Earthquakes and the Urban Environment

Volume II

Author

G. Lennis Berlin

Earthquakes and the Urban Environment

Volume II

Author

G. Lennis Berlin
Associate Professor
Department of Geography
Northern Arizona University
Flagstaff, Arizona

CRC Press, Inc.
Boca Raton, Florida

Library of Congress Cataloging in Publication Data

Berlin, Graydon Lennis, 1943-
Earthquakes and the urban environment.

Bibliography: p.
Includes index.
1. Earthquakes. 2. Earthquakes and building.
I. Title.
QE539.B48 551.2'2 77-16131
ISBN 0-8493-5174-1

This book represents information obtained from authentic and highly regarded sources. Reprinted material is quoted with permission, and sources are indicated. A wide variety of references are listed. Every reasonable effort has been made to give reliable data and information, but the author and the publisher cannot assume responsibility for the validity of all materials or for the consequences of their use.

Direct all inquiries to CRC Press, Inc., 2000 N.W. 24th Street, Boca Raton, Florida, 33431.

International Standard Book Number 0-8493-5173 (Volume I)
International Standard Book Number 0-8493-5174 (Volume II)
International Standard Book Number 0-8493-5174 (Volume III)

Library of Congress Card Number 77-16131
Printed in the United States

ACKNOWLEDGMENTS

I would like to express my deepest gratitude to the many people who contributed substantially to the creation of this book. The entire manuscript was reviewed by James R. Underwood, Jr., Chairman-Department of Geology, Kansas State University and John Kelleher, Seismologist, U.S. Nuclear Regulatory Commission. Their authoritative criticisms and suggestions are largely responsible for any success of this book. Because it was not possible to make all the changes suggested, the author is solely at fault for any errors or omissions that may remain. The following individuals reviewed portions of the manuscript related to their research specialities: Jack Barrish (Jack Barrish Consulting Engineers), James H. Dieterich (U.S. Geological Survey), Ajit S. Virdee (California State University at Sacramento), James H. Whitcomb (California Institute of Technology), and Peter I. Yanev (URS/John A. Blume & Associates, Engineers). The many individuals who provided photographs vital to the completion of this book are acknowledged in the figure captions.

Two colleagues at Northern Arizona University deserve special thanks. Dominic J. Pitrone provided countless constructive suggestions and invaluable data collection assistance, and Howard G. Salisbury, III, Chairman-Department of Geography and Planning, was untiring in his efforts to accommodate my many special requests. Cartographic assistance was provided by Michael Schramm and Nat Garcia. Carolyn Waller and Virginia Hall typed the entire manuscript.

The talented editors at CRC Press, namely Sandy Pearlman, Jeffrey Eldridge, Terri Weintraub, Beth Frailey, Barbara Perris, and Gayle Tavens, contributed a great deal to the refining of much of the text. These individuals also were most understanding concerning the many delays caused by the author.

My grateful thanks go to my wife Judy for her encouragement and forbearance over the several years that it took to complete this project.

Graydon Lennis Berlin
Flagstaff, Arizona
November 1978

THE AUTHOR

Graydon Lennis Berlin was born in St. Petersburg, Pennsylvania, on May 21, 1943, and educated in the public schools there. He received a B.S. degree in 1965 from Clarion State College (Earth-Space Science), an M.A. degree in 1967 from Arizona State University (Geography), and a Ph.D. degree in 1970 from the University of Tennessee (Geography). He began his educational career in 1968 as an Assistant Professor of Geography and Research Associate at Florida Atlantic University. He joined the faculty at Northern Arizona University in 1969, attaining the rank of Associate Professor of Geography in 1975. Between 1969 and 1978, Dr. Berlin was also a Research Geographer on a part time basis with the U.S. Geological Survey. At the present time he is the Director of the Advanced Training of Foreign Participants in Remote Sensing Program, a joint venture of Northern Arizona University and the U.S. Geological Survey.

Dr. Berlin is a member of several national professional organizations and was elected Chairman of the Geography Division of the Arizona Academy of Science in 1974. He is also a member of Gamma Theta Upsilon, the National Professional Geographic Fraternity and a Full Member of Sigma Xi, the Scientific Research Society of North America. Dr. Berlin is a biographee in American Men and Women of Science, Who's Who in the West, and the Dictionary of International Biography. He is the author of more than 30 journal articles and government reports.

