from increasing public awareness about the earthquake threat, to preparation of probabilistic seismic shaking maps for building code applications, and to research on earthquake mechanics, tectonic processes, and earth structure. Recordings from seismograph networks provide basic measures of seismicity, including the origin times, locations, sizes, focal mechanisms, and occurrence rates of earthquakes. Modern digital seismograph networks also yield data on characteristics of the earthquake rupture process, a critical ingredient for predicting earthquake effects. Fully computerized data processing allows nearly instantaneous determinations of size, location, and spatial extent of large earthquakes; such information is valuable for tsunami warnings and for responding to earthquake disasters and promptly implementing recovery measures.

Earthquakes are recorded by a variety of complementary seismograph networks, each designed to provide instrumental data relevant to a particular class of problems and range of earthquake size. The global seismograph network provides information about large earthquakes worldwide and global tectonic processes; the national network provides information on earthquakes large enough to cause damage or to be felt; and regional networks focus on the more abundant small shocks, the study of which are vital to fault-specific earthquake-hazard assessment. Historically, limitations in instrumentation have contributed to the evolution of separate networks, but this factor is disappearing with emergence of new digital technology (see section "Modern Technology for Seismograph Networks"), which permits high-fidelity recording of seismic signals over a broad range of earthquake magnitude.

The global monitoring of earthquakes should continue as a small but vital part of the EHRP. The global seismic record is important to the U.S. because the time between damaging earthquakes in most high-risk areas of the Nation is long relative to the recorded history. Accordingly, one must turn to the global record to observe phenomena that are not incorporated in the limited U.S. earthquake history and to obtain instrumental recordings of earthquake types and magnitudes whose occurrence in the U.S. predates the instrumental record.

The USGS, with major support from the Nuclear Regulatory Commission for the Eastern and Central U.S., is in the early stages of installing the U.S. National Seismograph Network, which, when fully implemented, will monitor the entire U.S. with broadly spaced, high-fidelity digital instruments linked to a central analysis facility by real-time, satellite telemetry. This network will provide the national capability for rapid, automated detection and location of shocks large enough to be felt by many people—larger than about magnitude 3.5—and for determination of focal mechanisms for shocks approaching the threshold of minor damage, about magnitude 4.5. The high-quality digital data can also be used to determine large-scale regional variations in attenuation of seismic waves and to investigate the effects of propagation path on seismic waves.

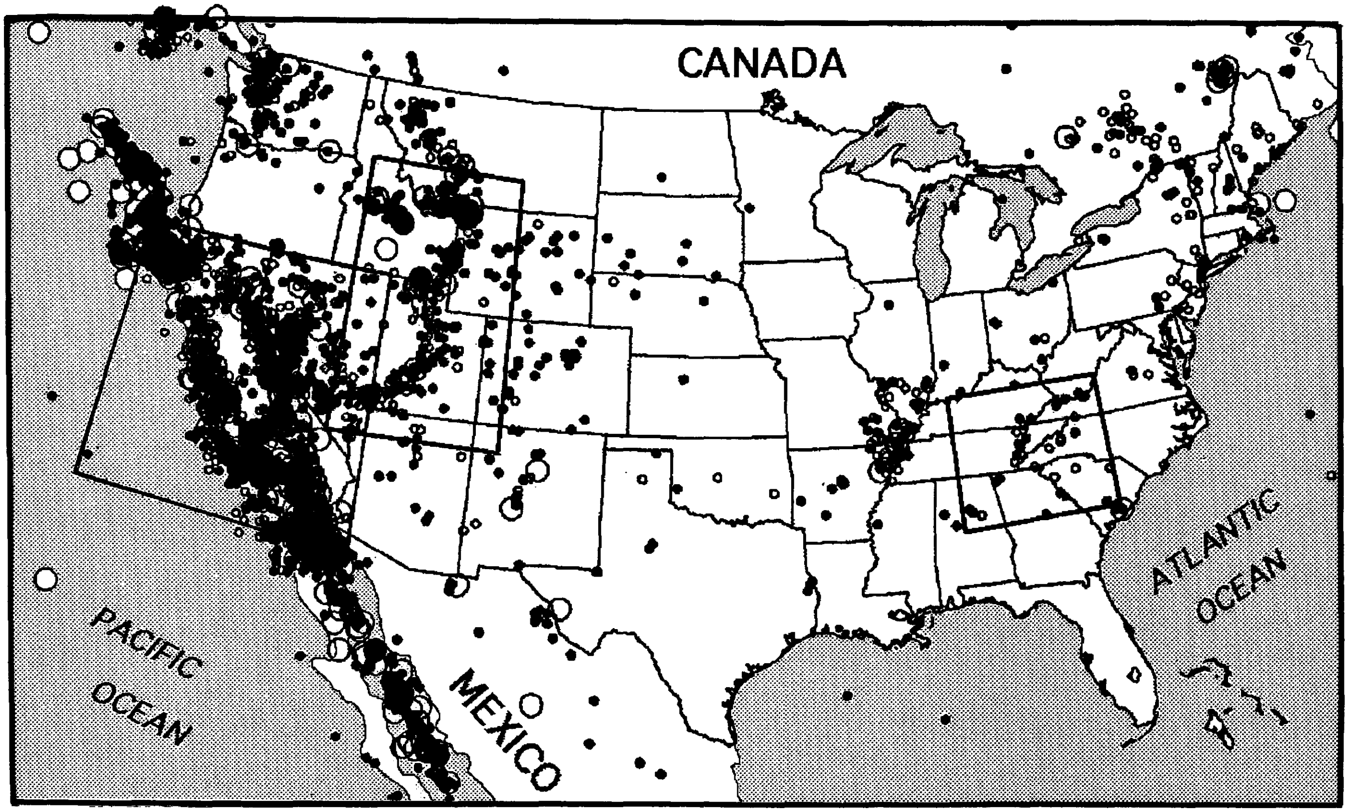
Regional seismograph networks are a necessary supplement to the national network and support more precise and detailed investigations of seismicity using the many shocks too small to be adequately recorded by the widely spaced stations of the national network. Regional seismicity data provide the primary data set for defining seismically active and inactive areas, as well as the patterns of seismicity within active areas, and yield information about tectonic stresses and processes operative within a seismic zone. Continuous monitoring provides a means of detecting changes in the pattern and characteristics of seismicity with time. Of particular importance to this objective are detailed, comprehensive records of seismicity, which provide a basis for relating earthquakes to subsurface geologic structures and to tectonic stresses and the modern deformation field.

Tasks:

- •Operate and maintain regional, national, and global seismograph networks to determine earthquake locations, seismicity levels, and earthquake source characteristics.
- •Improve methods for deriving information from seismograms on earthquake source characteristics and on earth structure.
- •Investigate seismic wave propagation and attenuation in realistic earth models.

•Analyze earthquake data to relate seismicity to geologic structures, to ongoing tectonic deformation, and to physical processes operative within the Earth.

•Operate the National Earthquake Information Center and implement complimentary regional earthquake information centers to collect, assemble, and



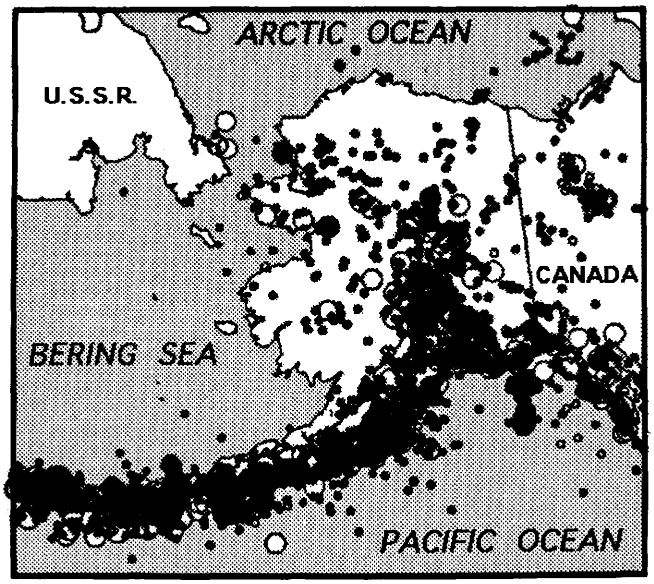
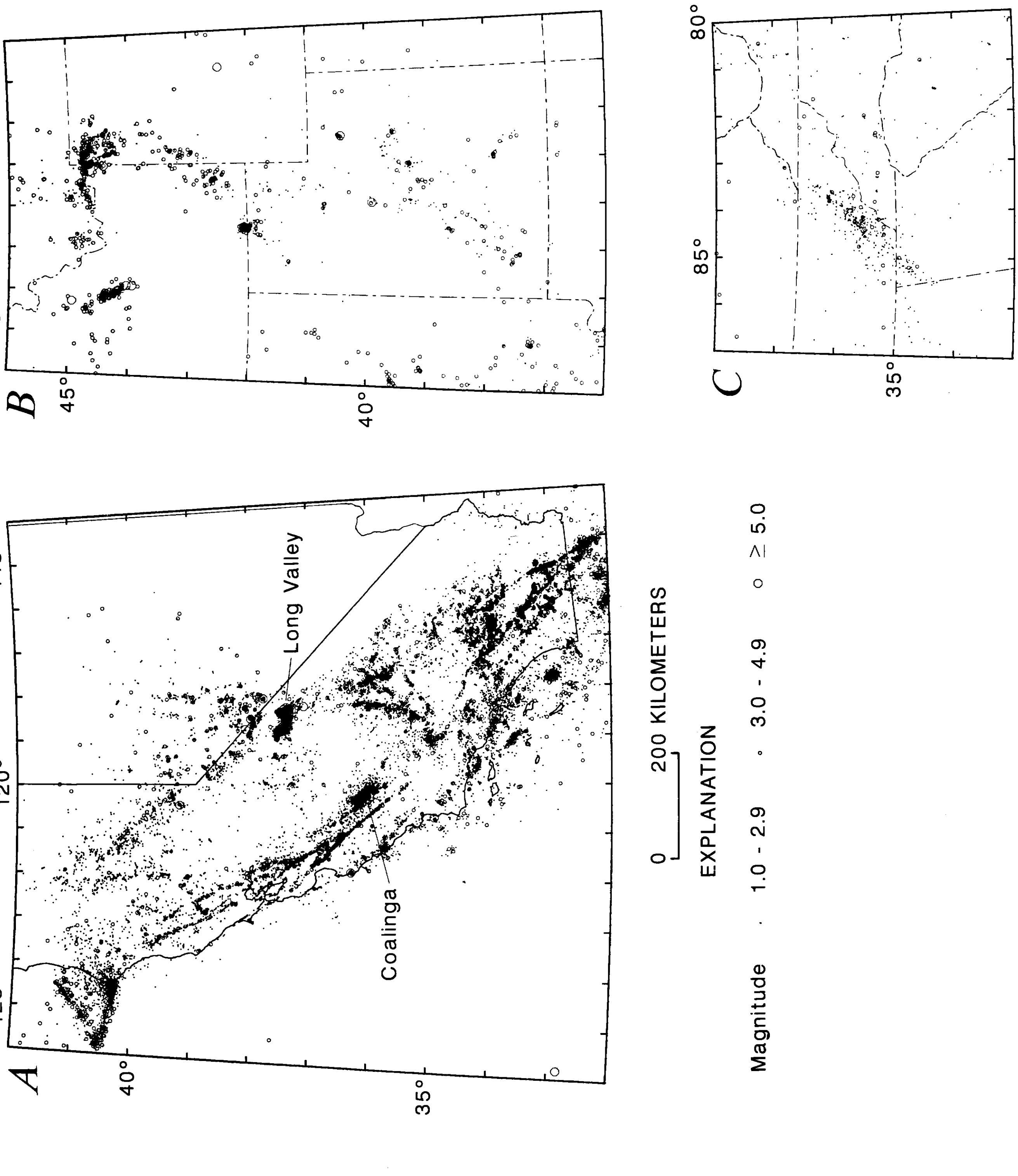


Figure 10. Few States are unaffected by earthquakes. Knowledge of the distribution of earthquakes derives from both historical accounts of earthquakes and, for the last several decades, from seismograph records. Earthquake activity concentrates in the Western U.S. and Alaska and reflects deformation along the boundary between the Pacific and North American plates. Most, but not all, of this deformation is localized along the Pacific coast; significant deformation extends inland several hundred kilometers into the continent. Large earthquakes also occur in the Central and Eastern U.S. The origins of these earthquakes are much less certain and are an important topic of research. Earthquakes shown are shallower than 50 km. Closed circles denote epicenters since 1962 for the conterminous U.S. and since 1968 for Alaska; open circles denote epicenters of earlier earthquakes determined from historical accounts or instrumental records. Large circles denote magnitude 6.0 or larger; small circles denote magnitude 4.0 to 5.9. The recent epicenters are more accurate. Boxes refer to areas shown in figure 11.



A
B
C
125°
120°
115°
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45°
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Long Valley
Coalinga
0 200 KILOMETERS
EXPLANATION
Magnitude · 1.0 - 2.9 ∘ 3.0 - 4.9 ○ ≥ 5.0

distribute earthquake data and information within high-risk seismic regions.

Objective II-3: Determine the Nature and Rates of Crustal Deformation

The rates and spatial distribution of current tectonic deformation can be determined from repeated geodetic surveys. Geodetic measurements complement seismic and geologic observations and can be used to infer fault slip rates and constrain mechanical models of the deformation process. At present, the EHRP particularly needs mapping of the contemporary deformation field in many unsurveyed regions, especially where there are existing seismic networks in subduction zone environments (southern mainland Alaska, the Aleutian Islands, Washington, and Oregon) and in the Inter-mountain seismic zone (Montana, Idaho, Wyoming, Utah, and Nevada), as well as in regions of low current seismicity with geologic or historical evidence of past activity. In many regions of the Central and Eastern U.S. the combination of seismic, geologic, and geodetic information may be crucial in defining active source zones for regional seismic zonation. Surveys of closely spaced benchmarks and (or) temporal monitoring are also important in regions where current fault slip rate information is needed or where earthquake prediction experiments are concentrated. All of these activities will be greatly facilitated in the future by the increased use of GPS technology for geodetic surveying, which makes high-precision field measurements less technically demanding and more cost effective.

Mapping the present-day deformation field in seismically active regions is basic to understanding regional tectonic framework and the earthquake-generating processes. It provides a guide to relative levels of long-term seismic activity, and in the absence of ongoing seismicity (for example, seismic gaps) it supplies an independent measure of earthquake potential. Information on fault slip rates can often be extracted from survey measurements and is one of the fundamental parameters required for long-term forecasting.

Tasks:

- Establish geodetic survey networks in areas of active deformation and seismicity.
- Continue geodetic monitoring in regions of identified high seismic potential.
- Expand or densify selected geodetic networks to obtain broader and more detailed spatial resolution of the deformation field, especially to obtain better fault slip-rate estimates.
- Survey the most seismically active regions in the Central and Eastern U.S. to determine whether detectable contemporary deformation is taking place.
- Explore new methods of measuring crustal deformation and fault slip rates.

Figure 11. Investigations of small earthquakes advance understanding of the origins of earthquake activity and the potential of future damaging shocks. Over the past two decades, regional networks of tens to hundreds of seismographs have provided a wealth of new information of unprecedented detail in several seismic regions throughout the U.S. Such information has supported rapid advances in delineating buried earthquake-generating structures, in identifying active faults and assessing their earthquake potential, in understanding the localization of slip on a fault during an earthquake, and in resolving the active geologic processes responsible for earthquakes. This figure compares epicentral patterns of recent earthquakes for three areas of the conterminous United Sates monitored by regional seismograph networks. *A*. In coastal California, south of 40° N. latitude, several segments of the major vertical faults that compose the primary plate boundary, such as the San Andreas fault, are sharply defined by well-aligned concentrations of earthquakes. Not all the seismicity is concentrated along the coast. Earthquakes shown are from California and western Nevada for 1980 through 1986 and are larger than magnitude 1.5. *B*. In the Intermountain region, earthquakes are not as numerous, their epicenters are more diffuse, and commonly the earthquakes are not clearly associated with known faults or other geologic structures visible at the Earth's surface. Earthquakes shown are larger than magnitude 2.5 from 1974 through 1985. *C*. East of the Rocky Mountains, the general rate of earthquake activity is lower than in the West, and the relationship of earthquakes to geologic structures is more poorly understood. However, alignments of small to moderate earthquakes, such as that documented in eastern Tennessee, suggest the presence of major active tectonic structures. Earthquakes shown are larger than magnitude 1.0 from 1977 through 1989.

Objective II-4: Characterize the Earthquake Potential of the U.S. on a Regional and National Basis

Synthesis of data collected under objectives II-1, II-2, and II-3 will improve our evaluation of the potential for damaging earthquakes throughout the U.S. by providing estimates of the rate of earthquake occurrence and the maximum expected magnitudes for different tectonic regions. Offering an overview of the earthquake hazard level throughout the country, these estimates furnish information needed for setting NEHRP priorities and making decisions on the allocation of resources. The data are also needed for construction of national and regional hazard maps and to provide a framework for fault-specific earthquake forecasts developed under objective II-6.

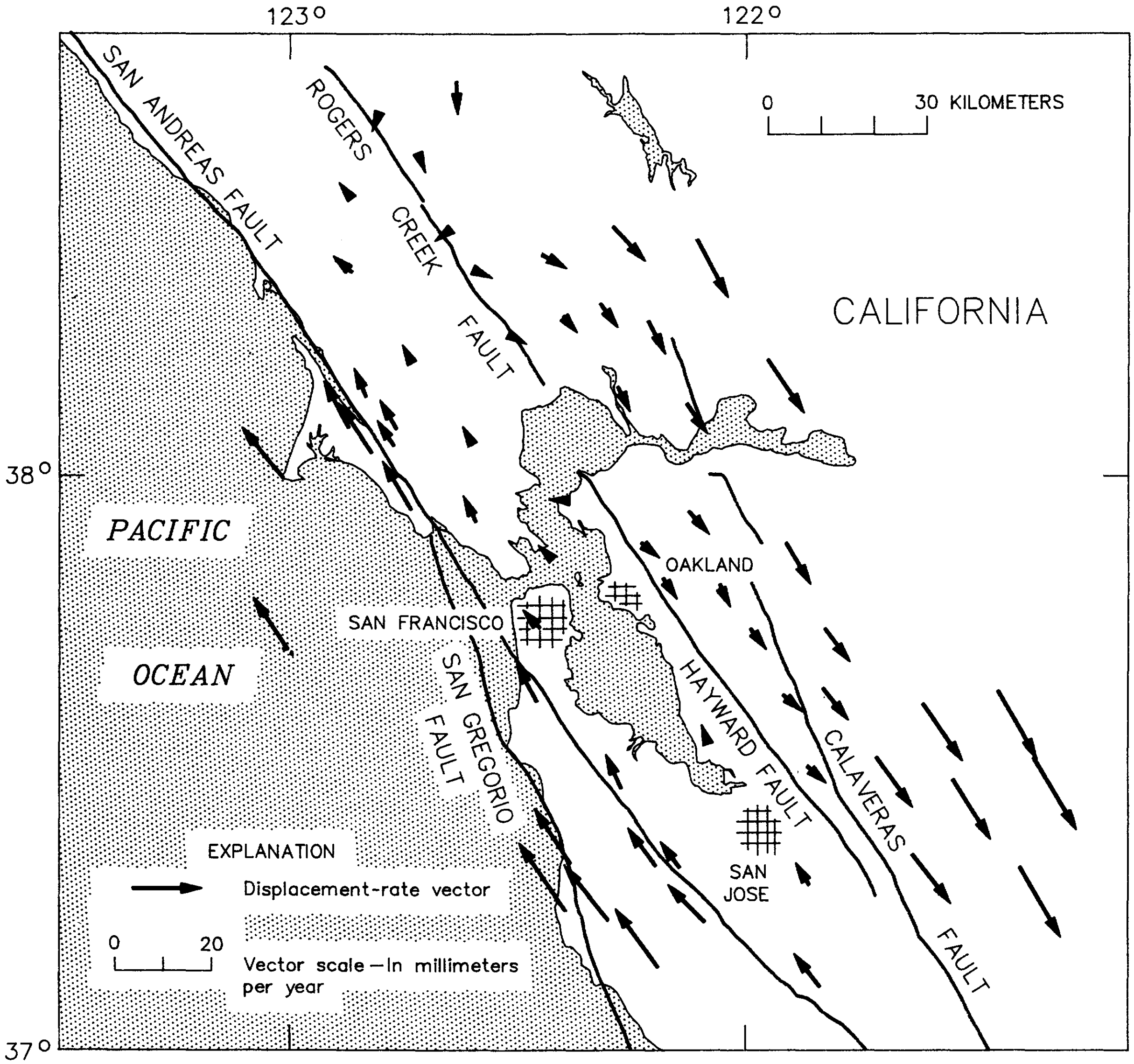


Figure 12. Precise geodetic surveys show that the motion between the Pacific and North American crustal plates is distributed across a complex system of active faults in central coastal California. Laser-ranging distance measurements across the San Andreas fault system in the San Francisco Bay region during 1970-1989 resolve average displacement rates across the complex array of active faults that traverse this major urban area. About 35 mm (about 1½ inches) of horizontal slip per year is distributed across the faults of the San Andreas system, indicating a high earthquake hazard for all of these faults. This amount of slip constitutes about three-quarters of the motion between the Pacific and North American plates; the remainder of the motion is distributed on faults in eastern California, Nevada, and western Utah. The arrows show the motion of geodetic reference marks relative to a stationary point at the center of the diagram.

