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EARTHQUAKES AND THE URBAN ENVIRONMENT

Volume II

G. Lennis Berlin

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Earthquakes and the Urban Environment

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Author

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

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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.

DEDICATION

To Judy, Jodi, Mom, and Dad

TABLE OF CONTENTS

EARTHQUAKES AND THE URBAN ENVIRONMENT
G. Lennis Berlin

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-

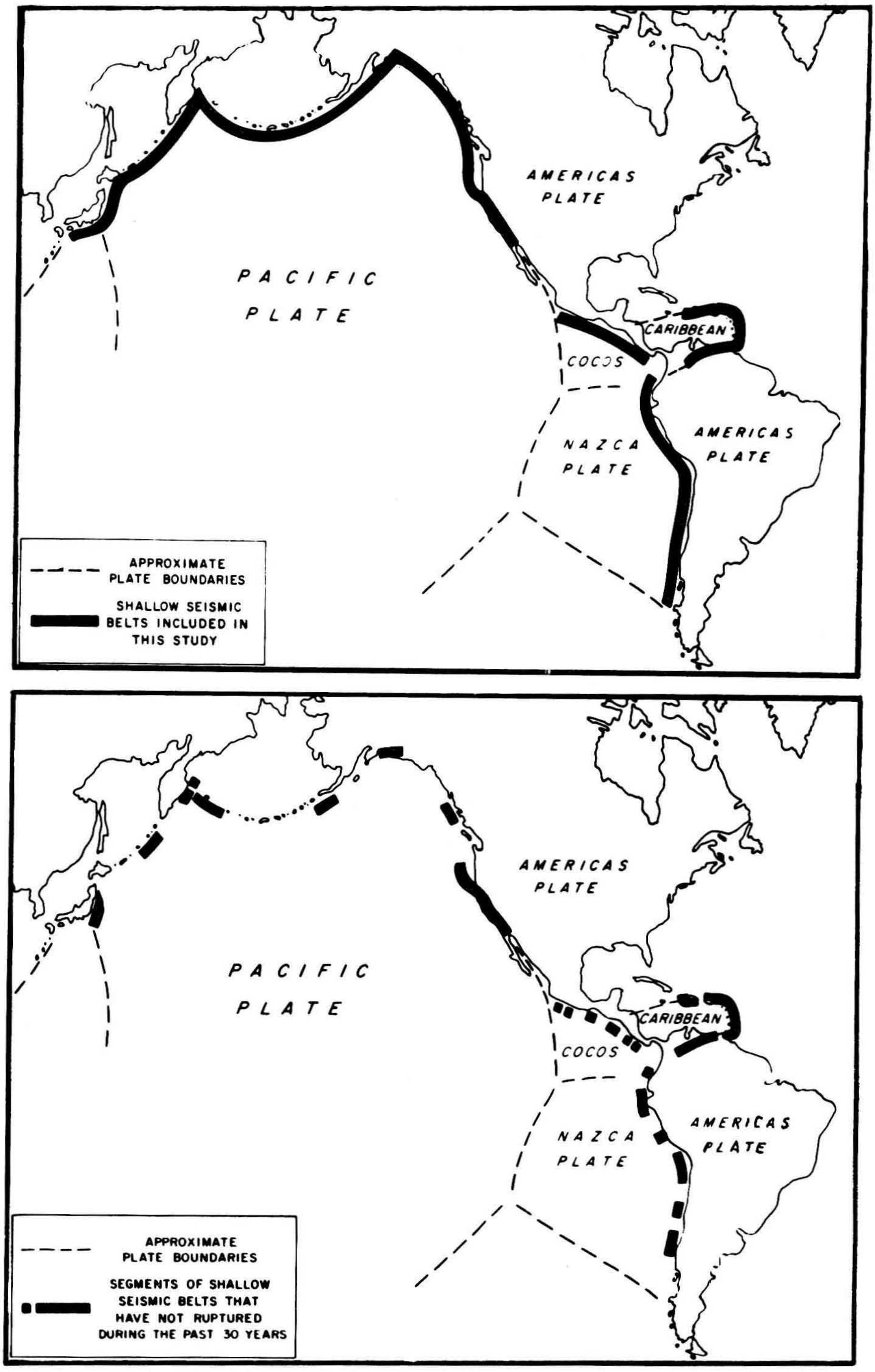