TABLE OF CONTENTS

Chapter 1

EARTHQUAKE PREDICTION

> The scientists first concluded in 1970 from anomalies in the earthquake pattern that an earthquake might be coming. In June 1974, observations of further changes in the earthquake pattern, tilting of the land surface, changes in water level in wells, changes in electric current in the ground, and strange animal behavior confirmed this conclusion. More seismographs and tiltmeters were moved into the area. On December 20, 1974, local government was warned to expect a large earthquake soon, and, in mid-January 1975, warning was given that the quake was imminent. On January 28, villages were warned to be prepared. Extra seismographs were set up.
>
> Observations in the threatened area continued until February 1, when indications of an impending earthquake began to mount. A minor tremor was detected in an area that had not recently experienced one. The next day, there were seven more. On February 3, the minor tremors increased further, and more shocks were felt.
>
> These events led the scientists to call an emergency conference at 7 p.m. on February 3 to report to authorities their prediction that a strong earthquake would probably occur in the very near future. By the afternoon of February 4, the seismic activity had leveled off, but this was judged to be the calm before the storm. At 2 p.m., people were told to expect a major quake within 2 days. Shops were shut, and general evacuation of buildings was ordered in two counties. At 6 p.m. that night in one village, the people were warned, "A strong earthquake will probably occur tonight. We insist that all people leave their homes and all animals leave their stables. The people from the cinema team will show four feature films outside for us tonight."
>
> One and one-half hours later, the earthquake, measured at 7.3 on the Richter scale, struck.[631]

As noted by Hamilton,[631] this passage was not extracted from the writings of science fiction; rather, it summarizes the course of events that reportedly preceded the February 4, 1975 earthquake that struck the Liaoning Province in the People's Republic of China. Because of the accuracy of the prediction, more than one million people were evacuated from their homes, an action that probably saved tens of thousands of lives.[632] The prediction emanated from a program that was less than 10 years old.

Most earth scientists believe that similar scenarios will become increasingly more common. In addition to the People's Republic of China, where several destructive earthquakes have been successfully predicted in the last 5 years, the development of a reliable earthquake forecasting capability is also a national goal in Japan, the Soviet Union, and the U.S. — countries where scientists have predicted several small seismic events.[633]

The prediction of shallow-focus earthquakes on a routine and reliable basis is, without question, one of the great challenges of science. However, significant strides towards the attainment of this goal have been realized in just the past few years. During this period, it has been established that a number of earthquakes were preceded by certain *geophysical anomalies* in their source regions[633] that had been predicted earlier from laboratory and theoretical studies. These anomalies are also called *precursors* or *premonitory phenomena.* The ability to detect, measure, and assess precursors will hopefully lead to predictions in their truest sense — that is, accurate and consistent specifications of a pending earthquake's location, time of occurrence, and size.

Several distinct models have been developed to explain the formation of earthquake precursors. The *dilatancy mechanism* of rock mechanics, *premonitory fault creep,* and a *propagating wave front* are key components in individual models. Dilatancy, as operative in laboratory studies, defines an inelastic volume increase in a rock that is undergoing deformation; the expanded volume is caused by the opening of microcracks in the specimen before it ruptures. In the fault creep model, two phases of premonitory fault creep prepare a fault for a seismic-slip event. A propagating wave front defines a *moving stress force* of a probable deep-seated origin that produces rapid regional deformation.

This chapter is concerned with an analysis of (1) high-priority precursor regions, (2) promising earthquake precursors, (3) various earthquake precursor models, and (4) prediction programs in Japan, the Soviet Union, the People's Republic of China, and the U.S. The social implications of earthquake predictions are discussed in Volume III, Chapter 2.

I. HIGH-PRIORITY PRECURSOR REGIONS

The components of plate tectonics can be used as a model for making generalized predictions. For example, earthquakes are much more apt to occur along plate boundaries than in plate interiors, and magnitudes are smaller for divergent plate boundary shocks than for those centered along transform and convergent boundaries. However, it may be possible to improve the geographic and magnitude specificity (especially the former) for large and great events by locating *seismic gaps* or temporary quiescent areas within active segments of plate boundaries. The seismic gap technique has also been used to predict potential minor and moderate earthquakes along relatively short fault segments.

Because seismic gaps identify potential high-risk areas, they can serve as high-priority locales for deploying dense arrays of instrumentation in the search for precursors that may predate small, moderate, large, and/or great earthquakes. This strategy is now being applied to the gap along the San Andreas fault which last ruptured in 1857 (Ft. Tejon earthquake).

Attempts have been made to automatically identify future earthquake sites by computer analysis of various geologic and seismologic parameters. This technique is termed *pattern recognition*. Suspected areas of high seismic risk, defined by pattern recognition, can also serve as sites for precursor searches.