Defining regions within which the geologic factors and tectonic processes that cause earthquakes are similar is a critical step in assessing earthquake potential, but at present there exists no strong physical or empirical basis for such definition. Much of the regional-scale geologic mapping and tectonic investigation of the U.S. has focused on pre-Quaternary or pre-Tertiary structures and tectonic events and provides little insight into the current tectonic regime. However, understanding the interaction of older structures with the current regional tectonic regime is essential to constructing integrated regional models of tectonic deformation as the basis for defining seismic source zones.

Better knowledge of the tectonic processes and geological factors that are responsible for earthquake occurrence would substantially enhance the ability to define earthquake potential, particularly in the Central and Eastern U.S., where the origins of seismicity are poorly understood. Improving such knowledge should be viewed as a long-term, continuous process, but data collected under objectives II-1, II-2 and II-3 will provide the basic information to begin modeling lithospheric structure and processes responsible for localizing earthquakes within a region.

Tasks:

- Develop integrated models of regional tectonic deformation and tectonic systems.
- Construct maps defining earthquake potential at national and regional scales.
- Model lithospheric structure and processes that may be responsible for the concentration of strain in the lithosphere.

Local Earthquake Potential and Fault-Specific Earthquake Forecasting

Studies conducted under this group of objectives focus on locating and characterizing individual active faults, estimating the likelihood of earthquakes occurring on them, and integrating this information to determine the aggregate earthquake potential of the region encompassing the faults. This group of objectives is thus more locally focused and emphasizes more detail than the broader objectives of the previous group. Estimates of fault-specific earthquake potential may be expressed in various ways. These range from a number expressing the rate of earthquake occurrence on a particular segment of a fault averaged over long timespans (centuries to hundreds of thousands of years) to long-term, probabilistic forecasts estimating the likelihood of a large earthquake during the next few years or decades, and finally, to specific short-term predictions of an earthquake occurring on a particular fault segment during a specified time interval, perhaps ranging from a few hours to a few months.

Research on the long-term earthquake potential of individual faults has contributed substantially during the past few years to a clearer understanding of the relative levels of hazard along several major active fault systems in parts of the Western U.S. where faults are exposed at the surface and accessible to detailed study of the geologic record of Holocene faulting episodes. In California, this research has also contributed to long-term probabilistic forecasts of earthquakes on specific faults and fault segments. Such long-term forecasts can be used in selecting sites for intensive monitoring in experiments on short-term earthquake prediction.

It is practical to make long-term probabilistic forecasts in well-studied areas with the concepts and methods available now. Forecasting will become more precise and reliable with increased completeness and detail of the record of past events on which forecasts are based, enhanced knowledge of how individual faults interact with structural systems in the regional tectonic regime, and a better understanding of the earthquake source.

Objective II-5: Identify Active Faults, Define Their Geometry, and Determine the Characteristics and Dates of Past Earthquakes

Knowledge of fault locations and the characteristics of earthquakes that occur on them is needed for estimating local earthquake potential and making long-term earthquake forecasts. Although many of the larger active faults with high slip rates in the U.S. are known, many less prominent faults, faults with low slip rates, or faults that do not extend to the surface remain unknown, or their activity not recognized. Systematic surficial geologic mapping and geophysical surveys should be undertaken in areas of suspected high earthquake potential and be combined with analysis of existing geologic maps and drill-hole and geophysical data to identify and characterize potentially active faults.

Estimates of the earthquake potential of individual faults require knowledge or assumptions about the segment of a fault that ruptures during an earthquake. In many cases, the zone of rupture coincides with a geometrically distinct segment of the fault. These fault segments are commonly believed to have broken repeatedly during past earthquakes occurring on the same segment. The assumption that a future earthquake will rupture the same segment as past earthquakes has a major influence on estimates of earthquake potential and on long-term earthquake forecasts. It is an assumption that needs careful testing through detailed surficial and bedrock geologic mapping and through geophysical and subsurface studies in and along fault zones. Tracing the spatial and temporal evolution of fault segments in three dimensions and assessing the factors that control the extent of rupture during individual earthquakes can provide important data for evaluating that assumption. Detailed mapping can also provide a basis for selecting sites likely to yield geologic evidence of prehistoric earthquakes and for interpreting geologic relationships at such sites. Further, it can provide a greatly improved framework for planning the intensive monitoring studies conducted in support of short-term earthquake prediction experiments (objective II-7) and interpreting the data collected under those studies.

The geologic record of prehistoric earthquakes, as disclosed through shallow excavations, has extended our knowledge of the timing and character of earthquakes well beyond that provided by the relatively short historical and instrumental record of seismicity. Systematic age determinations of fault displacements, combined with measurements of the amount of slip or associated deformation and with estimates of the dimensions of the rupture, provide information on the magnitudes and recurrence intervals of earthquakes large enough to produce slip or deformation at the surface and on spatial and temporal patterns of earthquake occurrence on a fault and within a region. With

Figure 14. Fault scarp yields evidence of very large prehistoric earthquakes in Oklahoma. Only a few recently active faults have been identified in the Central and Eastern U.S. One is the Meers fault in southwestern Oklahoma, whose scarp casts the linear, dark shadow extending horizontally across this low-sun aerial photograph. The Meers fault is a principal element of the Wichita frontal fault system—the structural boundary between the Amarillo-Wichita uplift to the southwest and the Anadarko basin to the northeast (see map). In the last few years, geologists have uncovered evidence for movement along the fault as recently as 1,200-1,300 years ago and for repeated episodes of slip during the past few hundred thousand years. The length of the scarp and the amount of recent fault displacement indicate that the scarp was produced by an earthquake of about magnitude 7. Historically, the Meers fault has been aseismic, and only a few scattered recent earthquakes lie in the vicinity the Wichita frontal fault system, as evident from the earthquake epicenters (dots) from 1977 through 1989. The largest historical earthquake in Oklahoma is magnitude 5.5, and prior to detailed studies of this fault, only low- to moderate-magnitude earthquakes were considered likely in the region.

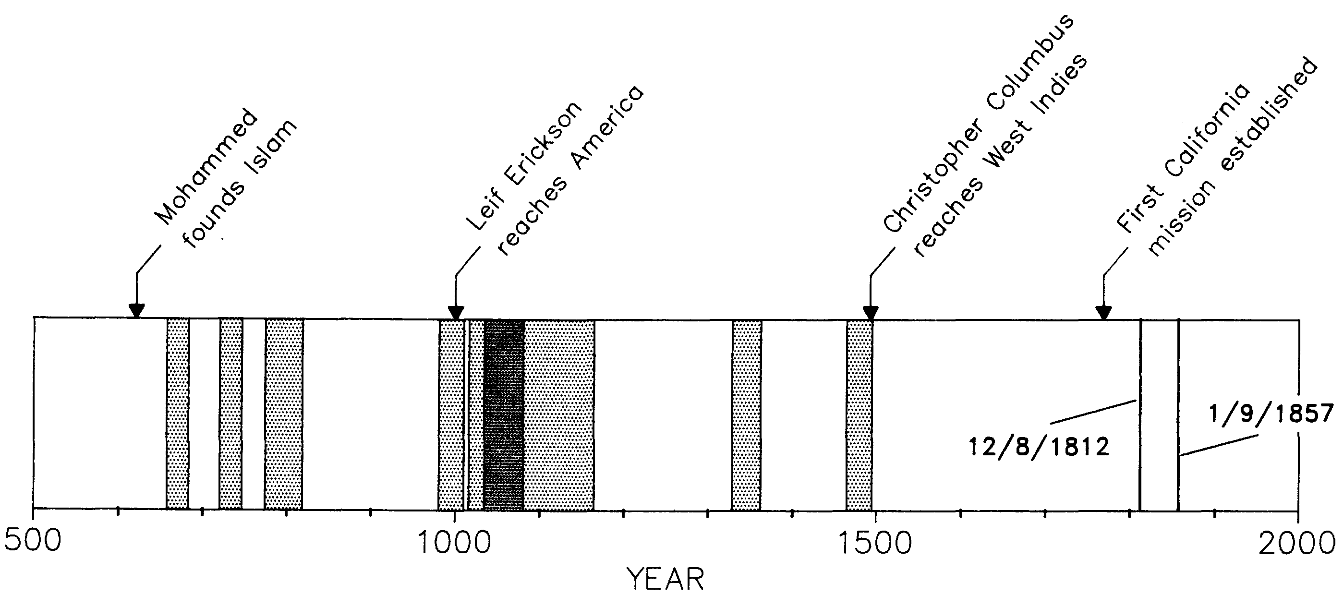
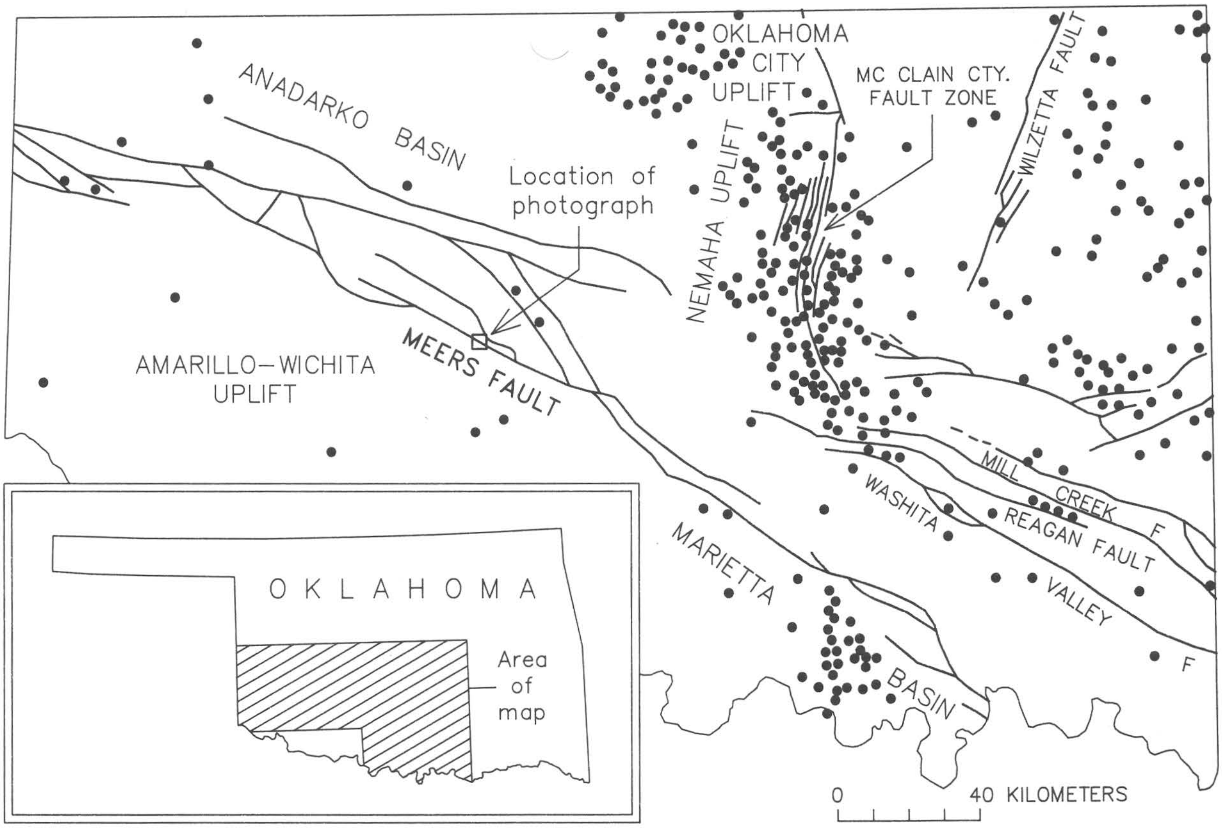


Figure 13. History of earthquake occurrence on the San Andreas fault extended 1200 years beyond written records by geologic investigations. Detailed geologic studies augment the relatively short historical and instrumental records of U.S. earthquake activity and yield critical information on the timing and character of prehistoric earthquakes. At a study site on the San Andreas fault northeast of Los Angeles, California, earthquakes have occurred in clusters of two or three events spanning several decades separated by dormant periods of two or three centuries. Precision radiocarbon dating of buried peat horizons in a faulted sequence of marsh and stream deposits have yielded age ranges (shaded bars) for eight earthquakes prior to the 1812 and 1857 shocks, which are documented in historical accounts. The observed pattern of earthquake clustering was not apparent in earlier studies, which used less precise, conventional radiocarbon-dating techniques. Knowledge of long-term patterns of earthquake occurrence is needed for probabilistic forecasting of future earthquake activity.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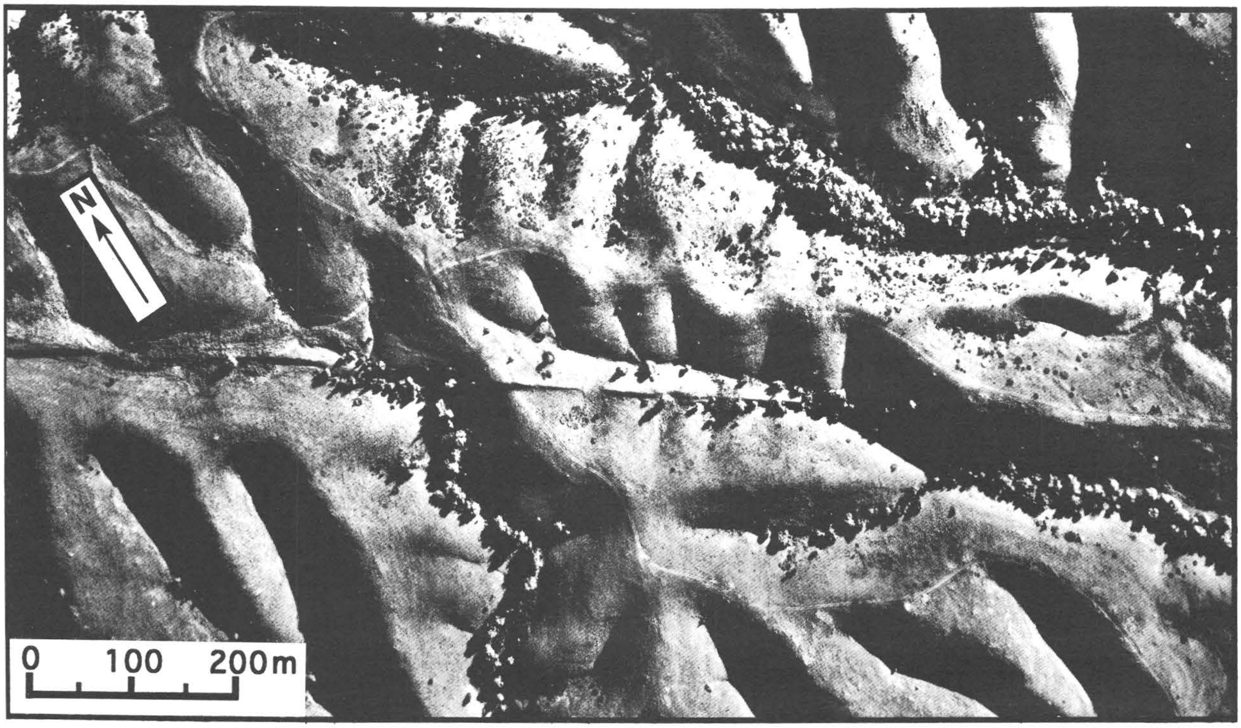
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faults that do not reach the surface, such as blind thrusts, geomorphic and stratigraphic studies are needed to determine the ages of episodes of surface deformation (for example, folding) produced by slip on a buried fault.

The most common material used in dating prehistoric earthquakes is organic matter, which can be dated by ^{14}C methods. Commonly, however, organic matter is scarce or absent, limiting the availability of well-constrained ages for faulting events determined at many points along a fault. There is a need to refine existing methods and develop additional methods for dating other materials to increase the quantity, resolution and accuracy of age determinations of tectonic events registered in late Quaternary surficial deposits.

Geologic studies of prehistoric earthquakes provide estimates of earthquake magnitudes, recurrence intervals, and slip rates needed for making long-term probabilistic forecasts of earthquakes along active faults (objective II-6) and are a critical component of regional studies involving the timing of faulting or deformation (objective II-1).

Tasks:

- Conduct geologic mapping and geophysical surveys to locate potentially active faults.
- Conduct detailed studies of the geologic record of faulting and deformation events along geologic structures with evidence of late Quaternary deformation.
- Conduct detailed geologic mapping and geophysical surveys in and adjacent to active fault zones to trace the spatial and temporal evolution of fault segments in three dimensions.
- Develop new methods for dating surficial materials of late Quaternary age commonly affected by earthquake deformation.

Objective II-6: Make Long-Term Probabilistic Forecasts of the Likelihood of Large Earthquakes on Active Faults

Probabilistic forecasts quantify estimates of earthquake hazard for a given fault or fault zone. Records of past earthquake activity and extrapolations of current seismicity can be used to estimate steady-state earthquake hazard on a regional basis, and such assessments have been widely used for seismic zoning. However, the concept of the earthquake cycle implies that earthquake risk is not stationary in time, since the likelihood of repetition of a large event on a specific fault segment is low immediately following a large earthquake and increases with time toward the end of the cycle. Provided the duration of the cycle is relatively constant through time and both this duration and the date of the most recent large event are known, the current stage in the cycle can be determined and some measure of time-dependent earthquake risk can be assigned. Such assessments can be cast in a statistical framework to specify the probability of an event of given magnitude on a particular fault segment within a specified time interval, as has been done for the principal segments of the San Andreas fault system in California and for the plate-boundary fault system separating the Pacific and North American plates in southern Alaska and the Aleutian Islands. As knowledge about the character and earthquake history of individual faults accumulates, forecasting can be extended to active faults elsewhere in the Western U.S. and someday possibly to the central and eastern parts of the country. Because historical seismic and prehistoric geologic evidence shows that earthquakes may cluster in time, integrating time-dependent physical models of the earthquake cycle with better knowledge of the interactions between individual faults and other tectonic elements may lead to more reliable long-term forecasts.

