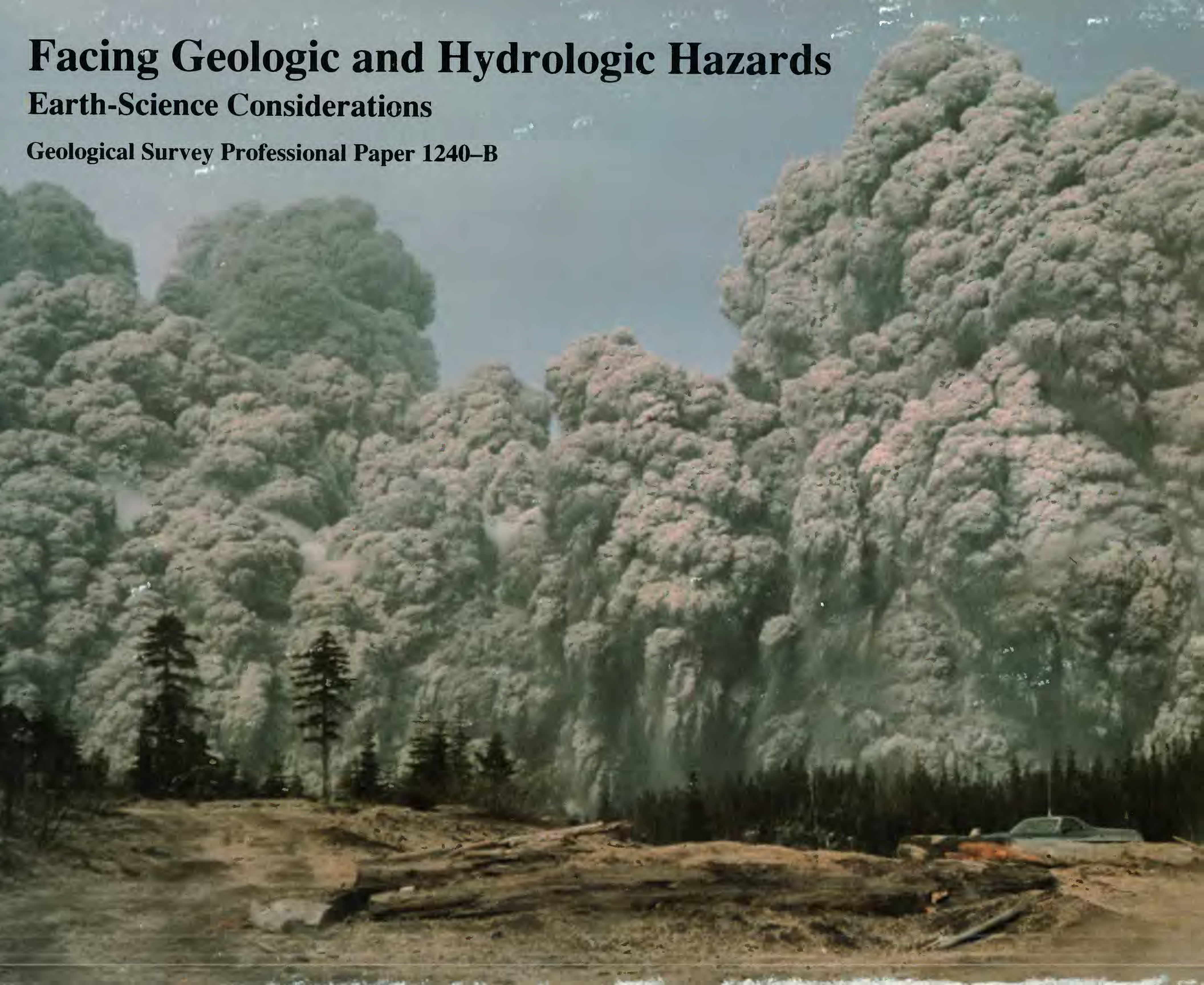
Facing Geologic and Hydrologic Hazards

Earth-Science Considerations

Geological Survey Professional Paper 1240–B



United States Department of the Interior

MANUEL LUJAN, Jr., Secretary

U.S. Geological Survey

DALLAS L. PECK, Director

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WE EXPRESS our appreciation to the several authors identified with the individual sections of this report, to P.F. Clarke, G.P. Eaton, F.N. Houser, D.A. Rickert, C.F. Shearer, and R.L. Wesson for numerous discussions that led to the content and organization of the report, to Ms. E.A. Buffa who prepared the manuscript, and to many other members of the U.S. Geological Survey staff who reviewed the report and provided technical assistance in its final preparation. Without all of these contributions, the expeditious preparation of this report would not have been possible.

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COVER: Towering clouds of scorching volcanic gases, ash, and rock from the May 18, 1980, eruption of Mount St. Helens.

Facing Geologic and Hydrologic Hazards
Earth-Science Considerations

Edited by W. W. Hays

Geological Survey Professional Paper 1240-B

This is the second in a series of Earth-Science Special Reports being prepared by the U.S. Geological Survey to provide the public with timely and useful information on earth-science considerations relative to critical land, mineral, and water resource issues that currently face the Nation.

U.S. Government Printing Office, Washington, D.C., 1981


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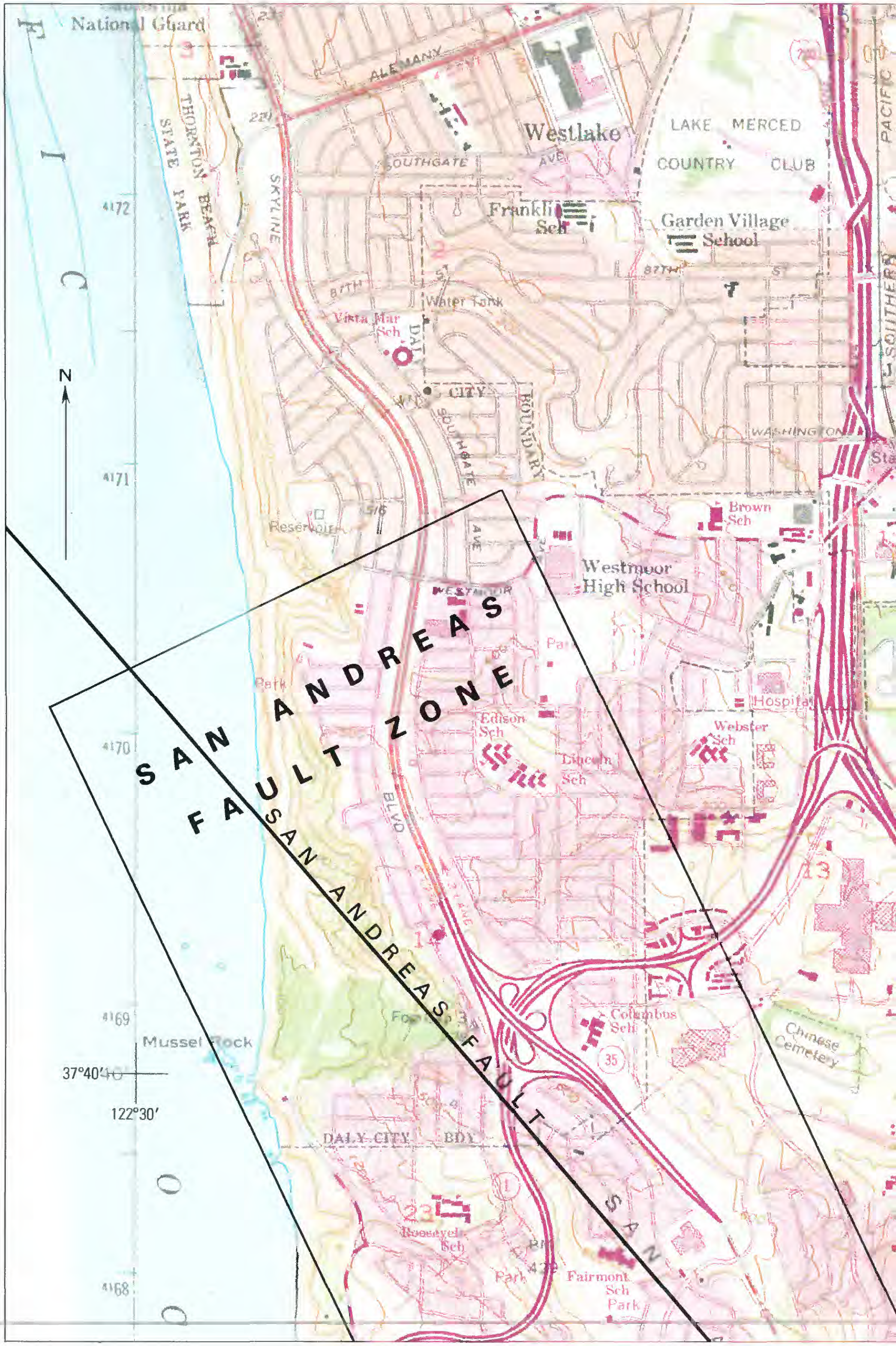
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Westlake
LAKE MERCED COUNTRY CLUB
SOUTHGATE AVE
THORNTON STATE BEACH PARK
SKYLINE
Franklin Sch
Garden Village School
Water Tank
Vista Mar Sch
CITY BOUNDARY
WASHINGTON
Reservoir
Brown Sch
Westmoor High School
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Foreword

Geologic and hydrologic hazards have affected the lives of many Americans. The recent eruption of Mount St. Helens has demonstrated that we cannot ignore any natural hazard, even one that happens as infrequently as a volcanic eruption.

Earthquakes, floods, ground failures, and volcanic eruptions will continue to occur in the future. The Nation must devise and implement a variety of actions to reduce losses when these hazards happen. Formulation and implementation of effective loss-reduction actions will require participation and cooperation of all levels of government and private industry. Many questions must be answered and many problems must be solved to achieve this national goal.

Information has been assembled in this report to answer some of the broader questions concerning earthquakes, floods, ground failures, and volcanic eruptions and their impact on our Nation. The report suggests actions based on earth-science considerations which may be taken to reduce losses. Although the report provides only a brief overview of these geologic and hydrologic hazards, I believe it will be useful to those making decisions in the future about reducing losses from geologic and hydrologic hazards.

Doyle G. Frederick
Acting Director

A high potential for loss of property and lives due to earthquake-induced ground shaking and movement of surface faults exists in the San Francisco metropolitan area. These illustrations (from left to right) are an aerial photograph of part of Daly City, a topographic map of the same area, and an aerial photograph of part of the San Francisco Peninsula. Outlined on each is the area of the San Andreas Fault Zone where the San Andreas fault (black line) enters the ocean from the land. Movement of this fault in the San Francisco earthquake of April 18, 1906, resulted in the loss of about 700 lives and millions of dollar's worth of damage. An earthquake of similar magnitude (8.3 on the Richter scale) today would result in about $24 billion worth of property damage and an estimated 5,000 deaths and 700,000 personal injuries from ground shaking alone! (See discussion on page 12.)

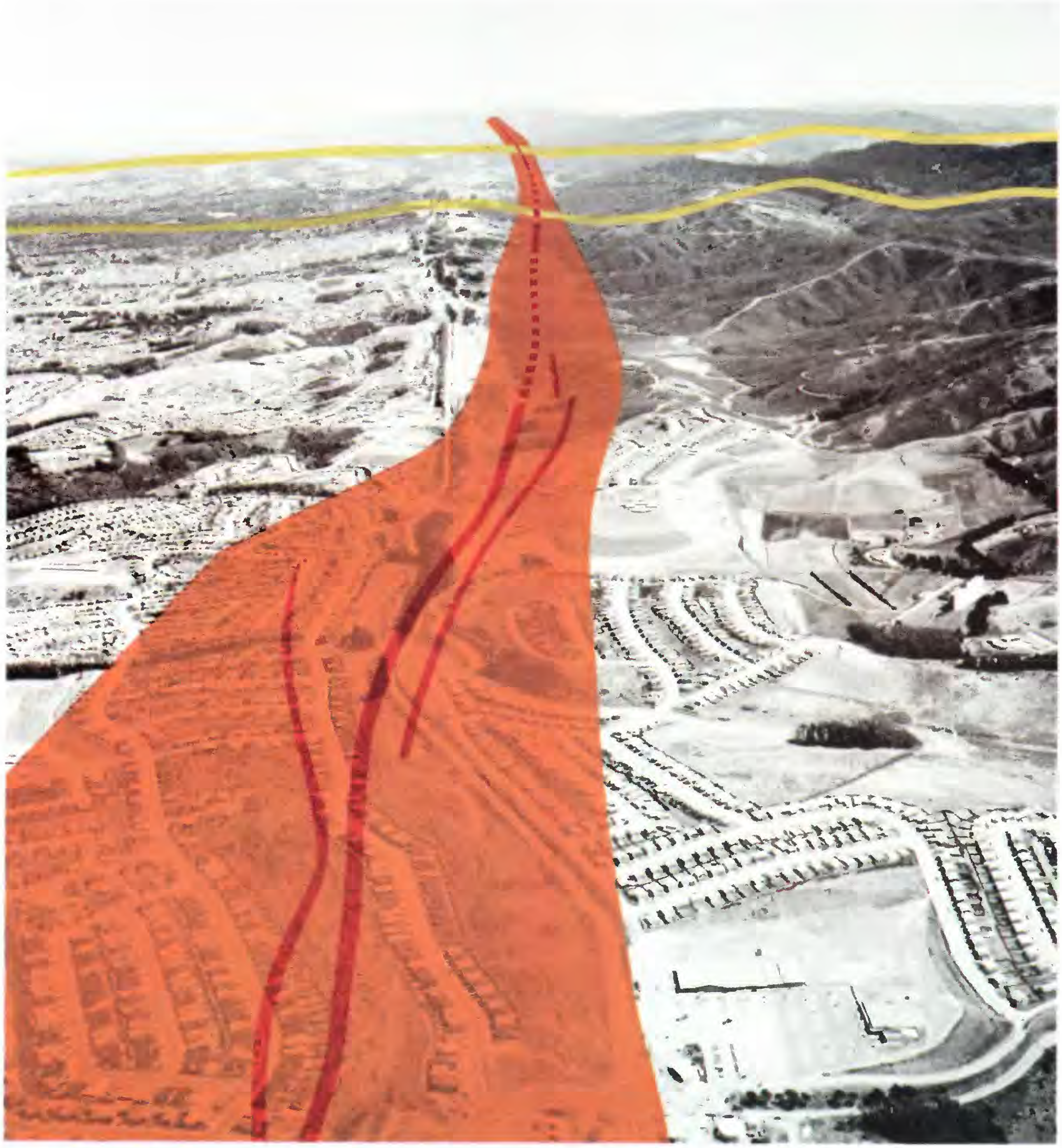
- *Daly City aerial photograph flown May 17, 1980. Color infrared, scale about 1:24,000, Frame 7121, U.S. Army Corps of Engineers.*
- *Topographic map, 1973. Scale 1:24,000. San Francisco South Quadrangle, U.S. Geological Survey.*
- *San Francisco Peninsula aerial photograph flown February 14, 1977. Color infrared, scale about 1:131,000, Frame ID No. 5770024660937, NASA U-2 photography.*

Facing Geologic and Hydrologic Hazards

4. Hazards From Ground Failures

5. Hazards From Volcanic Eruptions

6. Suggestions for Improving Decisionmaking To Face Geologic and Hydrologic Hazards



Example of a community where people are taking actions to reduce losses from geologic and hydrologic hazards. Some of the suburbs in this view, looking southeast from above Daly City, California, lie across strands of the San Andreas fault (red lines). The 1906 San Francisco earthquake caused as much as 8 feet of horizontal displacement along fault strands like these. Planners and decisionmakers in local communities such as Santa Clara County, identified approximately by the yellow lines at the top of the illustration, are using earth-science data to devise loss-reduction actions. State laws enacted in 1972 require geologic investigations prior to construction of a public structure in the "special studies zone" (area in orange) and prohibit building of public structures across the red lines. (From Robinson and Spieker, 1978. Photograph by R. E. Wallace.)

1. Introduction

Purpose and Scope of the Report

The purpose of this report is to suggest actions involving earth-science considerations that planners and decisionmakers can take to reduce losses from geologic and hydrologic hazards. These naturally occurring phenomena take place because of continuing natural processes. Throughout history, these hazards have impacted man and his activities, causing considerable damage, injury, and loss of life. Increasing losses are expected in the future unless man modifies his activities in light of experience and knowledge of the earth sciences.

This report provides basic information on the hazards from earthquakes, floods, ground failures, and volcanic eruptions. It describes their physical characteristics, identifies the locations in the United States where they tend to happen; specifies their impact on the Nation's population, buildings, structures, and economy; and discusses actions that can reduce losses. Information in the report is presented from a national and regional perspective; therefore, it generally will not be adequate for site-specific applications. Other natural hazards, although important, are not discussed. The role of man in triggering some of the geologic and hydrologic hazards is discussed; this role was also treated in *Synthetic Fuels Development* published in 1979 by the U.S. Geological Survey. The social issues concerning geologic and hydrologic hazards are beyond the scope of this report and will not be discussed except in a general way.

The report is organized in a manner that will make it easy for a reader to learn about a specific hazard of interest by reading the chapter describing the hazard and Chapter 6, Suggestions for Improving Decisionmaking To Face Geologic and Hydrologic Hazards. Selected references are provided for the reader who wishes more detail. Additional data can be obtained from the geologic survey in each State and from the U.S. Geological Survey.

Why Do We Study Geologic and Hydrologic Hazards?

Geologic and hydrologic hazards are studied to understand more completely the physical processes which cause them. Understanding these processes is a key step in devising methodologies for reducing losses to the Nation when these hazards occur in the future. The potential losses are high. According to J. H. Wiggins (1973), natural hazards in 1973 collectively accounted for direct costs each year exceeding 1 percent of the Nation's gross national product. Average annual losses and the potential for sudden loss from occurrences of earthquakes, floods, ground failures, and volcanic eruptions are greater now and increasing fairly rapidly as a consequence of factors such as:

- Increasing numbers of the Nation's population are living in flood-prone areas, areas of high seismic risk, exposed coastal locations, and landslide-prone areas and near potentially active volcanoes.
- Urban centers are growing annually through construction of homes, schools, hospitals, high-rise buildings, factories, utility systems, dams, oil refineries, airports, and other facilities. This growth causes greater valued property to be exposed to geologic and hydrologic hazards every year.

Planning and decisionmaking with respect to the hazards from earthquakes, floods, ground failures, and volcanic eruptions take place at all levels in our Nation. At each level, earth-science information is needed so that wise choices can be made from the possible responses. These choices are difficult to make for two reasons. First, future geologic and hydrologic hazards occur at uncertain times and places with great variation in magnitude and probability of occurrence. Second, reducing losses requires integration of earth-science information within the planning and decisionmaking process.

Decisionmakers sometimes wrongly conclude that actions to reduce losses, based on earth-science information, are incompatible with other important social or economic needs such as housing or industrial development. Recently, however, geologists, planners, and decisionmakers have been able to work together in some areas to achieve a balance between the conflicting goals of public safety and adequate housing or economic development.

The variety of actions for reducing losses from geologic and hydrologic hazards includes:

- *Avoidance*.—Avoid the hazard by selecting other appropriate areas in which to live and build where the probability of occurrence of the hazard is lowest.
- *Land-use zoning*.—Reduce losses to certain types of structures susceptible to a particular hazard either by reducing their density or by prohibiting them within parts of the area characterized by a relatively high severity or probability of occurrence of the hazard.
- *Engineering design*.—Allow all types of structures within a potentially hazardous area, but require site-specific engineering design and construction to increase the capability of the site or the structure to withstand the hazard.
- *Distribution of losses*.—Use insurance and other financial methods to distribute the potential losses in a potentially hazardous area.

By implementing one or more of these loss-reduction actions, a community can greatly increase public safety and achieve a higher standard of living.

The following chapters discuss the hazards from earthquakes, floods, ground failures, and volcanic eruptions and describe specific loss-reduction actions in more detail. Chapter 6 discusses the earth-science information needed by those devising and implementing loss-reduction actions.

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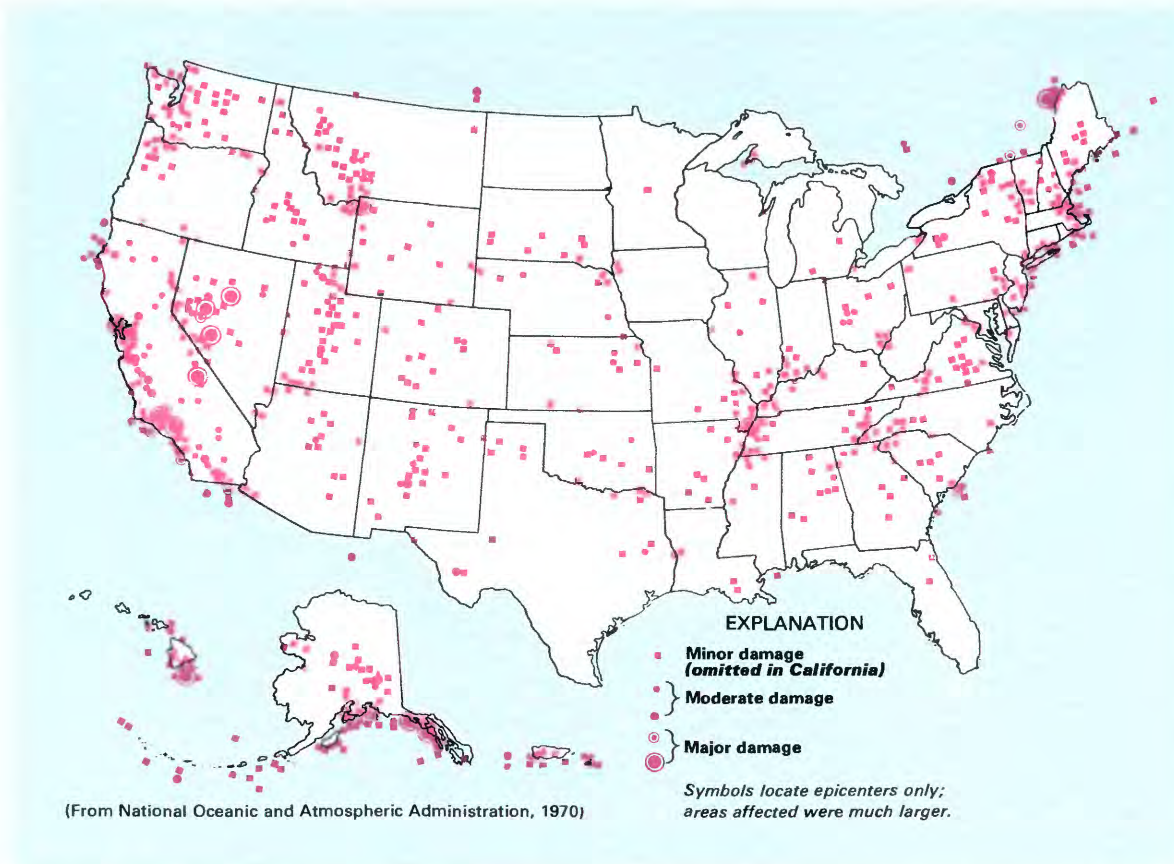
Wiggins, J. H., 1973., The risk in-balance in current public policies: Proceedings of Symposium on Risk Acceptance and Public Policy, Denver, Colo., International System Safety Society, p. 1–35.

Water level in chimney, approximately 6:00 p.m., May 9, 1981. Winter Park, Florida, sinkhole; view to the east. (Photograph by A. S. Navoy.)

2. Hazards From Earthquakes

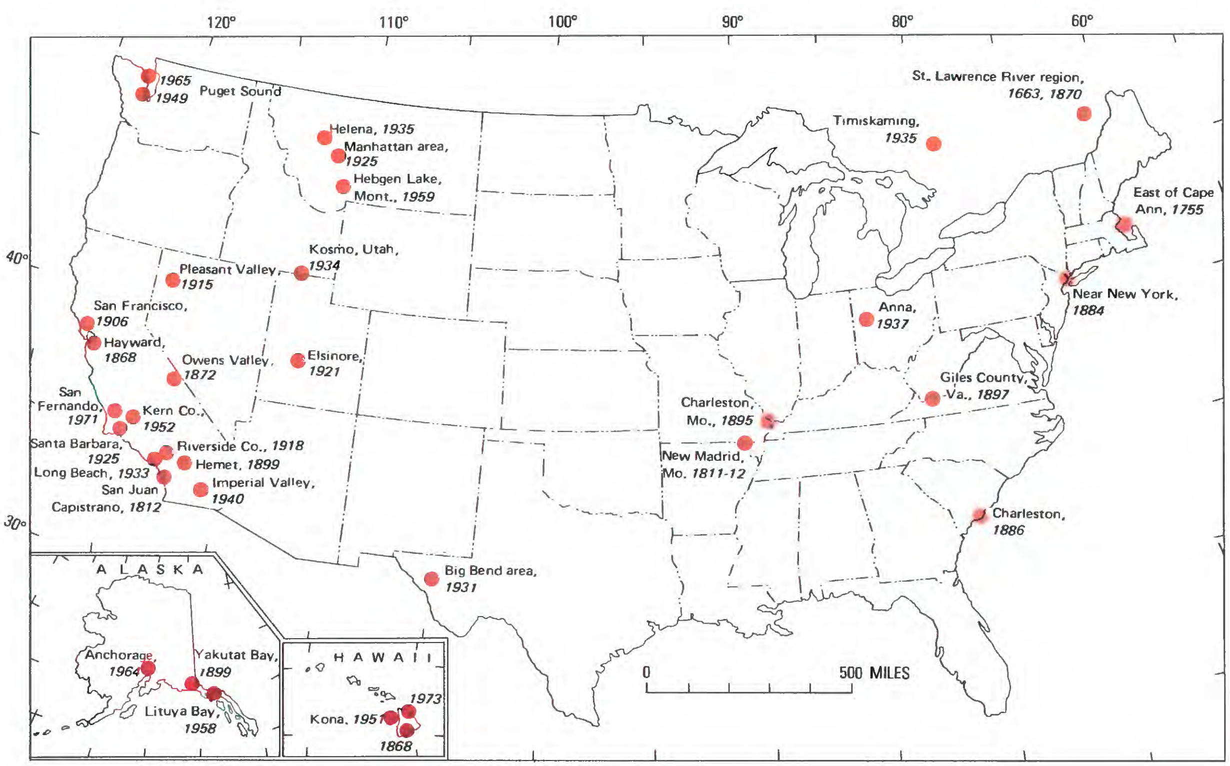


Location of damaging historic earthquakes through 1970 in the United States (from Robinson and Spieker, 1978). Earthquakes happen most frequently in Alaska and less frequently in California and are relatively infrequent in the Central and Eastern United States. Earthquakes cause loss from ground shaking, surface faulting, ground failures, and tsunamis. The economic loss increases as the magnitude increases and is most extensive for the infrequent great earthquakes of magnitude 8 and above. The 1906 San Francisco, California, and 1964 Prince William Sound, Alaska, earthquakes were the last great earthquakes. Communities throughout the Nation, however, face the greatest threat of potential loss from moderate and large earthquakes which happen more frequently than great ones.

Hazards associated with earthquakes include the phenomena of ground shaking, surface faulting, earthquake-induced ground failures, and tsunamis. Although earthquakes have caused much less economic loss annually in the United States than ground failures and floods, they have the potential for causing great sudden loss. Within 1 to 2 minutes, an earthquake can impact part or all of a city through ground shaking, surface fault rupture, and earthquake-induced ground failures. A tsunami can also be generated in some earthquakes and impact local and distant coastal communities. Depending on its location and magnitude (an indication of the energy released), an earthquake can damage buildings and homes valued collectively in billions of dollars, can cause loss of life and injury to tens of thousands, and can disrupt social and economic functions of communities.

Communities throughout the Nation face the possibility of loss from the several thousand earthquakes that happen each year. The greatest threat is from moderate (magnitudes of 6–7) and large (magnitudes of 7–8) earthquakes because they happen more frequently than a great one (magnitudes of 8 and above). For example, one moderate earthquake takes place on the average about once every 3 years in California, but a great one happens only about once every 100 to 150 years. Earthquakes happen most frequently in Alaska and least frequently in the Eastern United States. A large earthquake, such as the 1811–12 New Madrid, Missouri, earthquakes, happens about once every 600 to 700 years. Locations of moderate and large earthquakes in the east include the St. Lawrence River region from 1650 to 1928, in the vicinity of Boston in 1755, in the central Mississippi Valley in 1811–12, and near Charleston, South Carolina, in 1886.

In the past 20 years, the two most destructive earthquakes were the Prince William Sound, Alaska, earthquake of March 27, 1964 (a great earthquake), and the San Fernando, California, earthquake of February 9, 1971 (a moderate earthquake). Losses in comparable dollars of about $500 million and scores of deaths and injuries resulted from each earthquake.