A. Seismic Gaps for Large and Great Earthquakes

Page[634] offers the following explanation of the seismic gap principle:

> If there is relative motion between two plates at one point on their common boundary, then over a sufficiently long interval of time — a century or more — movement can be expected at every point on their boundary. Seismic gaps along plate margins are thus viewed as temporary features indicative of areas where elastic strain has been accumulating without release in earthquakes. The oldest seismic gaps are considered to be the likeliest sites for future large earthquakes.

Gaps are usually delineated by plotting the *rupture zones* of large earthquakes rather than by plotting epicenters which express only the points of initial rupture. Because it is often difficult to map ruptures directly (many are in submarine areas and others might not show breaks at the surface), the distribution of aftershocks is used to infer rupture lengths.[635]

Fedotov,[636] one of the first to use the seismic gap technique, plotted the rupture zones of large, near-surface earthquakes along the Japan-Kurile-Kamchatka arc. He identified several gaps where there had been no ruptures for many years and concluded that they were likely sites for large earthquakes in the future. Kelleher et al.[637] report that since Fedotov's 1965 predictions, three large earthquakes ($M_s \geq 7.0$) have filled gaps delineated by Fedotov.

Similar to the procedure used by Fedotov, Allen et al.[638] constructed a strain-release map of southern California for the period from 1934 to 1963 and identified several aseismic areas that they thought were likely sites for large earthquakes along the San Andreas fault. In addition, Tobin and Sykes[639] proposed that two zones along the seismic belt of the northeast Pacific Ocean were likely sites for future shocks because the areas had been essentially aseismic for many years.

Several investigators have identified seismic gaps in and near Japan.[640-643] To date, the sites of the August 11, 1969 Hokkaido-Toho-Oki (M_s = 7.8) and June 17, 1973 Nemuro-Oki (M_s = 7.7) earthquakes were successfully predicted by Mogi[640] and Utsu,[642] respectively. The gap struck by the 1973 earthquake had been designated an "area of special observation" (i.e., an area to monitor for short-term precursors) by the Japanese Government's Coordinating Committee for Earthquake Prediction (CCEP) in 1970.[644]

Sykes[645] relocated all aftershocks from M_s >7.0 earthquakes from the Aleutian Islands to offshore British Columbia from 1930 to 1970 to delineate rupture zones for each earthquake. Upon completion, it was observed that the plate boundary had been ruptured by large shocks except for three segments which Sykes concluded were likely sites for future earthquakes: (1) the western Aleutians — Commander Islands, (2) southern Alaska near a sequence of large earthquakes in 1899 and 1900, and (3) southeast Alaska. Page[634] reported that an M_s = 7.6 earthquake occurred near the community of Sitka (area #3) on July 30, 1972. The rupture was centered along a segment of the Fairweather fault that separates the American and Pacific plates. Kelleher and Savino[646] supported Sykes' analysis by noting that the Sitka region, although having moderate earthquakes in the mid-1960s, became extremely aseismic as the time of the main shock approached. Sykes[635] notes that the region of the great 1964 Alaskan earthquake had been inactive from at least 1900 to 1964.

A comprehensive study concerning potential sites for large earthquakes in the near future (i.e., 10 or a few tens of years) as determined by seismic gaps has been completed by Kelleher et al.[637] They studied parts of the Pacific and Caribbean plate margins (Figure 1) and determined two types of potential earthquake sites: (1) those having satisfied initial criteria — part of a major, shallow seismic belt dominated by strike-slip or thrust faulting with no rupturing for at least 30 years,and (2) those meeting initial criteria plus at least one supplemental criterion — a historical record of one or more large earthquakes occurring in a segment, historical data suggesting that a recurrence interval is near, or that the segment appears to be the next site for a migratory earthquake sequence progressing regularly in time and space (Figure 2).

The authors stress that Figure 2 should be regarded only as a most general type of prediction map. Its specific value lies in the fact that certain of the segments possess *special seismic potential.* These should be instrumented with a variety of seismological, geodetic, and geophysical sensors for analyzing possible precursors that might provide data for the accurate prediction of large earthquakes.[637]

In reference to the San Andreas fault, some scientists believe that creep and small- to moderate-sized earthquakes relieve an adequate amount of accumulating strain to prevent major earthquakes from occurring along those segments experiencing such activity. For example, Allen[647] divided this fault into five segments — three unlocked (active) and two locked (inactive). The two inactive zones coincide with the rupture zones of the January 9, 1857 Ft. Tejon and April 18, 1906 San Francisco earthquakes. Allen believes infrequent but great earthquakes will occur here in the future because strain continues to accumulate.