Long-term probabilistic forecasts are widely applicable to earthquake-hazard-mitigation activities and can be applied to zoning, land-use planning, assigning priorities to upgrading or demolishing unsafe structures or facilities, and preparing for and responding to emergencies. The forecasts can also provide a basis for long-term strategic planning within the NEHRP.

Tasks:

- Evaluate geodetic, geologic, and geophysical data to determine the influence of the interaction between regional tectonic elements on the earthquake cycle of individual fault segments.
- Develop improved probabilistic forecasting methods appropriate to different tectonic regimes.
- Make and periodically update probabilistic estimates of earthquakes on major active faults throughout the United States.

Earthquake Prediction and Focused Monitoring Experiments

Recent advances in identifying fault segments or regions of high seismic potential facilitate the acquisition of data critical for refining the understanding of earthquake source processes (objective I-2), searching for possible phenomena precursory to earthquakes (objective II-7), and documenting earthquake effects (objective III-1). It is now possible to focus intensive instrumental monitoring efforts on regions where significant earthquakes are most likely to occur within the next several years and thereby accelerate collection of instrumental data sets of unprecedented quality and detail.

The interrelatedness of various program objectives (for example, I-2, II-7, and III-1) is apparent in intensive earthquake-related monitoring efforts. The design of monitoring strategies themselves is predicated on models of the earthquake process; in turn, such monitoring contributes to a better understanding of the mechanics of the earthquake

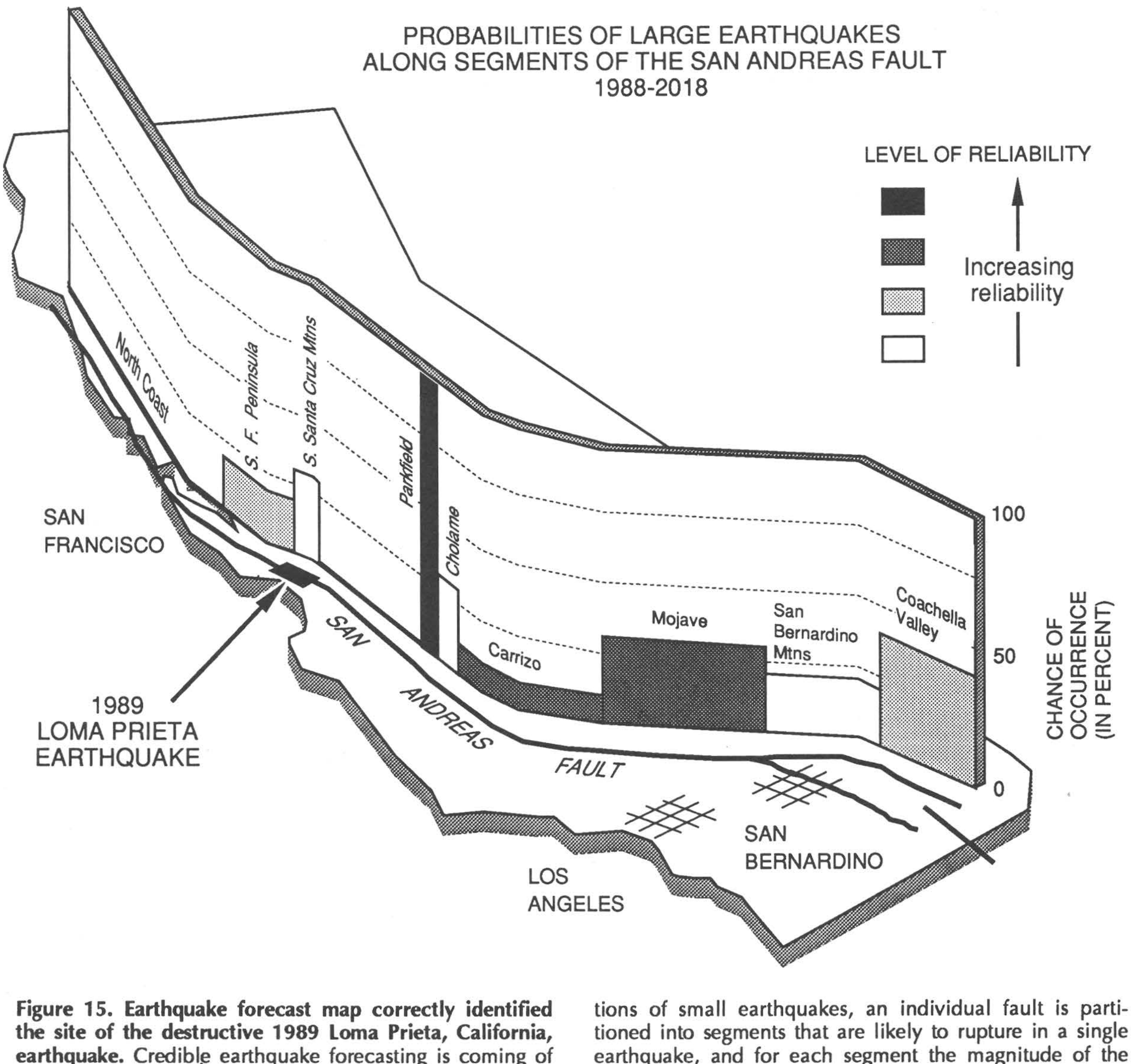


Figure 15. Earthquake forecast map correctly identified the site of the destructive 1989 Loma Prieta, California, earthquake. Credible earthquake forecasting is coming of age, as was demonstrated by the occurrence of the Loma Prieta earthquake on a segment of the San Andreas fault in the southern Santa Cruz Mountains in central coastal California. This figure, taken from a 1988 report of the Working Group on California Earthquake Probabilities, estimated the chance of a magnitude 6.5–7 earthquake for the interval 1988–2018 on that fault segment to be 30 percent, higher than any other segment in or near the San Francisco Bay region. Forecasts of future seismic activity over timescales of decades or longer are possible in regions where active faults are identified and where long-term rates of fault slip, maximum sizes of earthquakes, and dates of the last major earthquakes are known. Such knowledge can be derived from geological, geodetic, and seismological data, along with historical records of major earthquakes. On the basis of previous earthquake occurrence, slip in past events, fault geometry, or the distributions of small earthquakes, an individual fault is partitioned into segments that are likely to rupture in a single earthquake, and for each segment the magnitude of the maximum expected earthquake is assigned. Historic or prehistoric earthquake activity, slip in previous earthquakes, and the rate of fault slip are then used to determine the position of each segment in its earthquake cycle and to calculate the likelihood for an earthquake of specified size in a particular future time interval. Shading of the bars in the graph depicts levels of reliability of the likelihood estimates; the estimate for the southern Santa Cruz Mountains segment was assigned the lowest level of reliability. A new study published in 1990 places the aggregate 30-year chance for a magnitude 7 or larger earthquake on one or more of the active faults that traverse the San Francisco Bay region at 67 percent. Long-term forecasts have been made for the major active faults of the San Andreas fault system in California, and with enough data these methods can be applied to other seismically active regions of the United States.

source. Also, focused intensive monitoring is essential to documenting and evaluating possible earthquake precursors; advances in the capability to predict earthquakes accelerates collection of robust data sets to better understand and predict the effects of earthquakes. In addition, research on methods for short- and intermediate-term prediction improves understanding of the mechanics of earthquake occurrence, and the latter provides a basis for research on prediction strategies. Overall, monitoring instrumentation can simultaneously address several objectives. For example, digital seismographs deployed for regional or local seismic monitoring can also provide high-quality recordings of strong ground motion from local earthquakes and provide useful information on the effects of the source, propagation path, and site conditions on the recorded motion.

The only focused monitoring experiment underway in fiscal year 1990 is at Parkfield, California, where an event of magnitude 6 is expected within the next few years. For several reasons, any new focused-monitoring experiments will likely have differences as well as similarities to work currently underway at Parkfield. There are no fault segments in the U.S. for which the probability of a substantial earthquake is thought to be as high as for Parkfield, but in the San Francisco Bay region and southern California a number of fault segments are judged to have relatively high earthquake probabilities. These other segments are considerably longer than the 35-km-long Parkfield segment, and the likely zones of earthquake-initiation for these segments are not identified. With the present limited resources, several long fault segments cannot be monitored with the same density as at Parkfield. On the other hand, a more regional approach to monitoring may be promising in view of the possibility that broad-scale precursory changes in seismicity and strain occur months to several years before a large earthquake.

Objective II-7: Monitor Intensely a Few Selected Regions of High Seismic Potential

Progress in understanding the earthquake source and in predicting earthquakes requires high-quality measurements made both close to the causative fault and in the surrounding region. Primary emphasis will continue to be on observing seismic parameters and crustal deformation with high-resolution, low-noise, redundant sensors, because these observations provide valuable data on earthquake processes and effects even if precursors are not detected.

Intensified monitoring activities are critical to determining the degree of reliability with which the occurrence of damaging earthquakes can be predicted. Although precursory effects have definitely been associated with a few earthquakes (for example, 1975 Haicheng, China) and several theoretical models predict measurable precursors, no complete near-source observations of the closing stages of the earthquake cycle have yet been obtained and critical tests of suspected precursory activity have not been made. Observational networks like those at Parkfield monitor seismic parameters and crustal deformation at levels of sensitivity two to three orders of magnitude better than obtained previously in the source region of an impending earthquake. Such networks are well suited to detect premonitory changes and reveal unanticipated facets of fault mechanics. They may also contribute to understanding and predicting earthquake effects. For example, dense arrays of strong-motion seismographs not only can resolve the earthquake rupture process in detail but also can document the contributions of wave modulation and attenuation along the propagation path and of amplification at the site to patterns of ground shaking.

Tasks:

- Monitor seismic parameters continuously with a digital network of borehole seismographs with broad frequency response and high dynamic range.
- Monitor deformation by repeated dense geodetic surveys and borehole and (or) long-baseline, continuously recording strainmeters.
- Record dynamic and static effects of earthquakes with seismograph and geodetic survey networks.
- Conduct carefully controlled topical earthquake-prediction monitoring experiments incorporating, for example, electrical, magnetic, and geochemical methods.
- Review and evaluate frequently all experiments and all data obtained.

Objective II-8: Develop and Evaluate Methods of Short- and Intermediate-Term Prediction of Earthquake Occurrence

Developing a method to reliably predict the time, place, and magnitude of an earthquake would clearly be a major achievement of the EHRP. The increased availability of high-quality data and new theoretical source models will stimulate the development and testing of novel methods for predicting earthquake occurrence. Such methods can be applied to existing data sets but need rigorous statistical criteria for identifying and evaluating anomalies in the various data sets before they can be accepted and routinely applied to intensified monitoring experiments or regional network observations. Nonetheless, the development of new methods needs to be encouraged because of the great potential value of both short- and intermediate-term predictions for reducing deaths and damage in future earthquakes. Reliable identification of intermediate-term precursors (months to years duration) would allow warnings with sufficient lead time to brace, strengthen, or abandon collapse-prone structures. Short-term predictions (minutes to days) would allow hazardous operations to be suspended and hazardous structures to be evacuated.

Although the ultimate outcome of this research cannot be defined in advance, such activities are essential complements to the local and regional seismic and deformation monitoring carried out within the EHRP. The results will determine the worth of potential precursory monitoring strategies and indicate which can most profitably be applied to intensified observations, and these conclusions can have a significant impact on furthering understanding of the earthquake source (goal I).

Tasks:

- Develop rigorous methods, including statistical techniques, for identifying and critically evaluating potential earthquake precursors.
- Develop and apply techniques for proceeding from long-term forecasting of earthquake occurrence to intermediate and short-term prediction.

Goal III. Predicting the Effects of Earthquakes

Damage to property and loss of lives due to earthquakes is a direct consequence of ground shaking and ground failure. It follows that documenting, modeling, and predicting earthquake effects, especially ground shaking and ground failure, are essential activities for accomplishing the goals of the National Earthquake Hazards Reduction Program; these activities are directly and immediately useful in reducing losses from earthquakes. A data base of records of ground shaking and ground failure needs to be collected and maintained as a foundation for understanding and predicting ground shaking and ground failure. The results of such efforts can be used directly in specifying ground motions for engineering design and in assessing the potential ground failure at specific sites for postulated earthquakes. The results are also a prime ingredient in creating maps of potential hazards at local, regional, and national scales and earthquake-loss scenarios for urban areas.

Objective III-1: Acquire Data Needed for the Prediction of Ground Shaking, Ground Failure, and Response of Engineered Structures

An extensive data base of ground shaking and of resultant ground failure and structural response for a wide range of earthquake magnitudes, types of faulting, distances from the causative fault, geotechnical conditions at the site, and geologic structure between the source and the site is essential for predicting the consequences of an earthquake. For example, ground-shaking data are used directly to establish design levels of shaking for engineered structures and validate theoretical predictions of ground shaking. Furthermore, the data are critical for studies of the physics of the earthquake source, the mechanisms and consequences of ground failure, and the dynamic response of structures.

Although numerous important records have been collected, critical gaps exist, especially for the less frequent, larger earthquakes. In particular, few records have been obtained in the immediate vicinity of magnitude 7 and larger shocks, and records for even moderate-sized shocks are lacking or scarce for some U.S. seismic zones. Further, the relative dynamic response of various surficial geologic deposits is insufficiently documented. For example, although it has been recognized for more than 80 years that ground shaking is greater on the soft sedimentary deposits around the edges of San Francisco Bay than on adjacent rock sites, only a handful of records from these "soft sites" were obtained from the 1989 Loma Prieta earthquake. None of them were from San Francisco, even though the role of soft sediments in determining where the greatest losses occur was clear from the 1906 San Francisco earthquake. The likelihood that another large earthquake will strike the San Francisco Bay area during the next three decades creates the opportunity to correct this regrettable circumstance and to collect data from a wide range of "soft sites."

A high priority of data-collection efforts should be deployment of special-purpose arrays (closely spaced sensors with centralized recording) and networks (separated sensors with independent recording) of instruments designed to provide data related to ground shaking and its effects, principally ground failure and response of manmade structures. These deployments should include near-fault dense arrays and networks to resolve earthquake source processes, regional arrays to determine seismic-wave propagation characteristics between the source and the site, downhole arrays to study the role of local geologic conditions in modifying ground motions, special deployments to study soil-foundation interaction and the response of structures, and instrumentation of carefully chosen sites with the potential for liquefaction or landsliding. At sites of potential ground failure, pore-pressure sensors, displacement meters, and inclinometers should be deployed in addition to the usual sensors of vibratory ground motion.

The special arrays and networks should be located in regions identified as having a high probability of earthquake occurrence in the next few decades. Such regions, however, occupy only a small fraction of the earthquake-prone parts of the Nation. Accordingly, a nationwide network of strong-motion recorders needs to be deployed and maintained to assure the capture of ground-shaking and structural-response data from earthquakes originating outside the high-risk areas yet within areas recognized as having significant earthquake potential.

Often overlooked but essential for a complete analysis of strong-motion data is information about thickness, density, seismic velocities, and attenuation and constitutive properties of geologic foundation materials beneath the recording sites. The development of simple and reliable methods for obtaining this information for materials in their undisturbed state should continue, and special efforts should be made to collect such site information after important records are obtained, if not before.

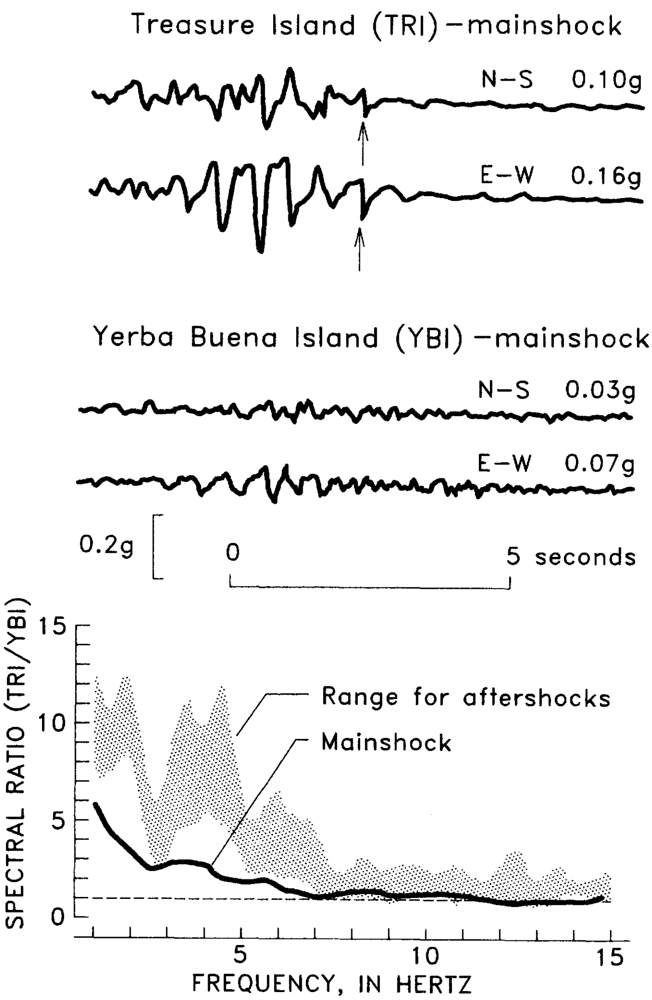
Tasks:

- •Deploy comprehensive special-purpose instrumental arrays and networks to determine wave-propagation effects and response of engineered structures.
- •Instrument potential sites of earthquake-induced ground failure to document the physics of permanent ground deformation.
- •Deploy and maintain a nationwide network of strong-motion recorders.
- •Document subsurface conditions including geotechnical properties at instrumental sites.
- •Archive and disseminate strong-motion and ground-failure data, including available information on site and structural conditions.

Objective III-2: Predict Strong Ground Shaking

Predicting ground shaking as a function of earthquake source characteristics, distance from the source, regional geologic structure, and local geotechnical conditions is an essential capability for most earthquake-hazard-reduction strategies. This capability is developed by complementary empirical and theoretical studies. Under the empirical approach, statistical equations relating ground-shaking characteristics to various source, path, and site parameters are derived from the existing data base, and these equations are then used to statistically estimate shaking in future shocks. As the amount of strong-motion data increases over the years, existing prediction equations can be refined and more precise and complete estimates of future shaking will be possible.

Theoretical studies are used to extrapolate ground-shaking predictions for conditions not represented in the existing data base, such as near-fault ground shaking in a magnitude 7.5 or larger earthquake. Theoretical studies encompass a wide variety of investigations, ranging from computer-modeling studies in which individual oscillations



◀ **Figure 16. Very weak ground can amplify shaking more during small earthquakes than during large earthquakes.** Recordings of the 1989 Loma Prieta, California, mainshock and its aftershocks obtained at two nearby island sites in San Francisco Bay document that the degree of amplification of seismic shaking on very weak ground depends on the amplitude of shaking in the underlying bedrock. In the mainshock traces (*above*), the ground acceleration recorded on artificial fill over soft muds (Treasure Island) was about two to three times that on nearby hard rock (Yerba Buena Island). Both horizontal components of motion are shown; numbers indicate maximum accelerations. See figure 1 for locations of the islands. The abrupt decrease in amplitude at the Treasure Island site (arrow) may mark the onset of liquefaction in the sandy fill, which liquified extensively in the vicinity of the recording instrument. To better assess the difference in site response on the two islands, sensitive portable seismographs were deployed to record aftershocks. Ratios of the spectral amplitudes of the north-south motions at Treasure Island to those at Yerba Buena Island (*below*) clearly show strong amplification at Treasure Island for frequencies less than about 5 Hz, both for the mainshock (solid line) and a group of seven aftershocks (shaded band). However, the ratios are smaller for the mainshock. This observation reflects nonlinear soil response, a phenomenon of much debate and for which there were few substantial data before the earthquake. The investigation of nonlinear behavior is critical because many seismic-design criteria and seismic-zonation methods are based on recordings of weak motions, under the assumption that the amplification patterns and dominant periods observed for the weak motions apply also to strong motions. More data of this type—adjacent sites with contrasting geologic properties—are urgently needed for a wide range of levels of ground shaking and a variety of geologic conditions.

of a seismogram are matched, to modeling based on the assumption that ground shaking is adequately represented by a random, stochastic time series. Theoretical studies will continue to be important because critical gaps in the ground-shaking data base will persist for decades. Values for many parameters needed to validate and apply theoretical models, such as information on geologic structure, source scaling laws, measures of seismic wave attenuation, and so forth, can be provided by studies under this objective and others.

