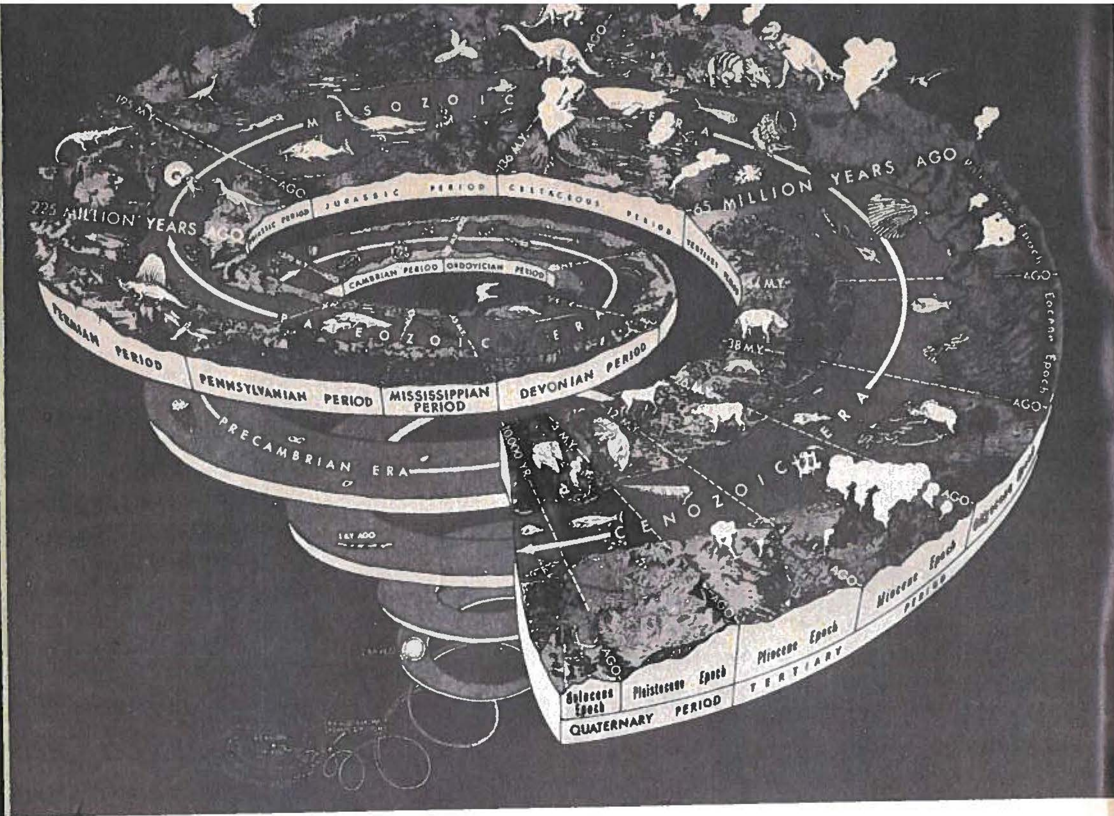

QUATERNARY GEOLOGY—
AN ESSENTIAL CLUE TO EVALUATING SEISMICITY

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The geologic record, particularly that of the late Quaternary period[1], is a far more valuable tool in estimating seismicity and associated seismic hazard than has generally been recognized. This is simply because, by looking into the recent geologic past, the geologist is able to overcome many of the statistical inadequacies of the relatively short instrumental and historic records. These shortcomings are best illustrated in those parts of the world with the longest historic records of earthquakes—2000 years for Japan and the Middle East and 3000 years for China—where surprising variations in both the rates of recurrence and places of recurrence are evident. These long records show that earthquakes are by no means uniform in space and time, at least over intervals of only 1000 or 2000 years.

[1] The Quaternary period represents the most recent 2 to 3 million years of geologic history. It is in turn divided into the Holocene epoch (the past 11 000 years) and the Pleistocene epoch (the preceding period of intermittent worldwide glaciation).