FIGURE 1. Major seismic belts examined (top) and seismic segments that have not ruptured during the past 30 years. (From Kelleher, J., Sykes, L., and Oliver, J., *J. Geophys. Res.*, 78, 2551, 1973. Copyrighted by American Geophysical Union. With permission.)

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

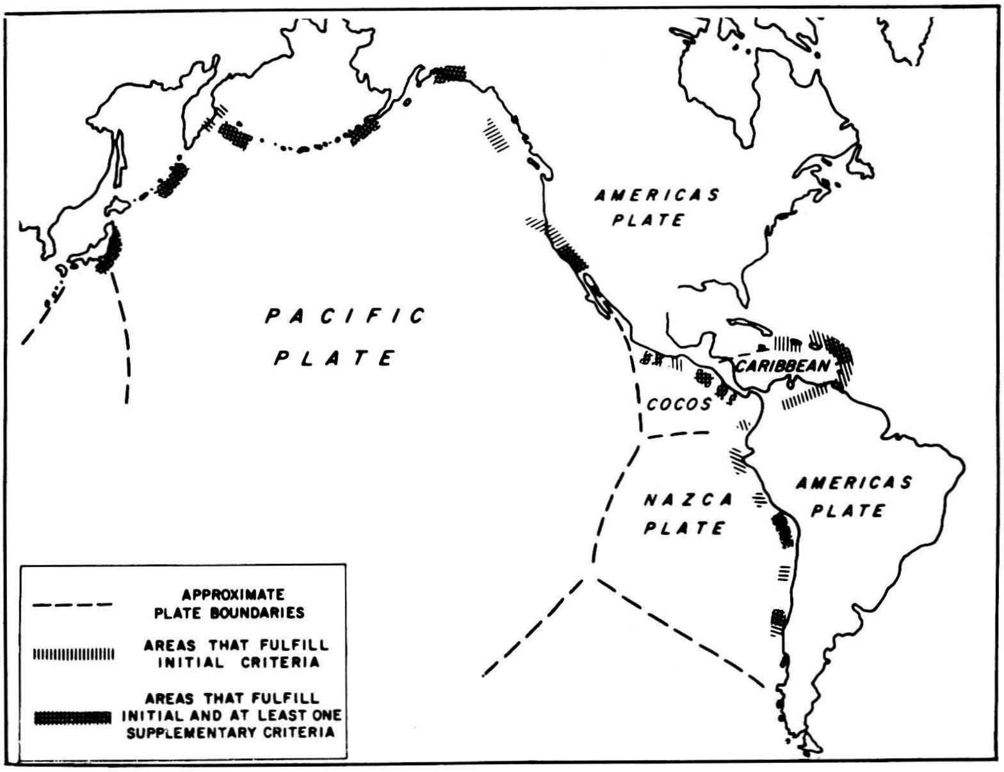

FIGURE 2. Likely locations for large earthquakes along segments of Pacific and Caribbean plate boundaries that fulfill initial or initial and supplementary criteria. See text for criteria definitions. (From Kelleher, J., Sykes, L., and Oliver, J., *J. Geophys. Res.*, 78, 2548, 1973. Copyrighted by American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