Although site response, including soil-foundation interaction, clearly has a major influence on ground shaking, many theoretical predictions of ground shaking do not encompass site response effects; moreover, the empirical data from large earthquakes samples the range of site conditions so sparsely that empirical estimates of site effects are unreliable. Data from special field experiments and from laboratory and computer modeling are needed to better understand and predict the effect of near-surface rock and soil conditions on strong ground shaking. This research will also help to account for site response effects in studies of the earthquake source.

Tasks:

- •Refine prediction equations for ground shaking through empirical analyses of strong-motion data.
- •Use deterministic and stochastic modeling methods to extrapolate prediction equations beyond the existing strong-motion data base.
- •Develop and verify methods for predicting the influence of near-surface geologic structure on ground shaking.

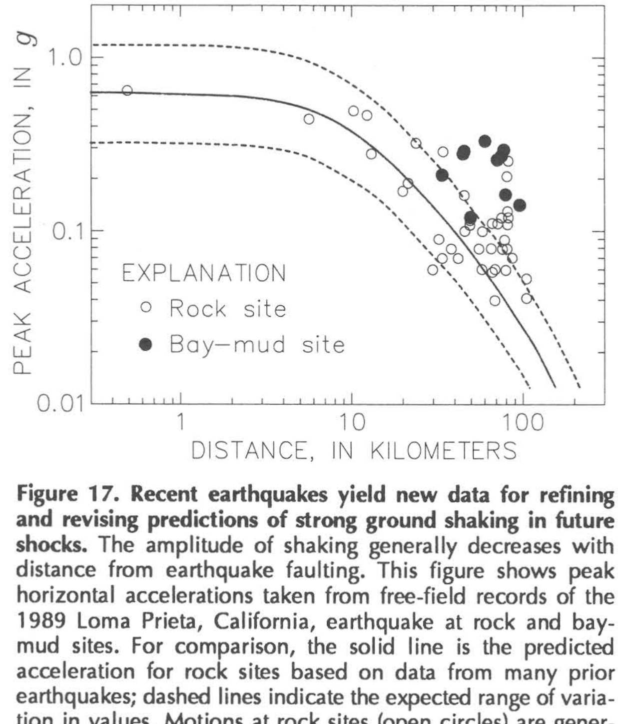


Figure 17. Recent earthquakes yield new data for refining and revising predictions of strong ground shaking in future shocks. The amplitude of shaking generally decreases with distance from earthquake faulting. This figure shows peak horizontal accelerations taken from free-field records of the 1989 Loma Prieta, California, earthquake at rock and bay-mud sites. For comparison, the solid line is the predicted acceleration for rock sites based on data from many prior earthquakes; dashed lines indicate the expected range of variation in values. Motions at rock sites (open circles) are generally consistent with those experienced in previous shocks, except for the group of higher-than-normal accelerations near 80 km, which may be due to focusing of seismic waves reflected from the base of the Earth's crust. However, motions at bay-mud sites (filled circles) are much larger than those at rock sites. Even larger amplifications at bay-mud sites have been observed in previous studies, but they involved much weaker levels of motion. Before this earthquake, there were no records of damaging levels of motion at bay-mud sites.

Objective III-3: Predict Ground Failure

A major cause of earthquake damage and casualties is ground displacement or ground failure, a secondary effect of strong ground shaking. Failures triggered by liquefaction or other weakening of the soil include massive flow failure, lateral spread, ground settlement, and loss of bearing strength. Failures in sloping ground triggered by the interaction of inertial forces and gravitational forces include avalanches, slumps, slides, falls, and debris flows. In spite of the high potential for ground failure to damage and disrupt constructed facilities, engineers and earth scientists have relatively primitive criteria for predicting the occurrence and magnitude of most types of ground failure and especially the amount of ground displacement, or deformation. A major reason for the inadequate criteria is the dearth of quantitative data from ground-failure sites, including instrumental recordings, material test data, and carefully measured site conditions.

Progress in predicting the occurrence of ground failures and the resulting displacements and deformations can be accelerated by carefully and quantitatively documenting case histories for various types of ground failure, by improving and increasing instrumentation of potential ground-failure sites, and by advancing analytical techniques of ground-failure modeling. Needed from case histories is documentation of the nature and extent of ground displacement, both at ground surface and at depth, site conditions, and material properties. Such information is required to better understand the physics of ground-failure processes, to verify and refine prediction criteria for failures, and to model the resulting ground deformation. Improved physical understanding will be useful in guiding the extrapolation of the data to potential ground-failure situations not represented in the existing data set.

Tasks:

- •Document, analyze, and construct a data base of earthquake-triggered ground failures.
- •Refine methods for predicting the occurrence of ground failure and develop methods for predicting the amount of ground displacement or deformation.
- •Develop improved methods for identifying and mapping areas of potential ground-failure hazard.

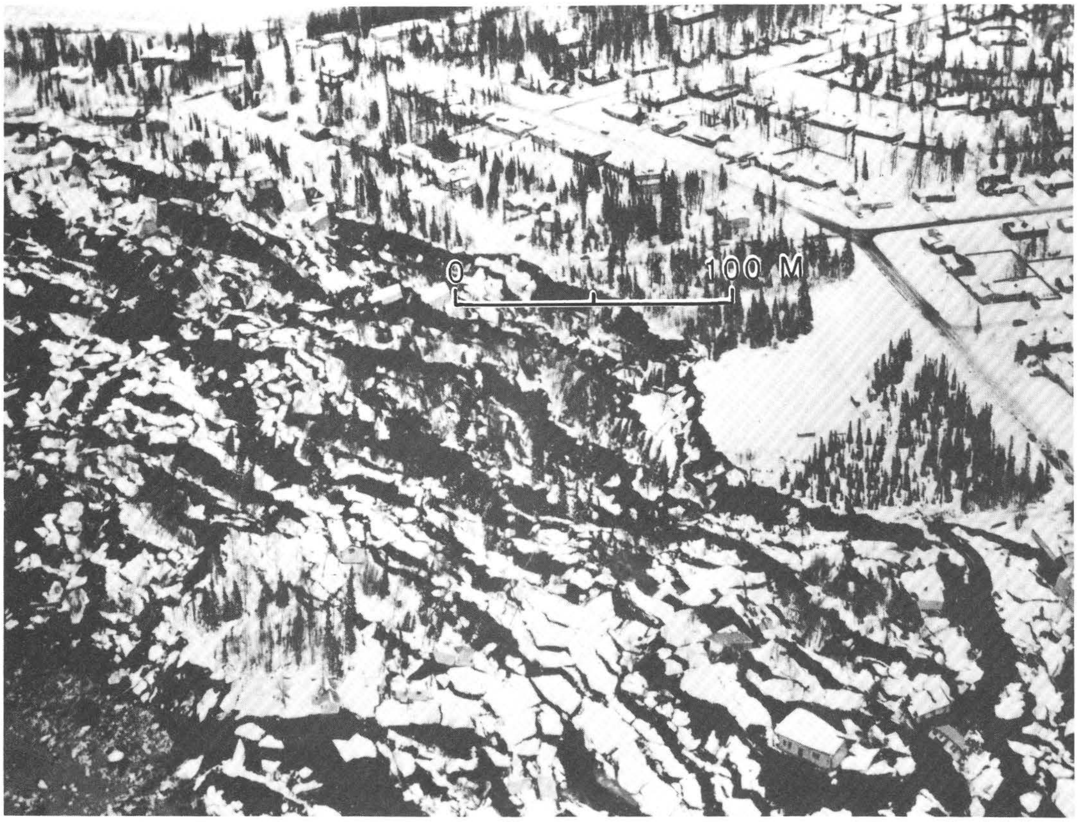


Figure 18. Ground failure causes much damage in most large earthquakes. About 60 percent of the damage in the great (magnitude 9.2) 1964 Alaska earthquake resulted from ground failure. A dramatic example was the massive 2.6-km-wide translational landslide that developed in the Turnagain Heights residential area of Anchorage. Three lives were lost in the slide and 75 homes destroyed. Snow covered the ground at the time of the earthquake; lateral movement of slide blocks exposed fresh faces of glacial outwash and clay (dark areas in foreground of aerial photograph). The cause of the ground failure was the loss of strength in clays or the liquefaction of sand layers in the Bootlegger Cove Formation; the relative importance of the two mechanisms is still debated. Although the State offered home sites in another region at nominal cost to residents of the slide area, it did not obtain title to the ruined lots and since 1964 new residences are being built on parts of the area that slid. There is clear geologic evidence that landslides have occurred in the past and must be expected in the future unless engineering measures can stabilize the area.

Objective III-4: Evaluate Earthquake Hazards and Losses

The coordinated application of results from a number of disciplines is typically needed for effective earthquake-hazard reduction. For example, evaluating the earthquake hazards in a given region combines specifying the magnitudes and locations of probable earthquakes and predicting ground shaking for the probable earthquakes; the shaking, in turn, depends on the characteristics of the seismic sources and also on the regional geologic structure and local site conditions. The resulting hazard-assessment product may take many forms including a thorough ground-motion study for an earthquake of specified magnitude at a particular site, a regional estimate of potential earthquake losses for a postulated earthquake or for the cumulative seismicity likely to occur during a specified time interval, or a national map of ground shaking that can be expected over a particular time period at a given probability level.

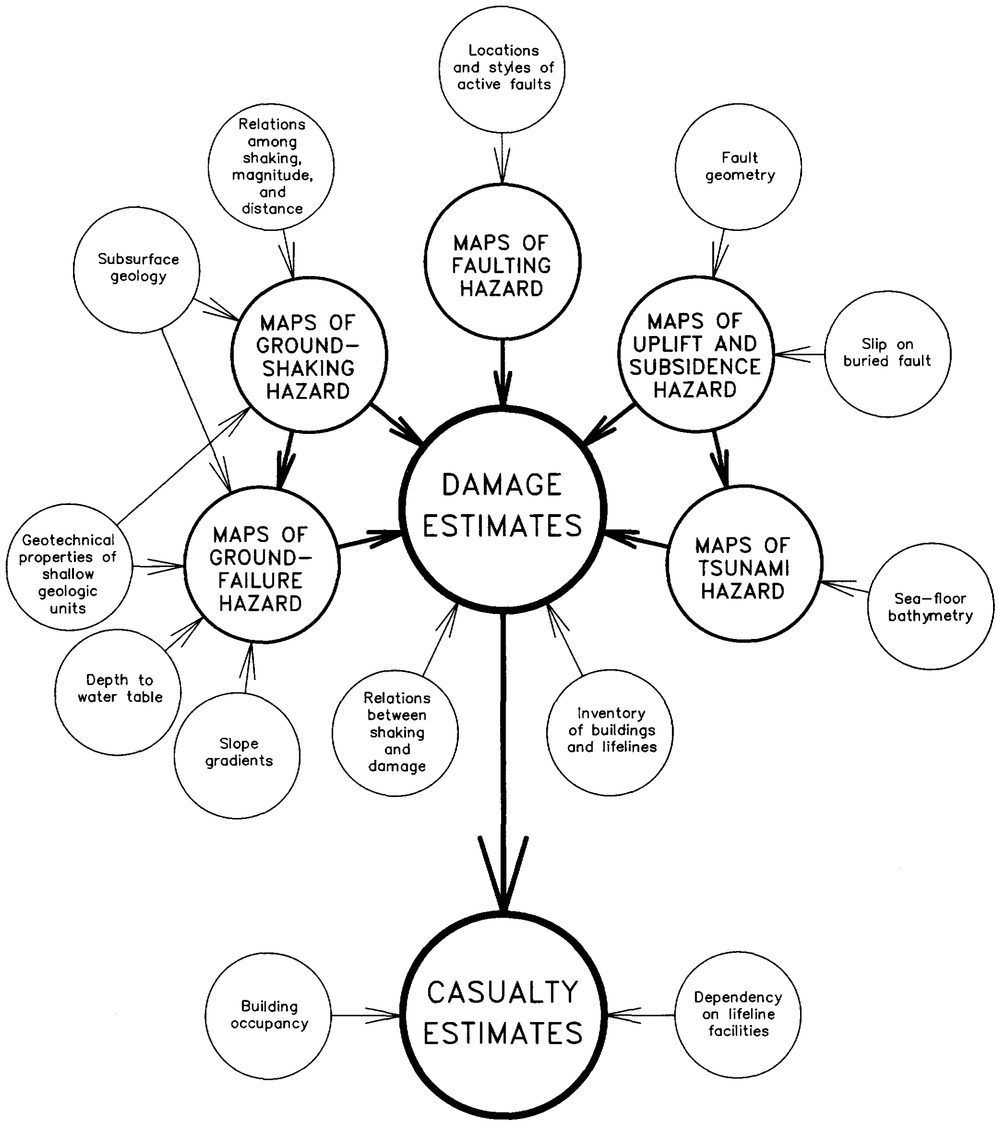


Figure 19. Estimation of damage and casualties from potential earthquakes requires synthesis of extensive and diverse earth-science and socioeconomic information into a series of hazard maps. Requisite to the hazard maps is knowledge of the potential for future earthquakes—how large, how often, where, and, if possible, when. Because obtaining the necessary earth-science and sociometric information for a single earthquake-prone metropolitan region requires years, the EHRP has limited its earthquake-hazard-mapping effort to pilot study areas within a few large metropolitan regions. This diagram concerns only direct damage and casualties; it does not address estimation of indirect losses, such as the loss of production capacity or business failures, which may exceed direct losses.

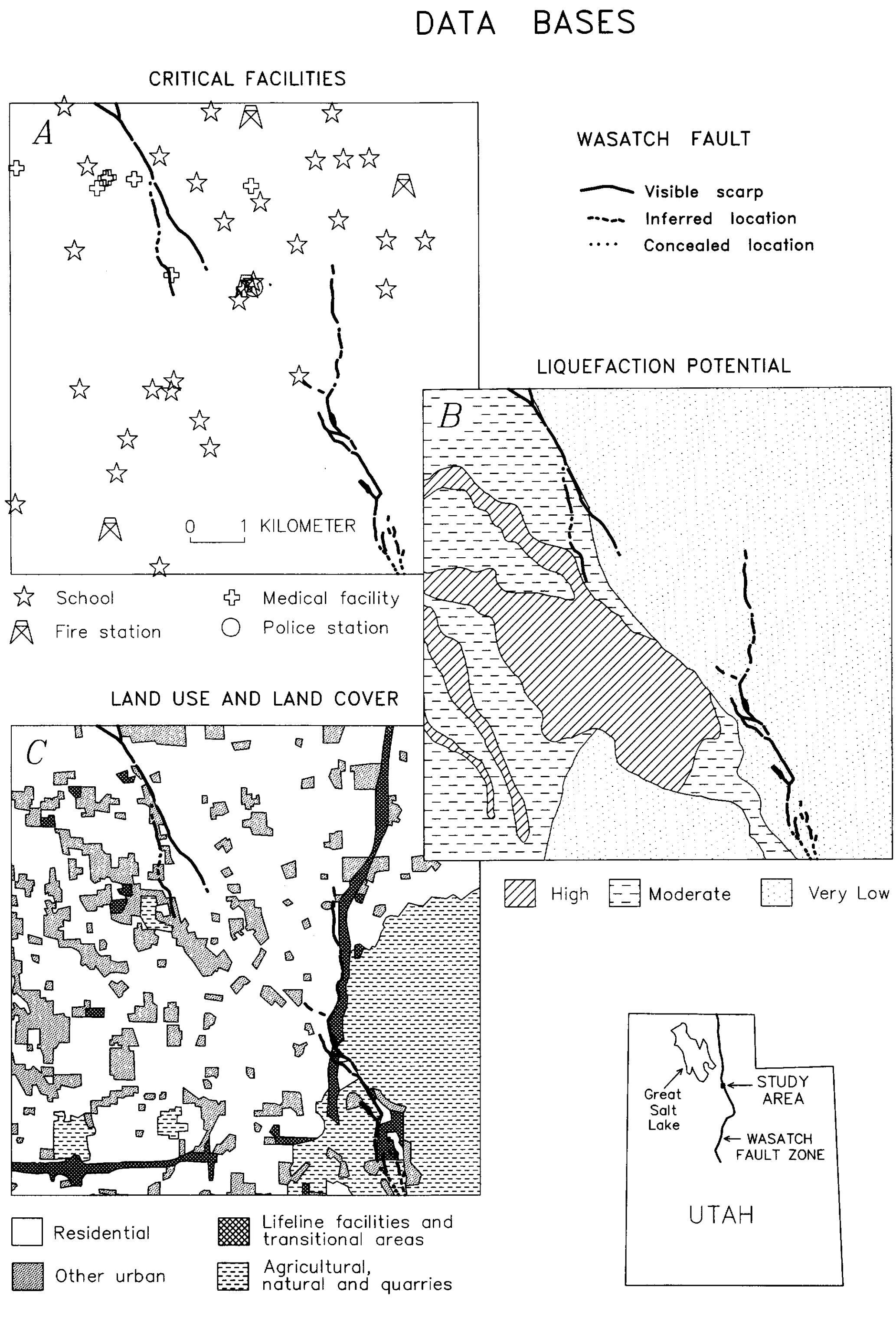

DATA BASES
CRITICAL FACILITIES
A
0 1 KILOMETER
School
Medical facility
Fire station
Police station
WASATCH FAULT
Visible scarp
Inferred location
Concealed location
LIQUEFACTION POTENTIAL
B
High
Moderate
Very Low
LAND USE AND LAND COVER
C
Residential
Other urban
Lifeline facilities and transitional areas
Agricultural, natural and quarries
Great Salt Lake
STUDY AREA
WASATCH FAULT ZONE
UTAH

Figure 20.