Kelleher et al.[637] contend that strain along a plate boundary is relieved primarily by periodic large earthquakes and not by creep or small shocks. They argue that areas experiencing creep should not be totally excluded as potential sites for large earthquakes. Part of the rationale supporting this view came from the laboratory studies of Scholz et al.[648] They discovered that stick-slip was always preceded by a small amount of creep or stable frictional sliding in granite specimens subjected to compres-

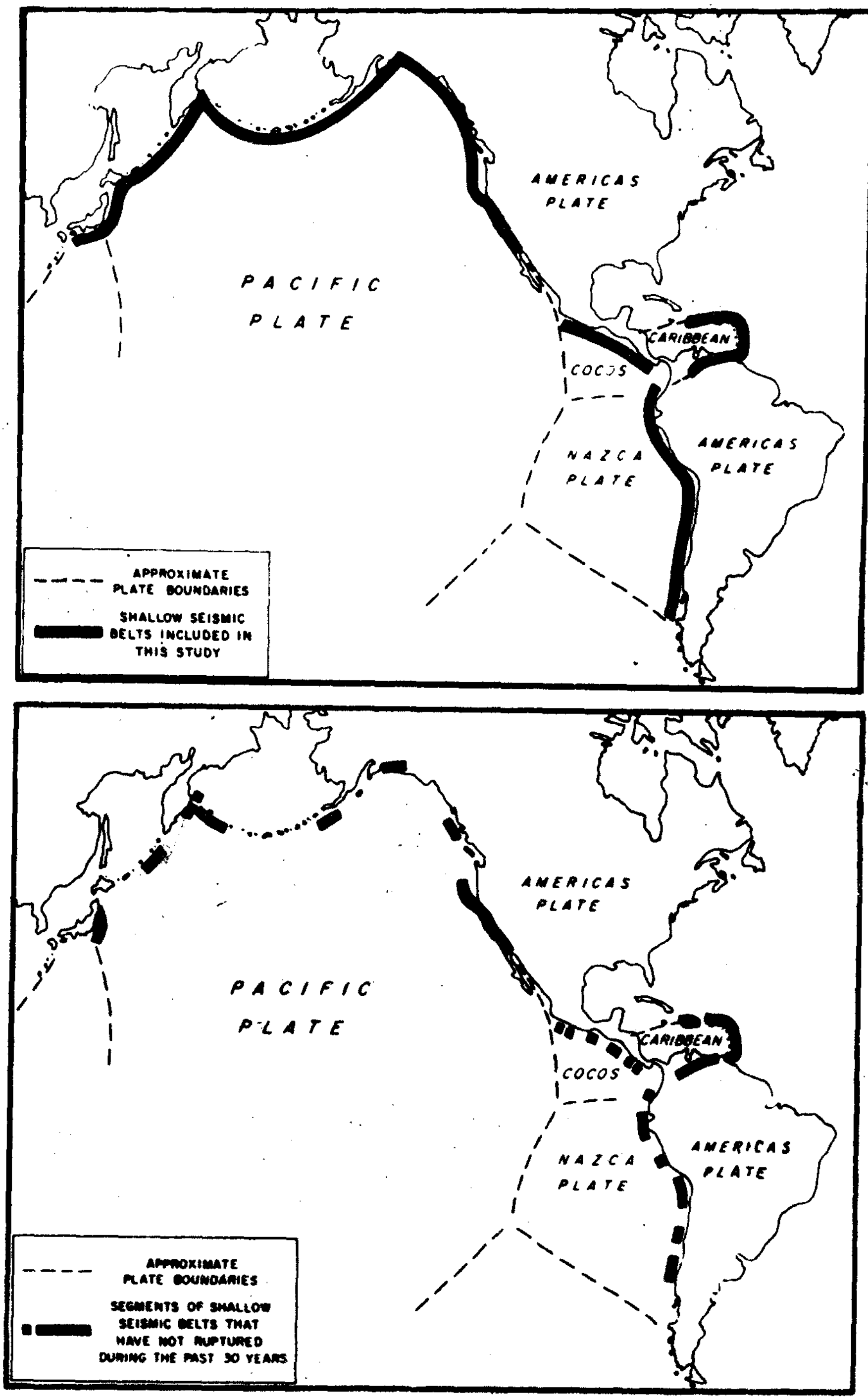

FIGURE 1. Major seismic belts examined (top) and seismic segments that have not ruptured during the past 30 years. (From Kelleher, J., Sykes, L., and Oliver, J., *J. Geophys. Res.*, 78, 2551, 1973. Copyrighted by American Geophysical Union. With permission.)