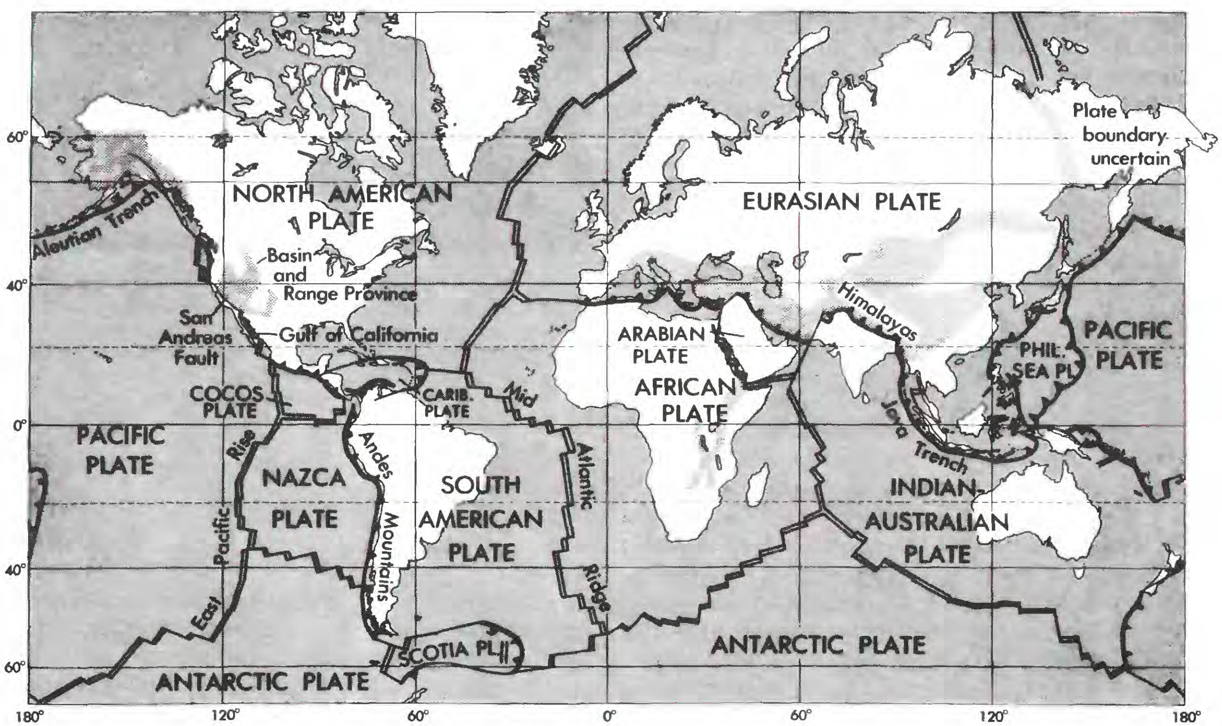
Location of notable historic earthquakes in the United States that have caused damage (from Hays, 1980). Although many earthquakes take place every year, most are small and do not cause damage. All or parts of 39 States lie in regions classed as having major and moderate seismic risk. Within these 39 States, more than 70 million people are exposed to earthquake hazards of ground shaking, surface faulting, earthquake-induced ground failures, and tsunamis.

Ground Shaking

What Causes Earthquakes?

An earthquake—the sudden motion or trembling in the Earth caused by an abrupt release of slowly accumulating strain—is one of the severest natural hazards. Each year, several million earthquakes happen throughout the world, varying in size from minor tremors that are perceptible only to sensitive instruments to a few great earthquakes that cause considerable damage, injuries, and loss of life. The theory of plate tectonics can explain earthquakes. In this theory, which was introduced in 1967, the "solid" Earth is broken into several major plates. These 50- to 60-mile-thick rigid plates or segments of the Earth's crust and upper mantle move slowly and continuously over the interior of the Earth, meeting in some areas and separating in others. Velocities of relative motion between adjacent plates range from less than a fraction of an inch to about 5 inches per year. Although these velocities are slow by human standards, they are rapid by geologic ones; a motion of 2 inches per year adds up to 30 miles in only 1 million years. As these plates move, strain accumulates. Eventually, faults along or near plate boundaries slip abruptly and an earthquake occurs.

Scientists monitoring borehole instruments.



Map showing the major tectonic plates of the world. Earthquake activity marks plate boundaries. The double line indicates a zone of spreading from which plates are moving apart. Line with barbs indicates a zone where one plate is sliding beneath another. A single line indicates a strike-slip fault along which plates are sliding past one another. (Compiled and adapted from many sources; much simplified in complex areas.)

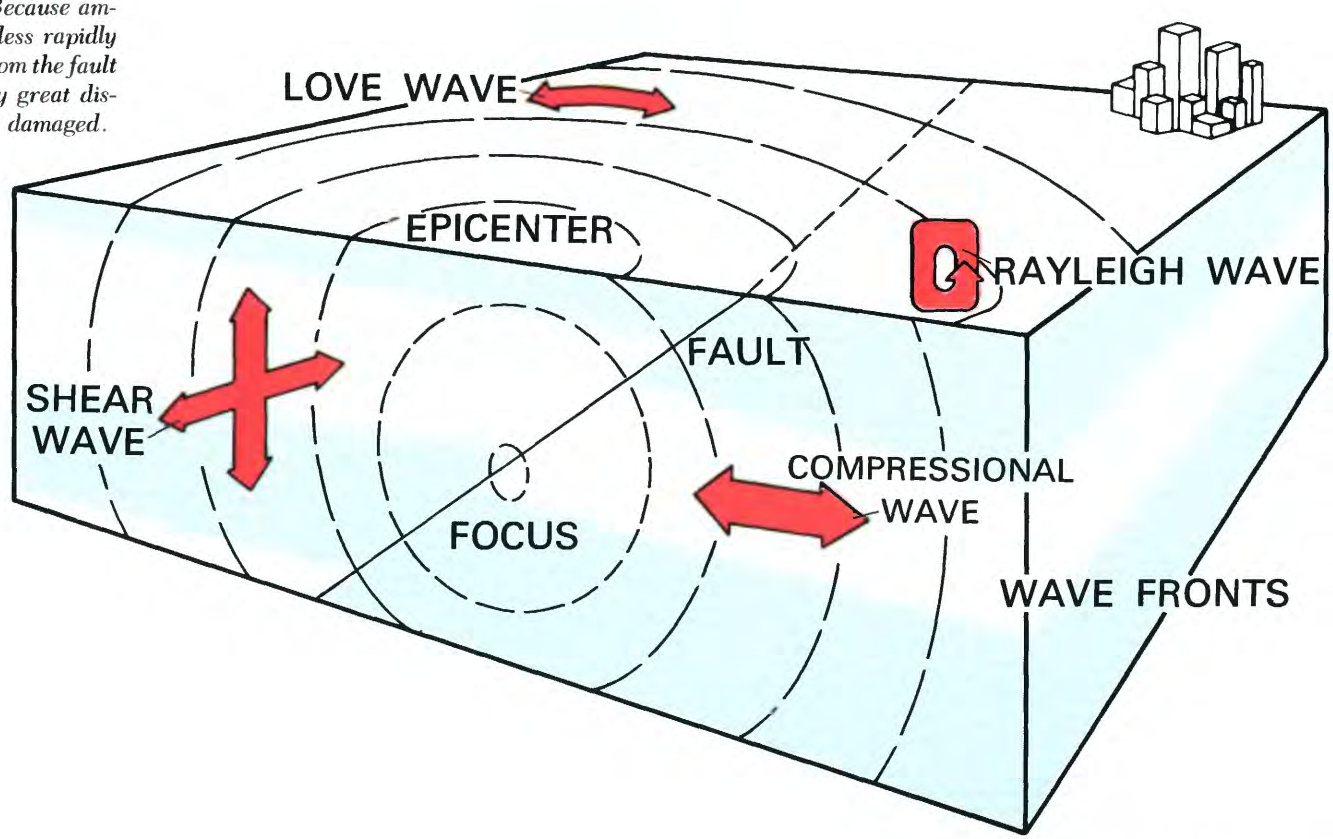
What Causes Ground Shaking?

Ground shaking is a term used to describe the vibration of the ground during an earthquake. Ground shaking is caused by body and surface seismic waves. As a generalization, the severity of ground shaking increases as magnitude increases and decreases as distance from the causative fault increases. Although the physics of seismic waves is complex, ground shaking can be explained in terms of body waves, compressional, or P, and shear, or S, and surface waves, Rayleigh and Love. P waves propagate through the Earth with a speed of about 15,000 miles per hour and are the first waves to cause vibration of a building. S waves arrive next and cause a structure to vibrate from side to side. They are the most damaging waves, because buildings are more easily damaged from horizontal motion than from vertical motion. The P and S waves mainly cause high-frequency vibrations; whereas, Rayleigh and Love waves, which arrive last, mainly cause low-frequency vibrations. Body and surface waves cause the ground, and consequently a building, to vibrate in a complex manner. The objective of earthquake-resistant design is to construct a building so that it can withstand the ground shaking caused by body and surface waves.

One of the partially collapsed reinforced-concrete columns of the heavily damaged six-story Imperial County Services Building, El Centro, California. Damage occurred during the October 15, 1979, Imperial Valley earthquake.

In land-use zoning and earthquake-resistant design, knowledge of the amplitude, frequency composition, and the time duration of ground shaking is needed. These quantities can be determined from empirical data correlating them with the magnitude and the distribution of Modified Mercalli intensity of the earthquake, distance of the building from the causative fault, and the physical properties of the soil and rock underlying the building. The subjective numerical value of the Modified Mercalli Intensity Scale indicates the effects of ground shaking on man, buildings, and the surface of the Earth.

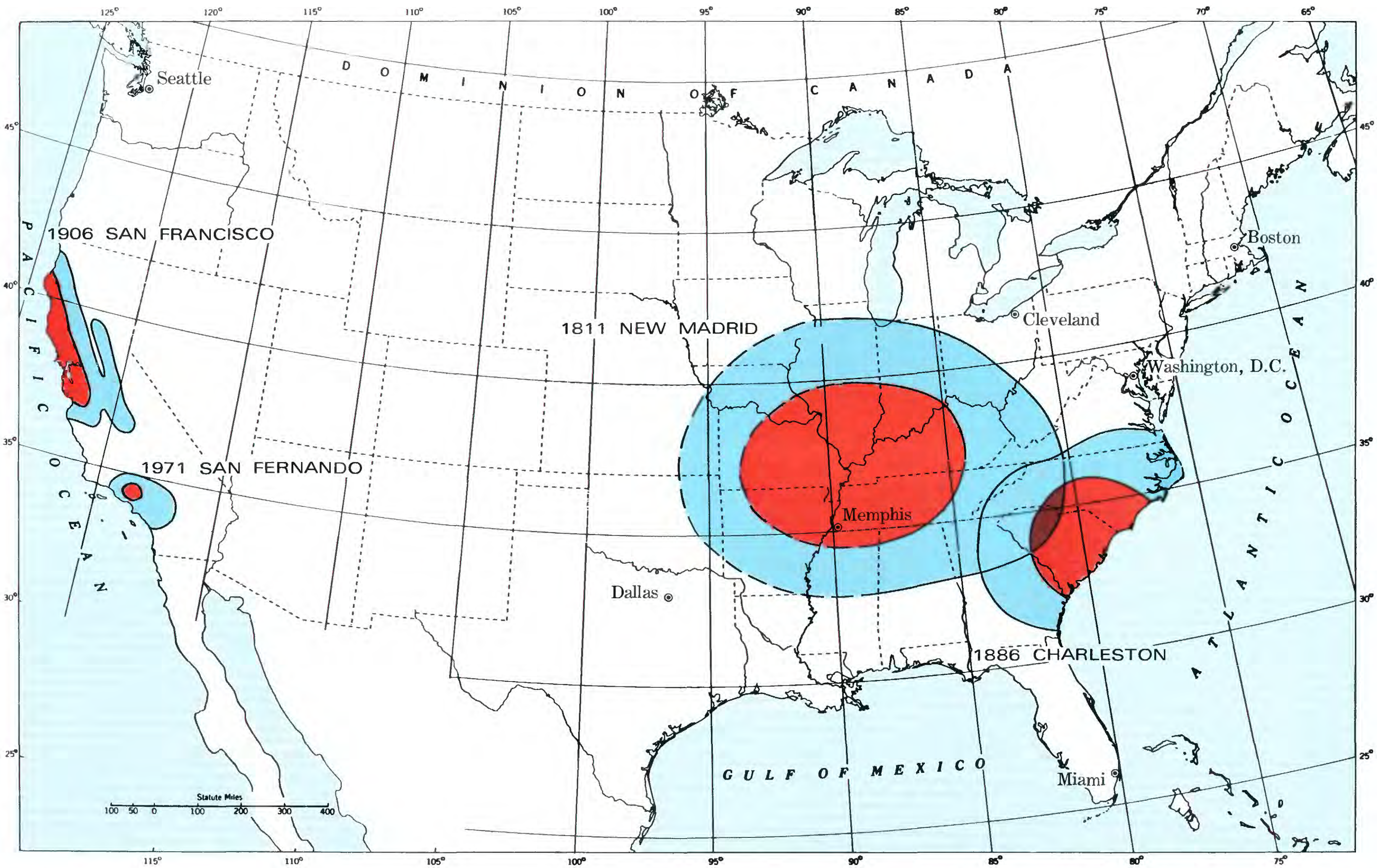
Schematic illustration of the directions of vibration caused by body and surface seismic waves generated during an earthquake. When a fault ruptures, seismic waves are propagated in all directions, causing the ground to vibrate at frequencies ranging from about 0.1 to 30 Hertz. Buildings vibrate as a consequence of the ground shaking; damage takes place if the building cannot withstand these vibrations. Compressional and shear waves mainly cause high-frequency (greater than 1 Hertz) vibrations which are more efficient than low-frequency waves in causing low buildings to vibrate. Rayleigh and Love waves mainly cause low-frequency vibrations which are more efficient than high-frequency waves in causing tall buildings to vibrate. Because amplitudes of low-frequency vibrations decay less rapidly than high-frequency vibrations as distance from the fault increases, tall buildings located at relatively great distances (60 miles) from a fault are sometimes damaged.



What Is the Size of the Area Affected by Ground Shaking?

The size of the geographic area affected by ground shaking depends on the magnitude of the earthquake and the rate at which the amplitudes of body and surface seismic waves decrease as distance from the causative fault increases. Comparison of the areas affected by the same Modified Mercalli intensity of ground shaking in the 1906 San Francisco, California, the 1971 San Fernando, California, the 1811–12 New Madrid, Missouri, and the 1886 Charleston, South Carolina, earthquakes shows that a given intensity of ground shaking extends over a much larger area in the Eastern United States. Ground shaking affects a larger area because amplitudes of seismic waves decrease more slowly in the east than in the west as distance from the causative fault increases.

A seismologist at the National Earthquake Information Service in Golden, Colorado, checks seismograph records from stations throughout the United States.

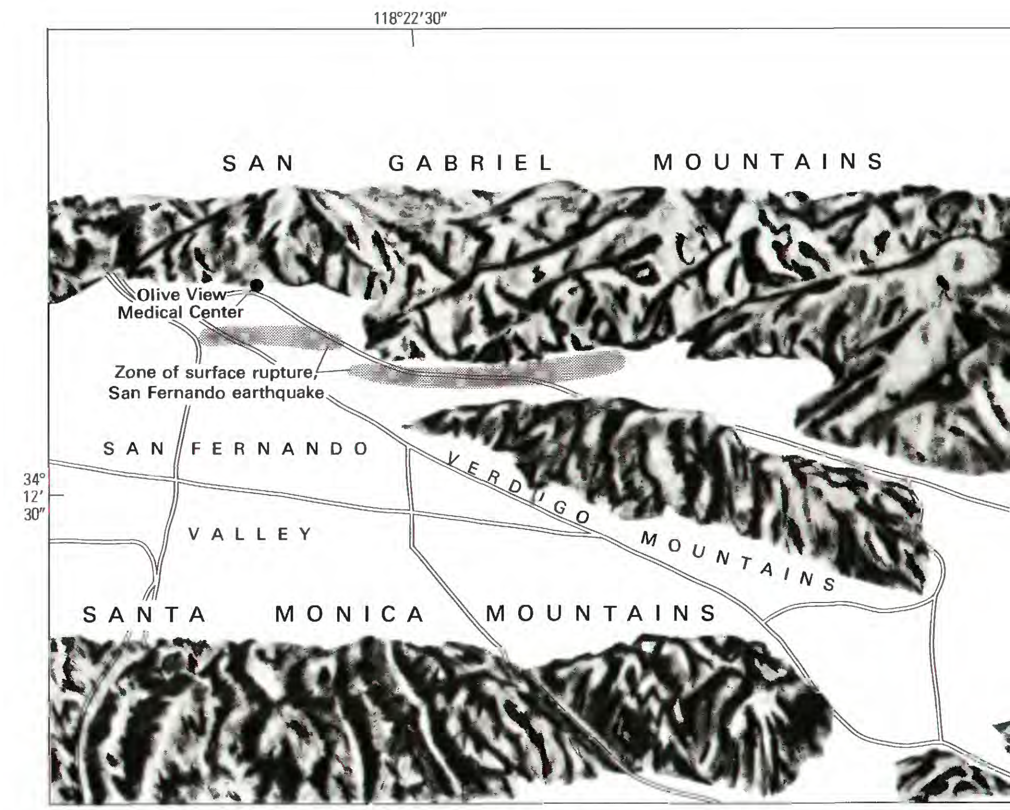


Comparison of isoseismal contours for a great earthquake, the 1906 San Francisco; a moderate earthquake, the 1971 San Fernando; and two large earthquakes, the 1811–12 New Madrid and 1886 Charleston. The contour lines connect sites having the same value of Modified Mercalli intensity, a numerical index of the effects of an earthquake on man, the Earth's surface, and on buildings. Each area shown in red corresponds to an intensity of VII or greater and denotes the zone of most severe ground shaking and damage. The area shaded blue corresponds to an intensity of VI; in this area, the ground shaking is felt by all, many are frightened and run outdoors, but damage is slight. The effects of ground shaking extend over a much larger area in the Eastern United States.

What Is the Economic Impact of Ground Shaking?

Most of the spectacular damage that takes place during earthquakes is caused by partial or total collapse of buildings as a result of ground shaking. In addition, ground shaking can induce destructive ground failures. In the 1971 San Fernando, California, earthquake, for example, a large part of the $500 million loss was caused directly by structural damage from ground shaking. A repeat today of the San Francisco, California, earthquake, which in 1906 destroyed buildings with costs translated into 1978 dollars of almost $170 million and took 700 lives, probably would cause $24 billion in building damage and (depending on the time of day of the occurrence) about 5,000 deaths and 700,000 injuries from ground shaking alone (Wiggins, 1979?). Much of this hundredfold increase in losses, relative to 1906, is due to the greater number and value of buildings and the growth in population. A similar estimate for a 1990 repeat of the 1906 San Francisco earthquake suggests losses of $30 billion from ground shaking, excluding losses from fire and damage to infrastructure (Wiggins, 1979?). Loss estimates for the Los Angeles area are slightly higher than for San Francisco. If an earthquake should occur today on the Newport-Inglewood fault near Los Angeles, it probably would cause losses of about $45 billion to buildings, and as many as 23,000 deaths, depending on whether the earthquake occurred at noontime or during the rush hours (the "worst" hazardous times) or in the early morning while most people are in bed (the "best" hazardous time) (U.S. Federal Emergency Management Agency, 1981).

A repeat of the 1811–12 New Madrid, Missouri, earthquakes is estimated to cause losses comparable with the "worst-case" estimates for San Francisco or Los Angeles.



Index map of California showing location of the San Fernando Valley

Sketch map showing San Fernando valley where the most severe ground shaking took place in the 1971 San Fernando, California, earthquake. Photograph shows damage from ground shaking at Los Angeles Olive View Medical Center. The 850-bed center, costing approximately $24 million, was heavily damaged. Three stair towers toppled and broke through the roof of the ground story, an ambulance port collapsed, and the first story of the psychiatric unit collapsed. Fortunately, only three persons were killed. At Olive View, the ground shaking was rated XI on the Modified Mercalli Intensity Scale; above VII throughout the valley. (Photograph by R. E. Wallace.)

What Can Be Done To Reduce Losses From Ground Shaking?

Old existing buildings that fail to meet present standards for earthquake resistance face the greatest threat from ground shaking. The number of such buildings in the United States is very large. Applying loss-reduction measures to these substandard buildings is a major unresolved problem because of economic, social, and political factors. The primary choices for reducing losses from substandard buildings include (1) engineering redesign and retrofitting to strengthen the structure, (2) reduction in intensity of use, and (3) removal.

To reduce losses in new buildings, the primary choices include (1) avoiding the areas of most severe ground shaking, (2) land-use zoning either to prohibit certain types of structures susceptible to damage or to reduce the density of certain uses in areas having a high probability of severe ground shaking, (3) incorporating the earthquake-resistant design provisions of the Uniform Building Code during construction, and (4) earthquake insurance.

Ground-shaking hazard maps can be used in selecting a loss-reduction action for new buildings. The map shown was used in the definition of seismic risk zones in the Applied Technology Council's model code of 1978. The ground-shaking hazard is presented in terms of contoured values of the peak horizontal ground acceleration expected in a 50-year period at the 90-percent probability level for sites underlain by rock. These values of peak acceleration must be modified to account for possible amplification of ground shaking by the soil column at the specific site before they are used in earthquake-resistant design.

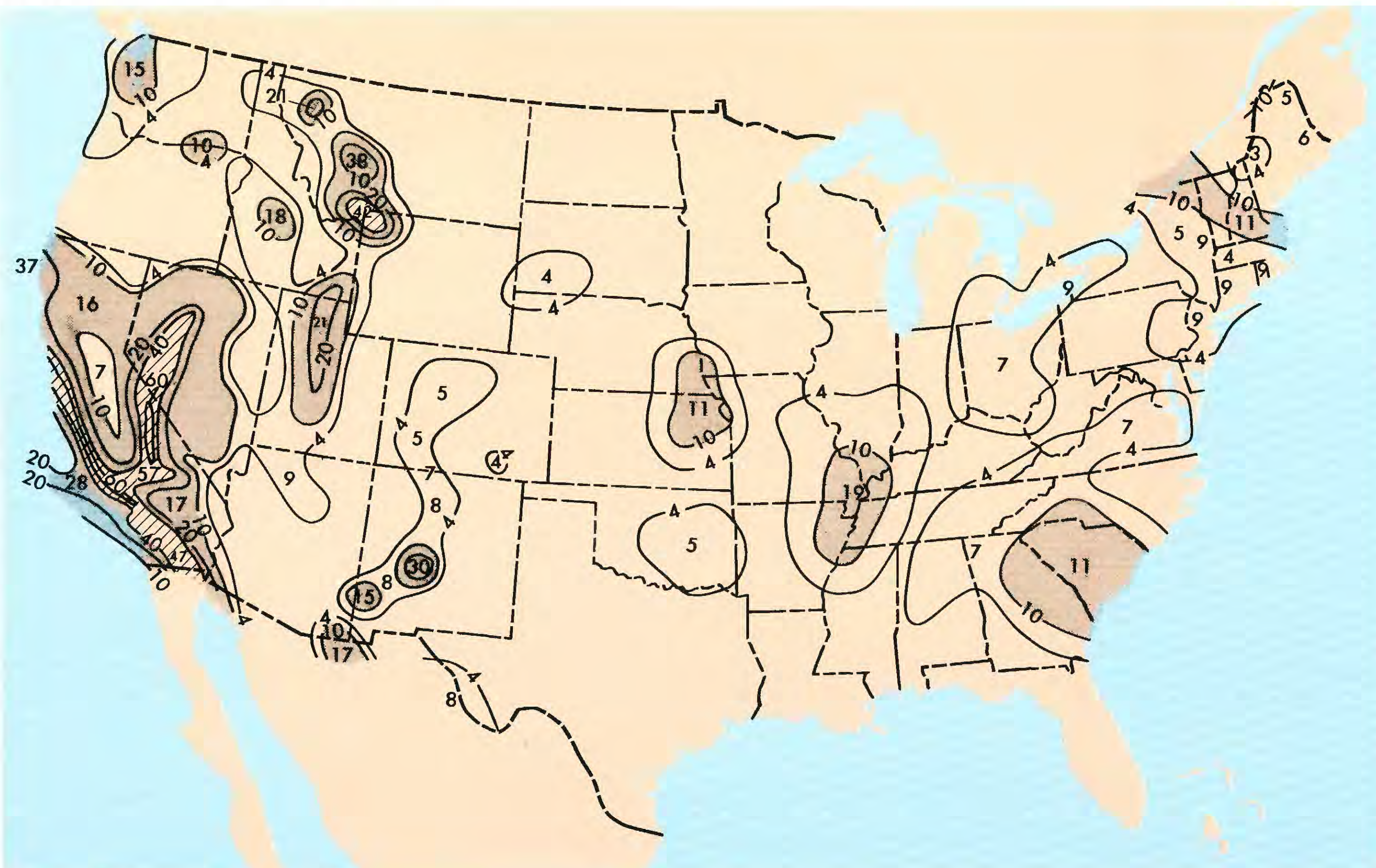
Can Earthquakes Be Predicted?

An effort to understand the physical conditions that precede an earthquake was initiated following the destructive Prince William Sound, Alaska, earthquake of March 27, 1964. This effort had the objective of predicting the size, time, and location of an impending shock. It was increased after the damaging San Fernando, California, earthquake of February 9, 1971. In 1977, the Earthquake Hazards Reduction Act was passed; it contained earthquake prediction as a major element of a national program to reduce losses from future earthquakes in the United States.

Earthquake prediction is a rapidly emerging scientific field offering great promise for loss reduction. Although accurate predictions of the size (magnitude), time, and location of future earthquakes in the United States may still be years away, scientific information needed for making reliable predictions within the next decade are emerging from studies by earth scientists from many different institutions in the United States and in several other countries, including the Soviet Union, Japan, and China.

As with most new technological developments, earthquake prediction must be approached carefully. Earthquake prediction will save lives; this has already been demonstrated by the successful prediction of the destructive earthquake that struck Haicheng, China, on February 4, 1975. However, in the United States, a prediction can cause serious socioeconomic problems if it is not properly implemented. Scientists, planners, and decisionmakers must be aware of and resolve complexly interrelated technical-socioeconomic-political factors to benefit from earthquake prediction (Hays, 1980).

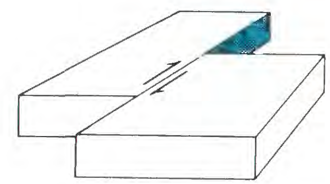
Map of peak horizontal ground acceleration expected at sites in the conterminous United States underlain by rock in a 50-year period (from Algermissen and Perkins, 1976). This map represents the ground-shaking hazard in terms of the peak amplitude of horizontal acceleration, one characteristic of the strength of the seismic shaking. Locations having the same value of peak acceleration are connected with a contour line. Values shown on each contour and on the map are percentages of the acceleration of gravity. There is a 10-percent probability that these values will be exceeded in a 50-year period. This map takes into account the relative differences in rate of seismic activity in the Eastern and Western United States. Areas where peak acceleration exceeds 10 percent of the acceleration of gravity are shaded. The largest values shown, along the California coast, are 80 percent of gravity.



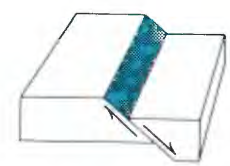
Surface Faulting

What is Surface Faulting?

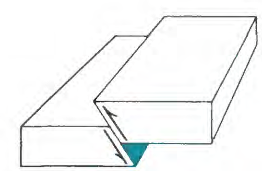
Surface faulting—the differential movement of the two sides of a fracture at the Earth's surface—is of three general types: strike-slip, normal, and reverse. Combinations of the strike-slip type and the other two types of faulting can be found. Although displacements of these kinds can result from landslides and other shallow processes, surface faulting, as the term is used here, applies to differential movements caused by deep-seated forces in the Earth, the slow movement of sedimentary deposits toward the Gulf of Mexico, and faulting associated with salt domes.



STRIKE-SLIP FAULT
Horizontal displacement



NORMAL FAULT
Principally vertical displacement with the side above the inclined fault moving downward



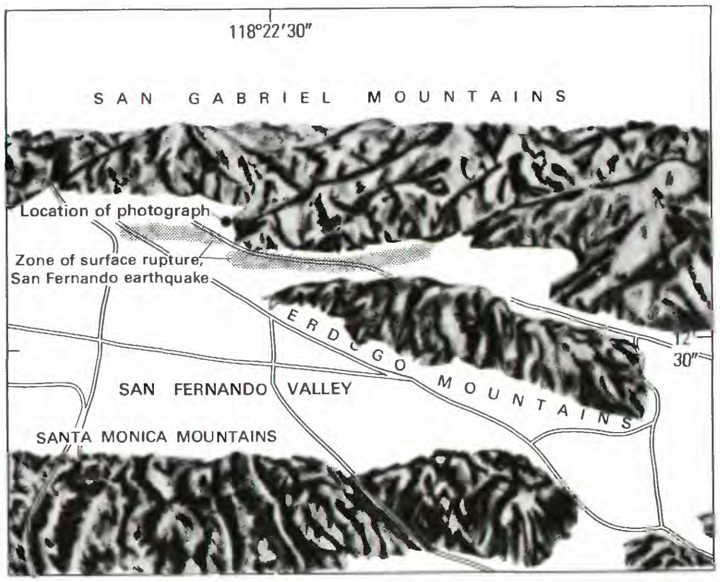
REVERSE FAULT
Principally vertical displacement with the side above the inclined fault moving upward

Types of displacements of faults. Actual ruptures are more complex than shown on these diagrams. (Modified from Borcherdt, 1975.)

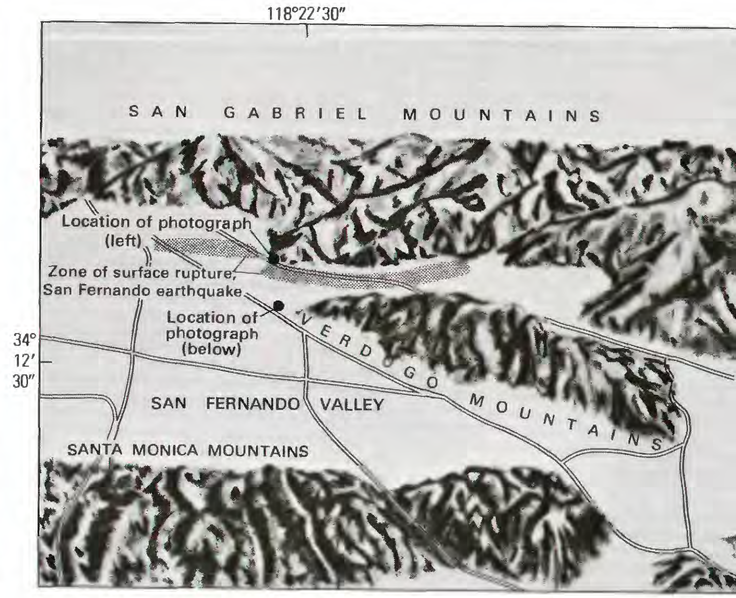
What Are the Effects of Surface Faulting?