A startling example has been pointed out in China by Shi-yun Mei. She plotted the strain release from 466 B.C. to the present for northern China (fig. 1), an area four times larger than that of California and Nevada combined. The seismic activity during the first and last parts of the period is relatively high, but during an 800-year period from A.D. 200 to 1000, large shocks are almost lacking. During this time, therefore, one might have estimated the regional seismicity to be insignificant. But the overall seismic hazard based on the longer historic record in this region obviously cannot be considered low; the historic record includes at least two shocks near magnitude 8½, one of which (in 1556) was the most disastrous earthquake in history, causing more than 820 000 deaths. The other great event, in 1668, occurred in a part of the region which neither before nor since has been characterized by high activity. Significantly, however, both of these disastrous events occurred in areas of major Quaternary faulting, which, had modern techniques been available to identify the areas as hazardous, could have been recognized by geologists before these events occurred.

This statistical inadequacy of the historic record means that we must be exceedingly cautious in using the historic record alone in estimating future seismicity, particularly in areas, such as California, that have very short histories. By looking instead at the geologic record, especially that of the Holocene epoch, seismologists are trying to show how this record can be used to supplement or even supersede the historic record in the evaluation of seismicity.

California

The seismicity of California is related to movement along the plate boundary between the North American and Pacific plates. It is dominated by the San Andreas fault system. The following five generalizations can be applied to California seismotectonics:

1. Virtually all large earthquakes (exceeding magnitude 6.0) have occurred because of ruptures on faults that *had* been recognized, *could* have been recognized, or *should* have been recognized by field geologists prior to the events.
2. All of these faults have been characterized by a history of earlier Quaternary (and possibly Holocene) displacements.
3. All earthquakes are shallow, not exceeding about 20 kilometers in depth. Most of those larger than magnitude 6.0 have been accompanied by surface faulting, as have many of lesser magnitudes.
4. The larger earthquakes have generally occurred on the longer faults.
5. Generally, only a small segment of the entire length of a fault zone has broken during any single earthquake, although there are some conspicuous exceptions.

The one-to-one relationship between active faults and major earthquakes in California is extremely clear. If one was faced with the task of making a seismic zoning map of the State based solely on geologic data or solely on geophysical and historical data, a more realistic map could be made with the geologic data. Of course, combining the two approaches would give a still better map.

An immediate reaction to a map showing Quaternary faulting in southern California might be that so much of the area is characterized by Quaternary faulting that the long-term seismic hazard must be considered relatively high throughout most of the region. This is exactly the conclusion that should be drawn, regardless of what very recent seismic history indicates.

A comparison of such a map with the actual distribution of large earthquakes since 1912 is instructive (fig. 2). With few exceptions, large

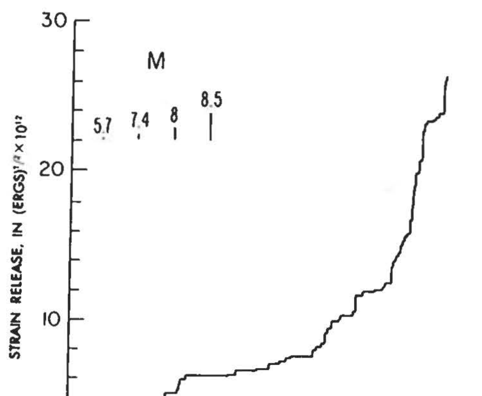

Figure 1.—Cumulative strain release from 466 B.C. to the present in northern China. Bars represent the strain release for earthquakes of various magnitudes.