sional stress (discussed later in this chapter). This would be indicative of high, not low,

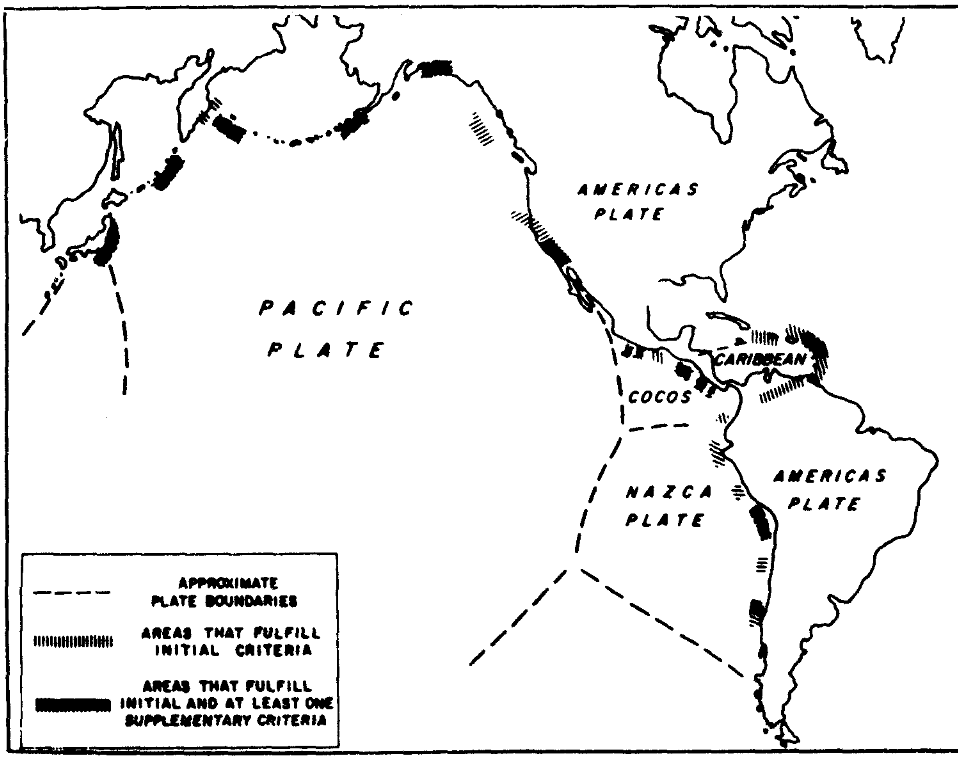

FIGURE 2. Likely locations for large earthquakes along segments of Pacific and Caribbean plate boundaries that fulfill initial or initial and supplementary criteria. See text for criteria definitions. (From Kelleher, J., Sykes, L., and Oliver, J., *J. Geophys. Res.*, 78, 2548, 1973. Copyrighted by American Geophysical Union. With permission.)

stress. Therefore, Kelleher et al. maintain that until clear evidence to the contrary is forthcoming large earthquakes should be anticipated along virtually all of the San Andreas fault (Figure 3).

B. Linear Migration of Large Earthquakes

Several investigators have reported on large shallow-focus earthquakes following a linear (sequential) migration along a fault zone. For example, Kelleher[649] and Sykes[645] note that five out of six large earthquakes occurring along the Aleutian arc (146° to 171°E) since 1938 progressed in space and time from east to west. Based upon this space-time trend, Kelleher[649] predicted a large earthquake at approximately 56°N, 158°W for sometime between 1974 and 1980. This area was struck by a large earthquake in 1938.

Kelleher[650] also discovered a north to south migration pattern for large earthquakes along much of the Chilean seismic belt. Subsequent to submitting his article for publication, a M_s = 7.6 earthquake occurred on July 9, 1971. Although the magnitude was smaller than expected, the event fits this predicted north to south trend.

Anderson[651] has proposed that the linear migration of larger earthquakes along a convergent plant boundary (e.g., Aleutians) might be caused by great *decoupling earthquakes* (i.e., a trench event in which the boundary separating the underthrusting plate and restraining plate is broken, resulting in a decoupling of the two converging plates). A decoupling event is thought to cause increasing stresses along adjacent arc segments