Death and injuries from surface faulting are very unlikely, but casualties can occur indirectly through fault damage to structures. Surface faulting, in the case of a strike-slip fault, generally affects a long narrow zone whose total area is small compared with the total area affected by ground shaking. Nevertheless, the damage to structures located in the fault zone can be very high, especially where the land use is intensive. A variety of structures have been damaged by surface faulting, including houses, apartments, commercial buildings, nursing homes, railroads, highways, tunnels, bridges, canals, storm drains, water wells, and water, gas, and sewer lines. Damage to these types of structures has ranged from minor to very severe. An example of severe damage occurred in 1952 when three railroad tunnels were so badly damaged by faulting that traffic on a major rail linking northern and southern California was stopped for 25 days despite an around-the-clock repair schedule.

The displacements, lengths, and widths of surface fault ruptures show a wide range. Fault displacements in the United States have ranged from a fraction of an inch to more than 20 feet of differential movement. As expected, the severity of potential damage increases as the size of the displacement increases. The lengths of the surface fault ruptures on land have ranged from less than 1 mile to more than 200 miles. Most fault displacement is confined to a narrow zone ranging from 6 to 1,000 feet in width, but separate subsidiary fault ruptures may occur 2 to 3 miles from the main fault. The area subject to disruption by surface faulting varies with the length and width of the rupture zone.



Sketch map of active fault zone crossing an urban area and an example of damage to a house caused by an abrupt fault rupture at the surface during the 1971 San Fernando, California, earthquake.



An example of damage to street pavement and sidewalks caused by surface fault rupture in the 1971 San Fernando, California, earthquake. Several commercial and industrial buildings nearby were damaged severely. The location of the photograph is shown on the sketch map.

An example of horizontal and vertical movement of pavement, curb, and sidewalk in the 1971 San Fernando, California, earthquake. The nursing home in the background was damaged severely and had to be removed. The location of the photograph is shown on the sketch map. (Photograph by T. L. Youd.)

Displacement of crop rows by strike-slip movement, Imperial Valley, California. This type of displacement damaged underground drain tile, canals, and highways over more than 15 miles.

Surface faulting (shown by white band) that occurred in Nevada in 1915. The faulting extended discontinuously for 38 miles and had vertical displacements as much as 22 feet. (Photograph by R. E. Wallace.)

Can The Location, Size, and Type of Future Faulting Be Predicted?

Almost all historic surface faulting has taken place on faults that exhibit geologically young displacements. Therefore, future faulting is expected to take place on geologically young faults, and prediction is based on identification of them. Such faults can be identified by the kind of topography along them, the displacement of young geologic units, and the occurrence of earthquakes on them. Faults that are young and active commonly disturb the land surface by creating scarps (small steps or cliffs), troughs, or ridges and by diverting streams. These and other characteristic features of faults can be recognized by geologic studies. When a geologic study shows that a fault displaces young geologic units, this indicates that the fault has been active since the units were formed. Faults which generate earthquakes can be considered to be active, but some active faults may be deeply buried and not capable of rupturing the ground surface. Thus, young faults reaching the ground surface are the ones most likely to produce surface faulting.

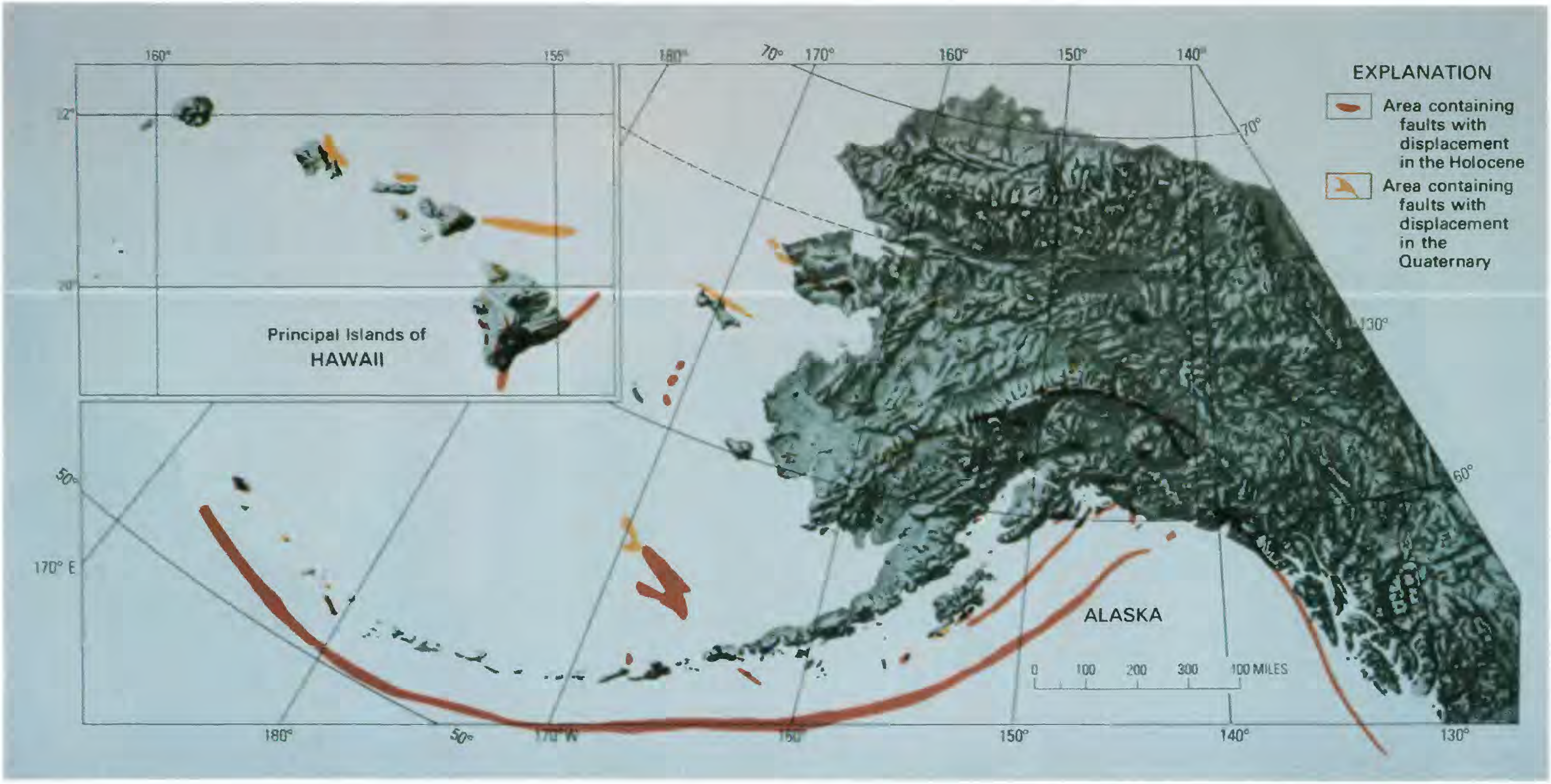
Prediction of future faulting is important in reducing losses from earthquakes. Sudden displacements on faults are the cause of damaging earthquakes, and, therefore, the locations of active faults (faults that can undergo movement in the immediate geologic future) give an indication of where earthquakes may originate. Also, the severity of damage from ground shaking is greatest near the fault. Not all active faults generate destructive earthquakes. Displacement on the gulf coast faults in Texas and Louisiana, for example, is a slow process that does not generally generate earthquakes.

Areas in the United States where young surface faults are known to exist have been mapped. These maps show faults in two general categories—those that have had displacement within the last 10,000 years and those that have had displacement within the last 2 million years. These time periods are long by human standards, but short with regard to geologic processes. Faults can lie dormant for many thousands of years between periods of vigorous activity, and, therefore, their behavior over a substantial part of their recent history must be considered. These maps also give an indication of the relative risk of surface faulting; surface faulting is most likely to take place in the areas of Holocene faulting (during the last 10,000 years), less likely in the areas of Quaternary faulting (last 2 million years), and least likely in the remaining area.

In looking at a map of young surface faulting, keep in mind that, for various reasons, more areas of young faulting probably exist than are indicated. Experience has shown that, as detailed geologic work is done at specific sites, additional young faulting is often recognized. In California, several known faults have recently been found to have young displacements on them, and some previously unknown young faults also have been discovered. Only in the last few years has evidence been found to prove surface faulting in the last 10,000 years in the area of the very severe New Madrid, Missouri, earthquakes of 1811–12. Many faults in the United States have not been examined thoroughly with regard to the time of latest displacement on them and other faults have geologic conditions that make recognition of young displacements very difficult.

Useful estimates can be made of the maximum surface length and displacement that a specific fault is capable of producing. These estimates are based on statistical data obtained from field studies following past earthquakes and theoretical considerations. The type of faulting to be expected is the same as has occurred previously on the fault. The type of earlier faulting can be learned from geological, seismological, and historical data. The size and the type of faulting are important factors in evaluating the damage that might be caused in the future.

Maps of young surface faulting. A, *Conterminous United States* (this page). B, *Alaska and Hawaii* (following page).



What Can Be Done To Reduce Losses From Surface Faulting?

Avoidance and engineering design to accommodate the differential displacements are the primary actions that will reduce losses from surface faulting. Avoidance requires accurate location of the fault and an assessment of its history of activity through a detailed geologic examination. For public safety or economic reasons in some areas, certain types of structures are not built across particular faults. For example, in California, various State, county, and city laws regulate the construction of schools, hospitals, and homes in areas susceptible to surface faulting. However, structures, such as pipelines, dams, bridges, and aqueducts, frequently cannot be built without crossing active faults. Some of these structures have been designed and constructed to accommodate fault displacements in an earthquake. These designs will probably be successful, but they have not yet been tested by actual large fault displacements.

Earthquake-Induced Ground Failures

The broad subject of ground failures is discussed in Chapter 4. Because certain types of ground failures are frequently associated with earthquakes, they will be discussed in this chaper for continuity.

What Is the Economic Impact of Earthquake-Induced Ground Failures?

Throughout the world, ground failures induced during earthquakes have caused many thousands of casualties and millions of dollars in property damage. Loss of life has been especially high in other countries. For example, soil-flow failures induced during the 1920 Kansu, China, earthquake killed an estimated 200,000 people. Fortunately, the impact in the United States has been limited mainly to economic loss. During the 1964 Prince William Sound, Alaska, earthquake, ground failures caused about 60 percent of the estimated $500 million total damage. In this earthquake, five landslides caused about $50 million damage in the city of Anchorage; lateral spread failures damaged highways and severely disrupted use of railway grades and bridges, requiring about $50 million in repairs; and flow failures in three Alaskan ports carried away docks, warehouses, and adjacent transportation facilities costing about $15 million.

Aerial view, looking east, of part of Turnagain Heights slide, Anchorage, shortly after Alaska earthquake, March 27, 1964

What Types of Ground Failures Are Caused by Liquefaction?

Liquefaction is not a type of ground failure; it is a physical process that takes place during some earthquakes that may lead to ground failure. As a consequence of liquefaction, clay-free soil deposits, primarily sands and silts, temporarily lose strength and behave as viscous fluids rather than as solids. Liquefaction takes place when seismic shear waves pass through a saturated granular soil layer, distort its granular structure, and cause some of the void spaces to collapse. Disruptions to the soil generated by these collapses cause transfer of the ground-shaking load from grain-to-grain contacts in the soil layer to the pore water. This transfer of load increases pressure in the pore water, either causing drainage to occur or, if drainage is restricted, a sudden buildup of pore-water pressure. When the pore-water pressure rises to about the pressure caused by the weight of the column of soil, the granular soil layer behaves like a fluid rather than like a solid for a short period. In this condition, deformations can occur easily.

Liquefaction is restricted to certain geologic and hydrologic environments, mainly areas where sands and silts were deposited in the last 10,000 years and where ground water is within 30 feet of the surface. Generally, the younger and looser the sediment and the higher the water table, the more susceptible a soil is to liquefaction.

Liquefaction causes three types of ground failure: lateral spreads, flow failures, and loss of bearing strength. In addition, liquefaction enhances ground settlement and sometimes generates sand boils (fountains of water and sediment emanating from the pressurized liquefied zone). Sand boils can cause local flooding and the deposition or accumulation of silt.

LATERAL SPREADS

Lateral spreads involve the lateral movement of large blocks of soil as a result of liquefaction in a subsurface layer. Movement takes place in response to the ground shaking generated by an earthquake. Lateral spreads generally develop on gentle slopes, most commonly on those between 0.3 and 3 degrees. Horizontal movements on lateral spreads commonly are as much as 10 to 15 feet, but, where slopes are particularly favorable and the duration of ground shaking is long, lateral movement may be as much as 100 to 150 feet. Lateral spreads usually break up internally, forming numerous fissures and scarps.

Damage caused by lateral spreads is seldom catastrophic, but it is usually disruptive. For example, during the 1964 Prince William Sound, Alaska, earthquake, more than 200 bridges were damaged or destroyed by lateral spreading of flood-plain deposits toward river channels. These spreading deposits compressed bridges over the channels, buckled decks, thrust sedimentary beds over abutments, and shifted and tilted abutments and piers.

Lateral spreads are destructive particularly to pipelines. In 1906, a number of major pipeline breaks occurred in the city of San Francisco during the earthquake because of lateral spreading. Breaks of water mains hampered efforts to fight the fire that ignited during the earthquake. Thus, rather inconspicuous ground-failure displacements of less than 7 feet were largely responsible for the devastation to San Francisco in 1906.

FLOW FAILURES

Flow failures, consisting of liquefied soil or blocks of intact material riding on a layer of liquefied soil, are the most catastrophic type of ground failure caused by liquefaction. These failures commonly move several tens of feet and, if geometric conditions permit, several tens of miles. Flows travel at velocities as great as many tens of miles per hour. Flow failures usually form in loose saturated sands or silts on slopes greater than 3 degrees.

Flow failures can originate either underwater or on land. Many of the largest and most damaging flow failures have taken place underwater in coastal areas. For example, submarine flow failures carried away large sections of port facilities at Seward, Whittier, and Valdez, Alaska, during the 1964 Prince William Sound earthquake. These flow failures, in turn, generated large sea waves that overran parts of the coastal area, causing additional damage and casualties. Flow failures on land have been catastrophic, especially in other countries.

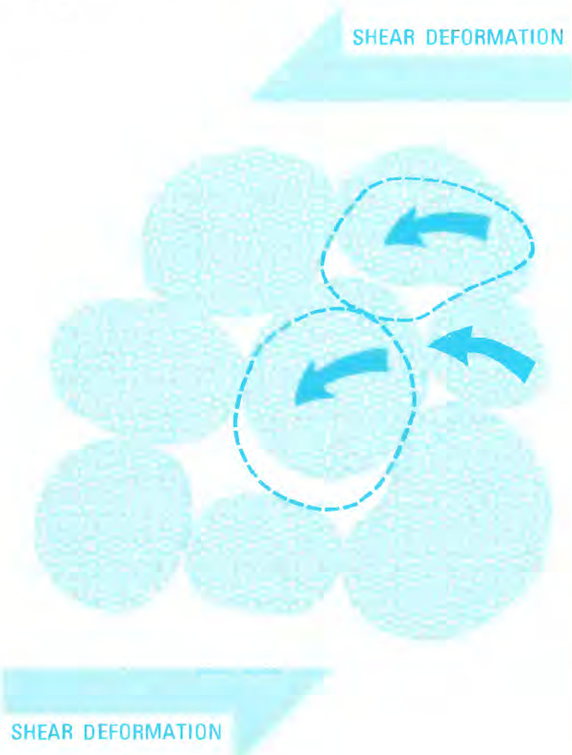
For example, the 1920 Kansu, China, earthquake induced several flow failures as much as 1 mile in length and breadth, killing an estimated 200,000 people.

LOSS OF BEARING STRENGTH

When the soil supporting a building or some other structure liquefies and loses strength, large deformations can occur within the soil, allowing the structure to settle and tip. The most spectacular example of bearing-strength failures took place during the 1964 Niigata, Japan, earthquake. During that event, several four-story buildings of the Kwangishicho apartment complex tipped as much as 60 degrees. Most of the buildings were later jacked back into an upright position, underpinned with piles, and reused.

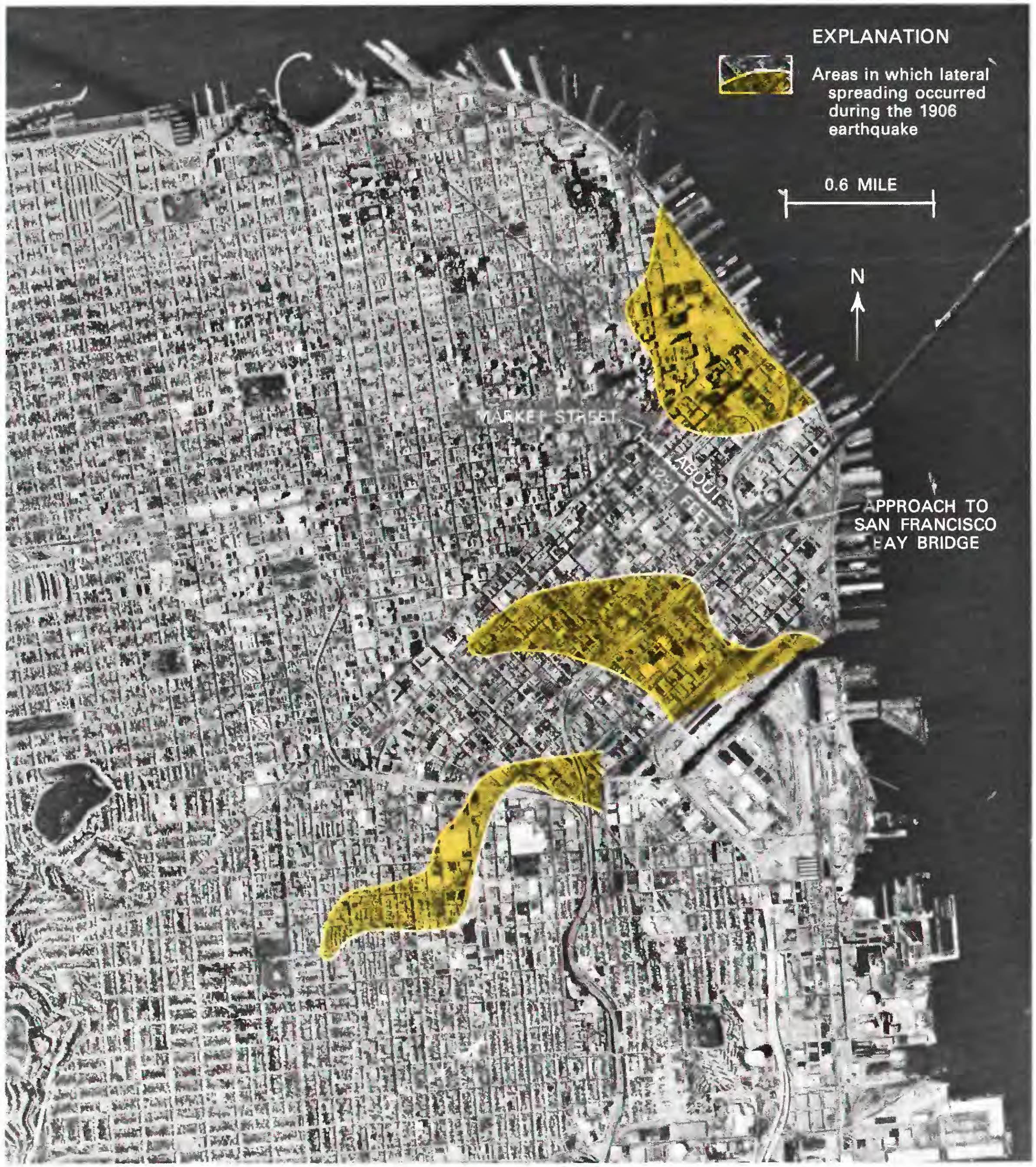
Soils that liquefied at Niigata typify the general subsurface geometry required for liquefaction-caused bearing failures: a layer of saturated, cohesionless soil (sand or silt) extending from near the ground surface to a depth of about the width of the building.

Sketch of water-saturated group of sand grains illustrating the process of liquefaction. Shear deformations (indicated by large arrows) brought about by earthquake ground shaking distort the granular structure causing some loosely packed groups to collapse as indicated by the small arrows. Each collapse transfers stress from grain-to-grain contacts to the pore water, increasing the pressure in that water. When pore-water pressures reach a critical level (grain-to-grain contact stresses approach zero), the granular material suddenly behaves as a liquid rather than as a solid. At this point, liquefaction has taken place.



Group of sand boils generated during the 1979 Imperial Valley, California, earthquake. Sand boils are caused by water laden with sediment venting from subsurface layers of sand or silt in which artesian pore-water pressures develop during the liquefaction process.

Alaska railroad bridge compressed and buckled by lateral spreading of flood-plain deposits toward the river channel during the 1964 Prince William Sound earthquake. Lateral spreads are caused by loss of strength in a subsurface soil layer because of liquefaction. This loss of strength allows overlying sediments to move laterally down very gentle slopes (usually between 0.3 and 3 degrees) in response to a combination of gravitational and earthquake loads.



Photograph of San Francisco, California, showing areas where liquefaction and lateral spreading took place during the 1906 earthquake. Lateral spreads disrupted many buildings and severed several water mains. Lack of water hampered efforts to contain the fire that broke out during the earthquake.

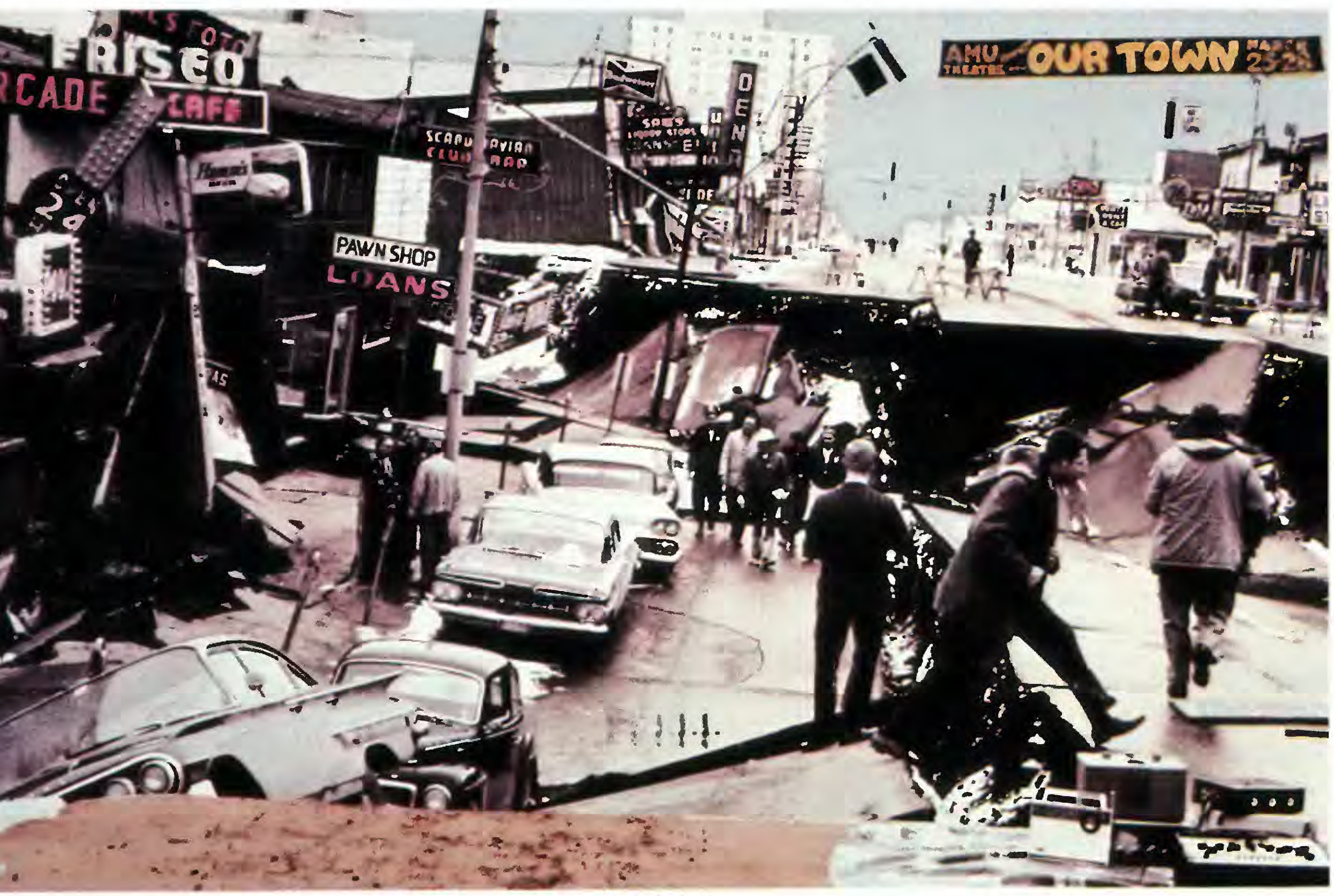
Seward, Alaska, before (A) and after (B) the 1964 Prince William Sound earthquake showing loss of docks, warehouses, and railroad facilities carried into the sea by a flow failure. Flow failures take place when loose sands and silts liquefy, lose strength, and flow down slope. Flows seldom are found on slopes less than 3 degrees. The view is to the south in the top photograph and to the northwest in the bottom photograph. Seventh Street is nearest the docks and runs from the oil tanks toward the sea in the top photograph and approximately left to right in the bottom photograph.

Four-story apartment buildings in Niigata, Japan, that settled and tipped because of loss of strength in supporting soils during the 1964 Niigata earthquake. Loss of bearing strength was caused by liquefaction of a sand layer that extends 10 to 15 feet below the base of the foundations.

What Can Happen to Quick Clays During Ground Shaking?

Most clays lose strength when disturbed by ground shaking, and, if the loss of strength is large, some clays, called "quick" or "sensitive," may fail. The five large landslides that affected parts of Anchorage during the 1964 Prince William Sound, Alaska, earthquake are examples of spectacular failures of sensitive clays. The failure zones of these slides passed through layers of the Bootlegger Cove Formation which contained layers of quick clay as well as lenses of saturated sand and silt. Loss of strength that took place in the clay layers and liquefaction that took place in the sand and silt lenses within the Bootlegger Cove Formation because of the severe ground shaking were major factors contributing to the landsliding. These landslides caused an estimated $50 million in damage.

Drilling a borehole.



Ground disruption and damage at the upper part of one of five major landslides that developed in Anchorage, Alaska, during the 1964 Prince William Sound earthquake. The landslides were induced by a combination of loss of strength in sensitive clay layers and liquefaction of sand and silt lenses in the Bootlegger Cove Formation.

What Types of Landslides Are Induced by Earthquakes?

Past experience has shown that several types of landslides take place in conjunction with earthquakes. The most abundant types of earthquake-induced landslides are rock falls and slides of rock fragments that form on steep slopes. Shallow debris slides forming on steep slopes and soil and rock slumps and block slides forming on moderate to steep slopes also take place, but they are less abundant. Reactivation of dormant slumps or block slides by earthquakes is rare.

Large earthquake-induced rock avalanches, soil avalanches, and underwater landslides can be very destructive. Rock avalanches originate on oversteepened slopes in weak rocks. One of the most spectacular examples occurred during the 1970 Peruvian earthquake when a single rock avalanche killed more than 18,000 people; a similar, but less spectacular, failure in the 1959 Hebgen Lake, Montana, earthquake resulted in 26 deaths. Soil avalanches occur in some weakly cemented fine-grained materials, such as loess, that form steep stable slopes under nonseismic conditions. Many loess slopes failed during the New Madrid, Missouri, earthquakes of 1811–12. Underwater landslides commonly involve the margins of deltas where many port facilities are located. The failures at Seward, Alaska, during the 1964 earthquake are an example.

The size of the area affected by earthquake-induced landslides depends on the magnitude of the earthquake, its focal depth, the topography and geologic conditions near the causative fault, and the amplitude, frequency composition, and duration of ground shaking. In past earthquakes, landslides have been abundant in some areas having intensities of ground shaking as low as VI on the Modified Mercalli Intensity Scale.

What Can Be Done To Reduce Losses From Earthquake-Induced Ground Failures?