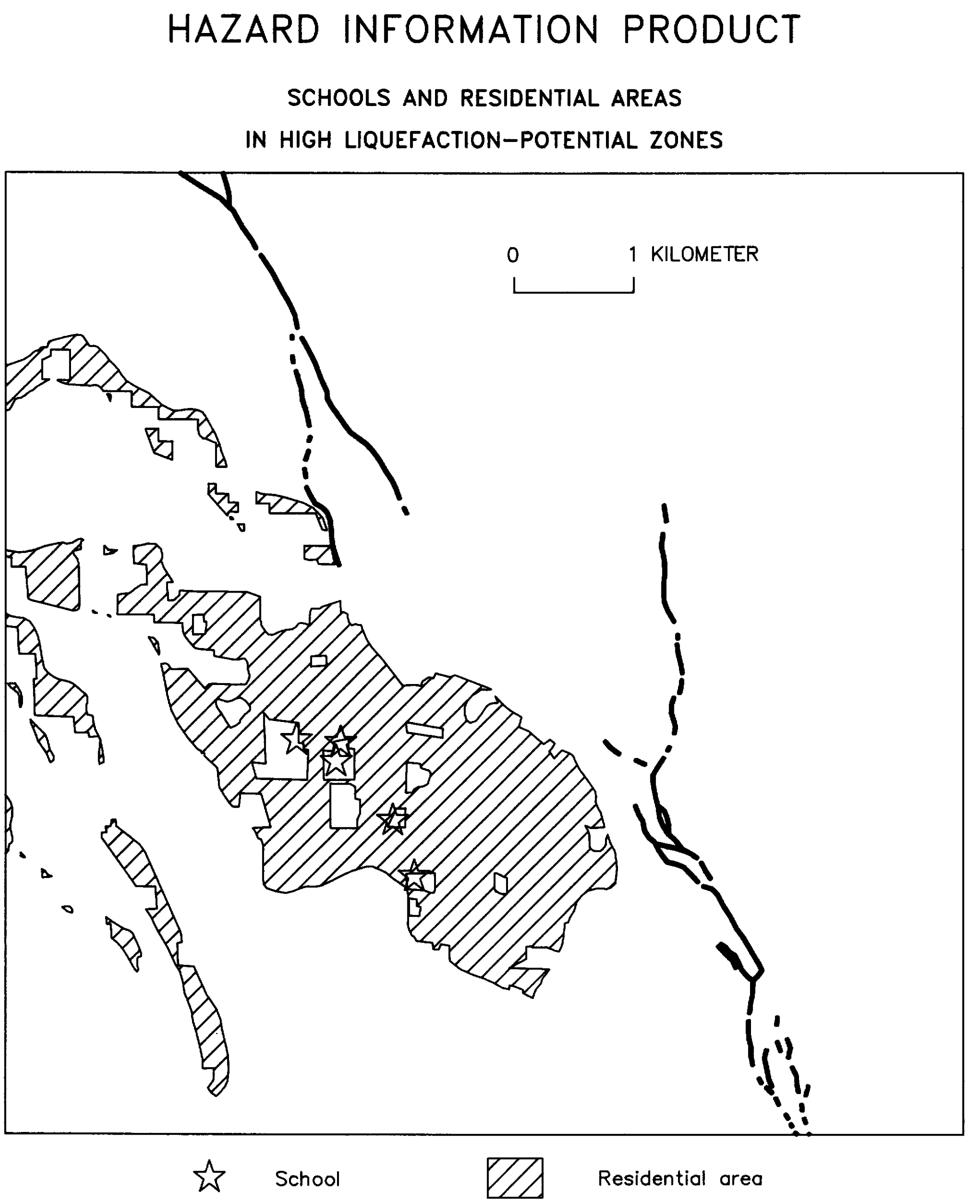


Figure 20. Digital data-base technology provides ready access to earthquake-hazard information critical for land-use planning and for disaster preparation, response, and recovery. Different types of geographically gridded geologic and cultural information (*left*) can be stored in a computer as digital data and easily and rapidly combined and manipulated to generate maps of various earthquake hazards (*above*) and to calculate potential earthquake losses. This figure illustrates derivation of a map for an area in east-central Salt Lake County, Utah, showing where liquefaction during a large earthquake on the Wasatch fault could occur and potentially cause severe damage to schools and residences (*above*). The maps are excerpted from a folio of digital 1:24,000-scale maps for the Sugar House quadrangle, which include standard topographic, geologic, hydrologic, and cultural information from U.S. Geological Survey base maps, such as critical facilities (*A*); geologic-hazard information, such as liquefaction potential (*B*); and land-use information (*C*). This quadrangle was selected as a test site in 1986 to develop and demonstrate applications of digital mapping technology to earthquake-hazard reduction.

Maps of ground shaking are widely used and are incorporated, in modified form, in national building codes. In the past these maps have depicted probabilistic estimates of the level of peak ground acceleration that might be exceeded during a specified time interval. Response spectral amplitudes are currently being incorporated in such maps, but other measures of ground motion should also be incorporated. For example, a map that includes some measure of the duration of shaking would be useful in assessing liquefaction potential in specific regions; the expected levels of shaking could then be combined with local information about soil conditions to assess liquefaction potential. The same could be done for landslide potential, if the research in the previous objective can identify the proper measures of ground motion. In this way, maps of liquefaction potential and landslide potential could be derived from ground-shaking maps.

Although the EHRP has clear responsibility for producing national-scale hazard maps, regional and local maps showing more detailed information are urgently needed by those charged with implementing hazard-reduction measures. With respect to regional and local maps, the EHRP seeks to advance and refine methods of preparation, formats, and content through cooperative pilot projects in high-risk urban regions. The pilot efforts focus on areas within urban regions rather than on the entire regions. An example of such a pilot effort is the U.S. Geological Survey Miscellaneous Investigation Series Map Folio I–1257 (scale 1:62,500) for San Mateo County, California. Produced in part from digital data bases and with Geographic Information System (GIS) technology, the folio includes a geologic map, which is the foundation for many of the other maps, and maps showing faults and earthquake epicenters, ground-shaking intensities, seismic slope stability, liquefaction susceptibility, and potential earthquake damage to types of buildings. Another pilot study has produced larger scale (1:24,000) hazard maps for an urban region in Salt Lake County, Utah (figure 20).

Estimates of future earthquake losses in a region are derived from knowledge of potential earthquake hazards and an inventory of buildings and other structures, including their seismic vulnerability. Methods for estimating losses include both deterministic and probabilistic approaches. The former assumes the occurrence of one or more specific earthquakes; the latter is based on a probabilistic assessment of ground shaking over a particular time interval. Loss estimation is currently limited by the general lack of adequate building inventories and by uncertainties in the vulnerability of various classes of structures to damage from shaking. The reliability of current loss estimates is an important topic for further investigation. Regional or local hazard studies are a good vehicle for demonstrating and improving loss-estimation methods because adequate inventories of structures are more readily assembled.

Tasks:

- Refine methods of mapping potential earthquake effects and estimating earthquake losses.
- Construct national maps of potential earthquake hazards.
- Demonstrate hazard assessment at regional and local scales in selected high-risk urban regions.

Goal IV. Using Research Results

The preceding goals address research directed toward understanding the earthquake process, determining earthquake potential, and predicting earthquake effects. This research will lead to more complete knowledge about the origins, properties, and effects of earthquakes and improved methods for assessing the likelihood, extent, and severity of consequences and losses in future earthquakes. To reduce future losses, however, the results of the research must stimulate, permit, and facilitate government agencies, corporate bodies, or individuals to take specific actions to mitigate earthquake risk. Thus, the success of the EHRP requires effective transfer of hazard information and methods for assessing hazards and risk.

Objective IV-1. Transfer Hazard Information and Hazard-Assessment Methods to Users

The term "transfer" is meant to encompass not just the delivery of information or an assessment method to a person or group interested in or responsible for mitigating risk but also the encouragement or assistance of the person or group in the use of the information or application of the method. Encouragement and assistance are critically important. Published reports may be misused or simply ignored for a variety of reasons: the reader is unfamiliar with or inexperienced in the subject area, the applicability of the report is not immediately evident, the implications of the report are ambiguous, or the reliability of the information is unknown. For effective transfer, the researcher must encourage and guide the use of information or the application of a method.

The transfer process results in rapid and effective use of research findings and also in greater support for and commitment to mitigating earthquake risk. Effective transfer is exemplified by the progress in addressing earthquake hazards along the Wasatch Front in Utah. Other examples of the specific use of technical information in actions to reduce earthquake hazards are found in table 3.

Tasks:

- Deliver hazard-information products and methods for hazard assessment in a usable format to those responsible for mitigating risk.

The Wasatch Front of Utah—An Integrated Earthquake Hazard Reduction Effort

Concern over the threat posed by earthquakes in Utah was expressed more than a century ago (1883) in a newspaper article published in the Salt Lake Tribune by G.K. Gilbert, who achieved pioneering insight into earthquakes through his geological studies of the Great Basin region. Gilbert argued that the presence of fault scarps along the base of the Wasatch Range was evidence of active uplift of the range. Referring to a portion of the Wasatch near Salt Lake City, where he noted that fault scarps were conspicuously absent, he wrote:

> "***the rational explanation of their absence is that a very long time has elapsed since their last renewal. In this period the earth strain has been slowly increasing, and some day it will overcome the friction, lift the mountains a few feet, and re-enact on a more fearful scale the catastrophe of [the 1872] Owens Valley [earthquake]."
>
> "It is useless to ask when this disaster will occur. Our occupation of the country has been too brief to learn how fast the Wasatch grows; and, indeed, it is only by such disasters that we can learn. By the time experience has taught us this, Salt Lake City will have been shaken down***"

To date, the State has been spared the disastrous learning experience that Gilbert foresaw. Extensive, broadly focused studies of the region carried out under the EHRP support a more optimistic outlook on the hope for understanding the earthquake hazards posed by the fault to Salt Lake City and to the Wasatch Front region in general. Today's knowledge clearly indicates the serious nature of the earthquake threat facing the state and provides a basis for coping with the threat through planning and decisions by engineers; by emergency management, zoning, and planning agencies; and by legislative officials.

The Wasatch fault is probably the most intensively studied normal-slip fault in the world. Geologic mapping and trenching of the fault at about 20 key sites have specifically addressed Gilbert's concern about learning "how fast the Wasatch grows" by developing a detailed chronology of Holocene movement on the fault zone. From these studies, large surface-faulting earthquakes are now known to occur somewhere along the Wasatch fault on the average of about once every 400 years.

Although the history of earthquake hazards studies began with Gilbert's concerns in 1883, efforts to systematically address the problem did not start until the 1970's. The State took the initiative in 1977 by forming the Utah Seismic Safety Advisory Council for a 4-year period to "***develop seismic safety programs and educate State and local agencies and the public at large concerning the possibilities for earthquake hazard reduction programs." In 1983, a 5-year integrated earthquake hazard assessment effort was undertaken by the USGS in collaboration with the Utah Geological and Mineral Survey with support from the EHRP. Elements of that effort addressed information systems, hazard evaluation and synthesis, ground-motion modeling, loss estimation, and implementation.

Major products resulting from that program were:

- Geological maps of the Wasatch fault and adjacent surficial geology at 1:50,000 scale
- A detailed history of large earthquakes on the Wasatch fault for the past 6,000 years
- Liquefaction-potential maps for urbanized counties along the Wasatch fault
- A demonstration atlas for earthquake hazard mitigation depicting geological hazard data compiled with digital mapping technology
- Earthquake loss estimates for central Utah

Significant hazard-mitigation activities that resulted from the program include:

- *Employment of county staff geologists.*—Program funds supported three geologists to work in the planning departments of five Wasatch Front counties under the coordination and direction of the Utah Geological and Mineral Survey. Onto 1:24,000-scale maps, they compiled published and unpublished reports containing information about geologic hazards in the five counties. These hazard maps provide a basis for the development and enforcement of hazard ordinances for Wasatch Front counties.
- *County action.*—A hazard ordinance requiring special studies for construction within the zone of fault deformation adjacent to the Wasatch fault was passed by Salt Lake County. In addition, the hazard maps compiled by the county geologists provide a basis for enforcement of existing hazard ordinances in several other counties.
- *State legislation*—Several State intergovernmental committees and a special task force are coordinating efforts to develop a broad package of bills to address issues related to seismic instrumentation, seismic safety of public schools, earthquake-rescue training of firefighters, a State earthquake building code, earthquake insurance, natural hazard notification, and earthquake education in public schools.

- Educate professional groups, government officials, the media, and the public about the nature, extent, and likelihood of earthquake hazards.
- Advise users of hazard-information products and hazard-assessment methods about the applicability and limitations of the information and methods.
- Review and comment on policies, procedures, regulations, and ordinances that cite, interpret, utilize, or apply earthquake-hazard information or hazard-assessment methods.
- Document and evaluate the effectiveness of the transfer process.

PROGRAM EXECUTION

As a problem-focused program aimed at reducing risk to life and property from future U.S. earthquakes, the EHRP encompasses the full spectrum of research from basic to applied and also the transfer of research results to the practitioner. The program incorporates the talents of scientists and engineers from universities, government agencies, private companies, and professional organizations. Success in the program demands the coordination and integration of research efforts and requires effective communication between the research and user communities. To expedite progress toward the goals, the program seeks opportunities to advance understanding of the causes and effects of earthquakes through post-earthquake studies and investigations in foreign countries.

Coordination Among NEHRP Programs

The principal agencies in the National Earthquake Hazards Reduction Program (NEHRP) each fill an important role, but the overall success of the program hinges on the close coordination of the various agency efforts. The primary areas of coordination between the USGS and NSF earthquake programs relate to fundamental earthquake studies, including research on earthquake mechanisms and processes, crustal deformation, and seismology; collection and modeling of strong-motion data; simulation and prediction of strong ground motion; documenting and modeling the dynamic response of structures to ground motion; investigation and prediction of liquefaction; and estimation of losses in future earthquakes. Between FEMA and USGS, coordination centers on the transfer of research results into hazard-reduction actions, education of the public about earthquake hazards, and preparedness for, response to, and recovery from damaging earthquakes. The coordination with NIST concerns the incorporation of earthquake-hazard information into building codes, standards, and practices.

Need for EHRP Advisory Panel

In the early years of the EHRP, the program benefitted from advice concerning the direction and operation of the program by a panel of scientists, engineers, planners, and social scientists from around the country. Not only were the recommendations of the panel helpful in the guidance and management of the program, but also the panel effectively articulated the goals and benefits of the program to various professional constituencies. The value of broadly interdisciplinary advice remains; however, there is currently no such advisory panel for the EHRP.

Role of Academia, State and Local Government, and the Private Sector

Scientists and engineers from academia, State and local government, and the private sector have played a vital role in the EHRP from the outset, both in advisory and planning capacities and also through research and implementation. Universities have also contributed through education and training of earthquake scientists and engineers, many of whom have engaged professionally in earthquake-related work. From the start of the EHRP, one-quarter of the base program funds have financed a vigorous program of competitive grants and cooperative agreements with universities, companies, and State and local governments to support research and to apply research results to hazard reduction.

Continued involvement of professionals from all segments of the earthquake research and hazard-reduction communities is essential to an effective, national hazard-reduction program. A vigorous extramural program of grants and cooperative agreements will be maintained. In high-risk seismic regions, State and local governments will be encouraged to engage in cooperative projects to evaluate and map potential earthquake hazards and estimate potential losses for pilot study areas and to assist in implementation through the application of research results.

Use of Working Groups

Effective hazard reduction demands not only coordination and integration of multidisciplinary research efforts spanning several professions and specialties, but also two-way communication between researchers and those individuals charged with adopting and enforcing hazard-reduction measures. Both these needs can be met through the use of working groups—teams of knowledgeable individuals charged with addressing a problem or issue that encompasses regional, national, or topical concerns. Commonly, these concerns involve recommending priorities for allocation of resources among competing interests.

Regional working groups. Under the EHRP, studies of earthquake potential are conducted in many regions of the country simultaneously; however, comprehensive investigations of earthquake hazards are focused in only a few high-risk regions. Currently, regional hazard studies are focused on the Los Angeles metropolis, the San Francisco Bay region, the Seattle-Portland area, and the Memphis-St. Louis area. Working groups are used to plan and guide the investigations within each of these regions.

Although the staffing composition and scope of activities of a working group varies from one region to another, regional working groups typically comprise seismologists, geologists, engineers, planners, and emergency management personnel. A working group often includes scientists who reside outside the region but are experts on the region. The tasks of a working group could be to define the earthquake hazard problems and issues to be addressed in the region, to identify the needs for information and knowledge, to define the scope and format of the products through which research results would be implemented into measures for reducing hazards and risk, to review research progress and needs, and to ensure the effective transfer of hazard information and hazard-assessment techniques to the local user community.

National working groups. Because certain EHRP activities are wide in scope and impact a large number of institutions or professionals, the planning, operation, coordination and oversight of these activities can be aided by working groups. Some activities involve several disciplines and demand that ideas and results from diverse but complementary disciplines be integrated or that competing interests be balanced; others encompass just a single discipline and require that standards be set—whether they be for instrumentation, data, or practice—or that limited resources be allocated.

Examples of effective national working groups include the National Earthquake Prediction Evaluation Council, which advises the Director of the USGS on the validity of earthquake predictions and forecasts, and those groups that deal with the construction of national ground-shaking hazard maps by the USGS. The latter groups have been established by a number of organizations outside the USGS, including the National Center for Earthquake Engineering Research, the Building Seismic Safety Committee of FEMA, and the Structural Engineers Association of California. The group members comprise practicing and research engineers and earth-science researchers. The working groups assure that the map products fill the needs of users and will be accepted by them.

Several other national-scale activities within the EHRP would benefit from working groups, including national and regional seismic monitoring, the nationwide strong-motion recording program, and geodetic surveying for crustal deformation. A working group on seismic monitoring could define standards for instrumentation and for analysis and archiving of data and could recommend priorities for preserving and upgrading regional networks in the face of limited resources. Strong-motion data collection and geodetic measurements, particularly those based on Global Positioning System technology, are activities involving many governmental and academic organizations. Working groups in these areas could assure that the most essential data are collected without unnecessary overlap, that the standards for data collection are appropriate, and that data are processed in a uniform manner and stored in common formats. Furthermore, the working groups could facilitate access to the data by all interested users.

The need for most national working groups would persist as long as the activity continued, although occasionally a group might be established to address a specific short-term issue.

Topical working groups. Working groups can also be assembled to address a single specific task, examples of which have included tabulation of slip-rate information for California faults as input data for the construction of probabilistic ground-motion maps, estimation of the probabilities of large earthquakes along the San Andreas fault system and along the faults in the San Francisco Bay region, and monitoring the Parkfield, California, area for possible precursory signals before the expected magnitude 6 earthquake. Working groups have very successfully dealt with such topics; their further use should be encouraged.

Topical working groups could also deal with program activities that require significant expenditures for instrumentation and personnel, such as focused fault-zone studies, investigations using portable seismic arrays, and studies of site response with integrated, three-dimensional special-purpose arrays. An important role of the working groups would be to choose between competing interests and priorities. In addition to working groups to oversee the collection of data, other topical groups might be involved with the synthesis of existing data into hazard-reduction products or to define critical gaps in knowledge and suggest appropriate experiments and studies to fill them. An example of the latter would be a working group concerned with subduction-zone processes common to the Pacific Northwest and southern Alaska.

Role of Post-Earthquake Investigations

Investigations of faulting, ground failure, and damage in the aftermath of large earthquakes, along with focused seismic and geodetic studies, are essential parts of the EHRP. Not only do they test the understanding of earthquake processes and effects, they also allow a wealth of valuable data to be collected in a short time. Among the important earth-science topics that can be studied following earthquakes are the extent and character of surface faulting, crustal deformation, and aftershock activity; the extent and geometry of faulting at depth; and the influence of geological, hydrological, and geotechnical subsurface conditions on patterns and severity of ground shaking, ground failure, and damage.

Role of Foreign Investigations

Earthquakes are a global phenomenon, and much information needed to fulfill the goals of earthquake-hazard reduction in the United States can be obtained more expeditiously from studies performed in other countries. For example, the large earthquakes that have occurred in the interior of Australia during recent years may be analogous to shocks that could occur in the Eastern U.S., a region for which few seismic data are available but one in which a large event could be particularly disastrous. Another example is the coseismic subsidence in southern Chile, study of which has aided interpretation of the possible seismic significance of coastal subsidence in the Pacific Northwest.