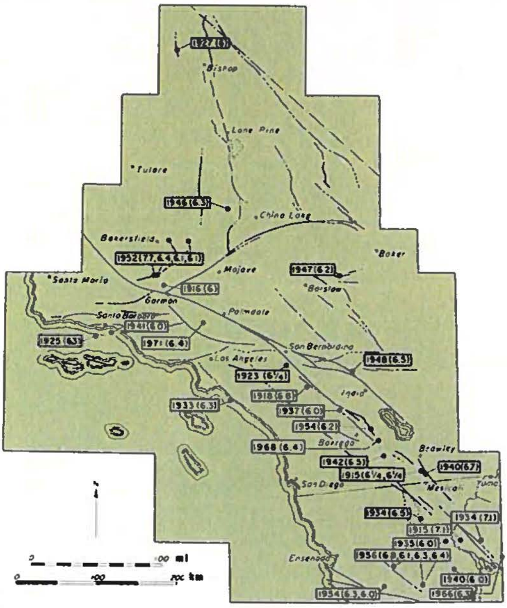

Figure 2.—Earthquakes of magnitude 6.0 and greater (in parentheses) in southern California, 1912–74. Heavy lines are the principal active faults, dashed where uncertain.

earthquakes have indeed occurred in areas of Quaternary faulting, and even the smaller earthquakes (not shown in figure 2) have generally followed the same trends. On the other hand, there are significant areas of Quaternary (and Holocene) faulting that have not experienced major earthquakes during this particular 62-year period. These areas should also be considered hazardous. Especially noteworthy in terms of inactivity are the Garlock fault and the Death Valley region. In addition, the central segment of the San Andreas fault, which last broke in 1857, has been almost completely seismically inert but is perhaps the prime candidate for a major earthquake in the near future. In a sense, this is nothing more than a restatement of the phenomenon of the temporal "seismic gap," which has long been recognized in California and elsewhere.

What is clearly needed to refine our seismic probability map is a better understanding of the Holocene movements on the various faults. Which ones have moved most recently and which ones have moved most often? Trenches excavated by geologists across active faults in the United States are increasingly revealing the answers to these questions. For example, Malcolm Clark of the U.S. Geological Survey demonstrated that the Coyote Creek fault in southeastern California (locus of the 1968 Borrego Mountain earthquake) has broken on the average of once in every 200 years for the past 3000 years. Using the spectacular series of trenches across the San Andreas fault northeast of Los Angeles, Kerry Sieh, California Institute of Technology, has shown that, prior to the great 1857 earthquake, this segment of the fault also broke in about A.D. 575, 665, 860, 965, 1190, 1245, 1470, and 1745. This is exactly the kind of information we critically need if we are to determine the long-term level of hazard and, therefore, to draw up realistic building codes and land use policies.

The claim has sometimes been made that the seismotectonic relationships in California are so unique that they have little relevance to the determination of seismicity and seismic hazard in most other parts of the world. Let us examine a number of foreign areas to judge the validity of this claim.

Turkey

Turkey has been the locus of numerous disastrous earthquakes in recent years, and a close geologic examination reveals many seismotectonic similarities to California. In particular, the North Anatolian fault (fig. 3) is a close analogy to California's San Andreas fault, except that it has generated a remarkable series of large and disastrous earthquakes within the last 38 years,

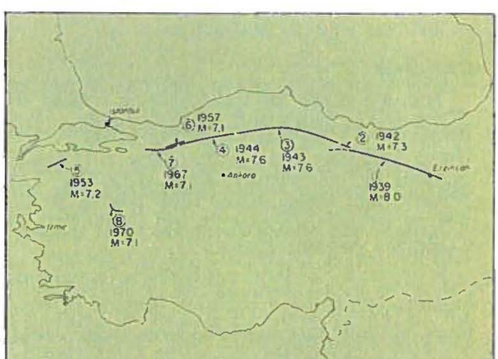

Figure 3.—Faulting (heavy lines; dashed where uncertain) associated with eight earthquakes of magnitude 7.0 and greater in Turkey since 1939. M indicates magnitude.

commencing with the great Erzincan shock of 1939. Historic records suggest that similar large events may not have occurred for several hundred years prior to 1939, but could the fault have been recognized by geologists as a dangerous feature in 1938? The answer is an unequivocal "yes"; physiographic features of Holocene faulting—scarps, sag ponds, offset streams, rift topography—are so similar to those in the Western United States that a California geologist feels strangely "at home" on the North Anatolian fault (fig. 4). N. N. Ambraseys of the University of London has pointed out, on the basis of thorough historical researches, that this fault and many others in the Middle East have had long-term episodic variations in activity. Thus, geologic studies here are particularly important in identifying active faults and in evaluating seismic risk.

