and 1812. Another intraplate earthquake, in 1886, caused moderate damage to Charleston, SC.

In addition to the tectonic types of earthquakes described above, some earthquakes are directly associated with volcanic activity. These volcanic earthquakes result from the motion of undergound magma that leads to volcanic eruptions.

Sequences. Earthquakes often occur in well-defined sequences in time. Tectonic earthquakes are often preceded, by a few days to weeks, by several smaller shocks (foreshocks), and are nearly always followed by large numbers of aftershocks. Foreshocks and aftershocks are usually much smaller than the main shock. Volcanic earthquakes often occur in flurries of activity, with no discernible main shock. This type of sequence is called a swarm.

Size. Earthquakes range enormously in size, from tremors in which slippage of a few tenths of an inch occurs on a few feet of fault, to the greatest events, which may involve a rupture many hundreds of miles long, with tens of feet of slip. Accelerations as high as 1 *g* (acceleration due to gravity) can occur during an earthquake motion. The velocity at which the two sides of the fault move during an earthquake is only 1–10 mph, but the rupture front spreads along the fault at a velocity of nearly 5000 mph. The earthquake's primary damage is due to the generated seismic waves, or sound waves which travel through the Earth, excited by the rapid movement of the earthquake. The energy radiated as seismic waves during a large earthquake can be as great as 10^{12} cal, ($10^{12} \times 4.19$ J) and the power emitted during the few hundred seconds of movement as great as a billion megawatts.

The size of an earthquake is in terms of a scale of magnitude based on the amount of seismic waves generated. Magnitude 2.0 is about the smallest tremor that can be felt. Most destructive earthquakes are greater than magnitude 6; the largest shock known measured 8.9. The scale is logarithmic, so that a magnitude 7 shock is about 30 times more energetic than one of magnitude 6, and 30×30, or 900 times, more energetic than one of magnitude 5. Because of this great increase in size with magnitude, only the largest events (greater than magnitude 8) significantly contribute to plate movements. The smaller events occur much more often but are almost incidental to the process.

The intensity of an earthquake is a measure of the severity of shaking and its attendant damage at a point on the surface of the Earth. The same earthquake may therefore have different intensities at different places. The intensity usually decreases away from the epicenter (the point on the surface directly above the onset of the earthquake), but its value depends on many factors in addition to earthquake magnitude. Intensity is usually higher in areas with thick alluvial cover or landfill than in areas of shallow soil or bare rock. Poor building construction leads to high intensity ratings because the damage to structures is high. Intensity is therefore more a measure of the earthquake's effect on humans than an innate property of the earthquake.

Effects. Many different effects are produced by earthquake shaking. Although the fault motion that produced the earthquake is sometimes observed at the surface, often other earth movements, such as landslides, are triggered by earthquakes. On rare occasions the ground has been observed to undulate in a wavelike manner, and cracks and fissures often form in soil. The flow of springs and rivers may be altered, and the compression of aquifers sometimes causes water to spout from the ground in fountains. Undersea earthquakes often generate very-long-wavelength water waves, which are sometimes called tidal waves but are more properly called seismic sea waves, or tsunami. These waves, almost imperceptible in the open ocean, increase in height as they approach a coast and often inflict great damage to coastal cities and ports.

[CHRISTOPHER H. SCHOLZ]

PREDICTION

Earthquake prediction involves research aimed at predicting the time, location, and size of earthquakes in order to reduce damage and especially to minimize injuries and loss of life. A prediction, to be socially relevant, must also include an estimate of how likely it is to be fulfilled.

The first successful prediction of a major earthquake that led to major lifesaving action was in 1970 in the region near Haicheng in northeastern China, a region designated as deserving special seismological attention. In June 1974, it was concluded that a magnitude 5–6 earthquake might occur within 1–2 years. On January 13, 1975, the prediction was narrowed to the first 6 months of 1975. On February 1, foreshocks began, and at 0:30 A.M. on February 4, an earthquake was predicted for that day. By 2 P.M. evacuation of dangerous structures and emergency preparations were underway. At 7:36 P.M. a magnitude 7.3 earthquake occurred, and it is estimated that the casualties would have been over 100,000 had it not been for the successful prediction.