The fact that few of the world's major earthquakes occur in the United States means that post-earthquake investigations in foreign countries can greatly expedite understanding of earthquake phenomena and the reliable prediction of earthquake effects in future U.S. shocks. Furthermore, the exchange of ideas and methods and the sharing of data with foreign colleagues often lead to significant advances in knowledge and stimulate new research. Although foreign studies may be expensive, their higher costs can be outweighed by the benefits to be realized. Foreign studies should be included in the EHRP.

PROGRAM OPTIONS AND ACTIVITIES

This chapter recommends the scope and balance of activities by which the reformulated program goals should be addressed in the context of two funding options—$50 million and $100 million. These recommendations derive from the intensive review of the EHRP conducted in 1990 (appendix 1). At that time, the cumulative effects of inflation seriously jeopardized the vitality and rate of progress of the EHRP. The base funding for the program was $35 million, which in terms of constant-value dollars was about 57 percent of the funding provided in 1978, the inaugural year of the National Earthquake Hazards Reduction Program. The destruction wrought by the Loma Prieta earthquake alarmed the Nation and spurred interest in intensifying efforts to reduce future earthquake losses. In this context, recommendations were developed for two enhanced funding options. The $50 million option would restore health to a successful but dwindling program; some of the additional funding would revitalize lagging critical areas of the program but most would be used to rebuild personnel, instrumentation and laboratory resources, all of which had been ravaged by years of increasing costs in the face of fixed-level funding. The $100 million option would support vigorous pursuit of the promising new directions, highlighted in the section "New Directions," significantly strengthen successful activities currently being pursued, and greatly accelerate progress toward the program goals.

The most informative way to discuss program scope, balance, and priorities is in terms of the activities by which the program goals are addressed. Activities that relate directly and primarily to one of the four program goals can be defined as follows:

Goal	*Activity*
Understanding the earthquake source	Laboratory and fault-modeling studies Fault-zone studies
Determining earthquake potential	Framework studies, fault studies, and forecasting Earthquake monitoring and seismic studies Geodetic surveys and crustal-deformation studies Intense local monitoring and prediction
Predicting earthquake effects	Ground-shaking studies Ground-failure studies Mapping effects and estimating losses
Using research results	Transferring information and methods

Some of the activities contribute to more than a single program goal; in such cases the activity is listed with the goal to which the activity is most central. For example, although data from seismograph networks are critical for studying earthquake source processes, earthquake monitoring is discussed under the goal of determining earthquake potential, where it plays a larger role.

Table 1 shows the recommended breakdown of funding to these activities for the two program options. Also included is the breakdown for fiscal year 1990, which is the base year to which the discussion of the $50 million expanded program option refers. Table 2 compares the levels of selected program activities to be realized in

1995 under the enhanced funding. options with the 1990 levels, under the assumption that the enhanced funding was to begin in 1991.

Fiscal Year 1990 Program

The largest activity—nearly 40 percent of the fiscal year 1990 program—comprised earthquake monitoring and seismic studies. Included in this activity are the operation of seismograph networks for the purposes of identifying seismically active regions and geologic structures, understanding the origins of seismicity and the generation and propagation of earthquake waves, and informing the public about earthquake occurrences. A third of the program comprised three activities of comparable size: framework studies, fault studies, and forecasting; intense local monitoring and prediction; and ground-shaking studies. The first activity includes geologic and geophysical investigations of the tectonic and structural framework of earthquake zones, geologic studies to determine slip rates of active faults and dates of prehistoric earthquakes, and long-term (scale of decades) forecasting of future earthquake activity. Intense local monitoring and prediction incorporates research on methods for predicting the occurrence of future earthquakes with a precision measured in hours to weeks and focused efforts to document precursory phenomena and co-seismic earthquake effects for the expected earthquake on the Parkfield segment of the San Andreas fault in central California. Ground-shaking studies encompass both the collection and interpretation of ground-shaking data and the development of improved methods for predicting the severity and character of shaking from postulated earthquakes for various geologic site conditions.

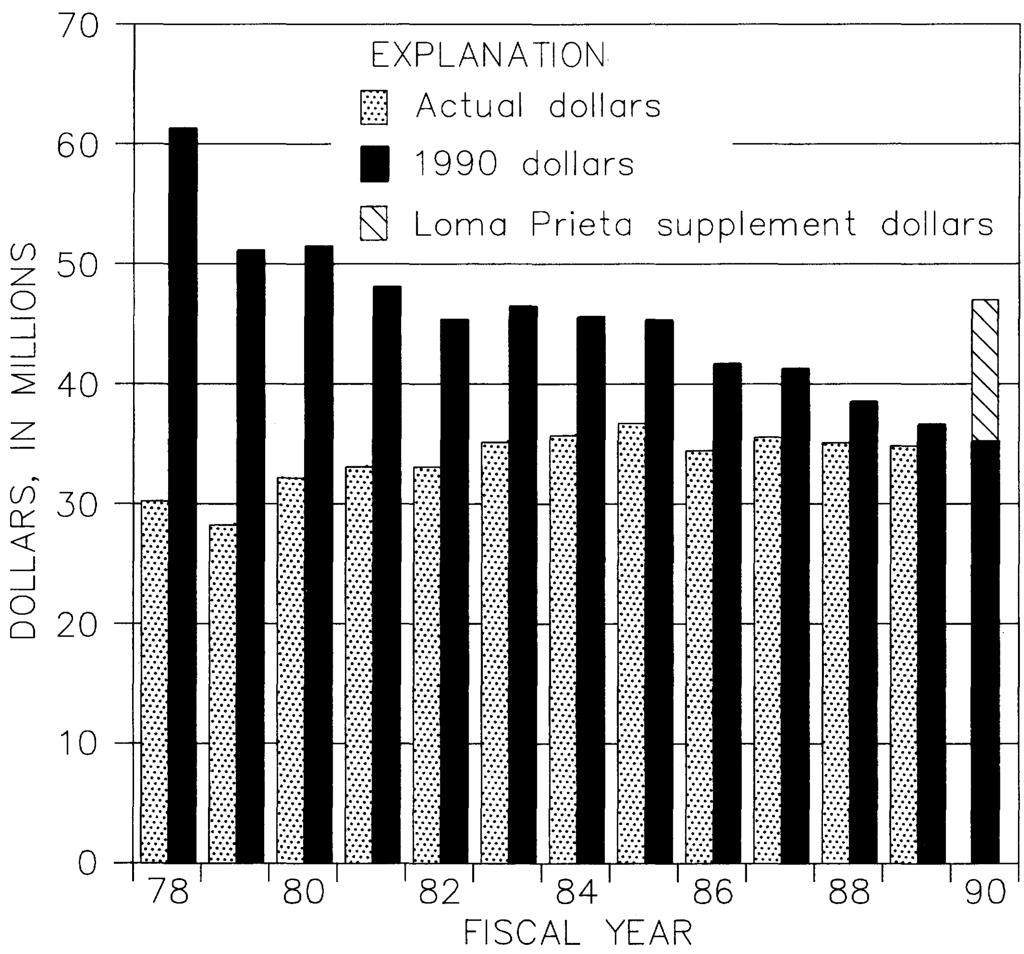


Figure 21. Real funding support for the Earthquake Hazards Reduction Program declined from 1978 through 1990. In fiscal year 1990, the base funding was supplemented with a $12 million emergency appropriation for investigations of the Loma Prieta earthquake. In terms of constant-value dollars referenced to the urban consumer price index, the base funding level of the EHRP in 1990 was 57 percent of the level in 1978, the first year of the National Earthquake Hazards Reduction Program.

Table 1. Funding options for the Earthquake Hazards Reduction Program

[Dollars in millions]

Goals and activities	FY 1990		$ 50 M Option		$ 100 M Option	
	Dollars	Percent	Dollars	Percent	Dollars	Percent
Understanding the earthquake source	**3.8**	**11**	**4.7**	**10**	**13.7**	**14**
Laboratory and fault-modeling studies	2.8	8	3.5	7	4.7	5
Fault-zone studies	1.0	3	1.2	3	9.0	9
Determining earthquake potential	**23.6**	**67**	**30.6**	**61**	**55.1**	**55**
Framework studies, fault studies, and forecasting	4.1	11	5.5	11	14.0	14
Earthquake monitoring and seismic studies	13.6	39	17.1	34	25.1	25
Geodetic surveys and crustal-deformation studies	1.7	5	2.7	5	5.2	5
Intense local monitoring and prediction	4.2	12	5.3	11	10.8	11
Predicting earthquake effects	**6.6**	**19**	**12.7**	**25**	**27.2**	**27**
Ground-shaking studies	4.0	11	6.6	13	12.1	12
Ground-failure studies	0.1	<1	1.6	3	4.6	5
Mapping effects and estimating losses	2.5	7	4.5	9	10.5	10
Using research results	**1.0**	**3**	**2.0**	**4**	**4.0**	**4**
Transfer of technical information and methods						
Totals	**35.0**	**100**	**50.0**	**100**	**100.0**	**100**

The remainder of the program comprised laboratory, modeling, and fault-zone studies directed toward achieving a physical understanding of the mechanics of earthquake faulting; geodetic surveys and crustal-deformation studies to document and model the accumulation and release of crustal strain during the earthquake cycle; development and demonstration of methods for mapping geologic earthquake hazards (ground shaking, landsliding, and liquefaction) and for estimating future earthquake losses; and transferring to practitioners and the public technical information on potential geologic earthquake hazards and methods for assessing such hazards. Little effort was directed toward ground-failure studies, that is, geologic and geotechnical studies to document and model earthquake-triggered liquefaction and landsliding and to predict ground failures in future earthquakes.

A strong consensus emerged from the 1990 program review (appendix 1) that all the activities in the fiscal year 1990 program were essential; that inflation during the 1980's had reduced the program to critical core activities, none of which was adequately funded; and that none of the activities should be eliminated to allow some other activity to proceed or start in its place. The review identified some acute deficiencies in the EHRP:

•The strong-motion recording effort was weak; there was a critical need to document ground motion near the source of earthquakes larger than magnitude 7.0 and the influence of weak soils, deposits, and fills on patterns of shaking, ground failure, and damage.

•Geologic and geotechnical studies of earthquake-triggered ground failures received little support, although ground-failure studies had been a high priority in the early years of the EHRP.

•Little attention was focused on earthquake investigations and regional seismic monitoring in the United States east of the Rocky Mountains; but until recently the Nuclear Regulatory Commission adequately supported such activities, while the resources of the EHRP were focused on earthquake problems in the Western States.

•Geodetic surveys were focused primarily on the San Andreas fault system; little attention was directed toward measuring current rates of crustal deformation in other active seismic regions and in other tectonic regimes.

•Although markedly increased scientific understanding of earthquake potential and hazards in much of the United States had provided the basis for educating government officials, business leaders, and the public about the earthquake threat, to realize the full benefits of this knowl-

Table 2. Projected levels of selected program activities in 1995 under the two funding options compared to levels in 1990

Program activity	Unit of measure	1990	1995* $50 M Option	1995* $100 M Option
Understanding the earthquake source				
Laboratory studies and fault modeling	Person-years	24	27	32
Fault-zone studies	Person-years	10	10	20
	Medium-depth holes	0	0	3
Determining earthquake potential				
Geologic mapping and prehistoric earthquake studies	Person-years	40	35	50
Geophysical surveys	Surveys/year	0	1	4
Seismic networks				
Global	Digital stations	30	128	200
National	Digital stations	0	140	150
Regional	Networks	12	12	15
	Analog stations	850	900	200
	Digital stations	20	50	1000
Geodetic surveys				
Geodolite	Lines/year	300	100	100
GPS	Stations/year	500	800	1200
Intensified local monitoring	Areas monitored	1	2	5
Predicting earthquake effects				
Strong-motion recorders	Stations	150	200	250
Ground-motion arrays	Surface arrays	5	10	15
	3-D arrays	0	2	6
Structural-response arrays	Arrays	20	30	45
Ground-failure arrays	Arrays	1	3	7
Focused regional hazard studies	Regions studied	1	4	8

* Figures for 1995 assume an annual inflation rate of 5 percent.

edge, better communication both with the planning, engineering, construction, and emergency-management communities and with the media and public was needed to ensure effective transfer of earthquake-hazard information and hazard-assessment methods.

$50 Million Option

The $50 million option would relax the financial squeeze that had been crippling the EHRP in 1990, increase funding for program activities that were suffering disproportionately, bolster support of ongoing efforts to make them fully effective again, and support a few modest new initiatives. Although this option represents a substantial increase in funding over the fiscal year (FY) 1990 base, it does not even equal the level of program support during 1978, as measured in constant-value dollars.

To address deficiencies in the FY 1990 program, increased emphasis would be placed on predicting the effects of earthquakes and transferring earthquake-hazard information and research results to the user community and the public. The following paragraphs outline activity and funding increments relative to the FY 1990 program.

Laboratory and Fault-Modeling Studies
Fault-Zone Studies

•Intensify laboratory, field, and theoretical investigations of rock physics, fault rupture nucleation and propagation, and modeling the earthquake cycle ($0.9

M). At this level of funding, fault-zone and induced-seismicity studies incorporating deep drilling and extensive three-dimensional geophysical investigations could not be undertaken. Rather the increased funding would support other field studies of fault-zone structure, plus laboratory and theoretical work related to the weak San Andreas fault, to other major faults, and to complex three-dimensional networks of faults.

Framework Studies, Fault Studies, and Forecasting

•Expand geologic studies to determine rates of tectonic deformation and fault slip and to date prehistoric earthquakes. Intensify efforts at long-term forecasting of earthquake potential. (Total $0.9 M).

•Initiate integrated geologic and geophysical studies to relate seismicity to buried geologic structures in regions of extensional or compressional tectonics and in States east of the Rocky Mountains ($0.5 M).

Earthquake Monitoring and Seismic Studies

•Support for this activity, the largest in the current program, would increase by 25 percent, still proportionally less than for other activities.

•Complete the U.S. National Seismograph Network with the installation of digital stations in the Western U.S., including Alaska and Hawaii ($1.0 M).

•Assume support for a number of regional networks in the Eastern U.S., maintain regional networks in the Western U.S., intensify analysis of data from all networks, and increase accessibility of regional network data ($2.5 M). Emphasis would be placed on expanding analysis of network data and preserving the existing regional networks; only limited, incremental upgrading of stations with digital, broad-band, wide-dynamic-range instruments could be contemplated. Half the increased support would be directed toward the Eastern and Central U.S. (States east of the Rocky Mountains) and one-third toward the Western U.S. exclusive of California.

Geodetic Surveys and Crustal-Deformation Studies

•Intensify and expand geodetic surveys to document rates of crustal deformation in areas monitored by regional seismograph networks, especially those in the Intermountain seismic belt and along the convergent plate margin in the Pacific Northwest and in Alaska ($1.0 M).

Intense Local Monitoring and Prediction

•Instrument a second moderate- to high-probability site for a large earthquake to document the physical processes leading to an earthquake ($0.6 M) and the shaking and ground-failure effects resulting from the earthquake (supported under "Ground-Shaking Studies" and "Ground-Failure Studies"). The Parkfield segment of the San Andreas fault system in central California is being intensely monitored by a broad suite of instruments in a real-time earthquake prediction experiment. The instrumentation is designed to monitor seismicity, strain changes, and changes in material properties within the Earth in preparation to the expected earthquake and to document the nucleation and propagation of fault rupture and the shaking effects of the earthquake. In 1990, Parkfield was the only comprehensive, intensive monitoring effort.

•Augment investigations of methods for intermediate- and short-term earthquake prediction ($0.5 M).

Ground-Shaking Studies

•Triple support for collection and dissemination of strong-motion data ($2.0 M). Emphasis would be placed on recording strong ground motion in source zones of earthquakes magnitude 7.0 and larger and on documenting, with special-purpose arrays, the response of various surficial geologic deposits and engineered structures to strong shaking. Digital recorders would be introduced into the national strong-motion instrument network, and a dial-up database would be established. A working group comprising seismologists and geotechnical and structural engineers would provide advice on the direction of the strong-motion recording program and on siting of integrated special-purpose arrays.

•Intensify analysis and modeling of strong-ground-motion data to identify and understand the factors that most strongly affect the character of shaking and its variability from site to site. Develop and improve methods for modeling and predicting ground shaking ($0.6 M).

Ground-Failure Studies

•Revitalize efforts within the EHRP to document, analyze, and predict ground failure and its displacement ($1.5 M). Instrument sites susceptible to failure in regions of high current earthquake potential to document permanent surface and subsurface displacements, seismic loading, and hydrologic effects. Document historical failures and investigate geological, geotechnical, and hydrological properties of the failed areas. Develop improved methods for predicting both the onset of failure and the resultant surface and subsurface displacement.

Mapping Effects and Estimating Losses

•Strengthen and expand national and regional mapping of geologic earthquake effects and improve and demonstrate methods for estimating earthquake losses

($2.0 M). Upgrade national-scale maps of ground shaking by incorporating improved evaluations of earthquake potential and regional attenuation relations and by depicting multiple parameters describing various characteristics of shaking. Conduct cooperative projects to map earthquake effects and estimate potential losses in demonstration areas within the San Francisco Bay region, southern California, the Pacific Northwest, and the central Mississippi Valley.

Transfer of Technical Information and Methods

•Augment communication with and education of user communities and the public ($1.0 M). Working groups would be supported to establish effective communication between the research and user communities. Individuals skilled in communicating technical information to engineers, planners, government officials and the public would be brought into the program. A small regional earthquake-information center would be established as a demonstration project in a region of high seismic risk outside of California in cooperation with a university or State agency operating a regional seismograph network.

$100 Million Option

The $100 million program would fund major new initiatives as well as strengthen current program activities and would greatly accelerate progress toward the EHRP goals. Though large, this increase in the EHRP budget is justified in terms of the magnitude of the earthquake threat to the country, the successful record of the program to date, the current state of scientific knowledge and capability, the recognition of research problems and opportunities, and the emergence of new, more powerful technologies.

Relative to the $50 million program, support for predicting earthquake effects would double; efforts to understand the earthquake source would triple, largely as a consequence of scientific drilling and detailed geophysical surveys to investigate the structure and physical conditions in an active fault zone; investigations of earthquake potential would nearly double; and support for communicating, transferring and using research results would double.

The following paragraphs outline the activity and funding increments relative to the $50 million program.

Laboratory and Fault-Modeling Studies

•Augment laboratory, field and theoretical studies of rock physics, fault rupture nucleation and propagation, and the earthquake cycle ($1.2 M).

Fault-Zone Studies

•Conduct detailed three-dimensional geophysical investigations to determine the structure and physical properties of the geologic materials within active fault zones. Undertake limited, deep scientific drilling to sample fault-zone materials and to monitor physical conditions at seismogenic depths in an active fault zone. Conduct comprehensive geophysical investigations into the mechanisms of induced seismicity. (Total $7.8 M).

Framework Studies, Fault Studies, and Forecasting

•Intensify geologic studies to determine rates of tectonic deformation and fault slip, to date prehistoric earthquakes, and to investigate the regularity or episodicity of earthquakes ($1.5 M).

•Support development and improvement of techniques to date late Quaternary tectonic events ($1.0 M).

•Support regional geologic mapping to identify rates and styles of Quaternary tectonic deformation in several seismic regions throughout the U.S. ($2.5 M).

•Conduct geophysical and seismic-imaging surveys to relate seismicity to buried geologic structures in several seismic regions throughout the U.S. ($3.5 M).

Earthquake Monitoring and Seismic Studies

•Maintain regional seismograph networks across the United States and upgrade instrumentation with broad-band, wide-dynamic-range digital seismographs and expand analysis of regional data ($5.0 M). The regional networks currently use instrumentation that was largely developed 20 years ago. Upgrading the networks to fully digital capability would revolutionize the amount and quality of information pertaining to earthquake source mechanisms, propagation and attenuation of seismic waves, Earth structure, and stresses within the Earth.