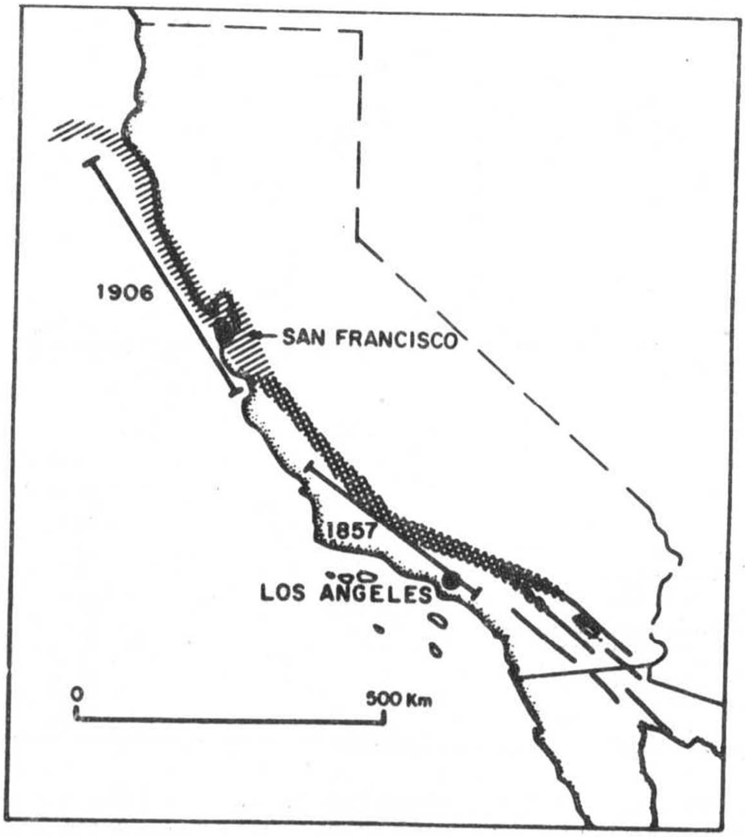

FIGURE 3. Segments of the San Andreas fault system fulfilling initial or initial and supplemental criteria. See text for criteria definitions. Line segments mark the approximate rupture zones of the January 9, 1857 Ft. Tejon and April 18, 1906 San Francisco earthquakes. (From Kelleher, J., Sykes, L., and Oliver, J., *J. Geophys. Res.*, 78, 2578, 1973. Copyrighted by American Geophysical Union. With permission.)

due to increased plate motions in the vicinity of the decoupling earthquake as well as stress wave diffusion from the event (i.e., a stress drop which diffuses in all directions, but especially along the plate boundary).

A progressional trend has also been discovered along the North Anatolian strike-slip fault in central Turkey.[652-655] Dewey[655] reports that the seven largest shocks (M_s = 6.8 to 8.0) occurring along the fault from 1939 through 1967 displayed a linear migration from east to west (Figure 4). These seven earthquakes ruptured the fault for an aggregate distance of approximately 800 km.

Savage[656] believes that the linear pattern is explainable by a kinematic-wave model. In this model, a creep wave is created by an earthquake releasing an avalanche of dislocations. The wave subsequently moves down the fault in the direction of dislocation flow until it strikes a locked section of the fault. The dislocations accumulate there, increasing the local stresses. If there are a sufficient number of dislocations in the wave, the stresses will increase to a level causing slip, and an earthquake, at the locked section. This earthquake gives rise to a new avalanche of dislocations. In the case of the right-lateral North Anatolian fault, the dislocations would migrate to the west.

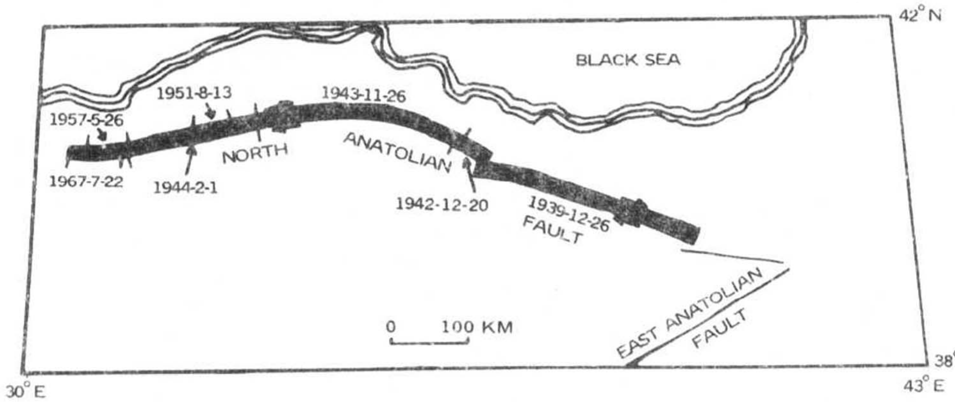

FIGURE 4. Surface faulting on the North Anatolian fault in central Turkey between 1939 and 1967. Note the temporal migration to the west. (From Dewey, J. W., *Earthquake Inf. Bull.*, 6, 13, 1974.)