At least a dozen smaller earthquakes in the Soviet Union, Japan, and the United States were predicted in the 1970s, but in most cases the predictions were not specific enough to lead to major social action. Furthermore, there have been a number of prediction failures, such as the magnitude 8.0 earthquake near Tangshan in China on July 27, 1976, where over 600,000 people were killed, as well as many false alarms. Earthquake prediction is an emerging science with some successes, some failures, and some total surprises. It may be one or a few decades before proved systems are available, but serious predictions of varying reliability could be issued at any time.

Earthquake-prone regions. Earthquakes tend to recur in the same general area over a long period of time. Thus, studies of historic seismicity provide estimates of where earthquakes are most likely to occur and of the magnitude of the largest earthquake in a given region. From such studies, for example, a prediction can be made that, on the average, an earthquake of magnitude greater than 6 can be expected each year in southern California and one of magnitude greater than 8 every hundred years. Such analyses are useful but must be treated with care, especially when data from only a few decades or a century are available. The Chinese maintain a remarkable historic record of seismicity for over 3000 years, which shows that regions may be very active and then quite inactive for hundreds of years. See SEISMOLOGY.

Seismic activity appears to occur in a systematic way along the boundaries of the large plates that move along the surface of the Earth. After an earthquake, thousands of smaller aftershocks occur along the same section of the fault that slipped in the main shock and thus show what part of the fault moved. A compilation of such aftershock zones (Fig. 4) shows gaps where no large earthquakes have occurred during the period studied. The largest earthquakes in the next few decades are most likely to occur in such gaps. See PLATE TECTONICS.

Earthquake precursors. Most research in prediction is aimed at measuring a wide variety of physical phenomena that may change prior to an earthquake. Measurements of earthquake precursors can be grouped into five categories: stress changes, strain changes, effects of strain changes, changes in seismic measurements, and other changes.

Stress changes. Measurements of stress levels or changes could potentially be among the most important earthquake precursors. A number of techniques are being tested, ranging from building gages for installation in boreholes, to measuring the fluid pressure required to fracture the walls of boreholes at depth. One technique has been developed to infer stress from the properties of seismic waves generated by moderate to large earthquakes in a region of interest. None of these methods, however, has yet proved fully satisfactory.

Strain changes. Measurements of strain changes, on the other hand, have been widespread. Uplift and subsidence of areas of thousands of square kilometers by amounts of several centimeters have been detected by using standard precise leveling techniques. A major uplift has been detected in southern California near a section of the San Andreas Fault that last slipped in a major earthquake in 1857. Research has been stepped up in this area to try to determine when the next earthquake will occur. Such uplifts can be related to mean sea level by using tide gages, and in some instances apparent local changes in sea level have been observed prior to earthquakes. Vertical motion is also detectable by using gravimeters sensitive to microgal (1 microgal = an acceleration of 10^{-3} cm $\cdot$ s^{-2}) changes in the force of gravity. Precise trilateration and triangulation techniques allow mapping of horizontal strain changes over survey lines of kilometers and tens of kilometers long. New methods being developed using laser ranging to satellites or to the Moon or using radio signals from distant quasars offer the possibility of measuring strain changes over distances of hundreds to thousands of kilometers. These techniques, particularly when refined to the ultimately expected precision of a few centimeters,