•Accelerate completion of the U.S. National Seismograph Network ($0.5 M).

•Expand the number of stations in the Global Digital Seismograph Network and bolster support for the network ($1.0 M).

•Support land-based and ocean-bottom seismograph array studies in support of EHRP goals ($1.5 M).

Geodetic Surveys and Crustal-Deformation Studies

•Intensify and expand geodetic surveys to document annual rates of crustal deformation in areas monitored by regional seismograph networks. Continuously monitor crustal deformation in selected regions of high seismic potential. (Total $2.5 M).

Intense Local Monitoring and Prediction

•Instrument three additional probable sites for large earthquakes to document the physical processes leading to an earthquake ($4.5 M) and the shaking and ground failure effects resulting from the earthquake (supported under "Ground-Shaking Studies" and "Ground-Failure Studies"). The sites should encompass different tectonic settings with at least one in a subduction zone environment. By extending focused arrays of integrated seismic and strain instruments to additional sites, the rate of return will be increased and the data base will be broadened to encompass faults in various tectonic settings.

•Intensify investigations of methods for intermediate- and short-term earthquake prediction ($1.0 M).

Ground-Shaking Studies

•Redouble support for collection and dissemination of strong-motion data ($3.0 M). The goal is to halve the acquisition time for significant suites of strong-motion data that document near-fault shaking and response of engineered structures in earthquakes of magnitude 7.0 or larger and that document effects of local site conditions on shaking.

•Double efforts to develop and improve methods for modeling and estimating ground shaking ($2.5 M).

Ground-Failure Studies

•Triple efforts to document, analyze, and predict seismically induced ground failure and its displacement ($3.0 M).

Mapping Effects and Estimating Losses

•Double efforts to map shaking and ground-failure potential and to estimate losses in at-risk urban areas ($6.0 M). Through cooperative programs with State or local governments, demonstration efforts would be conducted simultaneously in four additional high-risk urban areas across the country.

Transfer of Technical Information and Methods

•Expand communication with and education of user communities and the public ($2.0 M). Activities to transfer hazard information and hazard-assessment methods to user communities would be intensified. Five cooperative regional earthquake information centers would be established in high-risk seismic regions outside of California.

BENEFITS TO THE NATION

The EHRP benefits the Nation by providing a sound base of scientific knowledge regarding earthquakes and their geologic effects. Such knowledge is essential to formulating and implementing effective hazard-reduction measures. Although the EHRP funds few activities that of themselves directly reduce earthquake hazards, most hazard-reduction activities—land use, engineering, preparation, and recovery (see section "Research and Implementation: Two Parts of a Whole")—are based to varying degrees on the results of the EHRP.

Society is willing to support actions to reduce earthquake losses only when it perceives the risk of future losses as significant and when effective hazard-reduction strategies are available. The EHRP contributes to both these requisites. Major progress has been made in understanding and quantifying the potential for damaging earthquakes in several regions of the country, and this progress has led to increased demand and acceptance that efforts be taken to reduce earthquake hazards. For example, EHRP-supported investigations have convinced most earth scientists that magnitude 8 class earthquakes have struck the Pacific Northwest coast (see figure 4) and pose a serious continuing hazard; this recent realization has spurred efforts to assess and reduce earthquake hazards in the region. Another example is from California, where the recently demonstrated capability to estimate the likelihood of damaging earthquakes on specific segments of the San Andreas fault system (see figure 15) is quantifying the earthquake threat and making it more tangible to government officials, corporate leaders, and the public. When the threat can be quantified, the benefits of reducing the hazards are more easily understood and action is more likely to follow. In summary, information on earthquake potential developed by the EHRP has substantially increased awareness of the earthquake threat throughout much of the U.S. and stimulated greater efforts to reduce earthquake losses.

The EHRP has generated a wealth of information about earthquake effects and losses and has provided fresh insights into earthquake phenomena; both these advances have led to new or improved methods for reducing future earthquake losses. For example, the EHRP has developed methods for estimating losses to various classes of buildings for postulated earthquake scenarios, taking into account local variations in ground shaking relating to geology and depth to the water table. Such scenarios have been used as the basis for evaluating seismic vulnerability of urban areas and for planning earthquake-disaster-response exercises. A second example is the documentation and quantification of ground-shaking amplification on weakly consolidated or unconsolidated geologic deposits and artificial fills (see figures 1 and 17); this new knowledge is leading to the adoption of new provisions into building codes to deal with the problem of amplification on weak ground. A final example is the development of the capability to delineate areas of different hazard potential for various earthquake effects—ground shaking, liquefaction, and

Table 3. Earthquake Hazards Reduction Program information products and services for earthquake-hazard reduction

Product/service	FY 1990 program	$50 M option	$100 M option	Uses
Rapid notification of instrumental locations and magnitudes of felt earthquakes	30 minutes	3 minutes in California	3 minutes in all regions monitored by regional seismic networks	Emergency response; public awareness; warnings
Aftershock advisories following large earthquakes	Statement of probabilities in California	Statement of probabilities in Western U.S.	Alarm warnings in advance of strong shaking in pilot test areas	Emergency response and recovery; disaster management; warnings
Maps of current earthquake epicenters	Nation: weekly California: weekly	Nation: on-line California: on-line Other regions: weekly	Nation: on-line All regions: on-line	Education; public awareness
Historical earthquake information	Earthquake catalogs	National and regional on-line data bases	National and regional on-line data bases	Preparedness; engineering design
Long-term earthquake forecasts	San Andreas fault system	Add Cascadia and Gulf of Alaska subduction zones and Wasatch fault system	Extend to other major seismic zones, for example, central Mississippi Valley	Preparedness; long-term mitigation
Strong ground-shaking data and structural-response data from current earthquakes	Available in 6 to 12 months	Available in 1 week to 1 month	Available in 1 day for telemetered stations, 1 week to 1 month for standard stations	Engineering design; design and construction analyses; building codes
Shaking as a function of magnitude and distance	Account for attenuation differences between Western and Eastern U.S.	Account for regional attenuation differences	Account for local variations in geology and site conditions	Engineering design
Compilations of active faults and hypocenters	California	Extend to Pacific NW and central Mississippi Valley	Extend to other active seismic zones	Site investigations; land-use planning; codes
Regional compilations of near-surface geology and geotechnical properties	Miscellaneous maps and data bases for regions of focused hazard assessment	Start cooperative GIS data bases for San Francisco, Los Angeles, Pacific Northwest and central Mississippi Valley regions	Increase information in data bases, construct data bases in additional regions	Engineering design; site investigations; land-use regulations; selecting hazardous-waste sites
Regional ground-shaking maps	Earthquake scenario maps for regions of focused hazard assessment	Time-dependent, probabilistic maps of high-risk regions of focused hazard assessment	Extend time-dependent, probabilistic maps to high-risk regions as geologic/geotechnical data bases permit	Land-use planning; preparedness; disaster-response planning; retrofitting lifelines; damage scenarios; strengthening buildings
Regional ground-failure maps	Ground-failure-susceptibility maps	Earthquake scenario maps of ground failure for San Francisco and Los Angeles regions	Earthquake scenario maps of ground failure for other selected high-risk regions, including Pacific Northwest and central Mississippi Valley	Land-use planning; preparedness; disaster-response planning; site investigation; anticipating outages
Regional and national earthquake loss estimates	Aggregate losses for earthquake scenarios	Probabilistic and scenario loss estimates for California and other high-risk regions	Aggregate losses for selected classes of structures on a national basis	Insurance; cost/benefit studies; public awareness
National ground-shaking map	Probabilistic	Update with improved information, include additional shaking parameters	Update with improved information, include additional shaking parameters	Building codes; training emergency managers; engineering design
Rapid projection of earthquake effects	No capability	Develop capability for San Francisco and Los Angeles	Extend to other high-risk regions	Damage estimates; guide recovery efforts

Table 4. Examples of how information from the Earthquake Hazards Reduction Program is used to reduce earthquake hazards.

[A through Q, see notes below; X, information used in hazard-reduction technique; --, information not used]

Hazard-reduction techniques	Earthquake-hazard information						
	Earthquake likelihood	Earthquake prediction	Surface fault rupture hazard	Ground shaking hazard	Liquefaction potential	Landsliding potential	Tsunami hazard
Public awareness							
Disclosing hazards to homebuyers	X	--	A	X	X	A	X
Recording hazards on public records	X	--	B	X	X	B	X
Transferring information to potential users	C	X	C	C	C	C	C
Estimating losses and replacement costs	--	--	--	D	--	--	--
Emergency preparedness							
Anticipating damage to critical facilities	E	--	E	E	X	X	X
Training emergency managers	X	X	--	F	X	X	X
Securing nonstructural building components	G	--	--	G	--	--	--
Issuing warnings and advisories	X	H	--	H	--	--	X
Land-use planning and development							
Adopting seismic safety policies	X	--	I	I	I	I	I
Selecting hazardous waste sites	--	--	J	J	--	J	X
Estimating damage by building types	--	--	--	K	--	--	--
Regulations							
Requiring site investigations	X	--	L	X	X	X	X
Strengthening unsafe buildings	X	--	--	M	--	--	--
Supplementing building ordinances	--	--	X	X	N	--	--
Reducing development densities	--	--	O	--	--	O	X
Design and construction							
Retrofitting highway overpasses	--	--	X	P	--	--	--
Developing national building codes	Q	--	--	Q	--	--	--
Training design professionals	X	--	X	X	X	X	X

Notes:

A. California mandates sellers to disclose hazards to potential buyers; State association and local boards of realtors provide hazard maps and disclosure forms. Santa Clara County requires disclosure of other hazards.

B. Santa Clara County requires an owner's statement of acceptance of risk to be publicly recorded with land title records.

C. Transfer techniques include creation of seismic-safety organizations, technical assistance, guidelines, geographic-information-system data bases, workshops and their proceedings, education projects, guidebooks, press briefings, newspaper inserts, magazine articles, serial publications, outreach programs, and many others. Users have been targeted in western, southeastern, and northeastern United States, and in the central Mississippi Valley and Pacific Northwest regions. Individual states targeted include Alaska, California, Washington, Idaho, Utah, Arkansas, Tennessee, Missouri, South Carolina, and Massachusetts.

D. National Security Council has assessed consequences and preparations for a catastrophic earthquake.

E. California state geologist and managers of major state and multicounty facilities use scenarios of expected interruptions to utilities, transportation, and communication facilities for emergency planning and training. National Center for Earthquake Engineering Research investigates potential earthquake effects on several existing, large-diameter oil transmission pipelines traversing the New Madrid (central Mississippi Valley) seismic zone.

Table 4. Examples of how information from the Earthquake Hazards Reduction Program is used to reduce earthquake hazards—Continued.

F. Kentucky conducts special earthquake training for firefighters.
G. Federal Emergency Management Agency provides guidebook on evaluating existing safety conditions and vulnerabilities to earthquake damage and suggests protective countermeasures to reduce vulnerabilities.
H. California Governor's Office of Emergency Preparedness warns local governments and the public of increased earthquake probability on the basis of continuous seismic monitoring and analysis of potential earthquake precursors.
I. Santa Barbara County, California, aggregates hazards by computer to prepare seismic safety plans; three cities and three counties in the San Francisco Bay area use seismic zonation methods in their plans and development policies.
J. Association of [San Francisco] Bay Area Governments uses hazards as "strict criteria" in selecting potential toxic-waste sites.
K. Salt Lake City estimates losses and replacement costs for various building types. Association of [San Francisco] Bay Area Governments estimates cumulative damage potential for different building types.
L. California requires cities and counties to designate official, appropriately wide, hazard zones around active faults. Several counties in Utah require site investigations or review of development permit application in designated fault zones.
M. Los Angeles city ordinance requires strengthening or demolition of 8,000 unsafe masonry buildings; ordinance subsequently used as a State model.
N. Redwood City, California, incorporates a map of historic margins of marshlands into their building ordinance and increases standards on unstable baylands.
O. San Mateo County, California, substantially reduces residential densities in hazardous areas to effect seismic safety and resource conservation goals.
P. California Department of Transportation assigns priorities and determines design criteria for retrofitting of highway overpasses.
Q. International Conference of Building Officials relies on probabilistic maps of ground-shaking hazard for seismic risk zone regulations; Charleston, South Carolina, and the States of Kentucky and Massachusetts have adopted mandatory seismic design requirements; several other states are considering adopting such requirements.

earthquake-induced landslides. The 1989 Loma Prieta, California, earthquake validated a number of pioneering maps depicting these earthquake hazards for the San Francisco-Monterey Bay region; the observed patterns of damage corresponded closely to areas identified as hazardous. And, one year after the earthquake, the California legislature enacted the Seismic Hazards Mapping Act, which mandates the delineation of seismic hazard zones comprising areas of high potential for enhanced ground shaking, liquefaction, and landsliding. Within such zones, construction is permitted only when a special site hazard investigation demonstrates that the site is sufficiently safe. This law sharply increases the weight accorded issues of seismic safety in decisions regarding land use and development.

Products of the EHRP that support hazard-reduction practices include both technical information and also methods for determining earthquake potential and evaluating earthquake hazards. The matrix in table 4 illustrates how different types of earthquake-hazard information can be used in various hazard-reduction techniques; several specific applications are cited in the footnotes. The matrix is not meant to be inclusive, but rather to suggest the variety of ways in which technical information from the EHRP is incorporated in specific hazard-mitigation methods.

Of equal importance to technical information provided by the EHRP are the methods developed under the program for determining earthquake potential and predicting earthquake effects. These methods can be used by others in many ways to reduce the effects of earthquakes. Of most direct use are the methods for predicting effects. For example, construction of a shaking hazard map for an urban area requires the capability to predict ground shaking, allowing for earthquake size, distance from the fault, and local and regional variations in geologic structure. Private industry and government agencies can use this capability to predict potential site-specific motions, which are needed for the design of critical facilities, such as power plants, bridges, dams, schools, and hospitals.

Widespread availability of hazard assessment methods to the broad community of practitioners is essential. For example, the funding levels of the EHRP discussed in this report limit the scope of regional hazard studies to pilot mapping efforts focused on selected areas within a few high-risk urban regions, but these pilot efforts can be extended by local, regional, and State agencies to complete hazard mapping for an entire urban region and to map additional regions.

By building on what has been accomplished, the EHRP is positioned to strengthen the technical, earth-science basis for effective measures to reduce the loss of life and damage to property in future earthquakes. Augmented program funding would significantly expand the depth and scope of the EHRP information services and products that directly support hazard-reduction activities. Table 3 indicates how information products and services would be enhanced relative to those available in fiscal year 1990.

Improved information products would support and stimulate new hazard-reduction activities. For example, mapping of potential ground shaking, ground failure, and building damage is most commonly used today in the land-use, engineering, and preparation aspects of earthquake-hazard mitigation. But this capability could also be applied to enhance earthquake-disaster response and recovery through the immediate production of projected damage and loss maps upon the occurrence of a large earthquake (see figure 20). Such maps could define the probable location and severity of earthquake damage and could be used to guide disaster relief efforts in the critical first few tens of hours following a large shock, when the scope of the disaster is uncertain. A requisite for such maps is a large on-line computerized data base with sufficiently detailed geologic and socioeconomic information.

APPENDIXES 1–3

APPENDIX 1. CONTRIBUTORS

This document is intended to represent the current thinking of the earth-science and earthquake-engineering communities on the direction of the Earthquake Hazards Reduction Program (EHRP). To stimulate discussion and solicit views on program issues and priorities, written ideas and views were solicited by mail in May 1990 from over 600 colleagues with interest in the EHRP.

In addition, a series of six one-day workshops was held across the country in June 1990. These included four regional workshops: Alexandria, Virginia, for the Central and Eastern U.S.; Seattle, Washington, for the Pacific Northwest, Alaska and Hawaii; Salt Lake City, Utah, for the Intermountain region; and Belmont, California, for California. Each regional workshop involved about 25 invited participants from universities, the private sector, State governments, the USGS, and other Federal agencies. The participants represented the broad range of technical interests and roles in the EHRP. The regional workshops comprised small group discussions on research issues, implementation issues, and program priorities; and plenary sessions to hear and evaluate the conclusions and recommendations of the various discussion groups. Two similar workshops were held for U.S. Geological Survey staff: one in Menlo Park, California, and one in Golden, Colorado. The discussions and conclusions from these six workshops and the letters from colleagues provided common threads that were woven into the initial draft of this document.

The initial draft was mailed to about 200 people for review and comment, and a national workshop was held in Denver, Colorado, on August 7-8 to critique and discuss the draft. With the benefit of the criticisms and comments both from letters and from the national workshop, a second draft was prepared and mailed for review in late August. The final draft was prepared with the benefit of the further reviews.

The colleagues who contributed to the ideas in this strategic plan are too numerous to acknowledge individually. Deserving of special recognition, however, are the cochairpersons of the regional workshops, who assisted in planning, hosting, and running the workshops and, most important, prepared summary overviews of the workshops. The participants in the various workshops are recognized at the end of this appendix.

The process of formulating the strategic plan was intense and compressed into a four-month interval. Moreover, it followed only seven months after the Loma Prieta earthquake disaster, which placed extreme demands on the time and attention of most individuals who either participated in or supported this EHRP planning effort. The effort could not have been undertaken without the assistance, enthusiasm and dedication of several individuals in different USGS centers: Wanda H. Seiders, Barbara B. Charonnat, Muriel L. Jacobson, Pamela W. Marsters, Peggy Ann Randalow, and Eleanor M. Olmdahl.

The special contributions of certain individuals to the preparation and completion of this report are recognized. William J. Kockelman contributed table 3, illustrating some uses of information derived by the EHRP. Credits for the illustrations are recognized in appendix 3. The criticisms and review comments of Robert D. Brown, Bruce R. Clark, and Robert E. Wallace and the editorial criticisms and suggestions of Jeffrey A. Troll substantially improved the report. Cynthia C. Ramseyer ably compiled the first drafts of the report under very tight deadlines.