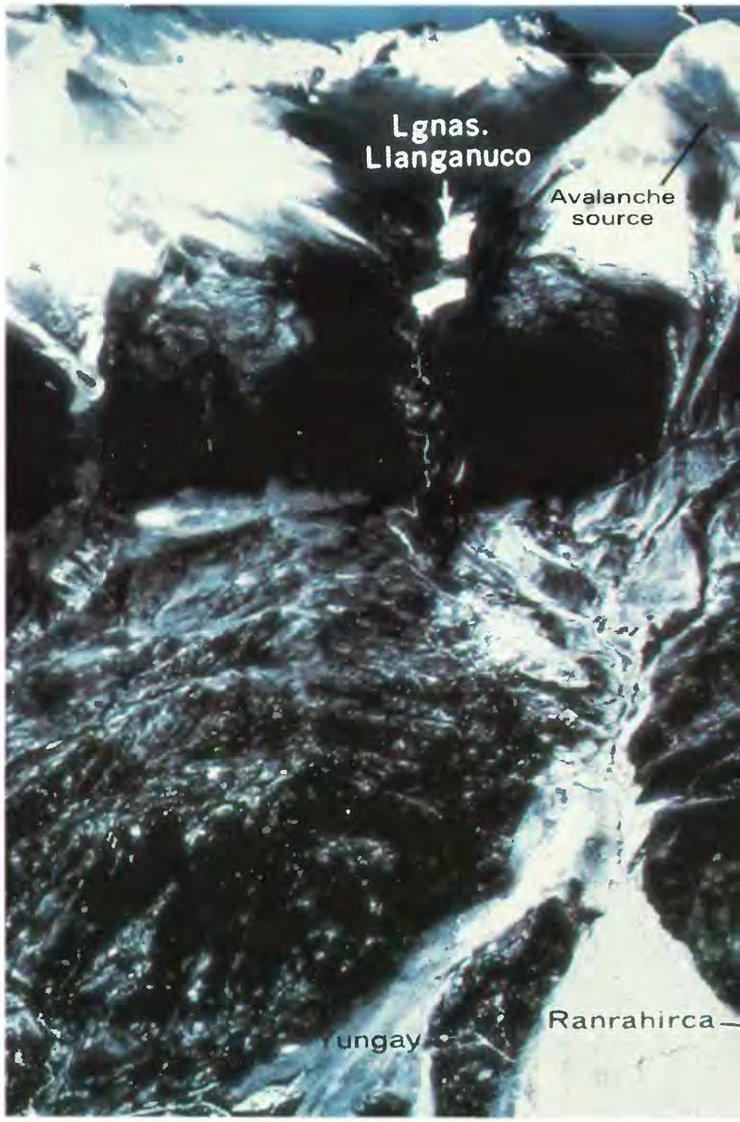
Actions for reducing losses from lateral spreading include zoning to limit building in susceptible areas, stabilization to prevent liquefaction and ground failure, and construction of displacement-resistant foundations. Engineering techniques for stabilizing sites against liquefaction include compaction, grouting, or drainage of susceptible soils. These techniques are generally expensive and, therefore, are not economically feasible unless critically important facilities are being built. Construction of displacement-resistant foundations is presently beyond the state-of-the-art for ground-failure displacements greater than 1 foot.

Avoidance and engineering design are the primary actions for reducing losses from flow failures. Avoidance of sites susceptible to flow failure is frequently possible. Sometimes, small areas can be stabilized by engineering techniques to prevent liquefaction. However, no practical means exist for stabilizing large geographic areas, such as those that failed in Alaska, against flow failure.

Actions for reducing damage due to loss of bearing strength include site selection to avoid the hazard, stabilization of liquefiable layers to prevent loss of strength, and use of deep foundations (such as piles) to transfer loads to stable layers underlying potentially liquefiable ones.

Avoidance, land-use zoning, and excavation are the primary actions for stabilizing areas susceptible to landslides. Specific actions are discussed in more detail in Chapter 4.

Rock falls and slides that took place on steep slopes of the eastern Sierra Nevada Mountains during the 1980 Mammoth Lakes, California, earthquakes are examples of the most abundant type of earthquake-induced landslides. Debris from the falls and slides accumulated in piles of loose fragments at bases of slopes or formed thin rock-and-snow avalanches that moved 0.5 mile down snow-covered slopes. Rock falls and slides are common on slopes greater than 30 degrees. Almost all types of rock are affected, although failures have been most common in rocks that are weathered, thinly bedded, poorly cemented, or closely jointed.



Sixty-five-million-cubic-yard rock-fall avalanche that cascaded from Mount Huascaran during the 1970 Peruvian earthquake, burying most of the city of Yungay and part of the city of Ranrahirca and killing 18,000 people. Massive rock-fall avalanches of this type, which took place in the 1959 Hebgen Lake, Montana, earthquake, usually form on high slopes oversteepened by recent or active erosion. Rock units most vulnerable to failure are those weakened by weathering, shearing, or unfavorably oriented beds, foliation, or joints.

Tsunamis

What Causes a Tsunami?

Tsunamis are water waves that are caused by sudden vertical movement of a large area of the sea floor during an undersea earthquake. Tsunamis are often called tidal waves, but this term is a misnomer. Unlike regular ocean tides, tsunamis are not caused by the tidal action of the Moon and Sun. The height of a tsunami in the deep ocean is typically about 1 foot, but the distance between wave crests can be very long, more than 60 miles. The speed at which the tsunami travels decreases as water depth decreases. In the mid-Pacific, where the water depths reach 3 miles, tsunami speeds can be more than 430 miles per hour. As tsunamis reach shallow water around islands or on a continental shelf, the height of the waves increases many times, sometimes reaching as much as 80 feet. The great distance between wave crests prevents tsunamis from dissipating energy as a breaking surf; instead, tsunamis cause water levels to rise rapidly along coast lines.

Tsunamis and earthquake ground shaking differ in their destructive characteristics. Ground shaking causes destruction mainly in the vicinity of the causative fault, but tsunamis cause destruction both locally and at very distant locations from the area of tsunami generation.

Sequence of photographs showing the arrival of the March 9, 1957, Oahu, Hawaii, tsunami at Laie Point. The time interval between the second and third photographs is about 5 minutes. If this were a tsunami having wave heights of 50 feet or greater, the man in the first photograph would have very little chance to escape. (Photographs by Henry Helbush.)

Where Have Tsunamis Occurred Historically?

EAST COAST

Historically, no tsunamis have been generated on the east coast, a consequence of the low level of seismic activity and the lack of vertical fault displacement. No tsunami occurred during the Charleston, South Carolina, earthquake of 1886, one of the largest earthquakes in the United States. In addition, none of the tsunamis occurring in the Atlantic Ocean region has significantly affected the east coast of the United States. The only tsunami known to have been recorded on the Atlantic Coast of the United States was generated by an earthquake off the Burin Peninsula of Newfoundland on November 18, 1929; it caused a wave height of 1 foot.

WEST COAST

Tsunamis generated by earthquakes in South America and the Aleutian-Alaskan region have posed a greater hazard to the west coast of the United States than locally generated tsunamis. For example, the 1946 Aleutian tsunami produced waves heights of 12 to 16 feet at Half Moon Bay, Muir Beach, Arena Cove, and Santa Cruz, California. The 1960 Chilean tsunami produced wave heights of 12 feet at Crescent City, California. The 1964 Alaskan tsunami generated waves of more than 20 feet at Crescent City, California, where it caused $7.5 million in damage and 11 deaths. It also produced waves ranging from 10 to 16 feet along parts of the California, Oregon, and Washington coasts. In contrast, for example, the 1906 San Francisco, California, earthquake produced local tsunami waves of only about 2 inches. The largest known locally generated tsunami on the west coast was caused by the 1927 Point Arguello, California, earthquake that produced waves of about 7 feet in the nearby coastal area.

ALASKA

The combination of seismic activity in the Aleutian-Alaskan trench where the Pacific and North American tectonic plates collide and the vertical displacements of faults make this region of Alaska a source of tsunamis. The earliest recorded tsunami in this region was in 1788. Four major tsunamis were generated in 1946, 1957, 1964, and 1965; the 1964 Alaskan tsunami caused over $80 million in damage and killed 107 people.

HAWAII

The Hawaiian Islands have experienced many destructive tsunamis because of their location in the Pacific Ocean where about 90 percent of all recorded tsunamis take place. Since 1819, more than 100 locally and distantly generated tsunamis have been recorded in the Hawaiian Islands with 16 of them causing significant damage. More than one-half of all tsunamis recorded in the Hawaiian Islands were generated in the Kuril-Kamchatka-Aleutian regions of the northern and northwestern Pacific. Tsunamis generated in that area produce the greatest waves on the northern side of the islands. About one-fourth of the historic tsunamis affecting Hawaii were generated along the western coast of South America. Tsunamis generated in the island areas of the Philippines, Indonesia, the New Hebrides, and Tonga-Kermadec have been recorded in the Hawaiian Islands, but they have not been damaging. The worst locally generated tsunamis were generated in 1869 and 1975 on the southeastern coast of the big island of Hawaii; they caused destructive waves of as much as 59 feet.

What Is the Economic Impact of Tsunamis?

Tsunamis have produced great destruction and loss of life in Hawaii and along the west coast of the United States. Since 1945, more people have been killed as a result of tsunamis than as a direct result of earthquake ground shaking. For example, the 1946 Aleutian tsunami killed 173 people in Hawaii and caused $26 million in property damage in the city of Hilo. The 1960 Chilean tsunami killed 61 people in Hawaii and caused $23 million in property damage. The 1964 Alaskan tsunami, the most recent major tsunami to affect the United States, killed 107 people in Alaska, 4 in Oregon, and 11 in Crescent City, California. This tsunami caused more than $100 million in damage on the west coast.

Destruction to structures and other facilities is a consequence of the time between successive wave crests, the wave heights at the shoreline and inland locations, and the wave and current velocities. The effects of tsunamis include structural failure, scouring at foundations, erosion, flooding, and movement of stone and debris.

Damage to the Scotch Cap lighthouse from the Aleutian tsunami of April 1, 1946, Umimak Island, Alaska. A, *Before.* B, *After. (Photographs by U.S. National Oceanic and Atmospheric Administration.)*

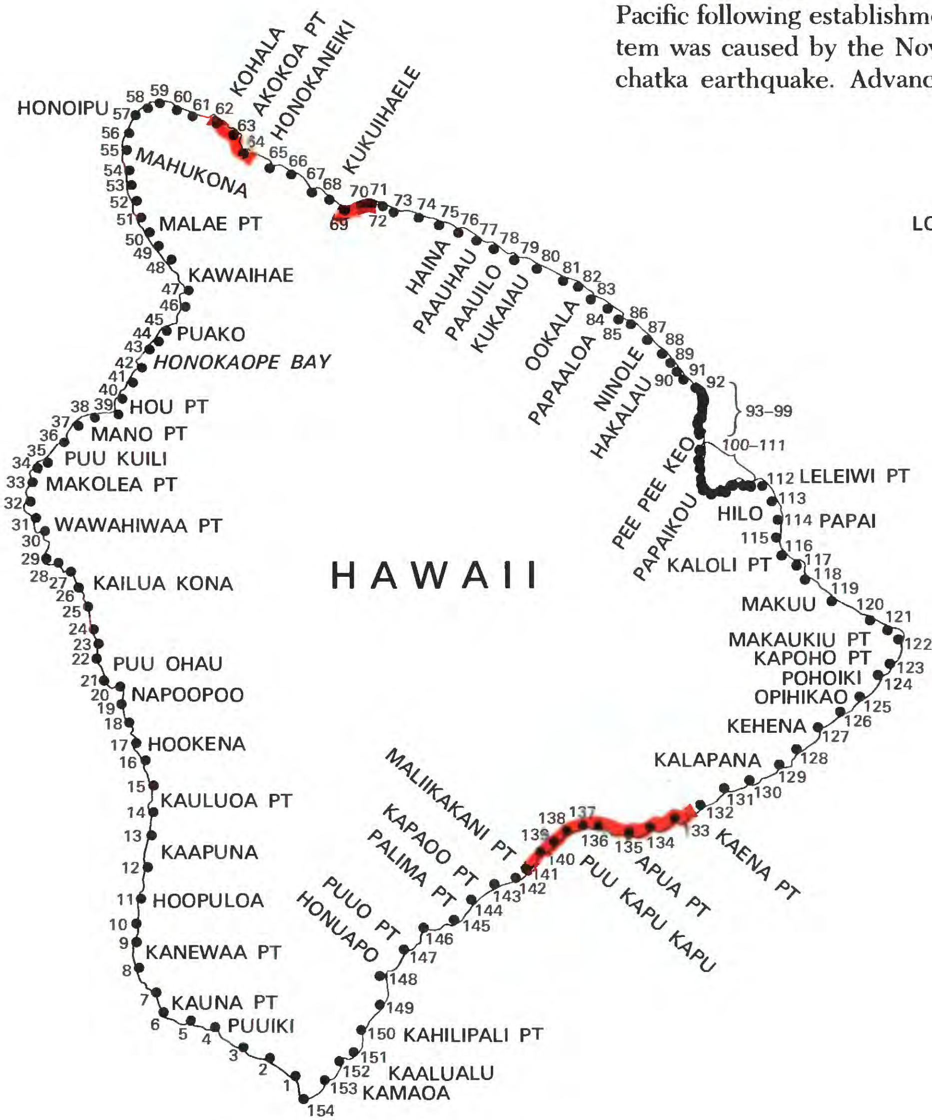

A


B

What Can Be Done To Reduce Losses From Tsunamis?

Because tsunamis cannot be prevented, a warning system that can give many hours of advance notice is the primary way used to reduce losses. The Tsunami Warning System was established in response to the Aleutian tsunami of April 1, 1946, which caused great damage and loss of life in the Hawaiian islands. This system, the responsibility of the U.S. National Oceanic and Atmospheric Administration, consists of 22 seismic observatories and 53 tide stations. The first major tsunami in the Pacific following establishment of the warning system was caused by the November 4, 1952, Kamchatka earthquake. Advance warnings were provided to communities in the path of this tsunami; the result was a reduction of damage and no casualties. The 1957 Aleutian tsunami, the second major Pacific tsunami following the establishment of the warning system, caused $3 million damage in the Hawaiian Islands, but no loss of life.

Land-use zoning of coastal areas is another way used to reduce losses from tsunamis. Such zoning is based on the heights of tsunami waves expected for exposure times of 20, 50, and 100 years. Tsunami hazard maps, such as shown in the text, are used in zoning.



EXPLANATION

LOCATION NUMBER	ZONE
154 TO 4	3
4 TO 11	2
11 TO 13	3
13 TO 17	2
17 TO 19	3
19 TO 27	4
27 TO 31	3
31 TO 48	2
48 TO 61	3
61 TO 62	4
62 TO 64	5
64 TO 66	3
66 TO 69	4
69 TO 70	5
70 TO 77	4
77 TO 82	3
82 TO 110	4
110 TO 124	3
124 TO 127	4
127 TO 130	3
130 TO 134	4
134 TO 141	5
141 TO 154	4

Map of the tsunami hazard for the island of Hawaii (from Houston and others, 1977). Various locations on the island are classified as being in Zones 2 through 5. Zone 2 denotes wave heights of 5 to 15 feet; Zone 3, 15 to 30 feet; Zone 4, 30 to 50 feet; and Zone 5, 50 feet or greater. There is a 10-percent probability that these wave elevations will be exceeded in a 50-year period. Shading denotes areas in Zone 5. The Island of Hawaii does not have a Zone 1.

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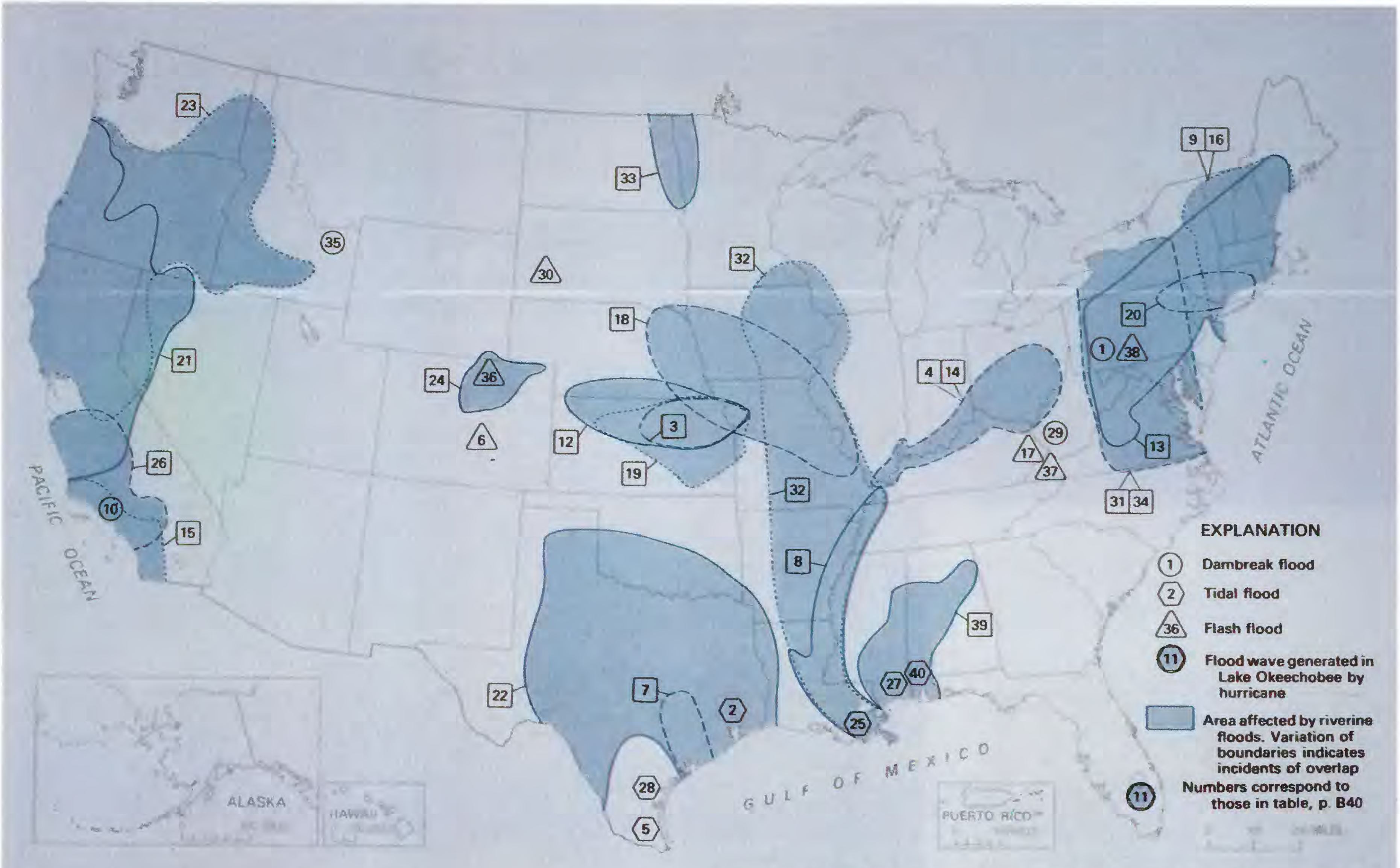


Map showing distribution of great floods in the conterminous United States since 1889.

3. Hazards From Floods

Floods

What is the Cause of Flooding?

Floods have been and continue to be one of the most destructive natural hazards facing the Nation. Moreover, the probability exists that a greater flood will take place than any experienced in the past.

A flood is any abnormally high streamflow that overtops the natural or artificial banks of a stream. Flooding is a natural characteristic of rivers. Flood plains are normally dry-land areas which act as a natural reservoir and temporary channel for flood waters. If more runoff is generated than the banks of a stream channel can accommodate, the water will overtop the stream banks and spread over the flood plain causing social and economic disruption and damage to crops and structures. The ultimate factor of damage, however, is not the quantity of water being discharged, but the stage or elevation of the water surface. Damage from high stages in streams having relatively low discharge can be caused by backwater from ice, channel constrictions, or a concurrent flood on another stream. Furthermore, floods can form where there is no stream, as, for example, when abnormally heavy precipitation falls on flat terrane at such a rate that the soil cannot absorb the water or the water cannot run off as fast as it falls.

Aerial view of western part of Fairbanks, Alaska, near crest of flood on Chena River, August 15, 1967. River flows from right to left. (Photograph by U.S. Bureau of Land Management.)

Floods take place in the United States in all seasons. Winter floods due to the rainfall and temperature pattern take place in the east progressing northward from the Gulf Coast States in January to the Ohio River valley in March. Winter floods caused by general cyclonic storms take place along the western slopes of California, Oregon, and Washington.

Spring floods are common in the Northwestern States, the Great Lakes area, the Missouri River basin, the eastern slopes of Washington and Oregon, and the mountains in California and Arizona. The floodwater comes from the melting of snows that accumulated during winter. Ice jams also frequently cause flooding. Early spring floods in the lower Mississippi River basin are caused by the seasonal rainfall pattern. Late spring floods in the mountain plateaus mainly result from melting of the snows at high altitudes.

Summer floods are likely to take place in any part of the United States except on the west coast. Although some summer floods have been caused by general cyclonic storms, most summer floods, except for those associated with hurricanes which occur in late summer and autumn, are caused by thunderstorms that affect small areas.

On the basis of present knowledge, the size, time, and place of floods cannot be predicted much in advance.

Storage, either natural or artificial, has a distinct influence on floods. Floods are seldom a problem downstream from a swampy region or a region containing numerous lakes and ponds because much of the runoff is retarded by storage.

Great floods in the United States since May 1889

[Adapted from Climatological Data, National Summary, 1977, National Oceanic and Atmospheric Administration, vol. 28, no. 13, and by information furnished from the Federal Disaster Assistance Administration]

Number[a]	*Type of flood*	*Date*	*Location*	*Lives lost*	*Estimated damages (millions of dollars)*
1	b	May 1889	Johnstown, Pennsylvania, dam failure	3,000	—
2	c	September 8, 1900	Hurricane—Galveston, Texas	6,000	30
3	d	May–June 1903	Kansas, Lower Missouri, and Upper Mississippi River	100	40
4	d	March 1913	Ohio River and Tributaries	467	147
5	c	September 14, 1919	Hurricane—south of Corpus Christi, Texas	600–900	22
6	b,e	June 1921	Arkansas River, Colorado	120	25
7	d	September 1921	Texas rivers	215	19
8	d	Spring of 1927	Mississippi River valley	313	284
9	d	November 1927	New England rivers	88	46
10	b	March 12–13, 1928	St. Francis Dam failure, southern California	450	14
11	f	September 13, 1928	Lake Okeechobee, Florida	1,836	26
12	d	May–June 1935	Republican and Kansas Rivers	110	18
13	d	March–April 1936	Rivers in Eastern United States	107	270
14	d	January–February 1937	Ohio and Lower Mississippi River basins	137	418
15	d	March 1938	Streams in southern California	79	25
16	d	September 21, 1938	New England	600	306
17	e	July 1939	Licking and Kentucky Rivers	78	2
18	d	May–July 1947	Lower Missouri and Middle Mississippi River basins	29	235
19	d	June–July 1951	Kansas and Missouri	28	923
20	d	August 1955	Hurricane Diane floods—Northeastern United States	187	714
21	d	December 1955	West coast rivers	61	155
22	d	June 27–30, 1957	Hurricane Audrey—Texas and Louisiana	390	150
23	d	December 1964	California and Oregon	40	416
24	d	June 1965	South Platte River basin, Colorado	16	415
25	c	September 10, 1965	Hurricane Betsy—Florida and Louisiana	75	1,420
26	d	January–February 1969	Floods in California	60	399
27	c,d	August 17–18, 1969	Hurricane Camille—Mississippi, Louisiana, and Alabama	256	1,421
28	c	July 30–August 5, 1970	Hurricane Celia—Texas	11	453
29	b	February 1972	Buffalo Creek, West Virginia	125	10
30	e	June 1972	Black Hills, South Dakota	237	165
31	c,d	June 1972	Hurricane Agnes floods—Eastern United States	105	4,020
32	d	Spring 1973	Mississippi River basin	33	1,155
33	d	June–July 1975	Red River of the North basin	<10	273
34	c,d	September 1975	Hurricane Eloise floods—Puerto Rico and Northeastern United States	50	470
35	b	June 1976	Teton Dam failure, southeast Idaho	11	1,000
36	e	July 1976	Big Thompson River, Colorado	139	30
37	e	April 1977	Southern Appalachian Mountains area	22	424
38	b,e	July 1977	Johnstown–western Pennsylvania	78	330
39	d	April 1979	Mississippi and Alabama	<10	500
40	c	September 12–13, 1979	Hurricane Frederic floods—Mississippi, Alabama, and Florida	13	2,000

[a] Number corresponds to those in the frontispiece of this chapter.
[b] Dam break flood.
[c] Tidal flood.
[d] Riverine flood.
[e] Flash flood.
[f] Flood wave generated in Lake Okeechobee by hurricane.

What Is Man's Role in Aggravating Flooding?

Floods are natural and recurrent events. They become a hazard when man competes for the use of flood plains. The natural function of a flood plain is to carry away excess water in time of flood. Man's failure to recognize this function has led to rapid and haphazard development on flood plains and a consequent increase in flood hazards. Flood-plain occupancy and use are often based on the economic advantages of level ground, fertile soils, ease of access, and available water supplies—without full consideration of flood risk (Waananen and others, 1977).

In recent years, the Federal Government has assumed more responsibility for providing relief and partial indemnification for property losses resulting from floods. In addition to relief, since 1936 the Federal Government has spent more than $9 billion on flood-protection works.

In spite of the flood-protection programs since 1936, the average annual flood hazard has become greater than before such programs began because people have moved to and built in flood-prone areas faster than flood-protection works have been constructed. The increased loss is apparently not due to greater floods but to increased encroachment of man on flood plains. Many factors have been responsible for man's development of flood-prone areas—the general growth of population, income, and wealth, among others; but it is also clear that the substantial separation of costs from benefits, whereby the general public bears most of the costs of flood-protection works while individual members primarily receive the benefits, has been a major factor encouraging such development. Many people in high-flood-risk areas are seriously uninformed about the risks which they face. Either they are grossly over-optimistic about the probability that their property will not be flooded or they expect public help to bail them out when the inevitable flood strikes (U.S. Congress, 1973).

A first magnitude flow from Floridian aquifer, St. Mark's Spring, Leon County, Florida, 1974.

What Is the Impact of Flooding on the Economy?

NATURAL

About 3 million miles of streams exist in the conterminous United States, and about 6 percent of the land area is prone to flooding. A proportionate percentage of the Nation's population and tangible property is concentrated in flood-prone areas. More than 20,800 communities have flood problems. About 6,100 of these communities have populations greater than 2,500. (U.S. Water Resources Council, 1977).

Floods are a source of great personal hardship. They threaten loss of life, cause suffering, damage property, destroy crops, and disrupt commerce.

The average annual flood loss in the United States (in current dollars), not to mention the suffering and death caused by floods, has increased from less than $100,000 at the beginning of the century to more than $3 billion today. By the year 2000, potential annual flood loss is expected to be greater than $4 billion on the average even with moderate application of flood-plain management measures.

The nature of flood damage varies widely. Some damage, or at least inconvenience, begins as soon as a stream overtops its normal banks and water begins to occupy the flood plain. A further rise in stage may cause flooding of ground floors of residences and other buildings. Eventually, as the velocity of the water in the flood plain increases, houses may be swept off foundations, and automobiles and other movable property may be carried away by the swift current. During most great floods of record, loss of human life takes place. Large floods in rural areas generally destroy crops and livestock and frequently render the land unfit for use, at least temporarily, by erosion in some places and deposition of sand and mud in other places.

DAM BREAK FLOODS

Disastrous floods caused by failure of dams, although not in the category of "natural events," have caused great loss of life and property damage. Dam failures frequently are associated with intense rainfalls and prolonged flood conditions. However, some dam breaks have taken place during dry periods as a result of progressive erosion of an embankment, which developed from seepage leaks.

Flood discharges decrease as the flood wave from a dam break moves downstream. The greatest threat from dam breaks, therefore, is usually in areas immediately below a dam. The following examples illustrate their impact.

Johnstown, Pennsylvania

The May 31, 1889, flood in the vicinity of Johnstown, Pennsylvania, which resulted from the failure of a large dam on the South Fork of the Little Conemaugh River, 13 miles upstream from Johnstown, was a major catastrophe in the Nation's history. More than 3,000 lives were believed lost. The day before the dam failed, streams were swollen as a result of 6 to 8 inches of storm rainfall. The water level behind the South Fork Dam rose far above normal and leaks formed in the earth embankment. About 3:00 p.m. (May 31), the dam suddenly burst. The resulting flood wave was estimated at 30 to 39 feet. Seven small towns were destroyed as the wave traveled the 13 miles to Johnstown in about 15 minutes. Johnstown, at the mouth of the Little Conemaugh River and directly in the path of the flood wave, was almost totally destroyed (Hoxit and others, in press).

Buffalo Creek From Saunders to Man, West Virginia

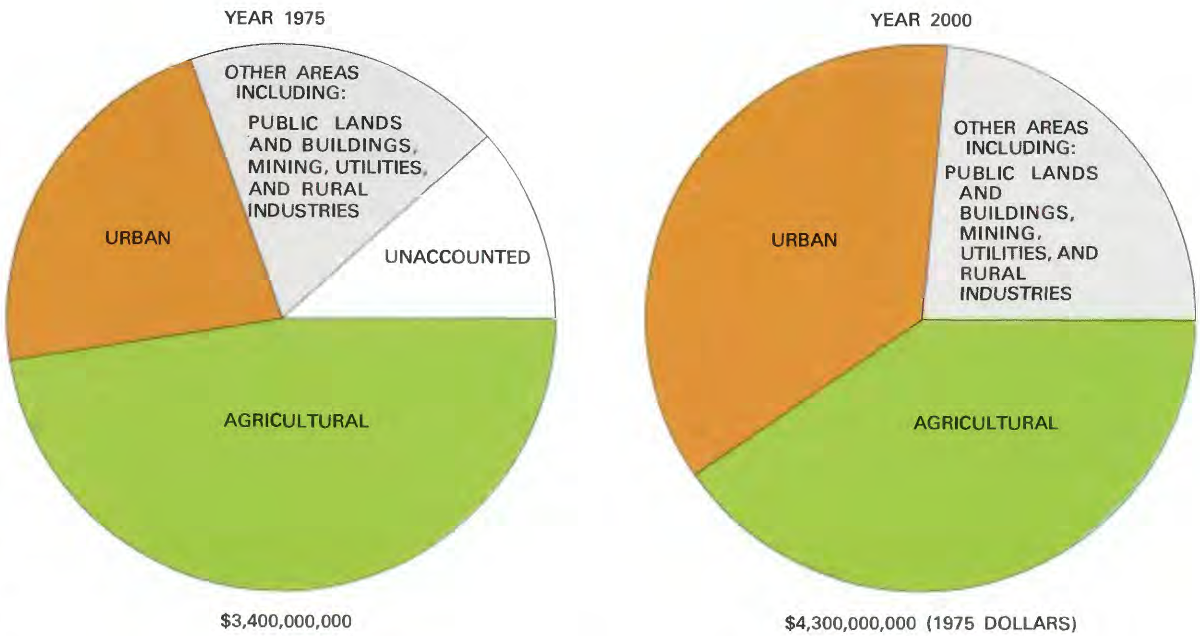
On February 26, 1972, at approximately 8:00 a.m., a coal mine refuse dam collapsed on Middle Fork, a tributary to Buffalo Creek. The resulting failure released some 0.7 million cubic yards of impounded water and sediment into the Buffalo Creek valley. The flood swept through the 16 miles of valley at an average speed of 3 miles per hour and reached the town of Man at the mouth of Buffalo Creek about 11:00 a.m. The traveltime for the 16 miles was about 3 hours. During these 3 hours, at least 118 lives were lost, 500 homes were destroyed, 4,000 people were left homeless; property damage exceeded $50 million, and highway damage exceeded $15 million (Davies, Bailey, and Kelly, 1972).