Nikonov's[657,658] spatial and temporal analysis of $M_s \geq 6.5$ earthquakes along the Gissar-Kokshaal and the Hindu-Kush-Darvaz-Karakul thrust-type fault zones in Soviet Central Asia indicates a progression from their flanks towards the center of the Parmir arcs. The rate of migration varies from 1 to 2 to 3 to 6 km/year. No systematic migrational pattern is discernible for $M < 6.5$ earthquakes. By using the rates and directions of migration, Nikonov has delineated possible sites for large earthquakes before the end of the century.

Nikonov[657] states that the main fault zones in Soviet Central Asia are controlled by a regional compressive system with the dominant principal stress oriented north-south. The lack of a pattern for smaller shocks would be caused "by the stress distribution in limited areas, and therefore . . . not directly governed by regional patterns."

C. Seismic Gaps for Minor and Moderate Earthquake Predictions

The seismic gap technique has been used in California to predict potential earthquakes of moderate and minor magnitudes. Like gaps that may be future sites of large or great earthquakes, these seismic gaps could also serve to locate high-priority sites to search for potential precursors.

Ellsworth and Wesson[659] analyzed a 21-km segment of the central San Andreas fault between Melendy Ranch and Cienega School where four moderate earthquakes (M_L's = 5.0, 4.7, 4.0, and 4.0) occurred between December 1971 and January 1973. It was discovered that (1) slip surfaces (determined by aftershock distributions) for earthquake pairs abuted each other with a slight overlap at both ends of the 21-km segment and (2) a 4-km-long gap existed between the two composite slip zones (Figure 5). Based upon the hypothesis that clusters of small shocks occurring in the vicinity of a main event hypocenter are symptomatic of conditions favorable for the initiations of rupture (small tremors had preceded the above four quakes in the immediate vicinity of their hypocenters), they concluded that a $M_L = 4.5$ earthquake would fill the gap within several months after April 1973 (Figure 5). The magnitude estimate was based upon the length of rupture needed to fill the gap. No single earthquake occurred, but the prediction was a milestone because it represented the first prediction made by scientists of the U.S. Geological Survey (USGS). The strain in the gap was subsequently released by several small-magnitude shocks and perhaps by creep.

Thatcher et al.[660] recently reported on two gaps along the San Jacinto fault (part of the San Andreas system) in southern California (Figure 5 in Volume I, Chapter 2); significant right-lateral slip has not occurred in either gap since 1890. One gap runs

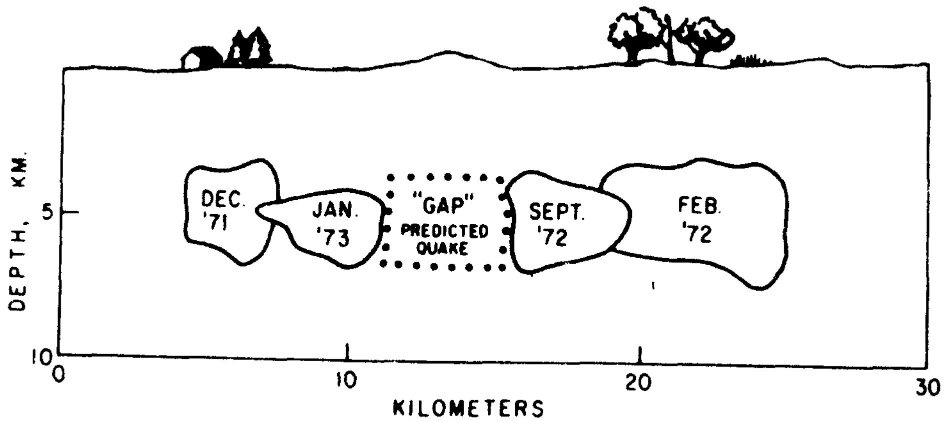

FIGURE 5. A 4-km *seismic gap* identified by Ellsworth and Wesson[655] as a site for a future earthquake of moderate size along the San Andreas fault between Melendy Ranch and Cienega School. (From Wallace, R. E., U.S. Geol. Surv. Circ., 701, 1974, 10.)

from Cajon Pass to the city of Riverside, and the other extends from Coyote Mountain to the community of Anza. Both are (1) approximately 40 km long, (2) void of fault creep, and (3) currently experiencing a sequence of small quakes. These researchers believe that strain has been accumulating in the gaps and that the next moderate shocks will occur there.