U.S. GEOLOGICAL SURVEY WESTERN REGION WORKSHOP

Menlo Park, California
June 5, 1990

David P. Schwartz, co-chairperson
Ross S. Stein, co-chairperson

D.J. Andrews
Brian F. Atwater
Michael J. Bennett
Manuel G. Bonilla
David M. Boore
Roger D. Borcherdt
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A. Gerald Brady
Thomas M. Brocher
Robert D. Brown, Jr.
Robert C. Bucknam
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Malcolm M. Clark
James H. Dieterich
Jerry P. Eaton
Donna M. Eberhart-Phillips
Stephen D. Ellen
William L. Ellsworth
John R. Evans
Jack F. Evernden
Gary S. Fuis
Jon B. Fletcher
Arthur D. Frankel
Thomas E. Fumal
Andrew Griscom
Thomas C. Hanks
Edwin L. Harp
Thomas H. Heaton
Jennifer W. Harden
Robert C. Jachens
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John C. Lahr
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John O. Langbein
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Walter D. Mooney
Carl E. Mortensen
Robert J. Mueller, Jr.
L.J. Patrick Muffler
Robert A. Page
Daniel J. Ponti
Carol S. Prentice
Paul A. Reasenberg
Erdal Safak
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Robert V. Sharp
John D. Sims
Paul A. Spudich
Wayne R. Thatcher
John C. Tinsley
Robert E. Wallace
Peter L. Ward
Ray E. Wells
Carl M. Wentworth
Colin F. Williams
Craig S. Weaver
Mary Lou Zoback

U.S. GEOLOGICAL SURVEY CENTRAL REGION WORKSHOP

Golden, Colorado
June 7, 1990

Stephen H. Hartzell, co-chairperson
Louis C. Pakiser, Jr., co-chairperson

R. Ernest Anderson
Sylvester T. Algermissen
David M. Boore
Robert C. Bucknam
Raymond P. Buland
William M. Brown III
Anthony J. Crone
George L. Choy
William H. Diment
James W. Dewey
Alvaro F. Espinosa
David V. Fitterman
Joan S. Gomberg
Susan K. Goter
Warren B. Hamilton
Margaret G. Hopper
Edgar V. Leyendecker
Frank A. McKeown
Carlos Mendoza
Richard F. Madole
Michael N. Machette
Stuart P. Nishenko
Alan R. Nelson
Sherry D. Oaks
Stephen F. Obermeier
Robert A. Page
David M. Perkins
Albert M. Rogers
William Z. Savage
Robert L. Schuster
Stuart A. Sipkin
William J. Spence
William D. Stanley
James N. Taggart
Arthur C. Tarr
Wayne R. Thatcher

EASTERN UNITED STATES REGIONAL WORKSHOP

Alexandria, Virginia
June 9, 1990

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Robert A. Page, co-chairperson	U.S. Geological Survey
Clifford Astill	National Science Foundation
David M. Boore	U.S. Geological Survey
Robert C. Bucknam	U.S. Geological Survey
Anthony J. Crone	U.S. Geological Survey
Ricardo Dobry	Rensselaer Polytechnic Institute
Thomas Durham	Tennessee Emergency Management Agency
John E. Ebel	Boston College
John R. Filson	U.S. Geological Survey
Lynn Glover III	Virginia Polytechnic Institute
Klaus H. Jacob	Lamont-Doherty Geological Observatory
Arch C. Johnston	Memphis State University
Charles A. Langston	Pennsylvania State University
Charles Lindbergh	The Citadel
Brian J. Mitchell	St. Louis University
Robert A. Phinney	Princeton University
James R. Rice	Harvard University
Lynn R. Sykes	Lamont-Doherty Geological Observatory
Wayne R. Thatcher	U.S. Geological Survey
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Kathleen J. Tierney	University of Delaware
Robert L. Wesson	U.S. Geological Survey
Russell L. Wheeler	U.S. Geological Survey
Charles Yancey	National Institute of Standards and Technology

PACIFIC NORTHWEST, ALASKA, AND HAWAII REGIONAL WORKSHOP

Seattle, Washington
June 11, 1990

Robert S. Crosson, co-chairperson	University of Washington
Robert A. Page, co-chairperson	U.S. Geological Survey
John L. Aho	CH2M Hill
Brian F. Atwater	U.S. Geological Survey
David M. Boore	U.S. Geological Survey
Robert C. Bucknam	U.S. Geological Survey
Gary A. Carver	Humboldt State University
Rodney A. Combellick	Alaska Division of Geological & Geophysical Surveys
C. B. Crouse	Dames and Moore
Eugene D. Humphreys	University of Oregon
Carl E. Johnson	University of Hawaii
Laverne D. Kulm	Oregon State University
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Carole Martens	Washington State Division of Emergency Management
Roger McGarrigle	Van Domelen, Looijenga, McGarrigle, Knauf Engineers
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Stephen P. Palmer	Washington State Division Geology and Earth Resources
Stewart W. Smith	University of Washington
Paul G. Somerville	Woodward-Clyde Consultants
Wayne R. Thatcher	U.S. Geological Survey
Randall G. Updike	U.S. Geological Survey
Craig S. Weaver	U.S. Geological Survey
Robert S. Yeats	Oregon State University

INTERMOUNTAIN REGIONAL WORKSHOP

Salt Lake City, Utah
June 13, 1990

Robert B. Smith, co-chairperson	University of Utah
Robert A. Page, co-chairperson	U.S. Geological Survey
M. Lee Allison	Utah Geological and Mineral Survey
John G. Anderson	University of Nevada, Reno
Walter J. Arabasz	University of Utah
David M. Boore	U.S. Geological Survey
Ronald L. Bruhn	University of Utah
James N. Brune	University of Nevada, Reno
Robert C. Bucknam	U.S. Geological Survey
Kenneth W. Campbell	Dames & Moore
Clifford Frohlich	University of Texas, Austin
Joan S. Gomberg	U.S. Geological Survey
James R. Harris	J.R. Harris & Co.
Carl Kisslinger	University of Colorado
William R. Lund	Utah Geological and Mineral Survey
Michael N. Machette	U.S. Geological Survey
Dennis S. Mileti	Colorado State University
Stuart A. Sipkin	U.S. Geological Survey
Wayne R. Thatcher	U.S. Geological Survey
James Tingey	Utah Division of Comprehensive Emergency Management
Randall G. Updike	U.S. Geological Survey
Terry C. Wallace, Jr.	University of Arizona
T. Leslie Youd	Brigham Young University

CALIFORNIA REGIONAL WORKSHOP

Belmont, California
June 15, 1990

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Robert A. Page, co-chairperson	U.S. Geological Survey
Duncan C. Agnew	University of California, San Diego
William H. Bakun	U.S. Geological Survey
James Begansky	Federal Emergency Management Agency
Vitelmo V. Bertero	University of California, Berkeley
David M. Boore	U.S. Geological Survey
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C. Allin Cornell	Stanford University
Richard K. Eisner	Bay Area Regional Earthquake Preparedness Project
N. Timothy Hall	Geomatrix Consultants
Thomas H. Heaton	U.S. Geological Survey
Donald V. Helmberger	California Institute of Technology
Thomas L. Henyey	University of Southern California
I. M. Idriss	University of California, Davis
David K. Keefer	U.S. Geological Survey
Alan T. Linde	Carnegie Institution of Washington
Thomas K. Rockwell	San Diego State University
David P. Schwartz	U.S. Geological Survey
J. Carl Stepp	Electric Power Research Institute
Wayne R. Thatcher	U.S. Geological Survey
Brian E. Tucker	California Division of Mines & Geology
Randall G. Updike	U.S. Geological Survey
Mark D. Zoback	Stanford University

NATIONAL WORKSHOP

Denver, Colorado
August 7-8, 1990

Robert A. Page, chairperson	U.S. Geological Survey
Keiiti Aki	University of Southern California
Sylvester T. Algermissen	U.S. Geological Survey
Roger G. Bilham	University of Colorado
Gilbert A. Bollinger	Virginia Polytechnic Institute
David M. Boore	U.S. Geological Survey
Roger D. Borcherdt	U.S. Geological Survey
William M. Brown III	U.S. Geological Survey
Ian G. Buckle	State University of New York, Buffalo
Robert C. Bucknam	U.S. Geological Survey
Gary A. Carver	Humboldt State University
Mehmet K. Celebi	U.S. Geological Survey
Brian A. Cowan	Federal Emergency Management Agency
Anthony J. Crone	U.S. Geological Survey
Robert S. Crosson	University of Washington
John N. Davies	University of Alaska
James F. Davis	California Division of Mines and Geology
James W. Dewey	U.S. Geological Survey
James H. Dieterich	U.S. Geological Survey
Ricardo Dobry	Rensselaer Polytechnic Institute
Russell Dynes	University of Delaware
Jerry P. Eaton	U.S. Geological Survey
Thomas C. Hanks	U.S. Geological Survey
James R. Harris	J.R. Harris & Co.
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Thomas H. Heaton	U.S. Geological Survey
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Arch C. Johnston	Memphis State University
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Carl Kisslinger	University of Colorado
Dennis H. Kwiatkowski	Federal Emergency Management Agency
Allan G. Lindh	U.S. Geological Survey
Ian Madin	Oregon Dept. of Geology and Mineral Industries
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Robin K. McGuire	Risk Engineering Inc.
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Sherry D. Oaks	U.S. Geological Survey
Norman K. Olson	South Carolina Geological Survey
Elaine R. Padovani	U.S. Geological Survey
William H. Prescott	U.S. Geological Survey
David P. Schwartz	U.S. Geological Survey
Kaye M. Shedlock	U.S. Geological Survey
Kerry E. Sieh	California Institute of Technology
James E. Slosson	Slosson and Associates
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Paul G. Somerville	Woodward-Clyde Consultants
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Charles C. Thiel, Jr.	Private Consultant
James Tingey	Utah Division of Comprehensive Emergency Management
Terry E. Tullis	Brown University
Gregory E. van der Vink	IRIS Consortium
Robert L. Wesson	U.S. Geological Survey
James H. Williams	Missouri Division of Geology and Land Survey
Richard N. Wright	National Institute of Standards and Technology
Robert S. Yeats	Oregon State University
T. Leslie Youd	Brigham Young University

APPENDIX 2. SYNOPSIS OF THE USGS EARTHQUAKE HAZARDS REDUCTION PROGRAM IN 1990

The goal of the Earthquake Hazards Reduction Program is to mitigate earthquake losses throughout the Nation by providing earth-science data and evaluations required for land-use planning, engineering design and emergency-preparedness decisions. Specific objectives are to: (a) evaluate the earthquake potential of seismically active areas of the United States; (b) predict damaging earthquakes; (c) perform concentrated assessments of earthquake hazards and risk in selected urban regions exposed to the earthquake threat; (d) provide data and information on earthquake occurrences to the public and scientific community; and (e) provide data on the estimates of the level and character of strong earthquake motion for architects, planners, and engineers.

The program is divided into five elements with supporting objectives:

Current Tectonics and Earthquake Potential Studies

Seismological and geological analyses of current seismic activity, active geologic faults, and earthquake potential of seismic regions throughout the United States.

Objectives:

•Delineate seismically active areas and the extent of seismic zones through monitoring with regional seismograph networks.

•Determine the geometry and structure of seismic zones through geologic mapping and geophysical analyses.

•Estimate fault slip rates, maximum earthquakes, and earthquake recurrence intervals for active faults and seismic zones.

Earthquake Prediction Research

Field experiments, laboratory studies and theoretical investigations of fault mechanics and earthquake physics to acquire the knowledge and to establish the procedures needed for reliable forecasting (long-term) or prediction (short-term) of the time, place and magnitude of specific earthquakes.

Objectives:

•Develop earthquake prediction methods and techniques to provide a rational basis for estimates of increased earthquake potential and reliable short-term predictions.

•Evaluate in probabilistic terms the relevance of various geophysical, geochemical, and hydrologic data to accurate earthquake prediction.

•Develop theoretical and laboratory models of the earthquake process to guide observational experiments and to test empirical prediction techniques.

•Determine the physical mechanism for induced seismicity caused by reservoir loading, fluid injection, or fluid withdrawal, and develop techniques for predicting and mitigating this phenomenon.

Regional Earthquake Hazards Assessments

Research on methods for evaluating and delineating earthquake hazards and risks and demonstration of such methods by application in selected high-risk regions of the United States.

Objectives:

•Prepare synthesis reports and maps based on current research results that assess earthquake hazards in urban regions at risk from damaging earthquakes.

•Test and apply techniques for estimating strong ground shaking, surface faulting, ground failure, and other earthquake-related hazards in urban regions.

•Conduct research and specific studies to estimate potential losses associated with earthquakes.

•Foster utilization of the results in terms of loss reduction measures.

Earthquake Data and Information Services

Collection and dissemination of data on earthquake occurrence to the public, other Federal agencies, State and local governments, emergency response organizations, and the scientific community.

Objectives:

•Operate national and global networks of standardized seismograph stations for the detection and location of felt and potentially felt earthquakes.

•Provide 24-hour reporting service for the occurrence of potentially damaging U.S. earthquakes.

•Disseminate earthquake data and information to the public and the seismological community.

Engineering Seismology

Documentation of and research on strong ground motion and its effects on manmade structures for the seismic-resistant design and construction of buildings, dams, and critical facilities.

Objectives:

•Operate a national network of strong motion recorders to document strong shaking of the ground and in structures near the source of damaging earthquakes.

•Archive these data and disseminate them to engineers, designers, private institutions, and government agencies concerned with the siting, design, and construction of critical facilities and the establishment of building codes.

•Develop techniques and standards for presenting the strong-motion data in a more useful context.

•Conduct research on the estimation of the level and character of strong motion for application in engineering design.

•Conduct research on the physics of earthquakes and the processes controlling strong ground motion.

APPENDIX 3. FIGURE CREDITS

Figure 1. Photograph courtesy of Lloyd S. Cluff, Pacific Gas and Electric, San Francisco, Calif. Seismic records from fig. 2 of S.E. Hough, P.A. Friberg, R. Busby, E.F. Field, K.H. Jacob, and R.D. Borcherdt, 1989, Did mud cause freeway collapse?: EOS, Transactions, American Geophysical Union, v. 70, no. 47, p. 1497 and 1504. Geology from R.D. Borcherdt, J.F. Gibbs, and K.R. Lajoie, 1975, Maps showing maximum earthquake intensity predicted in the southern San Francisco Bay region, California, for large earthquakes on the San Andreas and Hayward faults: U.S. Geological Survey Miscellaneous Field Studies Map MF-709, scale 1:125,000.

Figure 2. Courtesy of James J. Mori, U.S. Geological Survey, Pasadena, Calif.

Figure 3. Courtesy of Michael Lisowski, U.S. Geological Survey, Menlo Park, Calif.

Figure 4. Photograph courtesy of Brian F. Atwater, U.S. Geological Survey, Seattle, Wash.

Figure 5. Modified from fig. 1 of M.D. Zoback, M.L. Zoback, V.S. Mount, J. Suppe, J.P. Eaton, J.H. Healy, D. Oppenheimer, P. Reasenberg, L. Jones, C.B. Raleigh, I.G. Wong, O. Scotti, and C. Wentworth, 1987, New evidence on the state of stress of the San Andreas fault system: Science, v. 238, p. 1105-1111.

Figure 7. Modified from fig. 3 of H. Kanamori and K. Satake, 1990, Broadband study of the 1989 Loma Prieta earthquake: Geophysical Research Letters, v. 17, p. 1179-1182.

Figure 8. Courtesy of David H. Oppenheimer, U.S. Geological Survey, Menlo Park, Calif. Vertical section modelled after fig. 1 of C. Mendoza and S.H. Hartzell, 1988, Aftershock patterns and main shock faulting: Bulletin of the Seismological Society of America, v. 78, p. 1438-1449. Seismicity from the data files of the Northern California Seismograph Network, U.S. Geological Survey, Menlo Park, Ca. Slip contours from S.H. Hartzell and T.H. Heaton, 1986, Rupture history of the 1984 Morgan Hill, California, earthquake from the inversion of strong motion records: Bulletin of the Seismological Society of America, v. 76, p. 649-674.

Figure 9. Modified from fig. 5 of R.M. Hamilton and A.C. Johnston, eds., 1990, Tecumseh's prophecy: Preparing for the next New Madrid earthquake: U.S. Geological Survey Circular 1066, 30 p. Seismicity from the Central Mississippi Valley Earthquake Bulletin of St. Louis University. Original figure prepared by Frank A. McKeown, U.S. Geological Survey, Golden, Colo.

Figure 10. Courtesy of Susan K. Goter, U.S. Geological Survey, Golden, Colo. Seismicity from data base compiled by E.R. Engdahl for Seismicity map of North America, published by the Geological Society of America, Boulder, Colo. as part of the Decade of North American Geology Project.

Figure 11. Seismicity for California and western Nevada from data files of the northern and southern California seismograph networks operated, respectively, by the U.S. Geological Survey, Menlo Park in cooperation with the University of Nevada, Reno and by the U.S Geological Survey, Pasadena in cooperation with the California Institute of Technology; courtesy of Jerry P. Eaton, U.S. Geological Survey, Menlo Park. Seismicity for the Intermountain region from University of Utah regional seismograph network; courtesy of Susan J. Nava, University of Utah. Seismicity for eastern Tennessee region from bulletins of the Southeastern United States Seismic Network; courtesy of Matthew S. Sibol, Virginia Polytechnic Institute and State University.

Figure 12. Modified from fig. 7 of M. Lisowski, J.C. Savage, and W.H. Prescott, 1991, The velocity field along the San Andreas fault in central and southern California: Journal of Geophysical Research, v. 96, p. 8369-8389.

Figure 13. Data from K. Sieh, M. Stuiver, and D. Brillinger, 1989, A more precise chronology of earthquakes produced by the San Andreas fault in southern California: Journal of Geophysical Research, v. 94, p. 603-623.

Figure 14. Photograph courtesy of A.R. Ramelli and R.A. Whitney, University of Nevada, Reno. Geologic map features from K.V. Luza, R.F. Madole and A.J. Crone, 1987, Investigation of the Meers fault, southwestern Oklahoma: Oklahoma Geological Survey Special Publications 87-1, 75 p. Seismicity adapted from K.V. Luza, Oklahoma Geological Survey (written commun.) and from K.V. Luza, 1989, Neotectonics and seismicity of the Anadarko Basin, in K.S. Johnson, ed., The Anadarko Basin Symposium, 1988: Oklahoma Geological Survey Circular 90, p. 121-132.

Figure 15. Modified from fig. 3 of Working Group on California Earthquake Probabilities, 1988, Probabilities of large earthquakes occurring in California on the San Andreas fault: U.S. Geological Survey Open-File Report 88-398, 62 p.

Figure 16. Modified from fig. 4 of S.P. Jarpe, L.J. Hutchings, T.F. Hauk, and A.F. Shakal, 1989, Selected strong- and weak-motion data from the Loma Prieta earthquake sequence: Seismological Research Letters, v. 60, p. 167-176.

Figure 17. Adapted from fig. 3 of D.M. Boore, L. Seekins, and W.B. Joyner, 1989, Peak accelerations from the 17 October 1989 Loma Prieta earthquake: Seismological Research Letters, v. 60, p. 151-166.

Figure 18. Aerial photograph by U.S. Army. Ground photograph by Robert A. Page.

Figure 20. Adapted from plates 9, 13, 16, and 20 of R.H. Alexander, M.P. Crane, L.M. Firestone, E. Jessen, C.S. Mladinich, and C.L. Rich, 1987, Applying digital cartographic and geographic information systems technology and products to the USGS National Earthquake Hazards Reduction Program: U.S. Geological Survey, National Mapping Division, Final Report, Research Project RMMC 86-1.

SELECTED SERIES OF U.S. GEOLOGICAL SURVEY PUBLICATIONS

Periodicals

Earthquakes & Volcanoes (issued bimonthly).
Preliminary Determination of Epicenters (issued monthly).

Technical Books and Reports

Professional Papers are mainly comprehensive scientific reports of wide and lasting interest and importance to professional scientists and engineers. Included are reports on the results of resource studies and of topographic, hydrologic, and geologic investigations. They also include collections of related papers addressing different aspects of a single scientific topic.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers. They include the results of resource studies and of geologic and topographic investigations; as well as collections of short papers related to a specific topic.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrogeology, availability of water, quality of water, and use of water.

Circulars present administrative information or important scientific information of wide popular interest in a format designed for distribution at no cost to the public. Information is usually of short-term interest.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are reproduced on request unlike formal USGS publications, and they are also available for public inspection at depositories indicated in USGS catalogs.

Open-File Reports include unpublished manuscript reports, maps, and other material that are made available for public consultation at depositories. They are a nonpermanent form of publication that may be cited in other publications as sources of information.

Maps

Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7 1/2- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps are on topographic or planimetric bases at various scales; they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7 1/2-minute quadrangle photogeologic maps on planimetric bases which show geology as interpreted from aerial photographs. Series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

Oil and Gas Investigations Charts show stratigraphic information for certain oil and gas fields and other areas having petroleum potential.

Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases on quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects such as environmental studies or wilderness mineral investigations.

Hydrologic Investigations Atlases are multicolored or black-and-white maps on topographic or planimetric bases presenting a wide range of geohydrologic data of both regular and irregular areas; principal scale is 1:24,000 and regional studies are at 1:250,000 scale or smaller.

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