The Flood in Southeastern Idaho Caused by the Teton Dam Failure on June 5, 1976

The failure of the Teton Dam near Newdale, Idaho, June 5, 1976, caused a flood of unprecedented magnitude on the Teton River, lower Henrys Fork, and Snake River upstream from American Falls Reservoir. Eleven lives were lost. Water spread over more than 180 square miles, and damages reportedly were about $400 million.

The Teton Reservoir behind the 130-foot-high earth dam was being filled for the first time during spring 1976. About 7:30 a.m., June 5, two seepage leaks were observed. Another leak developed about 10:00 a.m., and the downstream dam embankment eroded progressively as the flow from this leak increased. About 11:00 a.m., a whirlpool formed in the reservoir. The crest of the embankment fell into the water at 11:55 a.m., and, at 11:57 a.m., the water breached the dam and cascaded into the canyon. As the fast-moving flood waters emerged from the canyon mouth 5 miles downstream, flood waves spread rapidly downgrade over the widening flood plain of the Teton River. The flooded area in the vicinity of Rexburg, Idaho, was more than 6 miles wide. The communities of Wilford and Sugar City were devastated by a 16-foot-high wall of water. Most of the city of Rexburg was inundated to depths of about 7 feet within a few minutes by rampaging flood waters carrying large trees and other floating debris. Water was about 7 feet deep throughout the town of Roberts and covered parts of Menan, Idaho Falls, Firth, and Blackfoot. By midnight on June 7, 1976, the crest of the main flood reached American Falls Reservoir about 100 miles downstream from Teton Dam. American Falls Reservoir stored the entire flow.

Flood warnings by the U.S. Water and Power Resources Service (formerly U.S. Bureau of Reclamation), local radio stations, and law enforcement agencies enabled nearly all of the people to vacate the flood plain; this action undoubtedly saved many lives (Ray and Kjelstrom, 1978).



Trends in the distribution of annual flood losses, 1975–2000. (Modified from U.S. Water Resources Council, 1978.)

Wrecked house and other debris, including large mobile home, lodged on a damaged private bridge 0.5 mile downstream from Drake, Colorado. Flood of August 1976, Big Thompson River, Colorado.

Looking upstream at Teton Dam near Newdale, Idaho, after collapse, June 6, 1976, 2:11 p.m. (Photograph by U.S. Army Corps of Engineers.)

Mouth of Teton River canyon afternoon of June 6, 1976, 5 miles downstream from collapsed Teton Dam. Devastated community of Wilford, Idaho, in distance. (Photograph by Perks Photo Service, Idaho Falls, Idaho.)

Flash Flooding

What Causes Flash Floods?

Flash floods, which have taken many lives and caused great property damage, are local floods of great volume and short duration. A flash flood generally results from a torrential rain or "cloudburst" on a relatively small drainage area. Cloudbursts, associated with severe thunderstorms, take place mostly in the summer.

Flash floods also result from the failure of a dam or from the sudden breakup of an ice jam. Each can cause the release of a large volume of flow in a short time.

What Are the Physical Characteristics of Flash Floods?

Violent thunderstorms or cloudbursts usually develop in a short time and produce floods on relatively small and widely dispersed streams. Runoff from intense rainfalls result in high flood waves that can destroy roads, bridges, homes, buildings, and other community developments. Discharges quickly reach a maximum and diminish almost as rapidly. Flood flows frequently contain large concentrations of sediment and debris collected as they sweep channels clean.

The disastrous nature of flash floods is illustrated by the Big Thompson River flood of July 31–August 1, 1976, in Colorado. As much as 20 inches of rain fell on about 60 square miles of the drainage area, causing a devastating flood on the Big Thompson River and its tributaries between Estes Park and Loveland, Colorado. The flood lasted only a few hours, but, during that time, it caused many deaths and much destruction; at least 139 lives were lost, and damages were estimated at more than $35 million. The flood crest on the Big Thompson River moved through the 7.6 miles between Drake and the canyon mouth in about 30 minutes, for an average speed of about 15 miles per hour.

Although the rainfall and flood discharges were unusually large, they are not unprecedented for some areas along the eastern foothills and plains of Colorado. The May 1935 and June 1965 floods on some streams along the eastern plains were much greater than the 1976 peaks in the storm area (McCain and others, 1979).

The eruption of Mount St. Helens Volcano (Chapter 5) in southwestern Washington, May 18, 1980, produced major debris and mudflows and severe flooding on the Toutle River and lower Cowlitz River. Runoff from melted glaciers and snow on the volcano's north slope, supplemented by outflow from Spirit Lake, was the source of the flow. The great volume of sediment and thousands of logs transported during the flood on the Toutle River destroyed most of the bridges. Much of the sediment was carried downstream into the Cowlitz and Columbia Rivers where it formed a shoal that blocked the shipping channel for several days.

Where Do Flash Floods Occur?

Flash floods can take place in almost any area of the country, but they are particularly common in the mountainous areas and desert regions of the West. Flash floods are a potential source of destruction and a threat to public safety in areas where the terrane is steep, surface runoff rates are high, streams flow in narrow canyons, and severe thunderstorms prevail.

Flood damage along the Big Thompson River near center of Drake, Colorado, August 1976.

Flooding along Cowlitz River May 19, 1980, at Castle Rock, Washington, following massive mudflows initiated by the eruption of Mount St. Helens Volcano. From 3 to 5 feet of sediment were deposited over the Castle Rock fairground. The business section of Castle Rock (in background) was protected by a levee.

Riverine Floods

What Causes Riverine Floods?

Riverine floods are caused by precipitation over large areas or by the melting of the winter's accumulation of snow or both. Riverine floods differ from flash floods in their extent and duration. Whereas flash floods are of short duration on small streams, riverine floods take place in river systems whose tributaries may drain large geographic areas and encompass many independent river basins. Floods on large river systems may continue for periods ranging from a few hours to many days.

What Are the Physical Characteristics of Riverine Floods?

Flood flows in large river systems are influenced primarily by variations in the intensity, amount, and distribution of precipitation. The condition of the ground—amount of soil moisture, seasonal variations in vegetation, depth of snow cover, and imperviousness due to urbanization—directly affects flood runoff.

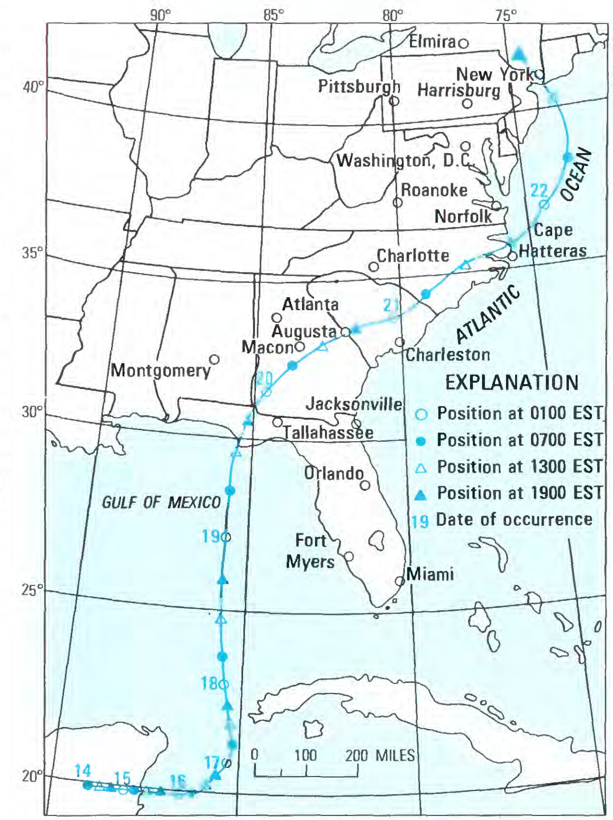
Three characteristics of river channels, channel storage, changing channel capacity, and timing, control the movement of riverine flood waves (Leopold and Langbein, 1960). As a flood moves down the river system, temporary storage in the channel reduces the flood peak. As tributaries enter the main stream, the river gets larger and larger downstream. Tributaries are not of the same size nor are they spaced uniformly; therefore, their flood peaks reach the main stream at different times. The difference of timing tends to modify peaks as a flood wave moves downstream.

Sediment sampling of a stream from a highway bridge. Note the water washing over the floor of the bridge.

Where Do Riverine Floods Occur?

Riverine floods take place throughout the United States. Although annual precipitation amounts vary widely, heavy rains can occur at various times in both arid and humid regions.

The catastrophic effects of riverine flooding are illustrated by the flood of June–July 1972 in the Middle Atlantic States resulting from the heavy rains associated with Hurricane Agnes. The storm originated in the Caribbean Sea region in mid-June, crossed the Florida panhandle coastline on June 19, 1972, and brought heavy rains from the Carolinas northward to New York. Many streams in the affected area experienced peak flows several times greater than the previous maxima of record. Suspended-sediment loads of most flooded streams were unusually high. The widespread flooding claimed 117 lives and caused damage of more than $3 million in 12 States (Bailey and others, 1975).



Hurricane Agnes storm track, June 14–22, 1972. (From U.S. National Weather Service.)

Tidal Floods

What Causes Tidal Floods?

Tidal floods are overflows of coastal lands bordering an ocean, an estuary, or a lake. These coastal lands, such as bars, spits, and deltas affected by the coastal current, occupy the same protective position relative to the sea that flood plains do to rivers.

Coastal flooding primarily is due to landward flows caused by high tides, waves from high winds, surges from distant storms, tsunamis (long waves produced by submarine earthquakes—see Chapter 2), or a combination of these events. Along shores, damage also can be caused by ice driven ashore by wind or wave action (U.S. Water Resources Council, 1972). Tidal floods can also be caused by the combination of waves generated by hurricane winds and flood runoff resulting from the heavy rains that accompany hurricanes.

What Are the Physical Characteristics of Tidal Floods?

Tidal floods may extend over large distances along a coastline. The duration of tidal floods is usually short, being dependent upon the elevation of the tide which rises and falls twice daily in most places. However, maximum tide elevations can be identical on consecutive days. In the case of tidal floods associated with hurricanes, the high velocities of hurricane winds often produce wave heights about 3 feet higher than the maximum level of the prevailing high tide.

Where Do Tidal Floods Occur?

Most of the severe tidal floods are caused by tidal waves generated by high winds superimposed on the regular cyclic tides. Tropical hurricanes are the primary sources of the extreme winds. Each year, several hurricanes enter the United States mainland, striking along the coasts of the Gulf of Mexico and the Atlantic Ocean.

Hurricane Frederic, one of the most intense hurricanes of record, struck the coastal areas of Mississippi, Alabama, and Florida on September 12–13, 1979. Maximum wind speed recorded at Dauphin Island, Alabama, was 144 miles per hour. Maximum prevailing flood elevations were about 11 feet at Mobile, Alabama, and about 14 feet at Gulf Shores, Alabama. The maximum wave height above the prevailing tide was about 8 feet. At least 13 lives were lost, and the total damage exceeded $2 billion (Bohman and Scott, 1980).

Most beachfront homes in the Gulf Shores, Alabama, area were either demolished or severely damaged by high winds and tidal surge from Hurricane Frederic, September 12–13, 1979. (Photograph by U.S. Army Corps of Engineers, Mobile District.)

What Can Be Done To Reduce Losses From Floods?

Substantial efforts have already been made by Federal and State Governments and the private sector to reduce losses from floods. In spite of these efforts, man's uses of flood plains and flood-prone areas continue to increase and, in direct relation, so have losses from floods. The message is clear—as long as flood plains and other flood-prone areas are occupied, the Nation will face continuing costs associated with losses and flood protection.

The key action in effective reduction of losses from floods lies in the intelligent planning for and regulation of the use of land exposed to the flood hazard (U.S. Congress, 1966). The National Program for Flood Plain Management, started in 1969, is directed toward this goal, among others. The U.S. Geological Survey and the U.S. Army Corps of Engineers have important responsiblities in the program. Since 1969, the Geological Survey, as its part in the program, has identified flood-prone areas throughout the Nation on more than 13,000 topographic maps. Currently, the Survey effort is directed toward mapping areas downstream from dams and reservoirs, areas having high potential for flash floods, and areas of potential future urban development. Prediction of the size, time, and place of floods is not yet an effective loss-reduction action because of limited knowledge.

The U.S. Flood Insurance Administration directs a program to make flood insurance available to property owners on a nationwide basis through cooperative efforts of the Federal Government and private industry. This program also encourages State and local governments to adopt sound programs of flood-plain management to reduce or eliminate future flood losses. Flood insurance studies in more than 6,000 of the 20,800 communities having known flood problems have been prepared for the Flood Insurance Administration by other government agencies and by consultants in the private sector. Flood-loss prevention and reduction measures are discussed in Waananen and others (1977).

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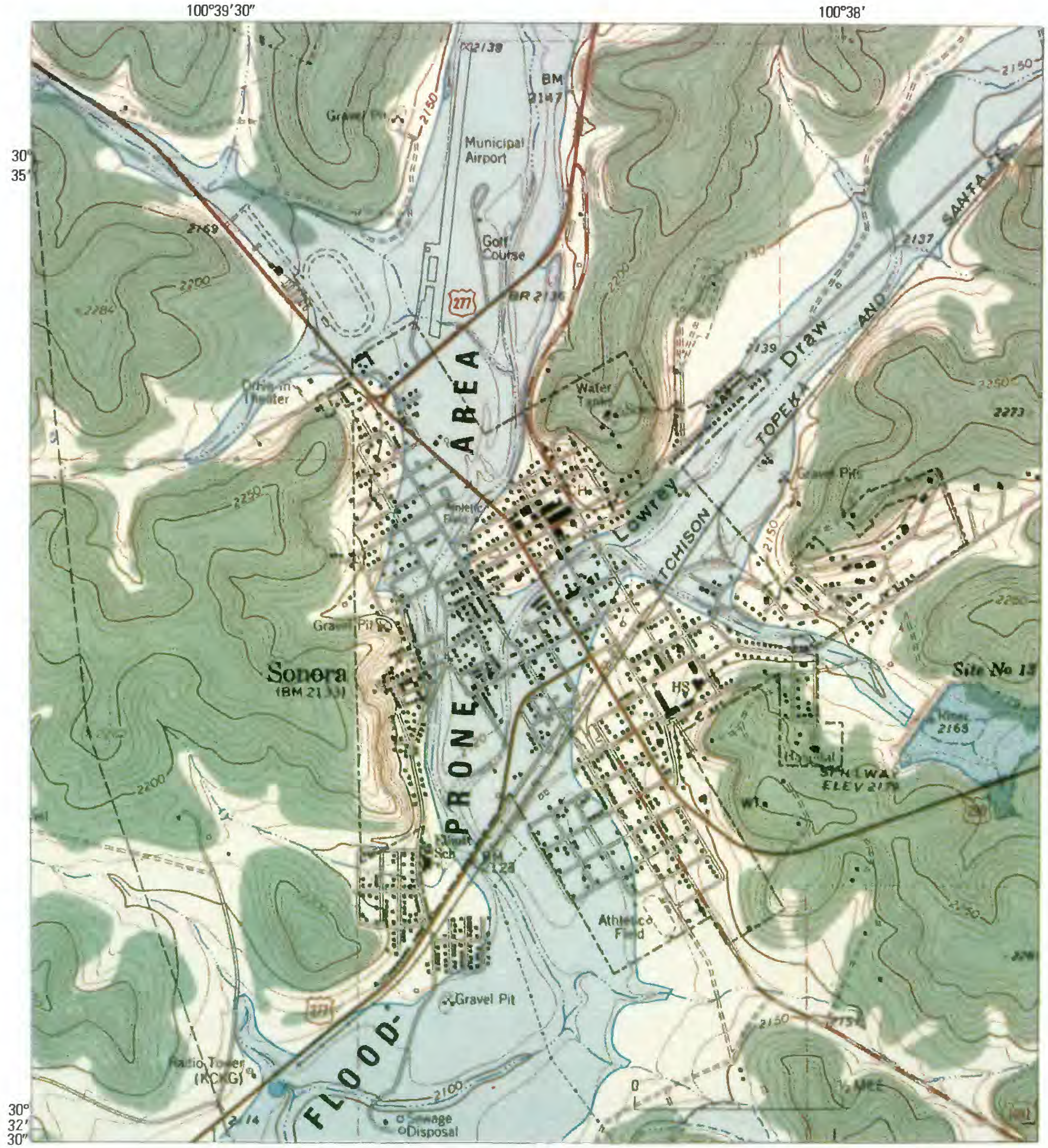
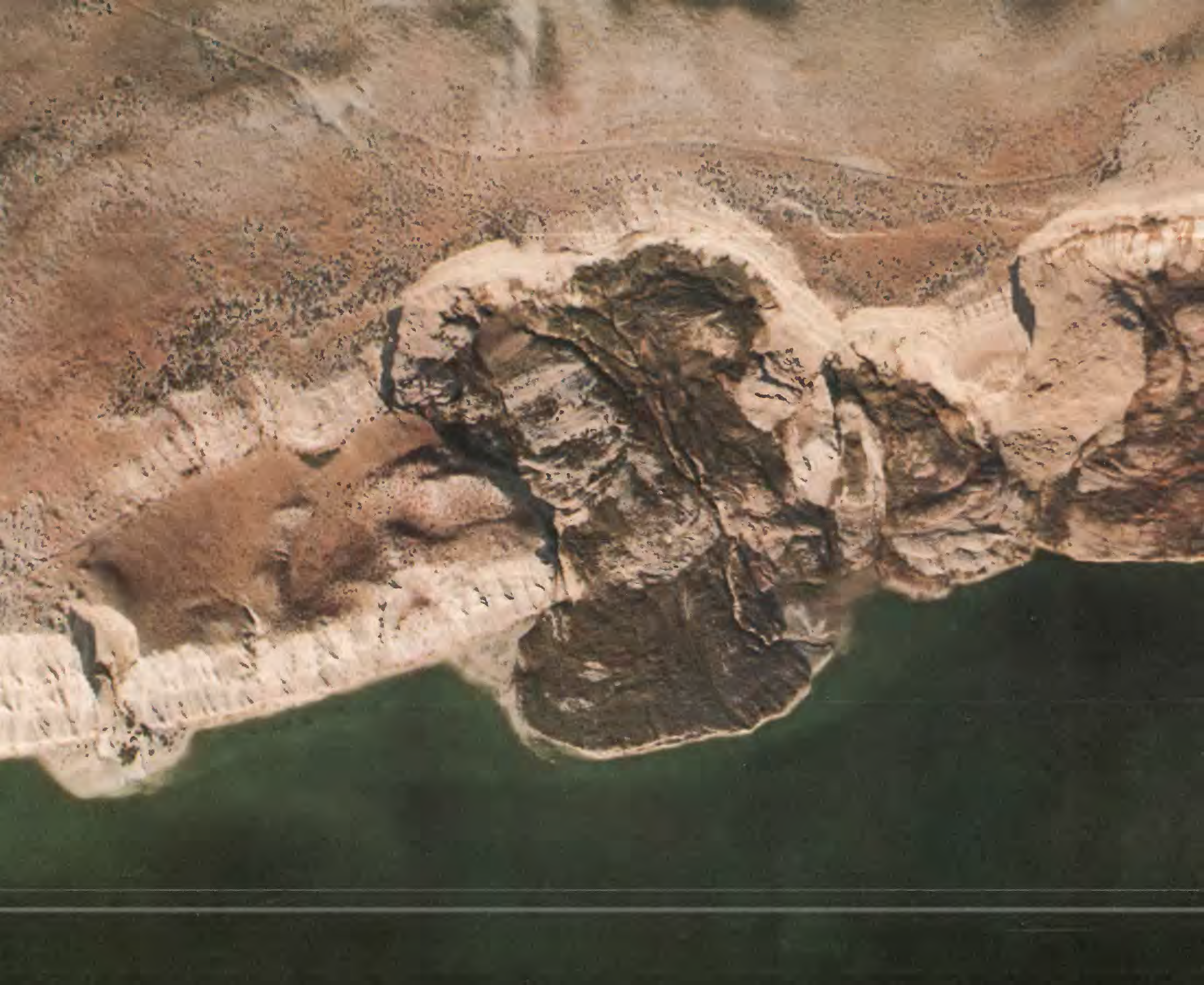


Portion of flood-hazard map of Sonora, Texas, showing approximate areas subject to inundation by a flood on Dry Devils River and Lowery Draw having an annual probability of 1 percent.



4. Hazards From Ground Failures

Ground failures involving landslides, expansive soils, and subsidence are a major threat each year to man and his works. Reduction of losses from each of these types of ground failures requires earth science information of the type discussed below.

Landslides

How Significant Are Landslides?

Landslides, a general term covering a wide variety of mass-movement land forms and processes involving the downslope transport of soil and rock material under gravitational influence, are a significant hazard in virtually every State. Although individual landslides generally are not as spectacular or as costly as some other geologic and hydrologic hazards, they are more widespread. Collectively, they cause major economic loss and casualties. In addition, landslides take place in conjunction with other hazards such as earthquakes (Chapter 2), floods (Chapter 3), and volcanoes (Chapter 5).

Photograph of complex landslide on the valley wall of the Columbia River approximately 40 miles upriver from Pasco, Washington. This slide began as a slump due to weakening of the 300-foot-high slope by irrigation water; the lower portion of the slide mobilized into an earth flow into the river. Slides of this type were common along this stretch of the river during the 1970's. These slides have caused only minor direct economic losses, but they have increased sedimentation (shown by discoloration of the water) in the river, have diminished water quality, and have impacted the spawning of steelhead trout and other game fish. (Photograph by Rockwell Hanford Operations, Richland, Washington.)

What Is the Economic Impact of Landslides?

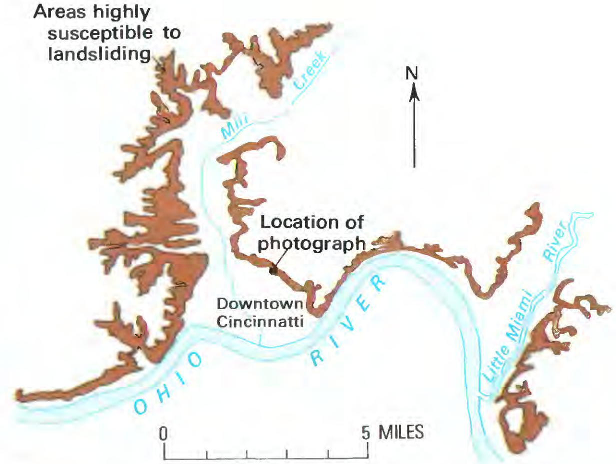
Because damages from landslides vary from subtle to dramatic over both short and long periods of time, an accurate estimate of their cost is very difficult to make. For this reason, direct and indirect costs are estimated. Direct costs relate to losses incurred in actual damages to installations or property. Indirect costs include loss of tax revenues on properties devalued as a result of landslides, reduced real estate values in areas threatened by landslides, loss of productivity of agricultural or forest lands affected by landslides, and loss of industrial productivity because of interruption of transportation systems by landslides. Indirect costs of landslides may be substantially larger than direct costs.

The Highway Research Board (Smith, 1958) made the first attempt to estimate costs of landslide damage in the United States. This study reported that "the average yearly cost of landslides in the United States runs to hundreds of millions of dollars," an estimate that was probably realistic at that time. J. P. Krohn and J. E. Slosson (1976) estimated the annual loss from landslide damage to buildings and their sites in the United States to be $400 million (1971 dollars). Combining the above estimates with indirect costs and estimated damages to facilities not classed as buildings gives losses of more than $1 billion per year (Schuster, 1978) as a reasonable estimate of present-day direct and indirect costs of landslides in the United States.

More accurate cost estimates can be made for individual landslides. For example, the Portuguese Bend landslide in Palos Verdes Hills, California, is estimated to have cost more than $10 million in damage to roads, houses, and other structures between 1956 and 1959. The filling of the reservoir behind Grand Coulee Dam in the State of Washington cost taxpayers and private property owners at least $20 million to avoid and correct the damage due to landslides that occurred between 1934 and 1952. A single landslide in Cincinnati, Ohio, has cost in excess of $22 million between 1974 and 1980.

As the result of a survey conducted by the U.S. Federal Highway Administration in 1973, R. G. Chassie and R. D. Goughnour (1976) concluded that total annual damages to highways due to landslides in the United States are well over $100 million. Landslide damages also are costly in urban areas. The annual per capita costs of damages have been estimated at $2.50 in Allegheny County (Pittsburgh), Pennsylvania, $5.80 in Hamilton County (Cincinnati), Ohio, $3.00 in Los Angeles, California, and $1.30 in the nine-county San Francisco Bay area, California (Fleming and Taylor, 1980).

Landslides in the United States have not resulted in major loss of life because most catastrophic slope failures have taken place in nonpopulated areas. However, a notable exception occurred in conjunction with the 1959 Hebgen Lake, Montana, earthquake which induced the Madison Canyon landslide. This landslide had a volume of about 37 million cubic yards and buried 26 people who were camped along the banks of the Madison River. Krohn and Slosson (1976) estimated that the total loss of life in the United States from landslides is more than 25 lives per year.



This building in Cincinnati, Ohio, was virtually destroyed by a landslide which crushed the rear of the building. Slide debris, including trees and rubble, has been pushed across the floor. This landslide is typical of many that occur in the metropolitan area; they involve a layer of surficial material sliding on bedrock of shale and limestone. The sketch map, which was compiled from various sources, shows areas in the highly urbanized part of Cincinnati that are very susceptible to ground failures of this type. Location of the photograph is shown on the map. (Photograph by J. O. Maberry.)

Sliding of unstable earth materials undermined this canyon rim home on a coastal terrace in the Pacific Palisades area of southern California. (Photograph by J. T. McGill.)

House on Oak Park Drive in San Francisco, California, damaged by landsliding on June 1, 1979. House is on the toe of the slide, and the major part of the landslide is out of the view to the right. (Photograph by E. E. Brabb.)

Failure of fill on Interstate Highway 80, east of San Francisco, California. (Photograph by F. A. Taylor.)

Aerial view of the Madison Canyon landslide in southwestern Montana. Rocks from the mountaintop dropped about 1,300 feet and reached a speed of about 100 miles per hour before striking the valley bottom and riding up the opposite valley wall. The lake filling the valley is Earthquake Lake. (Photograph by J. R. Stacy.)

Slope failures on the south face of an open-pit copper mine in Arizona. The slide is on the right half of the photograph.

What Are the Types and Processes of Slope Movement?

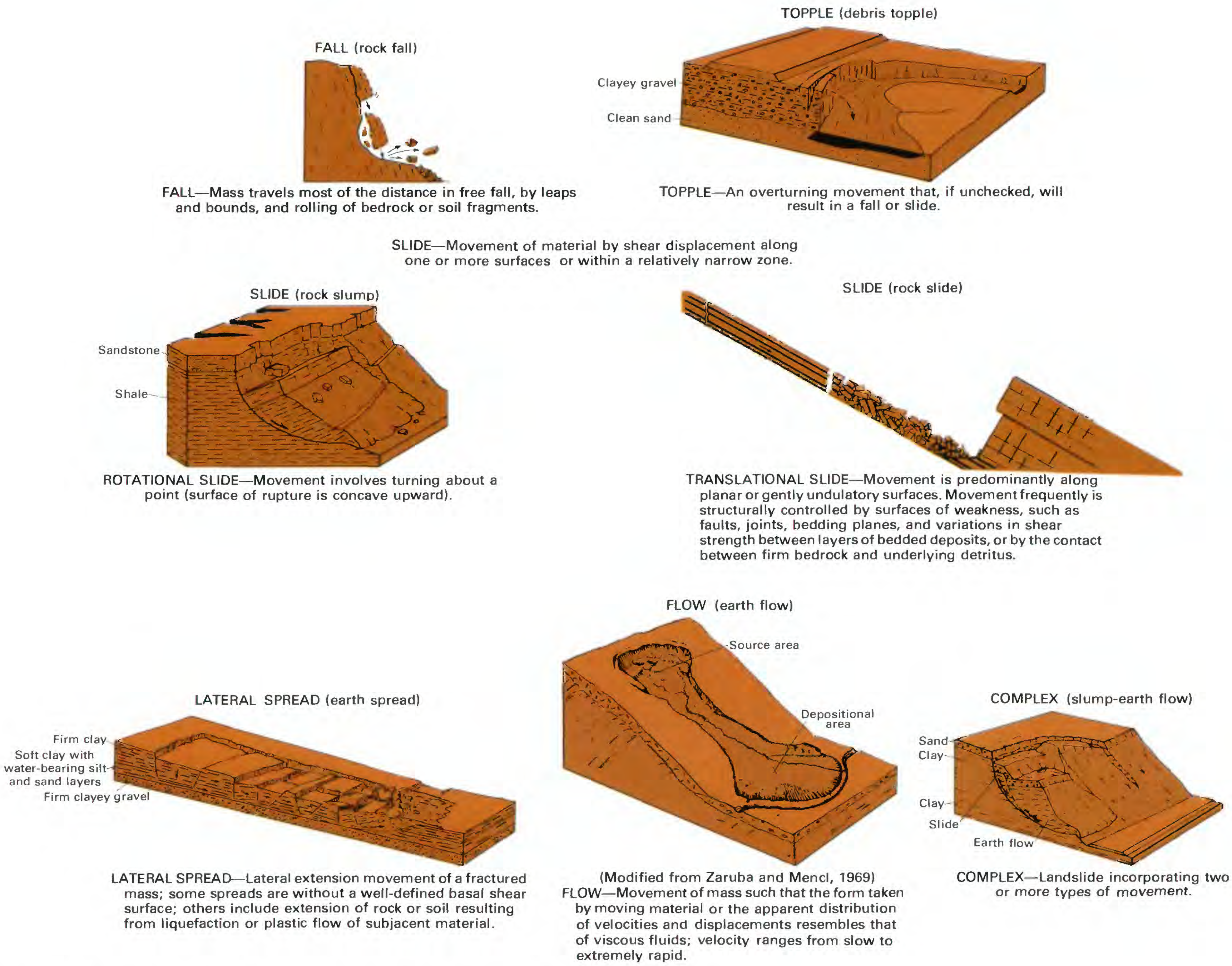
Landslides can be classified in many ways, each having some usefulness to planners in emphasizing features pertinent to recognition and reduction of losses from landslides. Two criteria, types of movement and types of material, are typically used. Types of movement include falls, topples, slides, spreads, flows, and combinations of two or more of these five types. Types of material include two classes—bedrock and soils, with soils being divided into debris and earth.