Japan

Most of the greatest Japanese earthquakes have been centered offshore, and large parts of Japan are adjacent to active offshore plate boundaries capable of generating major shocks fairly frequently. But numerous disastrous earthquakes have also occurred within Japan proper, and the question is: "Do these earthquakes follow any patterns that might be decipherable from geologic studies alone?" The answer again is clearly "yes," but in a somewhat qualified way. Most large, damaging earthquakes originating on land have been associated with surface displacements on faults with an earlier history of Quaternary activity, so they could have been recognized by geologists. On the

Figure 4.—View west along rift valley of North Anatolian fault from a point about 1 km west of Gerede. Note sag pond in distance. Remarkably similar physiography characterizes California's San Andreas fault.

Figure 5.—Aerial view of scarps of Philippine fault zone (arrows) east from near Bitulok, Luzon. Photograph taken with the help of W. R. Merrill.

other hand, this generalization has limited value in terms of seismic zoning, because there are so many faults throughout Japan that have had Quaternary displacements. Furthermore, some of the largest earthquakes have occurred on seemingly innocuous faults, and some of the most spectacular and throughgoing faults have had no significant earthquakes along them during the entire 2000-year historic record. Clearly the 2000-year record is inadequate in itself for predicting seismic hazard, but the unhappy conclusion from the study of Quaternary geology is that large earthquakes can and will occur over large parts of the country. Building codes and land use planning must take into account this unfortunate state of affairs, as is being increasingly recognized in Japan.

Philippines

To demonstrate that physiographic features of late Quaternary fault displacement are identifiable even in areas of tropical vegetation, we can turn to the Philippines. On the basis of field work and a study of aerial photographs, I argued some 15 years ago that the Philippine fault was a major active regional structure of predominantly left-handed displacement (fig. 5). It was, however, somewhat disconcerting that no major earthquakes were known to have occurred along the fault during the historic record. Thus, a magnitude 7.0 earthquake along the projected trace of the fault in 1973 in the Ragay Gulf was of particular interest (fig. 6). Subsequent field investigations showed that the Philippine fault had indeed broken entirely across the Tayabas Isthmus of Luzon; the maximum left-lateral offset was 3.2 meters at the point where the fault offset the beach line on the south coast (fig. 7). Two points should be emphasized: The fault

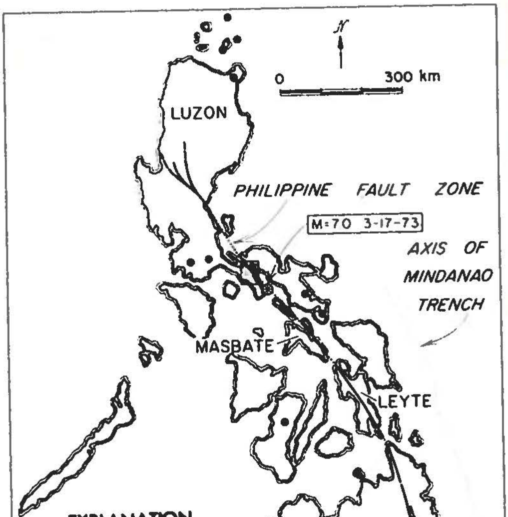

Figure 6.—Trace of Philippine fault zone and epicenter of 1973 Ragay Gulf earthquake. M indicates magnitude.

broke essentially along the exact line earlier identified from aerial photographs, despite the jungle environment, and the surface displacement probably would have gone unnoticed, as undoubtedly have many in the past, except that a railroad track had been deformed, attracting the attention of authorities.