D. Pattern Recognition

Historical seismicity data reveal that $M_s \geq 6.5$ earthquakes in Central Asia (36° to 44°N, 60° to 80°E) occur in certain "disjunctive knots" or areas where major faults (active since the Neogene Period) intersect. The knots occupy only a small percentage of the total area.[661]

Gelfand et al.[661] developed a computer program involving a *pattern recognition algorithm* to automatically categorize all knots regarding their potential as future sites for strong earthquakes. Input data in binary form included certain geomorphological characters for each knot (e.g., type of fault junction, number of faults, length of major faults, distance from faults separating mountain countries) and epicenters of strong earthquakes (1885 to 1971). Knots were classified as:

1. Dangerous — where strong earthquakes have occurred
2. Potentially dangerous — where strong shocks are unknown but possible
3. Nondangerous — where strong earthquakes are not possible

The results were most promising. For example, from a historical perspective, the pattern recognition algorithm identified all knots where strong shocks had occurred between 1911 and 1971. Six knots were categorized as potentially dangerous for future (post 1971) strong earthquakes.

The group did not use data sets such as microearthquake histories, various geophysical anomalies, crust and upper mantle structures, and the tectonic history. Although they do not rule out the use of these data for other areas, for the present, at least, they believe they can predict earthquake sites in Central Asia from pre-existing geomorphological descriptors and histories of strong earthquakes.

Press and Briggs[662] applied standard geologic data in binary form to a pattern algorithm to identify earthquake-prone areas in California and Nevada. Experimental attempts at predicting earthquake sites showed positive results, and several predictions have been made for future sites.

II. EARTHQUAKE PRECURSORS

Seismological, geophysical, and geodetic methods are being used to isolate and monitor potential precursors or nonlinear changes in the physical state of the earth prior to the occurrence of earthquakes. This section describes the precursors that offer potential for predictions in a single or multiple seismic region(s).

A. Fault Creep

As was previously discussed, fault creep is currently found along certain segments of the San Andreas and branch faults. Sometimes within a creep zone, near-surface *patches* or gaps become stuck or locked and subsequently experience stick-slip events once accumulating strain exceeds the frictional resistance of the locked patches. Based upon these parameters, Wesson et al.[663] maintain that it may be possible to formulate a prediction framework for a 200-km section of the San Andreas fault between Cholame and Corralitos.

Using a *steady-state seismic slip model,* Bufe et al.[664,665] of the USGS predicted a small earthquake (M_L = 3.2) on a 9-km segment of the Calaveras fault approximately 15 km southeast of San Jose. Basically, the model is comprised of the following elements:

1. Strain is stored in the vicinity of a stuck patch that is tectonically driven at a constant rate within a "field" of constant fault creep.
2. The patch experiences stick-slip when the strain accumulates such that the stress across the patch exceeds the static frictional resistance.
3. The stick-slip interval is the time span required to reestablish the stored strain released in the previous quake; microearthquake activity can delay the interval.

Based upon these model parameters, in October 1976, a $3 \leq M_L \leq 4$ earthquake was forecast at 37°17′ ± 2′N, 121°39′ ± 2′W within a 48-day time window commencing on January 1, 1977. The earthquake occurred on December 8, 1976 — 24 days before the window was to commence. However, the epicenter (37°16.1′N, 121°38.1′W) and magnitude (M_L = 3.2) fell within the predicted ranges.[665]

Another shock of the same magnitude range has been predicted for this patch. If the slip is steady, the quake is forecast for early July 1977, but if there is above average, interim microearthquake activity within the patch, the shock is expected to occur sometime in August 1977. Time-window parameters will be refined as July approaches.[666]

Bufe et al.[665] suggest that because of the elongate shape of the patch on the Calavaras fault, their prediction model may be applicable to major strike-slip faults such as the San Andreas and North Anatolian.

Anomalous creep episodes have preceded several small- to moderate-sized earthquakes along the central section of the San Andreas fault. By using data from the USGS creepmeter network (Figure 21 in Volume I, Chapter 2), Nason and Tocher[667] discovered an increase in creep movement before two earthquakes (M_L = 5.6 and 5.5) in April 1961 near Hollister. The average rate of creep had been 1.2 cm/year prior to 1958; but by 1959 and 1960, the rate increased to 1.9 and 2.0 cm/year, respectively. The two shocks occurred on April 9, 1961. In addition, a 3-mm creep event preceded, by approximately 20 hr, the Melendy Ranch M_L = 4.6 earthquake (near San Juan Bautista) of September 4, 1972.[668]