Summary classifications and definitions of slope movements (from Varnes, 1978)

[See figure for definitions.]

Type of movement	Type of material		
	Bedrock	Soils	
		Coarse-grained (debris)	Fine-grained (earth)
Falls	Rock fall	Debris fall	Earth fall
Topples	Rock topple	Debris topple	Earth topple
Slides	Rock-block slide	Debris-block slide	Earth-block slide
Rotational	Rock slump	Debris slump	Earth slump
Translational	Rock slide	Debris slide	Earth slide
Lateral spreads	Rock spread	Debris spread	Earth spread
Flows	Rock flow	Debris flow	Earth flow
Complex	Combination of two or more of the above		

A rock topple and fall halted traffic on this highway in the central Santa Monica Mountains of southern California. The sequence of failures began at the left with a small block slide on bedding surfaces dipping out of the roadcut. This slide removed support that resisted overturning of joint-bounded blocks higher in the roadcut, which then tumbled one after another onto the road. (Photograph courtesy of the Department of the County Engineer, Los Angeles County, California.)



Examples of landslides by type of movement. (Modified from Varnes, 1978.)

What Is the Distribution of Landslides?

The map of landsliding in the conterminous United States provides an overview of the distribution and relative severity of landslide hazards. The map shows two important aspects of landsliding—incidence and susceptibility. Incidence of landsliding refers to areas where landslides have actually occurred. For example, areas of high incidence contain more than 15 percent slope failures. Areas of moderate incidence contain 1.5 to 15 percent failed slopes. Susceptibility to landsliding refers to the strength of the earth materials in the area. Areas of high susceptibility are underlain by very weak or fractured materials.

Areas in the Appalachian Mountains, Rocky Mountains, and the coastal ranges along the Pacific Ocean have the most severe landslide problems. All types of slope movements occur in these areas, including debris flows, the most dangerous form of slope movement with respect to human life. The large areas in the midcontinent region colored blue are underlain by relatively weak shales. In these areas, landsliding is prominent on moderate to steep slopes, and, because the materials are weak, large excavations commonly produce landslides even in flat areas.

Although not shown on the map, large parts of Alaska and Hawaii also are severely affected by landslides.

What Causes Landslides?

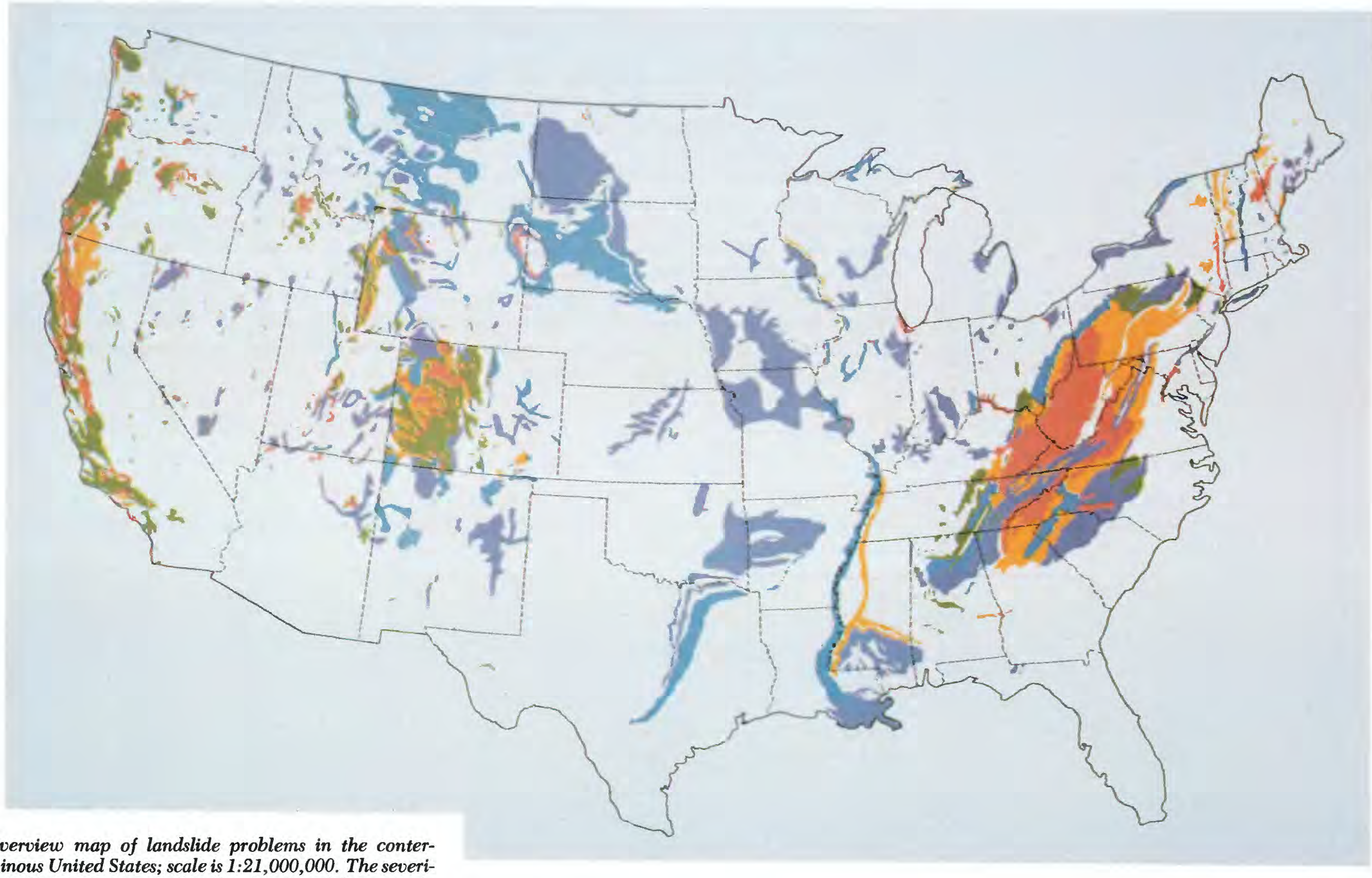
All slides involve the failure of earth materials under shear stress. The initiation of the process can, therefore, be thought of in terms of the factors that contribute to increased shear stress and the factors that contribute to low or reduced shear strength. Although a single action, such as addition of water to a slope, may contribute to both an increase in stress and a decrease in strength, it is helpful to separate the various physical results of such an action.

The principal factors contributing to increased shear stress are:

- Removal of lateral support by such means as erosion by streams and rivers, glaciers, or waves and longshore or tidal currents; previous slope failure; and results of construction, especially where cuts, quarries, pits, and canals are established, retaining walls and sheet piling are removed, or lakes and reservoirs are created and their levels altered.
- Loading by such natural or human means as weight of rain, hail, snow; accumulation of loose rock fragments or accumulated volcanic material; stockpiles of ore or rock; waste piles; and weight of buildings and other structures.
- Vibrations from earthquakes, blasting, machinery, traffic, and even thunder.

The principal factors contributing to low or reduced shear strength include:

- The initial state or inherent characteristics of the material—its composition, texture, structure, slope geometry.
- Changes due to weathering and other physicochemical reactions.
- Changes in direct water content and pore pressure and in structure.



Overview map of landslide problems in the conterminous United States; scale is 1:21,000,000. The severity is highest in areas colored with red and decreases in order of yellow, green, blue, and purple. Areas which may contain landslides or be susceptible to landsliding on a scale too small to be shown are not colored (modified from Radbruch-Hall and others, 1976). The map is based on computer techniques described by Radbruch-Hall (1979) and Edwards and Batson (1980).

What Can Be Done To Reduce Losses From Landslides?

A community faced with a landslide is primarily interested in preventing the harmful effects of the slide. Many times, the physical cause of the slide cannot be removed, so it may be more economical to reduce losses continually, or intermittently, without actually removing the physical cause.

Various studies have shown that the most damaging landslides are closely related to the activities of man and that substantial loss reduction can be achieved by regulating land use *before* man's activities take place. Effective regulation, involving measures such as land-use controls, drainage or runoff controls, and improved grading ordinances, requires close cooperation among geologists, engineers, and planners to evolve a process that begins with research, continues with synthesis of information and communication with others who generally are not trained in earth science and engineering, and ends with action on the part of an individual, a group, or a governmental organization. The benefits warrant this effort. For example, J. T. Alfors and others (1973), in a study by the California Division of Mines and Geology, estimated that losses of $9.9 billion expected in California from landslides from 1970 to 2000 could be reduced 90 percent or more by a combination of actions involving geologic investigations, good engineering practice, and effective enforcement of legal restraints on land use.

With respect to highways, R. G. Chassie and R. D. Goughnour (1976) showed that the application of scientific methods and engineering principles to the acquisition and use of earth materials could significantly reduce the landslide hazard in New York State. They noted that improved procedures in the 7 years prior to 1976 had already reduced landslide repair costs by as much as 90 percent.

Trenching operation at a recent earthflow to learn more about subsurface slippage, Greene County, Pennsylvania. (Photograph by J. S. Pomeroy.)

An earth-moving equipment operator receiving instructions from a geological engineer at an earthflow site, Greene County, Pennsylvania. (Photograph by J. S. Pomeroy.)

Expansive Soils

What Are the Parent Materials of Expansive Soils?

Soils and soft rocks which tend to swell or shrink due to changes in moisture content are commonly known as expansive soils. In the United States, two major groups of rocks serve as parent materials of expansive soils. Both groups are more common in the Western United States than in the Eastern United States. The first group consists of ash, glass, and rocks from volcanic eruptions. The aluminum silicate minerals in these volcanic materials often decompose to form expansive clay minerals of the smectite group, the best known of which is montmorillonite. The second group consists of sedimentary rocks containing clay minerals, examples of which are the shales of the semiarid West-Central United States.

What Is the Economic Impact of Expansive Soils?

As of 1973, expansive soils in the United States were estimated to cause over $2 billion per year in damages to homes, commercial buildings, highways and streets, buried utilities, and other structures. Some sources now estimate the annual costs of expansive soils to be as high as $7 billion (Krohn and Slosson, 1980). Of the more than 250,000 new homes built annually on expansive soils in the United States, 10 percent undergo significant damage during their useful lives—some beyond repair—and 60 percent undergo minor damage (Jones and Holtz, 1973).

Annual structural damage in the United States due to expansive soils (Jones and Holtz, 1973)

[In millions of dollars]

Single family homes	$ 300
Commercial buildings	360
Multistory buildings	80
Walks, drives, and parking areas	110
Highways and streets	1,140
Buried utilities and services	100
Airport installations	40
Involved in urban landslides	25
Other	100
Total annual damage	$2,255

Crack in wall of public building caused by expansive soils. (Photograph by the Colorado Geological Survey.)

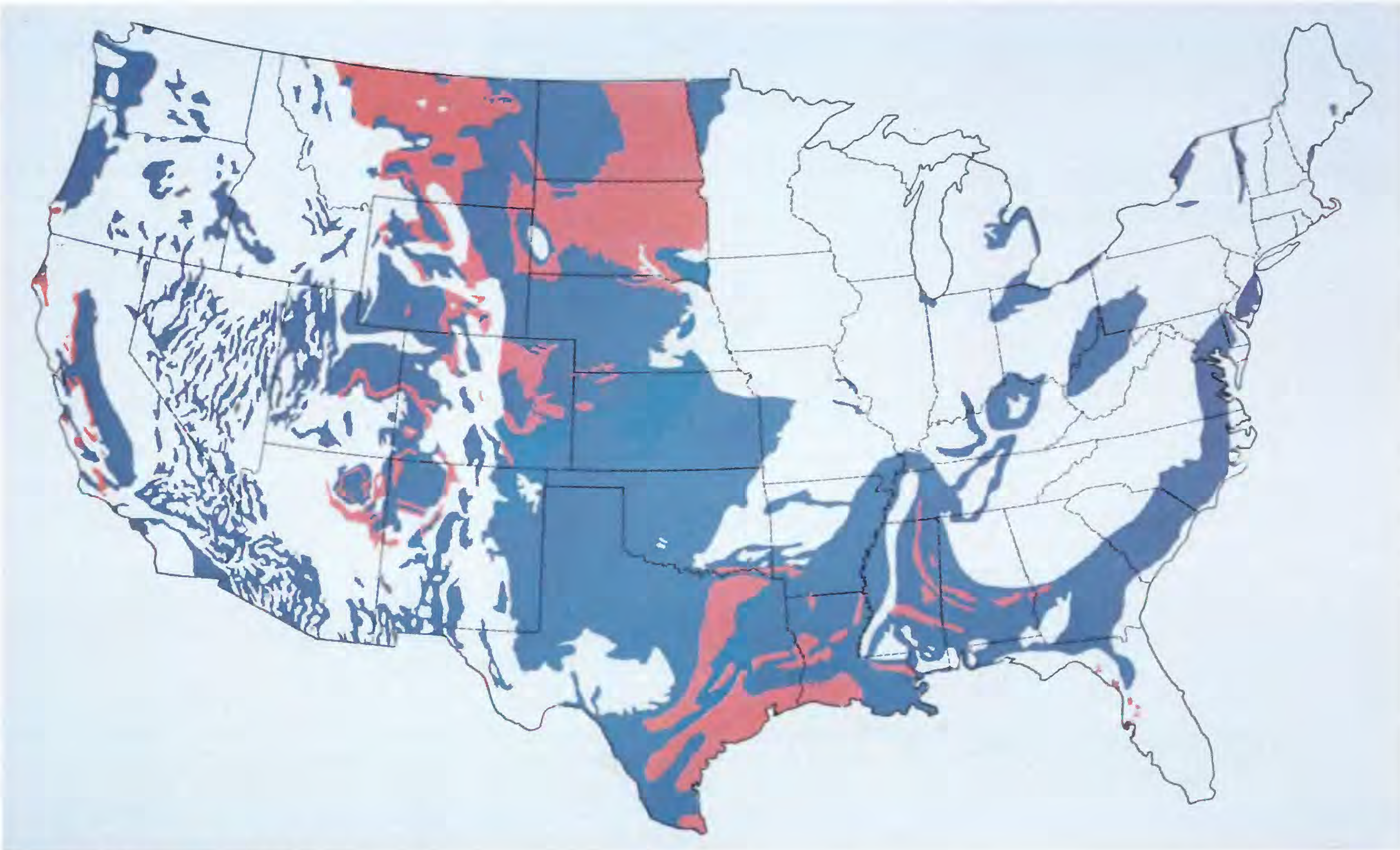
Differential heave of concrete floor in a school building caused by expansive soils. Floating floor slab inside has risen 4 inches. (Photograph by the Colorado Geological Survey.)

Vertical displacement of 1 inch along crack in concrete floor slab caused by expansive soils. (Photograph by the Colorado Geological Survey.)

What Is the Distribution of Expansive Soils?

The general distribution in the United States of smectite-rich parent materials which serve as sources of expansive soils is shown in the map. Smectites are regionally abundant in geologic formations throughout the Rocky Mountains, most of the Great Plains, much of the Gulf Coastal Plain, the lower Mississippi River Valley, and the Pacific Coast. They are locally abundant in geologic formations along the Atlantic and Gulf Coastal Plains and in the Great Basin region. They are a very minor constituent of geologic formations in the rest of the United States, but they may be abundant locally in surficial deposits along both coasts and in the western and west-central parts of the Nation (Tourtelot, 1974).

In situ weathering of expansive clay-shale beds in the Monterey Shale, Santa Monica Mountains, southern California. Adjacent interbeds of more dolomitic or siliceous composition are disrupted increasingly as they approach the ground surface.



Overview map of expansive soils in the conterminous United States; scale is 1:21,000,000. Expansive soils are most abundant in areas colored red and decrease in order of blue and purple. Areas which may contain expansive soils on a scale too small to be shown are not colored (modified by D. H. Radbruch-Hall from Patrick and Snethen, 1976). The map is based on computer techniques described by Radbruch-Hall (1979) and Edwards and Batson (1980).

What Is the Physical Mechanism Causing Expansive Soils?

All clayey soils swell or shrink when subjected to moisture change; some simply undergo greater volume change than others. The physicochemical processes which cause moisture-induced volume changes, both swelling and shrinking, are complex and will be described simplistically here. Volume change in clays caused by change of moisture content has two components—interparticle volume change and intracrystalline volume change (Tourtelot, 1974). Because interparticle swelling and shrinking are functions of physical properties such as particle size of the clays imvolved rather than their mineralogical characteristics, interparticle volume changes, which are reversible processes, occur in all clay minerals. Intracrystalline volume change occurs within individual clay lattice systems.

What Geologic Factors Cause Swelling and Shrinking?

Two requirements must be met before swelling or shrinking of soil or soft rock can take place. First, the soil or rock must have the potential for volume change. Second, in the case of swelling, water must be available and must be able to move freely to the expansive soil.

The potential for volume change of a soil or rock depends on the type and amount of clay minerals it contains. The potential of a clay to change volume is considerably greater for smectites than for other clay minerals such as kaolinites and illites. Because pure smectite is seldom encountered, the potential for volume change of a soil or soft rock depends also on the percentage of clay minerals it contains.

In situations where the external load is constant, volume will not change without moisture change. Changes that man makes in the environment often will cause moisture changes. For example, the discharge of roof gutters and downspouts on houses in semiarid areas often causes swelling by concentrating rain water into foundation soils. In areas having wet climates, planting trees may reduce the available soil moisture causing shrinking; conversely, the removal of existing forest cover can result in increased soil moisture and swelling of expansive foundation soils.

The geometry of the mass of expansive soil is also important when determining the potential for volume change. A thick layer of expansive soil has the potential for greater total volume change than a thin layer, if each has the same physical properties, availability of water, and confining pressure. An increased load on a soil causes increased pressure and a reduction in the amount of swelling, or, if the load is great enough, it can cause consolidation of the soil. A clay-rich soil or soft rock at the surface of the ground has a greater tendency for swelling than one at depth, because the latter is subject to confining pressure from the material above it.

Can Expansive Soils Be Recognized?

Expansive soils can be recognized either in the field or by means of laboratory analyses. Shales, clay shales, weathered volcanic rocks, and residual soils containing smectite will often have a characteristic "popcorn" texture, especially in semiarid areas. The most successful methods of recognizing expansive soils involve laboratory analysis of the clay-mineral content in soil and soft rock. These methods are X-ray diffraction, differential thermal analysis, and microscopic examination. The most common laboratory methods used for identifying expansive soils on the basis of physical characteristics related to volume change are free swell test, Atterberg limits (a test of soil plasticity), and direct measurement of volume change.

Characteristic soft puffy expansive soil showing desiccation cracks. Note pen for scale. (Photograph by the Colorado Geological Survey.)

What Can Be Done To Reduce Losses From Expansive Soils?

The best means of preventing or reducing damage from expansive soils is to avoid them. However, when no other choice is possible except to place a structure on a potentially expansive soil, engineering procedures such as the following are necessary: (1) removal of the soil, (2) application of heavy loads, (3) preventing access of water, (4) prewetting, and (5) stabilization.

Removal of expansive soils and replacing them with nonexpansive soils is sometimes possible. Usually, however, the expansive soil extends to such a great depth that complete removal and backfill are not economical. Thus, the amount of excavation and backfill needed to prevent the occurrence of destructive volume change must be determined. Backfill of nonexpansive material must be placed to a sufficient depth to provide the necessary weight to restrain the uplift of the remaining expansive soil.

Swelling can be prevented by loading an expansive soil so that the confining pressure is greater than the swelling pressure developed by the soil. Load can be applied to a foundation soil by means of an embankment or blanket of nonexpansive soil or by construction of large buildings.

The water entering expansive soil units is usually surface water that has moved downward into the expansive soil. However, in semiarid areas, water often moves upward by means of capillary flow from the ground-water table to expansive soils at the surface. Methods for isolating expansive soils from moisture include installation of ditches or pipes to carry away surface water, use of sand and gravel to break the continuity of the capillary flow, and enveloping expansive soil masses with impermeable membranes.

Concrete slabs and bituminous pavements on clay soils in semiarid areas inhibit the normal evaporation of capillary water; this increases the moisture content near the surface. The increased moisture causes swelling of expansive soils and subsequent damage to the slabs and pavements. The potential for damage can be reduced by prewetting the underlying soils to the moisture contents expected while the slab and pavement are in service.

Chemical stabilization has also been used successfully to prevent or minimize volume change of expansive soils. The ionic character of the soil and water combination can be modified by the addition of certain chemicals, such as hydrated lime, $Ca(OH)_2$, to prevent volume change. This action is based on studies that show that the ionic character of water has a major effect on volume change.

Subsidence

What Is the Economic Impact of Subsidence?

Subsidence, the lowering or collapse of the land surface either locally or over broad regional areas, has taken place in nearly every State. Although subsidence is usually not spectacular or catastrophic, it causes several tens of millions of dollars in damages annually in the United States. Losses amounting to $109 million from 1943 to 1973 in the Houston-Baytown area of Texas are an example of the magnitude of costs caused by subsidence resulting largely from withdrawal of fluid. In addition, damages of $30 million per year are estimated to be caused by subsidence over abandoned coal mines. Loss of life due to subsidence is rare; however, a catastrophic mine collapse in South Africa that caused the deaths of 29 people in 1962 serves to remind of the potential danger. To reduce the potential losses that can result from subsidence, planners and decisionmakers must be aware of and understand the effects of this hazard.

This 324-foot-wide and 100-foot-deep sinkhole in Winter Park, Florida, collapsed on May 8 and 9, 1981. The collapse was caused in part by the prevailing drought. Economic loss is estimated to exceed $2 million. The losses include a house, several cars, portions of several business establishments, streets, and the city swimming pool. View to the south. (Photography by A. S. Navoy.)

What Are the Locations and Causes of Subsidence?

Subsidence is caused by a large number of natural and man-made activities. They are discussed below.

NATURAL SUBSIDENCE

Natural processes causing subsidence include the dissolving of limestone and other soluble materials, earthquakes, and volcanic activity. Large areas of the United States are underlain by limestone and other soluble minerals. As underground water percolates through such materials, soluble minerals dissolve, forming cavities or caverns. Land overlying these caverns can collapse suddenly, forming sinkholes of 100 feet or more in depth and 300 feet or more in width. Other times, the land surface can settle slowly and irregularly. The landscape created by such subsidence is called karst terrane. This type of subsidence usually causes extensive damage to structures located over pits formed by dissolving of the soluble minerals; sometimes it has even caused deaths. Although the formation of sinkholes is a natural phenomenon, the process can be accelerated by man's practices with regard to ground-water withdrawal, land development, and disposal of water.

The major locations of karst terrane and caverns in the United States, as shown by the maps, are in parts of many of the Southeastern and Midwestern States. Sinkholes also are found in some of the Western and Northeastern States. Alabama, where soluble limestone and other rocks are present in nearly one-half of the State, has thousands of sinkholes that pose serious problems for highways and construction.

Earthquake-related subsidence has taken place mainly in Alaska, California, and Hawaii and to a lesser extent in other States. This type of subsidence can result from vertical movement on faults and may effect broad areas. This process took place in 1964 in southern Alaska in conjunction with the Prince William Sound, Alaska, earthquake. More than 70,000 square miles were tilted downward more than 3 feet and subsequently flooded. Subsidence resulting from intense earthquake ground shaking involves somewhat smaller areas than that resulting from regional vertical faulting. Intense ground shaking generated during the 1811–12 New Madrid, Missouri, earthquakes caused subsurface sand and water to be ejected to the surface. This ejection left voids in the subsurface, causing local compaction of subsurface materials and settling of the ground.

Volcanic-related subsidence is a potential problem in parts of Alaska, California, Hawaii, Oregon, and Washington. Subsidence usually is caused by local collapses above shallow tunnels formed by flow of lava. Collapses over much broader areas can also occur as magma chambers are emptied by volcanic eruptions.

MAN-INDUCED SUBSIDENCE

The withdrawal of oil, gas, and water has increased dramatically since 1940. Because underground fluids fill intergranular spaces and support sediment grains, removal of such fluids results in a loss of grain support, reduction of intergranular void spaces, and compaction of clays. The land surface commonly subsides wherever widespread subsurface compaction has taken place, causing damage to canals, aqueducts, sewer systems, and pipelines and increasing the probability of flooding in some areas.

The most dramatic examples of subsidence caused by withdrawal of oil, gas, and water are along the Gulf Coast of Texas, in Arizona, and in California. The harbor at Long Beach, California, has subsided as much as 27 feet from withdrawal of gas and oil. The Houston-Galveston area of Texas has experienced as much as 7.5 feet of subsidence locally. An area of about 2,500 square miles has subsided 1 foot or more. Subsidence in the Houston-Galveston area appears to have been caused mainly by the withdrawal of large amounts of ground water, although some areas of local subsidence have been caused by the extraction of gas and oil. Coastal towns in Texas, such as Baytown and Seabrook, have subsided about 3 feet and are now susceptible to flooding from storm surges and hurricanes.

Recent research suggests that subsidence caused by withdrawal of ground water can also cause fissuring or renewal of surface movement in some areas cut by preexisting faults. Fissuring is the formation of open cracks. Surface faulting and fissuring associated with withdrawal of ground water are believed to have either taken place or to be a potential problem in the vicinity of Las Vegas, Nevada, as well as in parts of Arizona, California, Texas, and New Mexico (Holzer, 1977).

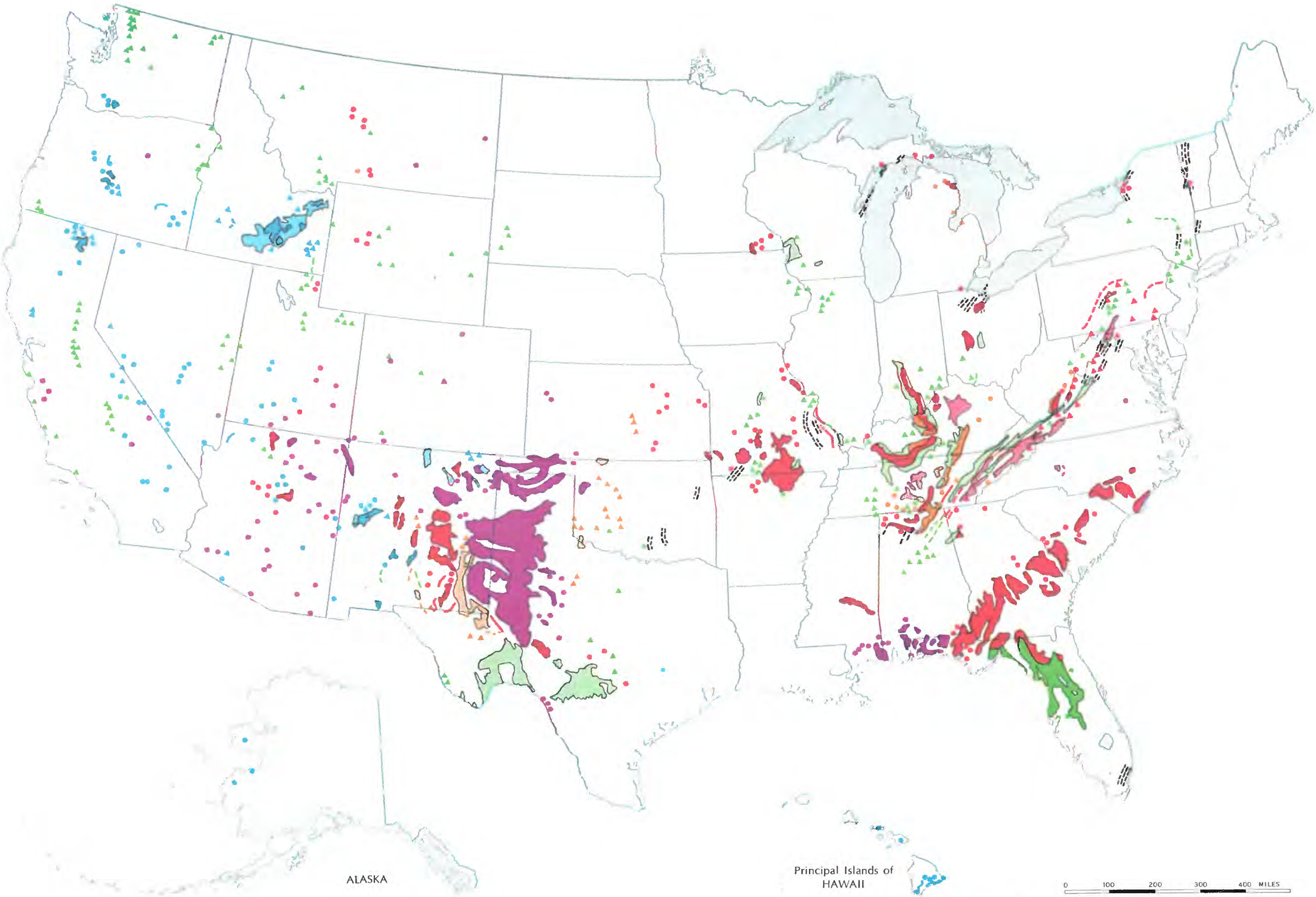
Underground mining, especially shallow coal mining, is another significant cause of subsidence. The rocks above mine workings may not have adequate support and can collapse from their own weight, either during mining or long after mining is completed. Subsidence in areas of underground mining has caused hazardous conditions in parts of Pennsylvania and other Appalachian States, Colorado, North Dakota, Wyoming, New Mexico, Washington, Iowa, and Illinois. Subsidence-related damage to surface structures is common in the area around Pittsburgh, Pennsylvania, where coal has been mined extensively. Subsidence depressions and pits, forming above abandoned underground mines, are a hazard in the Sheridan, Wyoming, area.