China

China is particularly intriguing because of its many great, disastrous earthquakes. Earthquake-related deformation appears to be taking place well within a single tectonic plate, or at least along miniplate boundaries that are not yet understood in the overall context of plate tectonics. But the seismotectonic relationships are remarkably similar to those of California. One of the disastrous earthquakes of Chinese history occurred in 1303 near Lin-fen, farther northeast in the Shansi graben area of northern China than the great 1556 earthquake mentioned earlier. A glance at the Landsat image (fig. 8) shows that this region could have been recognized as earthquake prone on the basis of geology alone; this is true of most of the other active earthquake areas of China. In addition to the spectacular normal faults of the Shansi graben, numerous great linear faults of probable strike-slip origin are visible on satellite images of western China. One of these along the axis of the Altyn Tagh Range (fig. 9) may be the longest continental strike-slip fault in the world, with active strands extending some 1200 km. No great earthquakes are known along this and parallel structures, but the exceedingly sparse population probably explains this.

Thrust faults

Thus far, little has been said about thrust faults, which have caused many of the world's most disastrous earthquakes. They represent a difficult problem for the geologist because thrust faults are difficult to map; determining the degree of activity may be even more difficult. The problem is that the traces of active thrust faults tend to be very irregular, and they often lie within areas of high relief because of the very nature of their movements. Furthermore, they are often concealed by massive landslides, an indirect result of the thrust displacements (fig. 10). Perhaps no part of the world better dramatizes the problem of thrust faults than does the Himalayan front, which has been the locus of four earthquakes exceeding magnitude 8.3 in the past 75 years. But we know so little of the Quaternary history of the range front that we cannot say whether these four areas or the intervening areas that have not broken during the short historic record are currently the most dangerous.

The San Fernando earthquake of 1971 in southern California also points out some problems in understanding active thrust faults. On the day after the earthquake, much of the fault was already difficult to recognize in the field because of slumping and landsliding which tended to conceal the evidence of surface displacement. Particularly in areas such as California where strike-slip and normal faults are more obvious to the geologist, we have probably been negligent in not giving active thrust faults the attention that they deserve in evaluating seismicity.

Figure 7.—Left-lateral offset of beach line (3.2 m) at time of 1973 Ragay Gulf earthquake. Offset was confirmed by numerous other displaced features nearby, such as rows of coconut trees. Break followed low preexisting scarp.