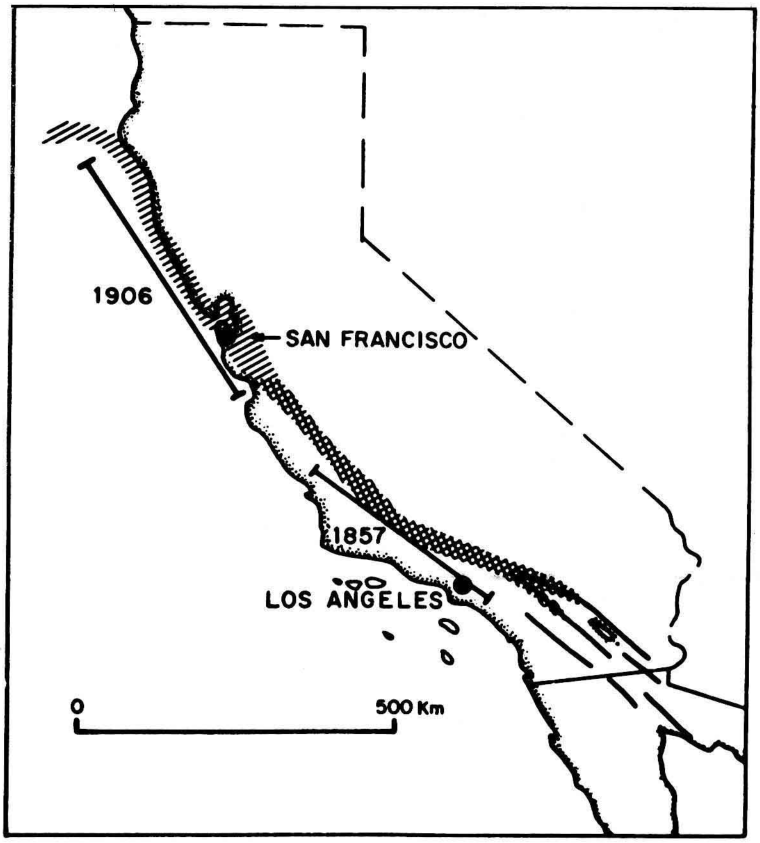

FIGURE 3. Segments of the San Andreas fault system fulfilling initial or initial and supplemental criteria. See text for criteria definitions. Line segments mark the approximate rupture zones of the January 9, 1857 Ft. Tejon and April 18, 1906 San Francisco earthquakes. (From Kelleher, J., Sykes, L., 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.

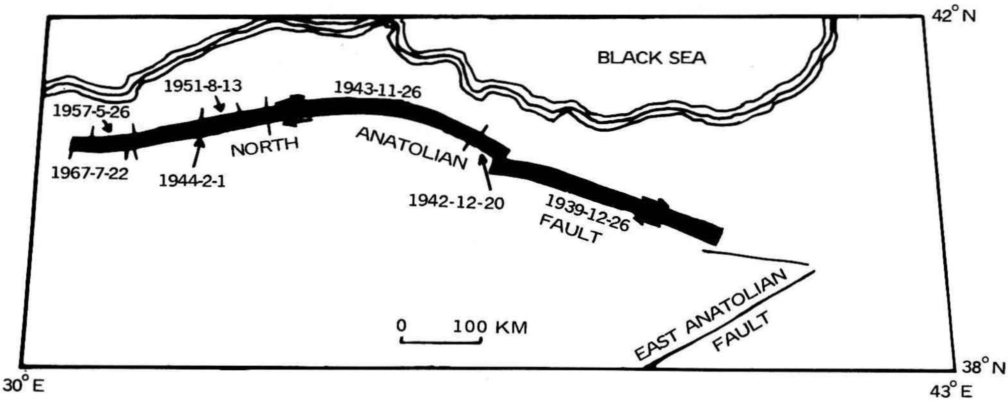

FIGURE 4. Surface faulting on the North Anatolian fault in central Turkey between 1939 and 1967. Note the temporal migration to the west. (From Dewey, J. W., *Earthquake Inf. Bull.*, 6, 13, 1974.)

Nikonov's[657,658] spatial and temporal analysis of $M_S \geqslant 6.5$ 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