Solution mining also can cause subsidence. In solution mining, water-soluble minerals such as salt, gypsum, and potash are dissolved and pumped to the surface so that the water can be evaporated. Huge underground cavities are formed, causing surface subsidence. Examples of this hazard, whose locations are not well known, include the sudden collapse of a street at Grand Saline, Texas, in 1976, into an abandoned salt mine cavity created between 1924 and 1949, the subsidence in 1974 near Hutchinson, Kansas, and subsidence in 1971 near Detroit, Michigan.

Additional activities of man that either cause subsidence or increase the potential for subsidence include leaching of intergranular elements such as uranium and copper from subsurface rocks, coal gasification, and oil shale retorting.

Hydrocompaction, or the settling of sediments after water is added, is another significant cause of subsidence, especially in the arid to semiarid Western and Midwestern States. The areas of known compaction include San Joaquin Valley, California, Heart Mountain–Chapman Beach and Riverton, Wyoming, areas, Hysham Bench, Montana, Columbia Basin, Washington, Denver, Colorado, Washington-Hurricane area in southwest Utah and central Utah, and Missouri River Basin. Hydrocompaction takes place when dry surface or subsurface deposits are extensively wetted for the first time since their deposition as, for example, when arid land is irrigated for crop production or an irrigation canal is built on loose dry uncompacted sediments. Wetting causes a reduction in the cohesion between sediment grains, allowing the grains to move and to fill in the naturally occurring intergranular openings. The result is a lowering of the land surface of from 3 to 6 feet, although subsidence of as much as 15 feet has been recorded. The effects of hydrocompaction on the land are usually uneven, causing depressions, cracks, and wavy surfaces. As a result, canals, highways, pipelines, buildings, and other structures can be seriously damaged.

House in sinkhole. (Photograph by U.S. Federal Housing Authority.)



Map of karst terrane. (From Davies, 1970.)

EXPLANATION

LIMESTONE AND DOLOMITE TERRAIN

- Shafts and sinkholes on plains and valley floors; undissected plateau uplands
- Shafts and sinkholes with extensive limestone ledges on plains and valley floors
- Sinkhole ponds and lakes on plains
- Sinkholes on ridges and dissected uplands
- Collapsed sinkholes on dissected plateaus and plains

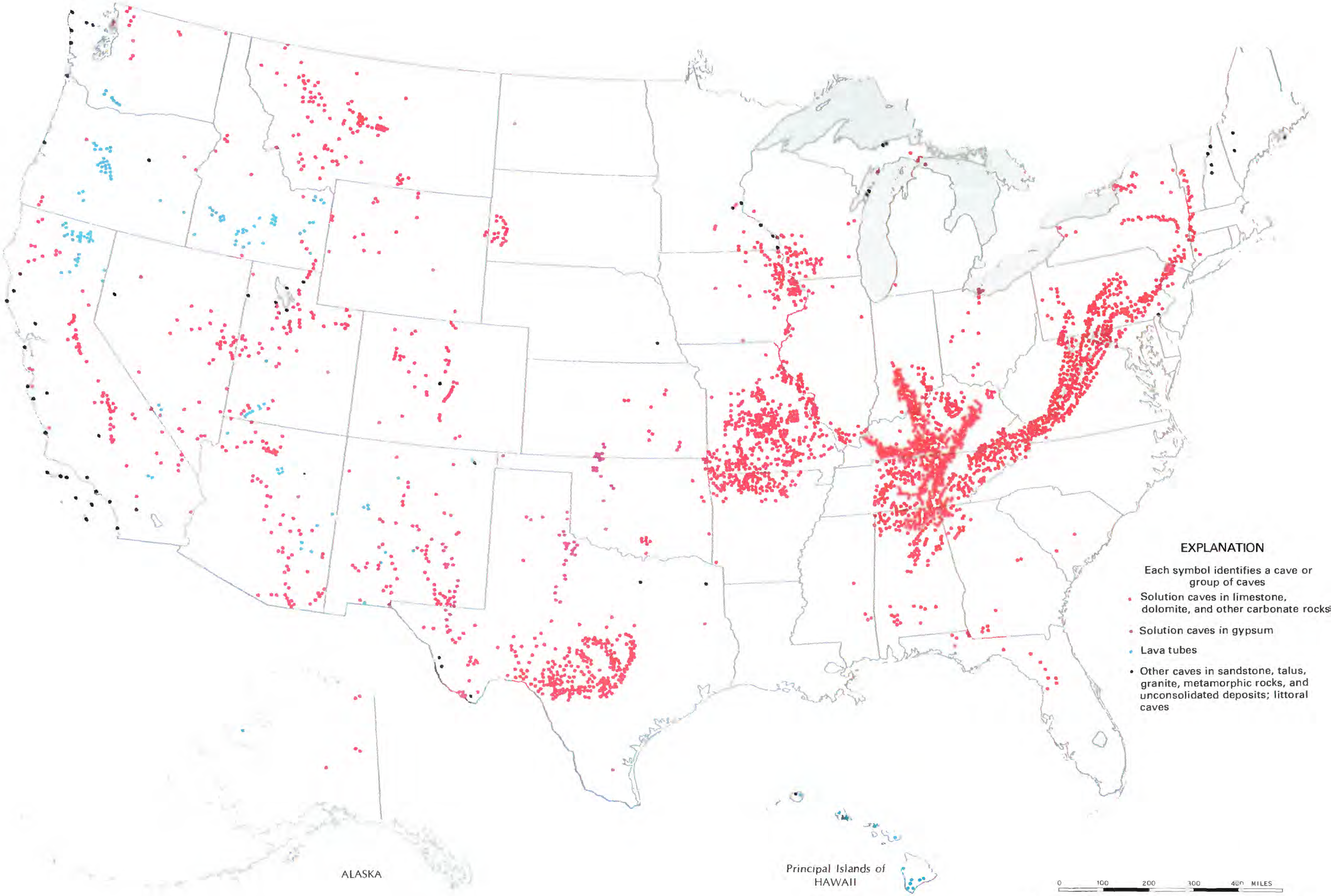
GYPSUM AND SALT TERRAIN

- Sinkholes and shafts on plains

PSEUDOKARST TERRAIN

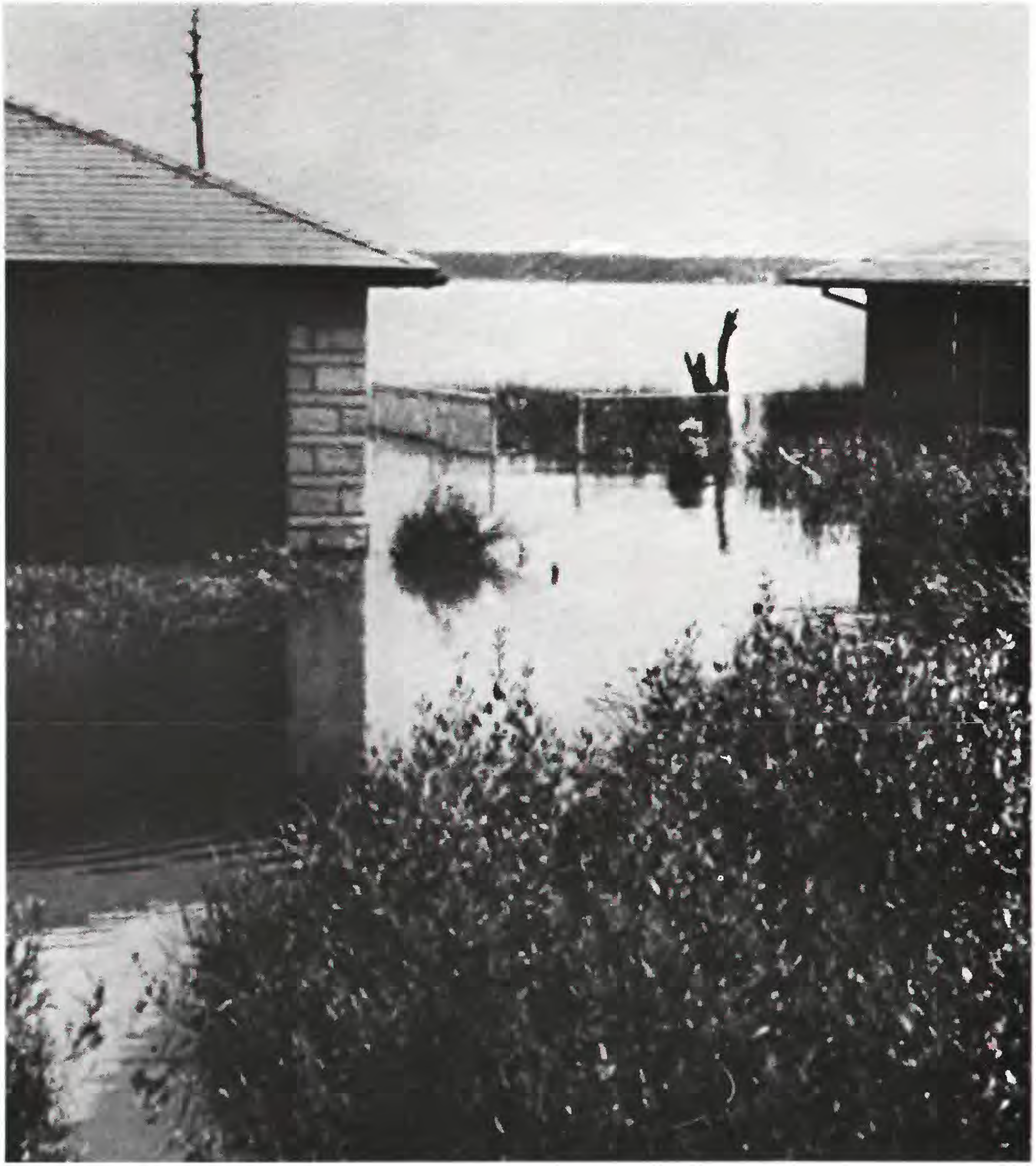
- Sinkholes on lava plains
- Basins on plains of weathered lava
- Sinkholes and basins on gravel and sand plains, and plateaus
- Small shallow sinkholes on granite and diorite uplands
- Limestone ledges outside of areas of other karst types

The Portage area, Alaska. Widespread flooding caused by regional subsidence took place as a result of the 1964 Prince William Sound, Alaska, earthquake.

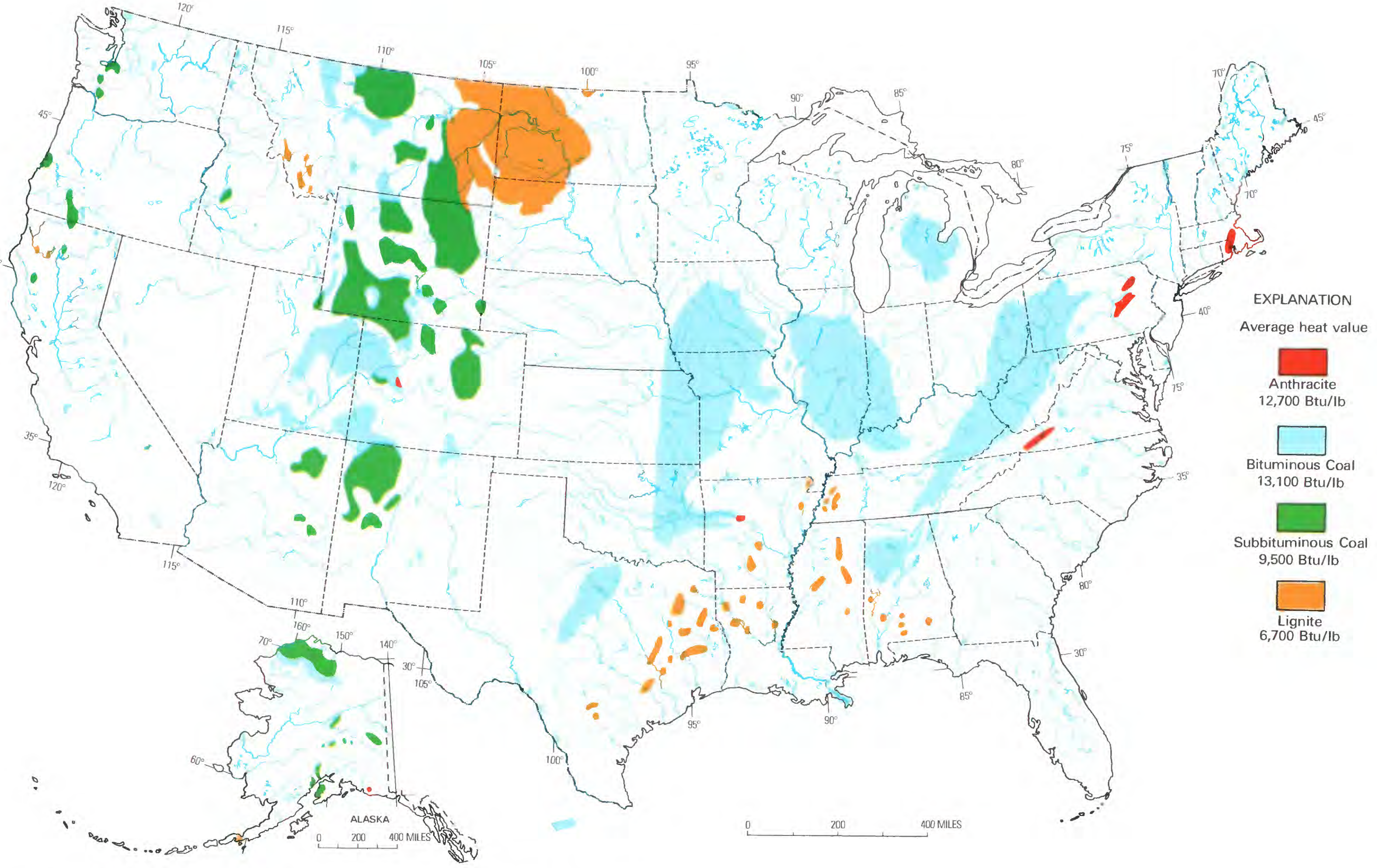


Map of cavern areas. (From Davies, 1970.)

Withdrawal of ground water in south-central Arizona has caused as much as 12 feet of local subsidence and numerous fissures like the ones shown here. (Photograph by T. L. Holzer.)



Subsidence in coastal Baytown, Texas, has caused this housing development to be flooded by daily tides. (Photograph by T. L. Holzer.)



Location of coal fields in the United States (modified from Rickert and others, 1979).

Subsidence pits resulting from collapse of the surface into voids left by underground coal mining in Wyoming. The mine was abandoned in 1914. (Photograph by F. W. Osterwald.)

What Can Be Done To Reduce Losses From Subsidence?

Use of geological and geophysical information to identify areas susceptible to subsidence is a key to devising loss-reduction actions. Such information often is available from the U.S. Geological Survey, State surveys, other geologic-related agencies of States and communities, geology departments of local colleges and universities, and consultants in the private sector. Because subsidence can be caused by many combinations of natural and man-made conditions or processes, potential hazards must be identified on the basis of a site-by-site evaluation. City or county engineers, consulting engineers, engineering geologists, and geologists may be sources of the types of site-specific information needed. Mine development plans on file with Federal, State, or local agencies and local mining firms may indicate areas of past, present, or future underground openings. In regions of karst terrane or where mine plans do not exist, it may be necessary to undertake geophysical exploration and drilling programs to insure that a site is free of caverns, cavities, or mine openings.

Restriction of man's activities in areas identified as being potentially susceptible to subsidence is the best overall strategy for reducing losses. For example, to prevent compaction, the water needs of a community may have to be supplied from surface sources rather than withdrawn from the ground. Underground coal mining can be limited to areas where future subsidence will not endanger property or lives, or mining methods can be used that will not leave areas susceptible to future subsidence.

If the potential for subsidence is known to exist in an area, land-use zoning can protect property and lives. Nonintensive land uses such as parks or golf courses can be planned for areas where subsidence is prevalent.

Engineering methods can be used to help stabilize the land in subsidence-prone areas where development has already taken place or cannot be avoided. For example, subsidence caused by the withdrawal of underground oil, gas, or water can be dealt with by several methods. In the Los Angeles–Long Beach, California, area, where oil and gas have been withdrawn from beneath the harbor district for several decades, subsidence was reversed by the injection of water into sediments to replace the oil being withdrawn. In areas such as the San Joaquin and Santa Clara Valleys in California, subsidence was either reduced or stopped when additional imported water was returned to subsurface sediments to replace the ground water that was withdrawn.

Subsidence associated with coal mining can be prevented best by taking actions during or immediately following the mining operation. If mining is carried out in such a way that enough coal is left to support the roof of mine workings, the chance of later subsidence is reduced. Also, the voids remaining when coal is removed can be filled with compacted mine waste or other industrial wastes. This action will prevent or significantly reduce surface subsidence but may introduce the risk of contaminating ground water unless noxious substances in the wastes are neutralized.

Legislative measures have been enacted in several States to reduce losses. For example, the Mine Subsidence Insurance Act became effective in Pennsylvania in 1962. This act allowed some property owners to buy insurance from the Commonwealth at rates established after an inspection of the premises. In 1966, Pennsylvania enacted the Bituminous Mine Subsidence Land Conservation Act, which entitles property owners, where coal has not yet been mined, to purchase the coal under their property at a fair price. The potential for local subsidence associated with mining is thereby controlled by the property owner. House Bill 525 was passed by the Texas Legislature in 1979, creating the Harris-Galveston Coastal Subsidence District. The purpose was to control the subsidence and thereby prevent coastal flooding in the area. The Subsidence District's Board of Directors (15 members, representing city and county governments, industry, agriculture, and science) has the power to regulate the amount of water withdrawn. This legislation, along with an increase in the use of surface water, has sharply reduced subsidence in this part of coastal Texas.

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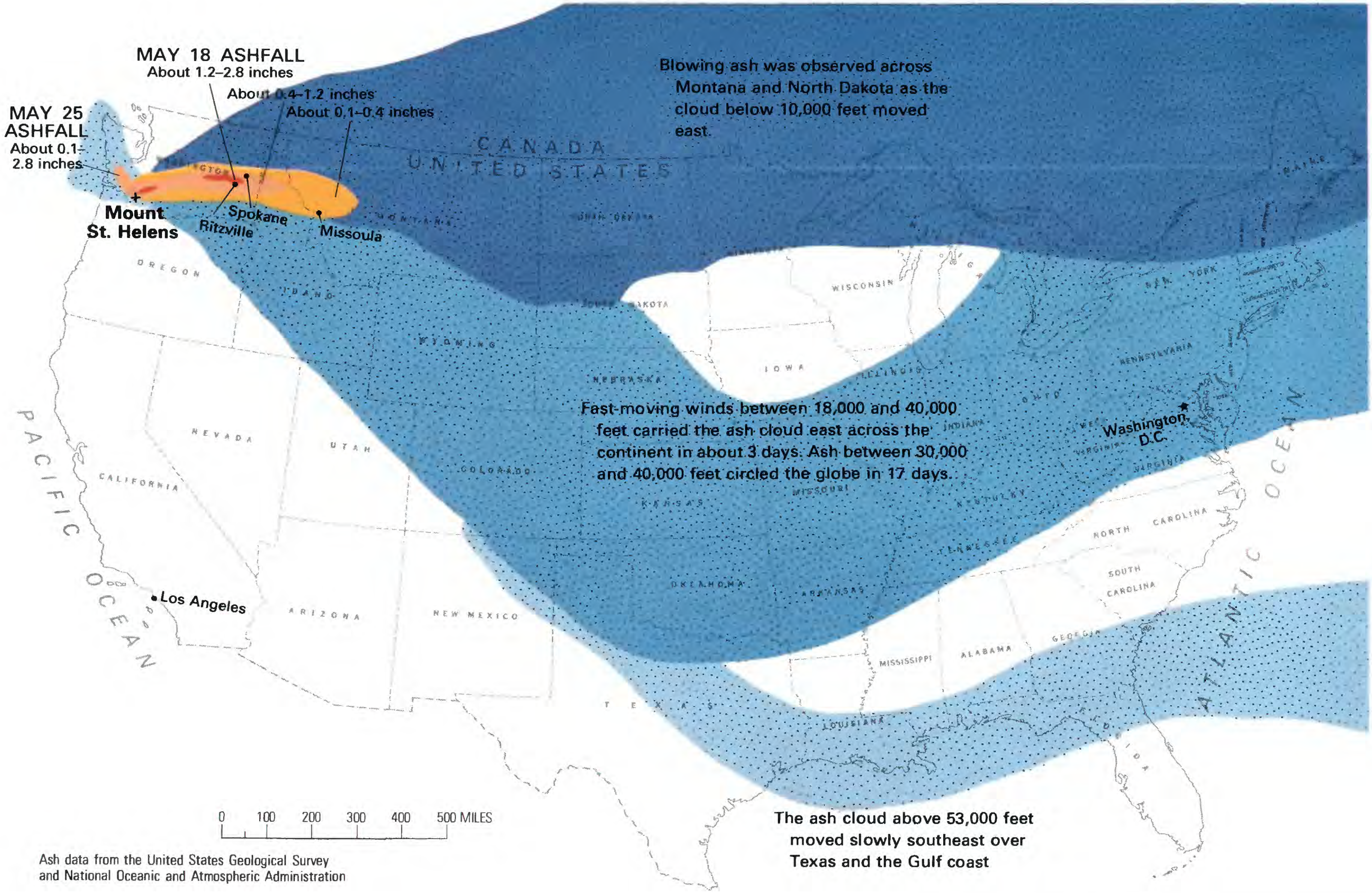
House and street damaged by small movement on landslide caused by the San Fernando, California, earthquake. (Photograph by Les Youd.)



Map showing distribution of ash from the May 18, 1980, eruption of Mount St. Helens. Some communities were covered by as much as 3 inches of ash. (Adapted from National Geographic, January 1981.)

5. Hazards From Volcanic Eruptions

Volcanic Eruptions

What Are the Hazards From Volcanic Eruptions?

Volcanic hazards—events and conditions that result from volcanic eruptions—include airfall debris called tephra, lateral blasts, hot avalanches called pyroclastic flows, mudflows, and lava flows. Except for ashfalls, volcanic hazards are restricted to regions around active volcanoes. Volcanic hazards can occur suddenly with little or no warning. In addition, volcanic eruptions can induce earthquakes (Chapter 2), floods (Chapter 3), and landslides (Chapter 4).

What Is the Economic Impact of Volcanic Hazards?

Eruptions take place infrequently, and, relative to other hazards, such as those from earthquakes, floods, and ground failures, they cause low annual losses. Nevertheless, an eruption can have a significant short-term economic impact. For example, the total cost of the Mount St. Helens eruptions, from March through August 1980, is expected to reach about $2 billion to $3 billion. Volcanic eruptions have been infrequent in the conterminous United States during the last 2 centuries, and few would be expected to take place during a person's lifetime. Moreover, the most destructive effects of eruptions, other than very infrequent ones which affect very large areas, are usually limited to areas within several tens of miles downvalley or downwind from the volcano. Loss from each type of volcanic hazard generally decreases as distance from the volcano increases.

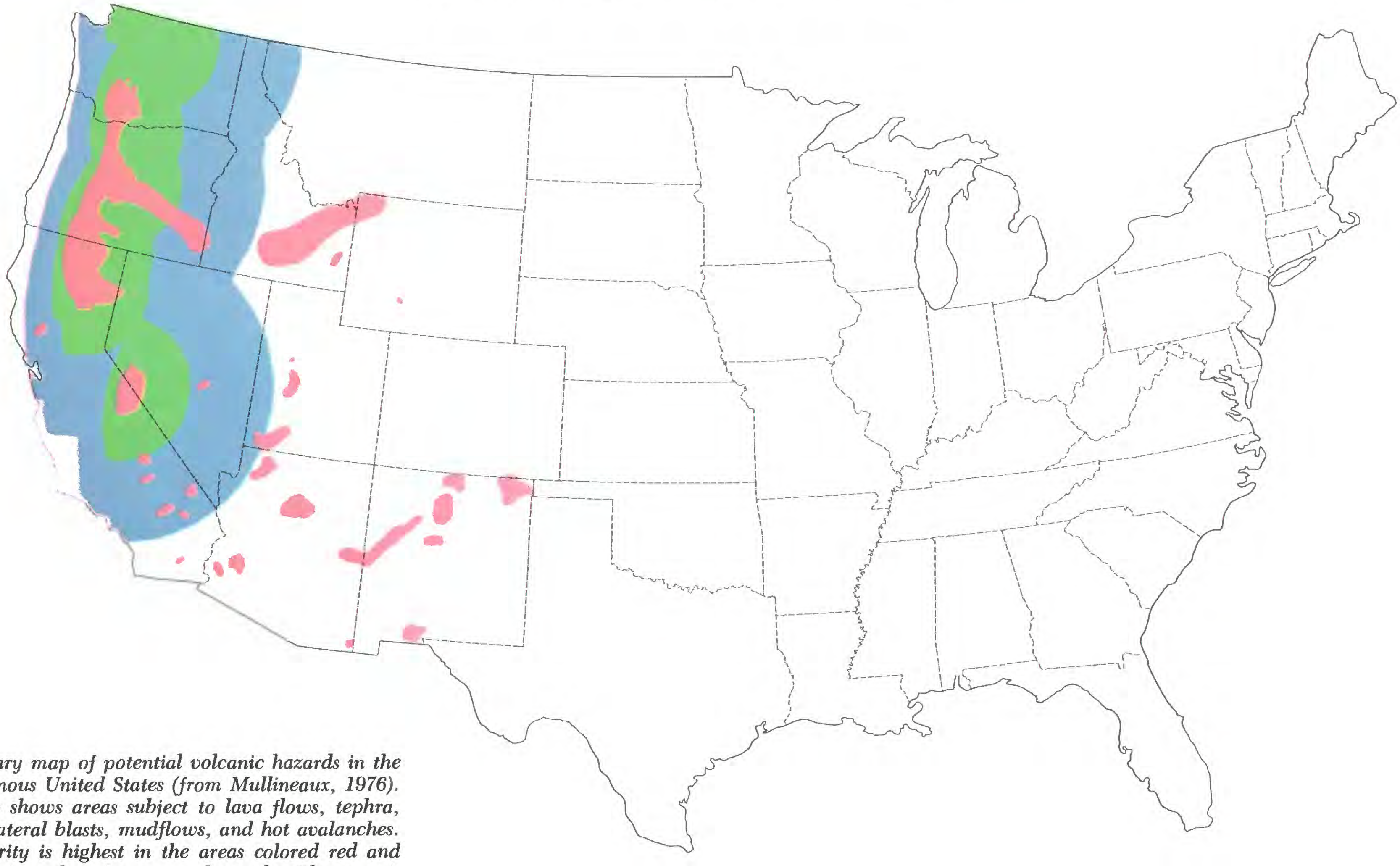
Although volcanic eruptions have happened infrequently in the Western United States during the 19th and 20th centuries, eruptions will surely occur in the future at some volcanoes in the United States now dormant. The severity of the hazards caused by these potential eruptions is great enough that loss from them is being considered in land-use decisions in some communities by both public and private interests. Land-use decisions are being made on the basis of such earth-science considerations as the distance and direction of a community and its stream drainage system from volcanoes, the history of eruptive behavior of these and other volcanoes, and the potential impact of each type of volcanic hazard on land use.