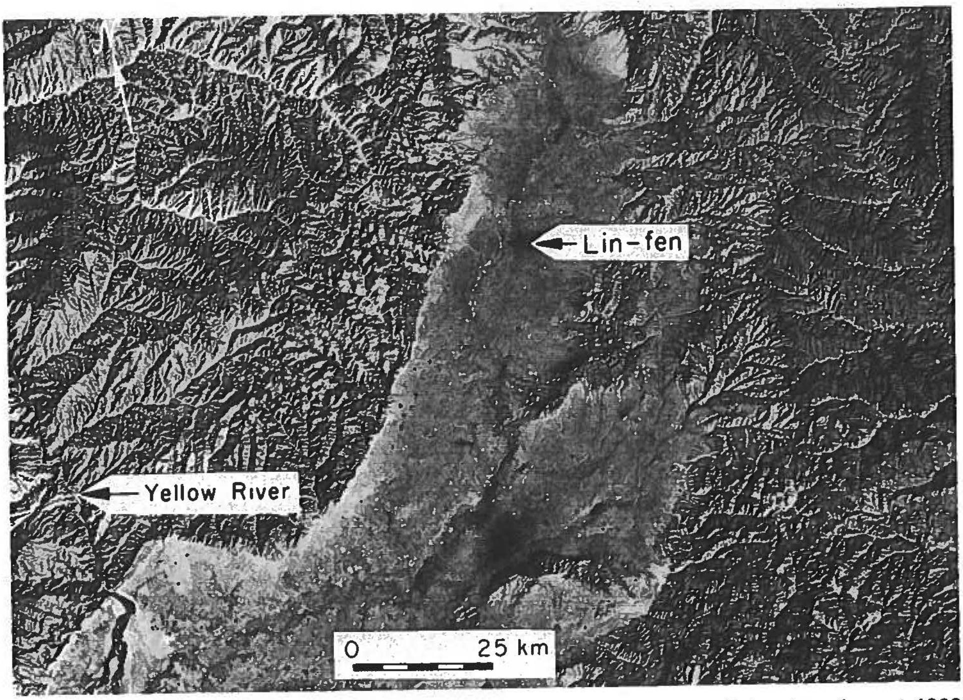

Figure 8.—Landsat image of Lin-fen region, Shansi Province, China. Epicenter of great 1303 earthquake is thought to have been just north of Lin-fen. Note numerous fault scarps. Intricately dissected area is underlain mainly by Pleistocene loess.

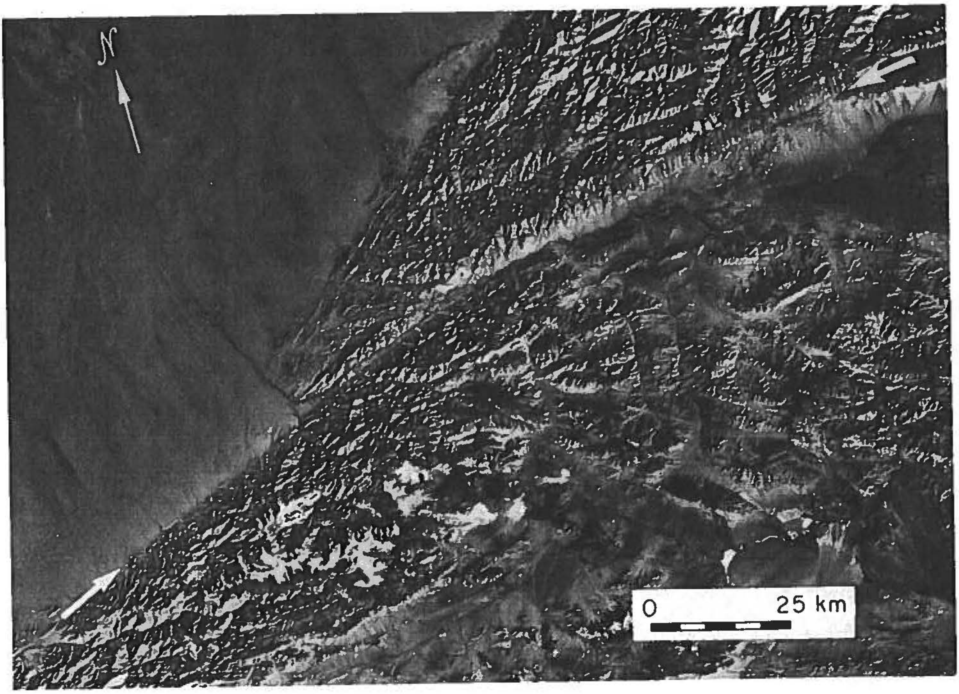

Figure 9.—Landsat image of active fault (arrows) along axis of Altyn Tagh Range, China. Linearity of fault for almost 1200 km suggests strike-slip origin.