Description of volcanic hazards

	Lava flows	Hot avalanches, mudflows, and floods	Volcanic ash (tephra) and gases
Origin and characteristics.	Result from nonexplosive eruptions of molten lava. Flows are erupted slowly and move relatively slowly; usually no faster than a person can walk.	Hot avalanches can be caused directly by eruption of fragments of molten or hot solid rock; mudflows and floods commonly result from eruption of hot material onto snow and ice and eruptive displacement of crater lakes. Mudflows also commonly caused by avalanches of unstable rock from volcano. Hot avalanches and mudflows commonly occur suddenly and move rapidly, at tens of miles per hour.	Produced by explosion or high-speed expulsion of vertical to low-angle columns or lateral blasts of fragments and gas into the air; materials can then be carried great distances by wind. Gases alone may issue nonexplosively from vents. Commonly produced suddenly and move away from vents at speeds of tens of miles per hour.
Location	Flows are restricted to areas downslope from vents; most reach distances of less than 6 miles. Distribution is controlled by topography. Flows occur repeatedly at central-vent volcanoes, but successive eruptions may affect different flanks. Elsewhere, flows occur at widely scattered sites, mostly within volcanic "fields."	Distribution nearly completely controlled by topography. Beyond volcano flanks, effects of these events are confined mostly to floors of valleys and basins that head on volcanoes. Large snow-covered volcanoes and those that erupt explosively are principal sources of these hazards.	Distribution controlled by wind directions and speeds, and all areas toward which wind blows from potentially active volcanoes are susceptible. Zones around volcanoes are defined in terms of whether they have been repeatedly and explosively active in the last 10,000 years.
Size of area affected by single event.	Most lava flows cover no more than a few square miles. Relatively large and rare flows probably would cover only hundreds of square miles.	Deposits generally cover a few square miles to a few hundreds of square miles. Mudflows and floods may extend downvalley from volcanoes many tens of miles.	An eruption of "very large" volume could affect tens of thousands of square miles, spread over several States. Even an eruption of "moderate" volume could significantly affect thousands of square miles.
Effects	Land and objects in affected areas subject to burial, and generally they cause total destruction of areas they cover. Those that extend into areas of snow, may melt it and cause potentially dangerous and destructive floods and mudflows. May start fires.	Land and objects subject to burning, burial, dislodgement, impact damage, and inundation by water.	Land and objects near an erupting vent subject to blast effects, burial, and infiltration by abrasive rock particles, accompanied by corrosive gases, into structures and equipment. Blanketing and infiltration effects can reach hundreds of miles downwind. Odor, "haze," and acid effects may reach even farther.
Predictability of location of areas endangered by future eruptions.	Relatively predictable near large, central-vent volcanoes. Elsewhere, only general locations predictable.	Relatively predictable, because most originate at central-vent volcanoes and are restricted to flanks of volcanoes and valleys leading from them.	Moderately predictable. Voluminous ash originates mostly at central-vent volcanoes; its distribution depends mainly on winds. Can be carried in any direction; probability of dispersal in various directions can be judged from wind records.
Frequency, in conterminous United States as a whole.	Probably one to several small flows per century that individually cover less than 10 square miles. Flows that cover tens to hundreds of square miles probably occur at an average rate of about one every 1,000 years. (In Hawaii, eruption of many flows per decade would be expected.)	Probably one to several events per century caused directly by eruptions. Probably only about one event per 1,000 years caused directly by eruption at "relatively inactive" volcanoes.	Probably one to a few eruptions of "small" volume every 100 years. Eruption of "large" volume may occur about once every 1,000 to 5,000 years. Eruption of "very large" volume, probably no more than once every 10,000 years.
Degree of risk in affected area.	To people, low. To property, high.	Moderate to high for both people and property near erupting volcano. Risk relatively high to people because of possible sudden origin and high speeds. Risk decreases gradually downvalley and more abruptly with increasing height above valley floor.	Moderate risk to both people and property near erupting volcano; decreases gradually downwind to very low.

What Areas Are Likely To Be Affected by Future Volcanism?

With the exception of ashfalls, which can cover very broad regions downwind from volcanoes, the parts of the United States that could be severely affected by a volcanic eruption are probably no more than a few percent of either the Western counterminous United States or Hawaii. Areas considered most likely to be affected by future eruptions can be divided into several hazard zones on the basis of evidence from past eruptions in the Cascade Range of the Northwestern United States (Crandell, 1976; Mullineaux, 1976, 1980). These zones chiefly denote differences in the kinds and extents of volcanic hazards, but they also mark differences of anticipated severity and frequency of occurrence. For example, zones defined at some volcanoes outline the extent of the ashfall hazard; areas most likely to be affected by ashfall are certain sectors downwind from explosive relatively active volcanoes.



Preliminary map of potential volcanic hazards in the conterminous United States (from Mullineaux, 1976). The map shows areas subject to lava flows, tephra, ashfall, lateral blasts, mudflows, and hot avalanches. The severity is highest in the areas colored red and decreases in order of green and purple. The map is based on computer techniques described in Radbruch-Hall (1979) and Edwards and Batson (1980).

What Are the Kinds of Volcanic Eruptions and Their Effects?

Volcanic eruptions can be broadly classed as nonexplosive or explosive. Nonexplosive eruptions are generally caused by an iron and magnesium-rich magma (molten rock) that is relatively fluid and allows gas to escape readily. Lava flows that are common on the island of Hawaii are the characteristic product of nonexplosive eruptions. Explosive eruptions, in contrast, are violent and are derived from a silica-rich magma that is not very fluid; these eruptions are common at volcanoes in the Cascade Range and in the volcanic chain of Alaska. Explosive eruptions produce large amounts of fragmental debris in the form of airfall ash, pyroclastic flows, and mudflows on and beyond the flanks of the volcanoes.

Tephra is one of the products of an eruption. Tephra is a term used to describe rock fragments of all sizes erupted into the air above a volcano, often in a vertical column that reaches into the outer layer of the stratosphere. Large rock fragments generally fall back onto, or near, the volcano. Small fragments are carried away by wind and fall to the ground at a distance determined by the grain size and density, the height to which the fragments are erupted, and the velocity of the wind. Eruption of a large volume of tephra will cause a distinct layer of ash to accumulate. The spatial distribution of ash accumulation is generally in the form of a lobe which is thickest directly downwind from the volcano and thinnest toward the boundaries; the thickness decreases as distance from the volcano increases. Tephra can endanger lives and damage property at considerable distances from a volcano by forming a blanket at the ground surface and by contaminating the air with abrasive particles and corrosive acids. Close to a volcano, people can be injured or killed by breathing tephra-laden air; damage to property is caused by the weight of tephra and its smothering and abrasive effects.

For a tephra eruption of any given volume and height, the probability that ash will affect a specific location in the tephra-hazard zones depends on the frequency that winds above the volcano blow in the direction of that location. The severity of the tephra hazard, however, depends on the thickness of ash deposited, which is governed by the volume of the eruption and the wind speeds. The tephra hazard zones depict potential thicknesses of ash at different distances and directions from the volcanoes; the shapes and extents of these zones are based on wind speeds in various directions.

Hot fragments and gases can be ejected laterally at high speed from explosive volcanoes and can be extremely dangerous. Lateral blasts, the term for this phenomenon, commonly leave deposits that are no more than 3 to 6 feet thick near their source vent; these deposits thin rapidly as distance from the vent increases. They generally do not extend more than several miles from the vent, but occasionally, as at Mount St. Helens, a blast can reach as far as about 15 miles. Lateral blasts endanger people chiefly because of their heat, rock fragments carried, and high speed which may not allow sufficient time for them to escape or to find adequate cover. Damage to structures results chiefly from impact and high-speed "wind." Lateral blast phenomena can grade outward to pyroclastic flows that move down slopes. The effects of the two events are similar.

Pyroclastic flows are masses of hot dry rock debris that move like a fluid. They owe their mobility to hot air and other gases mixed with the debris. They often form when large masses of hot rock fragments are suddenly erupted onto a volcano's flanks. Pyroclastic flows can move downslope at speeds of as much as 100 miles per hour and tend to follow and bury valley floors. Clouds of hot dust generally rise from the basal coarse part of the flow and may blanket adjacent areas, especially downwind. Because of their great mobility, pyroclastic flows can affect areas 15 miles or more from a volcano. The principal losses from a pyroclastic flow are caused by the swiftly moving basal flow of hot rock debris, which can bury and incinerate everything in its path, and the accompanying cloud of hot dust and gases, which can extend beyond the basal flow and cause asphyxiation and burning of the lungs and skin. Losses from pyroclastic flows decrease as height above the valley floor and the distance from the volcano decrease.

Mudflows are masses of water-saturated rock debris that move down slopes in a manner resembling the flowage of wet concrete. The debris is commonly derived from masses of loose unstable rock deposited on the flanks of a volcano by explosive eruptions; the water may be provided by rain, melting snow, a crater lake, or a lake or reservoir adjacent to the volcano. Mudflows can also be induced by a pyroclastic flow or a lava flow moving across snow and melting it. Mudflows can be either hot or cold, depending on the presence or absence of hot rock debris. The speed of mudflows depends mostly on their fluidity and the slope of the terrane; they sometimes move 50 miles or more down valley floors at speeds exceeding 20 miles per hour. Mudflows may reach even greater distances than pyroclastic flows, about 60 miles from their sources. Losses from mudflows decrease rapidly as the height above the valley floor increases and gradually as distance from the volcano increases. The chief threat to man is burial. Structures can be buried or swept away by the vast carrying power of the mudflow.

Vertical eruption column from Mount St. Helens, July 22, 1980, viewed from southwest. Ash clouds from pyroclastic flows in the crater and on the north flank drift eastward at low altitudes. (Photograph by R. P. Hoblitt.)

Lava flows are generally erupted quietly, although they are often preceded by explosive volcanic activity. Lava flows from volcanoes like Mount Rainier, Mount St. Helens, and Mount Shasta, for example, typically appear only after an eruption has been in progress for hours, days, or a few weeks, rather than at the outset of the eruption. However, flows from small basaltic volcanoes like many near Bend, Oregon, often take place soon after an eruption begins. The fronts of lava flows usually advance at speeds ranging from barely perceptible to about as fast as a person can walk. Lava flows typically cause no direct danger to human life, but they generally cause total destruction in the areas they cover. Lava flows that extend into areas of snow may melt it and cause floods and mudflows; lava flows that extend into vegetated areas can start fires. On large central-vent volcanoes, such as Mount St. Helens and Mount Shasta, lava flows generally are short; therefore, lava-flow hazard zones include only the flanks of the volcano and the nearest 1 to 2 miles of adjacent valleys and basins. In many parts of the Western United States, a slight risk exists from lava flows and small-volume ashfalls that are not associated with large volcanoes.

Flood-hazard zones extend considerable distances down some valleys. For some volcanoes in the western Cascade Range, these zones reach the Pacific Ocean.

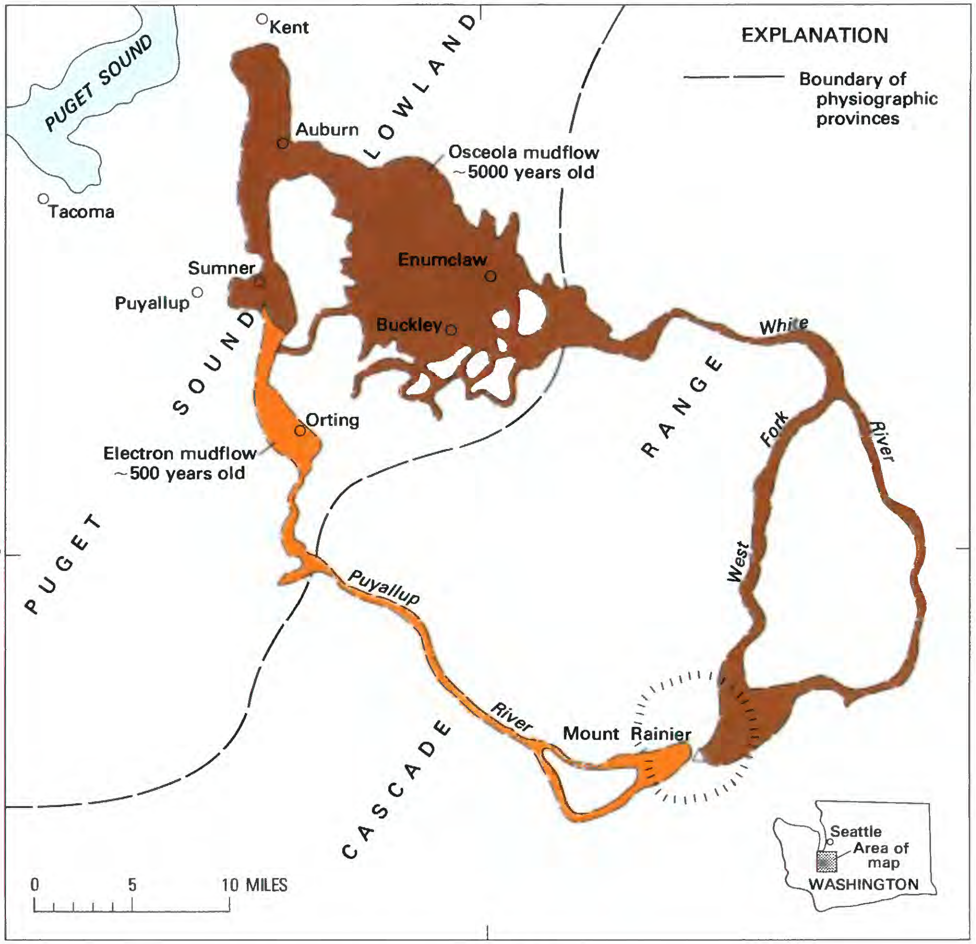
Thick pumice layers about 4 miles northeast of center of Mount St. Helens. Maximum height of outcrop is about 30 feet. Entire sequence above shovel (lower center) was erupted within the last 4,500 years.

Thin white volcanic ash from Crater Lake, southern Oregon, interbedded with valley-floor deposits 15 miles west of Wenatchee, Washington, and 300 miles north of the source of the ash. River cutbank is about 16 feet high.

Logging truck, 7.5 miles north-northwest of Mount St. Helens, destroyed by lateral blast of May 18, 1980. Truck was overturned and propelled downslope until restrained by heavy cable installed to anchor other logging equipment. (Photograph by R. P. Hoblitt.)

View to west over ridge 6 miles northwest of Mount St. Helens, swept by lateral blast of May 18, 1980. Blast moved from left to right. (Photograph by C. D. Miller.)

View of pyroclastic flows with phreatic explosion pits, Mount St. Helens, May 8, 1981. Rapid erosion of recent deposits by stream action has occurred over the past year.



Sketch map showing the extent of the Osceola and Electron Mudflows. The photograph shows the mudflow exposed in the face of a terrace 2 miles southeast of Greenwater, Washington, in the White River Valley. The largest boulder in the center of the photograph is about 6 feet in diameter. (Photograph by D. R. Crandell.)

▲ *Mudflow-damaged house along the Toutle River about 25 miles west-northwest of Mount St. Helens. End section of house was torn free and lodged against trees. Mudflow height is recorded by mud coatings on tree trunks. (Photograph by D. R. Crandell.)*

Southwest flank of Mount St. Helens in late summer 1979. Dark lava flows cover the south flank of volcano to right; "mitten" flow at right center and "two-finger" flow at left center reach approximately to the base of the volcano. (Photograph by R. P. Hoblitt.) ▶

What Is the Frequency of Occurrence and Volume of Volcanic Eruptions?

An inverse relation exists between the size of eruptions (volume of material erupted) and how often they occur. Small eruptions occur much more frequently than large ones. The volumes and frequencies of past eruptions provide the major criteria for defining the various hazard zones. For example, tephra-hazard zones are defined on the basis of eruptions of four different volumes: small, moderate, large, and very large. Evidence suggests that an eruption of small volume may be expected at some place in the Cascade Range once every 100 years, one of large volume about once every 1,000 to 5,000 years, and an eruption of very large volume about once every 10,000 years.

During the last 2 million years, a few eruptions having very large volume have occurred in the Western United States. Locations of these eruptions include in and near Yellowstone National Park, Wyoming, at Long Valley, California, and in the Jemez Mountains of New Mexico. These eruptions deposited ash over very large regions of the Western United States.

Can Future Volcanism Be Forecast?

Each volcano or volcanic area has its own unique record of eruptive activity; it may have remained relatively constant for thousands of years, or it may have gradually or suddenly ungergone dramatic physical changes. The record of activity in prehistoric and historic time provides a basis for defining the hazards of specific volcanic eruptions. This record tells what kinds of eruptions have occurred, what areas have been affected, and how often they have taken place. Although not an infallible guide, such a record provides the best data for forecasting the kinds, distribution, frequency, and effects of future volcanism.

Scientific instruments are used to forecast the possible locations and times of future eruptions. The seismometer is one of the most effective instruments used to monitor a volcano. It is used to detect earthquakes which typically increase in size and number just before a volcanic eruption. In Hawaii, the number of shallow earthquakes at depths of about 1 mile usually increases greatly several days to several hours prior to an eruption. Ground deformation also commonly precedes volcanic eruptions and can be used to forecast the locations of possible eruptions.

Looking south into the crater of Mount St. Helens shows prominent growth of the new dome and past eruption snow cover. (Photograph taken on May 8, 1981.)

What Can Be Done To Reduce Losses From Volcanism?

Losses from a volcanic eruption can be reduced in several ways (Warrick, 1979). These include (1) use of knowledge of the past eruptive activity of a volcano to define the potential kinds, scales, locations, extents, effects, and severity of future eruptions and to define hazard zones, (2) establishment of monitoring systems to forecast an impending eruption and to provide warning, (3) disaster preparedness and emergency evacuation, (4) protective measures, (5) risk assessment and land-use planning, (6) insurance, and (7) relief and rehabilitation.

Activities associated with forecasting depend on the reliable detection and monitoring by scientific instruments of physical changes preceding an eruption. Phenomena that can be reliably monitored include earthquakes, ground deformation, changes in composition of volcanic gases, and changes in electrical and magnetic fields.

Forecasts of impending eruptions are most reliable at frequently active volcanoes such as Kilauea Volcano in Hawaii. Kilauea has been carefully monitored for many years at the Hawaiian Volcanic Observatory operated by the U.S. Geological Survey. Too little is known about volcanoes in Alaska and the Cascade Range to anticipate a reliable capability for forecasting eruptions there in the near future. Seismic monitoring of Mount St. Helens by the U.S. Geological Survey and the University of Washington detected the earthquakes preceding the volcanic eruption that began March 27, 1980. Advance warning, based on the earthquakes together with knowledge of the potential hazards, provided an opportunity for State and local officials to prepare and implement emergency plans.

Disaster preparedness and emergency evacuation plans can provide substantial loss reduction when the locations and types of hazards for a particular volcanic eruption are taken into consideration. These plans should be based on volcanic-hazard zones showing the relative severity, extents, and effects of specific volcanic eruptions.

Protection from volcanic hazards can be effective in reducing losses for some events, but not for others. Relatively simple actions can reduce losses. For example, providing high-efficiency dust masks and goggles can protect individuals from respiratory damage and eye irritation; changing oil and air filters can reduce loss of vehicles from ashfalls.

Insurance can reduce the economic impact. However, the sales record of earthquake insurance in California and flood insurance throughout the Nation suggests that insurance for volcanic hazards would not be widely purchased, even if it were widely available at reasonable cost. Rate schedules, keyed to areas of the highest probable loss, such as the floor of a valley that heads on a volcano, might focus public attention and limit development of the most hazardous areas.

Risk assessment, coupled with land-use planning, provides a strategy for reducing losses from volcanic hazards. Assessment of the risk involves weighing the value of the community resources in danger, the vulnerability of the valued resources, and the probability that a volcanic eruption of a certain volume will take place within a certain period of time. On the basis of the risk assessment, a community can make decisions about land use that are consistent with their needs and goals of public safety.

Relief and rehabilitation actions are adjustments after the volcanic hazard has happened. Together with predisaster planning, such actions keep the cost of recovery from being too much of a burden on the community. The Federal Government now provides partial relief and rehabilitation assistance, but such assistance is not a substitute for preparedness and planning.

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The late Dr. David Johnston, U.S. Geological Surve using a correlation spectrometer which measures ultr violet radiation as an indicator of the sulfur dioxide co tent of gases ejected from Mount St. Helens, Washingto

Tree protected by snow bank, Toutle station, Mount S Helens, May 1980. (Photograph by Peter W. Lipman.

View of Salt Lake City, Utah, looking southeast toward the Wasatch Mountains. About 85 percent of the State's population lives within 6 miles of the 230-mile-long Wasatch fault zone that trends along the mountain front. No moderate to large earthquakes have taken place since the settlement of the area in 1847. However, geologic evidence suggests that a moderate to large earthquake happens on the average about once every 50 to 430 years along the Wasatch fault zone. Because of the possibility of a damaging earthquake, the State created a Seismic Safety Council in 1977 to recommend public policy and loss-reduction programs to the Governor and Legislature. (Photograph by Richard Vanhorn.)

6. Suggestions for Improving Decisionmaking To Face Geologic and Hydrologic Hazards

What Is the Cost of Not Attempting To Reduce Losses From Geologic and Hydrologic Hazards?

Decisionmakers must weigh the cost of potential losses from geologic and hydrologic hazards against the cost of loss-reduction actions. Economic loss is one measure of the cost of geologic and hydrologic hazards to the Nation. The table gives estimates of both the average annual loss and the potential for sudden loss as a result of earthquakes, floods, ground failures, and volcanic eruptions. Economic loss, however, is only a fraction of the true impact because these hazards cause considerable hardship to individuals and communities, including death and physical injury, psychological trauma, disruption of lives, and a reduction in the overall stability of the community. For example, even though the 1972 Hurricane Agnes is recognized in terms of economic impact as the greatest natural disaster in the United States, its total impact should also include more than 118 deaths, more than 250,000 families uprooted in Pennsylvania, upturned graves and markers, reduced salinity in the Chesapeake Bay which affected the shellfish industry, and interrupted power and transportation.

The history of the Nation's long-term response to natural disasters suggests that public policy and action are not always adequate to reduce the very large and increasing economic and social costs. Hence, public officials and the populace must be continuously reminded of the threat and the magnitude of the economic and social disruptions that will accompany future earthquakes, floods, ground failures, and volcanic eruptions.

Recent information (Schiff, 1980; Moorhouse and others, 1980; Smith, 1980) suggests that significant loss reduction can be achieved for some hazards with the use of simple low-cost practices. Such practices must be identified and implemented for all geologic and hydrologic hazards.

Estimates of average annual losses and the potential for sudden loss from geologic and hydrologic hazards in the United States

[Note: Some loss estimates may be too high or too low by a factor of 2]

Hazard	Annual loss (in billion dollars)	Sudden loss potential (in billion dollars)
Earthquakes—ground shaking, surface faulting earthquake-induced ground failures, tsunamis).	0.6	50
Floods—flash floods, riverine floods, tidal floods.	3	5
Ground failures—landslides, expansive soils, subsidence.	4	6
Volcanic eruptions—tephra, lateral blasts, pyroclastic flows, mud flows, lava flows.	[1]	3

[1] Past data are too limited to determine average annual losses for volcanic eruptions. The 1978 eruption of Mount St. Helens in the State of Washington will provide a reference for the future.

What Is the Difference Between Good and Bad Decisions?

Earth-science information is only one of several types of information needed to devise methodologies for reducing losses from geologic and hydrologic hazards. Decisionmaking on matters concerning a community's vulnerability to earthquakes, floods, ground failures, and volcanic eruptions typically involves choosing from a variety of different alternatives. Decisionmakers have been described "as sociopolitical men who must bargain with diverse clients, knowing that the "public good" is defined in many conflicting ways by intensely competitive and self-interested groups. Such decisionmakers know that goals are fluid, multiple, inconsistent, multidimensional, and incommensurable. They also know that no fixed solutions are possible, regardless of their technical or economic elegance" (Alston and Freeman, 1975).

In spite of the difficulties in reaching decisions which meet the various definitions of the public good, the process of decisionmaking to reduce losses from natural hazards must include information about the land—surface form and drainage pattern, soil and rock properties, and its historical record of responding to natural hazards and man's activities. To neglect this type of information has proved to be costly and unwise.

View of San Fernando Valley, California, looking south from the Pacoima Dam.

What Can Communities Do?

Decisionmaking to avoid or to reduce losses from geologic and hydrologic hazards is restricted by economic, social, and public policy factors. The principal restraint is stated by the question, "How much will it cost?" If a community decides to attempt to reduce losses from geologic and hydrologic hazards, its planners and decisionmakers must face the possibility of increased costs and decide what actions are conservative and prudent.

As communities accept the premise that costs associated with specific loss-reduction actions such as avoidance, land-use zoning, engineering design, and insurance are prudent, the question that will be asked is, "How much are we willing to pay?" An initial requirement for answering this question is for the community to determine:

- The physical causes of each natural hazard and the probability of each hazard occurring locally.
- The current local annual loss and the potential for sudden loss from each hazard.
- The local distribution of levels of relative severity expected from each hazard.
- The potential loss as a function of time and loss-reduction actions.

The table is a summary of earth-science information needed in planning and decisionmaking to reduce losses from hazards.

Earth science information needed to reduce losses from geologic and hydrologic hazards

Reduction decision	Technical information needed about the hazards from earthquakes, floods, ground failures, and volcanic eruptions
Avoidance	• Where has the hazard occurred in the past? Where is it occurring now? Where is it predicted to occur in the future? • What is the frequency of occurrence?
Land-use zoning	• Where has the hazard occurred in the past? Where is it occurring now? Where is it predicted to occur in the future? • What is the frequency of occurrence? • What is the physical cause? • What are the physical effects of the hazard? • How do the physical effects vary within an area? • What zoning within the area will lead to reduced losses to certain types of construction?
Engineering design	• Where has the hazard occurred in the past? Where is it occurring now? Where is it predicted to occur in the future? • What is the frequency of occurrence? • What is the physical cause? • What are the physical effects of the hazard? • How do the physical effects vary within an area? • What engineering design methods and techniques will improve the capability of the site and the structure to withstand the physical effects of a hazard in accordance with the level of acceptable risk?
Distribution of losses	• Where has the hazard occurred in the past? Where is it occurring now? Where is it predicted to occur in the future? • What is the frequency of occurrence? • What is the physical cause? • What are the physical effects of the hazard? • How do the physical effects vary within an area? • What zoning has been implemented in the area? • What engineering design methods and techniques have been adopted in the area to improve the capability of the structure to withstand the physical effects of a hazard in accordance with the level of acceptable risk? • What annual loss is expected in the area? • What is the maximum probable annual loss?

What Is the Benefit-Cost Ratio of Reducing Losses From Geologic and Hydrologic Hazards?

No widely accepted method exists for determining benefit-cost or risk-benefit ratios for specific loss-reduction actions. However, the following excerpt from *The Nature, Magnitude, and Costs of Geologic Hazards in California and Recommendations for Their Mitigation* (1973) provides some insight into benefit-cost analysis of the ground-shaking hazard:

> Given a continuation of present conditions, it is estimated that losses due to earthquake shaking will total $21 billion (in 1970 dollars) in California between 1970 and 2000. Most of the damage and loss of life will occur in zones of known high seismic activity; structures that do not comply with the Field and Riley Acts, passed in 1933, will be especially vulnerable. If the present-day techniques for reducing losses from earthquake shaking were applied to the fullest degree, life loss could be reduced up to 90 percent, and the total value of losses could be reduced by as much as 50 percent. Total costs for performing the loss reduction work would be about 10 percent of the total project loss, which with 50 percent effectiveness provides a benefit to cost ratio of 5:1.

According to Terry Margerum (1980), "for most geologic hazards, the loss amount is generally reduced well over 90 percent when construction codes are applied.

Damage to fish shop in Japan caused by rock fall. (Photograph by Kapsuyoshi Uchiyama.)

What Are the Local-State-Federal Roles in Reducing Losses From Geologic and Hydrologic Hazards?

A program for reducing losses from geologic and hydrologic hazards is likely to be more effective if plans are formulated and conducted by local governments. Because geologic and hydrologic hazards may well extend beyond the jurisdiction of a single local government, neighboring governments must avoid conflicting plans and policies. This consideration is particularly important in flood-plain management; for example, one community's plan to zone flood-prone land for aesthetic and recreational use may be jeopardized by another community's plan to reserve the opposite stream bank for industrial uses. Alternatively, an upstream community could conceivably adopt a policy of urbanization and structural flood protection that would lead to an increased probability of floods for a downstream community.

R. A. Platt and others (1980) suggest that the substate regional level is the most appropriate one for coordinating local plans and policies. Regional coordination units are more effective if they are able to offer incentives to the communities that enter into agreements and coordination of loss-reduction plans.

A team of interdisciplinary experts from all levels of government and the private sector can provide guidance for planning and decisionmaking to reduce losses. Each expert and representative of government and the private sector contributes whatever they do best.

	Suggested contributions for government
Federal	• Provide national and regional earth-science information on each hazard. • Develop federal legislation and policy to support short- and long-term loss-reduction programs. • Provide technical assistance. • Provide advice on preparedness. • Encourage short- and long-term planning to reduce losses. • Provide support for research on scientific, engineering, and socioeconomic problems. • Conduct postdisaster surveys.
State	• Formulate preparedness plans. • Adopt legislation. • Enforce State laws and regulations designed to reduce losses from specific hazards. • Create councils of interdisciplinary experts, such as the California Seismic Safety Commission and the Utah Seismic Safety Advisory Council, to recommend public policy and loss-reduction programs. • Aid in identifying risks to communities. • Aid in identifying sources of funding and technical expertise to use in loss reduction programs. • Provide support and, whenever possible, funding for research.
Local	• Identify a community leader to rally local support for loss-reduction actions, favoring short-term solutions. • Collect, archive, and update earth–science information which affects loss-reduction actions. • Modify land-use and development ordinances to reflect the best available knowledge of geologic and hydrologic hazards. • Increase public awareness and encourage individual preparedness.

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This remarkable set of photographs is part of a sequence that shows the eruption of Mount St. Helens on May 18, 1980. These photographs show the beginning of a landslide, induced by an earthquake, on the bulging north face of the mountain (8:32:33.9 a.m.) and the subsequent blasts that sent ash, gas, and fragments of rocks into the air and horizontally across the area.

The sequence ends with the shot (on the front cover) of the cloud of volcanic gases, ash, and rock fragments approaching the car in which the photographer is fleeing. (Photographs by Gary Rosenquist. Copyright 1980.)

The volcano ejected 400 million tons of ash into the atmosphere. Ash was blown as high as 11 miles into the air, and winds carried it as far away as the Atlantic Ocean within 3 days. The human toll was 62 killed or missing (Decker, Robert, and Decker, Barbara, 1981, The eruption of Mount St. Helens: Scientific American, v. 244, no. 3, p. 77).

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