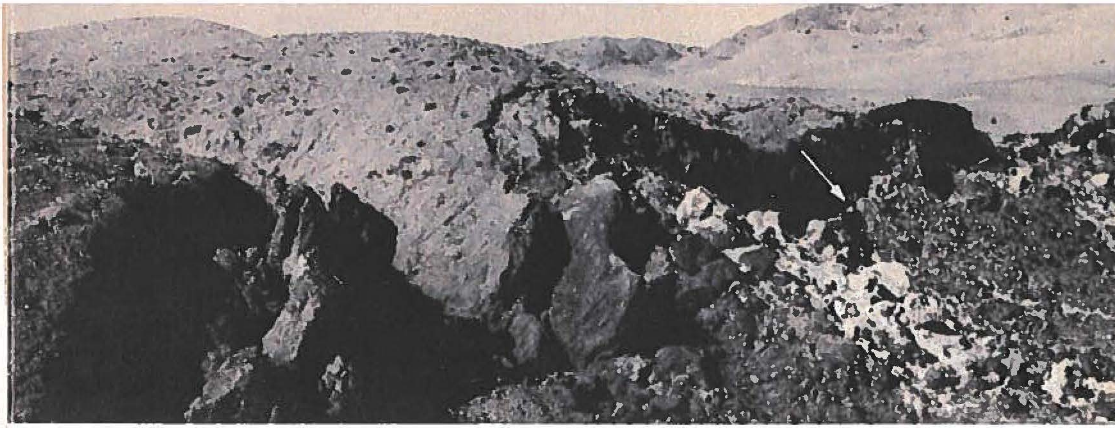

Figure 10.—Slumping along scarp of thrust fault formed in association with 1957 Gobi-Altai earthquake in Mongolia (magnitude, 8.3). Vertical movement here is 5–6 m. Note man for scale (arrow). Photograph by N. Florensov.

Earthquakes in areas of no faults?

Although I am convinced that surface rupture along preexisting Quaternary faults has been far more widespread during major earthquakes than has generally been appreciated in the past, the fact remains that a few large shocks have occurred in areas where even the most careful geologic searches have revealed no surface faults. An example is the area of the large 1886 earthquake near Charleston, S.C. How could a geologist have recognized this area as being one of seismic hazard before 1886? The answer is not at all obvious, as is demonstrated by the prolonged debates on nuclear-plant siting in the region. But it is clear that the Charleston earthquake took place on *some* fault, even if it was buried at a depth of several kilometers. Perhaps we must use more sophisticated geophysical tools to identify such concealed structures. However rare they may be, such earthquakes remain a challenging and critically important problem.

Summary

What lessons can be drawn from this brief geological look at a number of seismic areas around the world?

1. Surface faulting during large shallow earthquakes has been more common and universal than is generally appreciated in many parts of the world.

2. Because of widespread faulting during large shallow earthquakes, perhaps the most significant geologic criterion for identifying areas of high seismicity is the late Quaternary record of similar events in the recent geologic past. Most pertinent of all is the Holocene record.

3. Those parts of the world that have the longest historic records of earthquakes are the areas that should give us the greatest pause in extrapolating that history into the future. It is clear that even a 2000- or 3000-year history is not a sufficiently valid statistical sample to use as a firm guide to overall activity. In areas such as California and Nevada, where our historic record barely exceeds 1 century, we must be exceedingly cautious in extrapolating from this very short history. The problem gets even more difficult as we get farther and farther away from active plate boundaries and into areas of low, long-term seismicity, for example, New Madrid, Mo., or Charleston, S.C.

4. In view of the difficulties of interpreting the historic record and the large variation of geological environments in which major earthquakes have occurred, geologists and geophysicists must continue to be exceedingly conservative in their estimates of the likelihood of major damaging earthquakes in specific areas. We have been surprised too often in the past, and we cannot afford to be surprised too many times in the future. Every year, more and more is at stake in terms of the effects on humans of major earthquakes.

5. The most important single contribution to gaining a better understanding of long-term seismicity, which is critical to the siting and design of safe structures and to the establishment of realistic building codes, is to learn more—region by region—of the late Quaternary history of deformation.

Further reading

Allen, C. R., 1975, Geologic criteria for evaluating seismicity: Geological Society of America Bulletin, v. 86, p. 1041–1057.

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