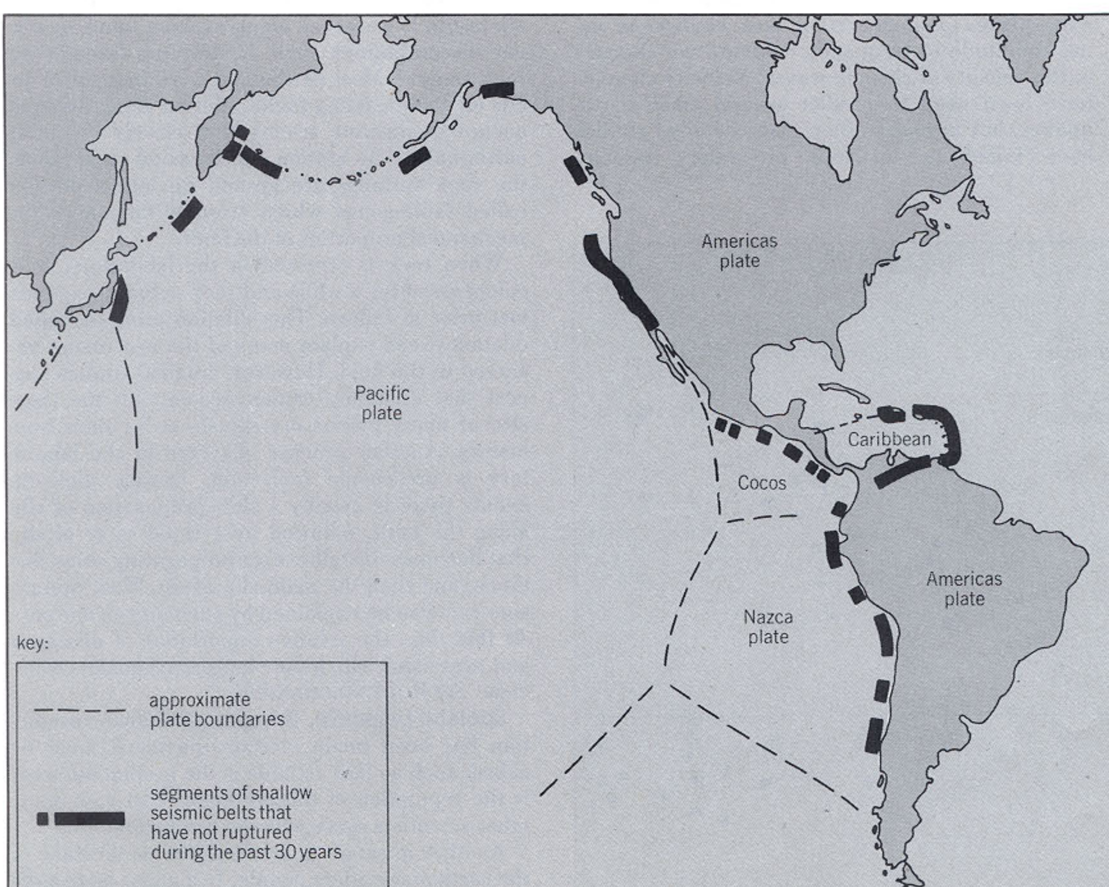

Fig. 4. Major seismic gaps, western Pacific. (*From J. Kelleher et al., J. Geophys. Res., 78:2547–2585, copyright 1973 by the American Geophysical Union*)

offer a unique chance to measure plate motion and strain within plates. See LUNAR LASER RANGING.

Strain can also be measured over distances of meters to a kilometer by using strain meters, small trilateration networks, and tiltmeters. Over 70 detectors that measure small tilts of the ground surface have been installed in California. Strain in fault zones and aseismic fault slip or creep are measured with creep meters and alignment arrays.

Strain associated with the tidal pull of the Moon or of other planets can be measured using microgal gravimeters and strain meters. Many earthquake predictions issued by persons not in the mainstream of scientific research are based on alignment of planets. While it is conceivable that such small forces could trigger earthquakes, there is no clear correlation between these forces and damaging earthquakes.

Effects of strain changes. Many precursory changes have been observed to be the result of strain in the region of impending earthquakes. These range through changes in electrical conductivity and generation of electrical potentials in the ground, changes in the magnetic field and atmospheric electric fields, changes in the quality or level of groundwater, and changes in the emission of various gases in well water or in soil. One of the most remarkable changes reported so far is that of radon content in water wells.

Seismic measurement changes. Changes in seismic measurements range through changes in the distribution of earthquakes in location, time, or depth, changes in the ratio of numbers of large earthquakes to small earthquakes, changes in signal amplitude or frequency content, and changes in the velocity of seismic waves. Velocity changes have been used to predict several small earthquakes, but in many other cases detailed studies have failed to measure precursory velocity changes. In some cases foreshocks have been observed to increase and then decrease prior to large earthquakes, but many earthquakes are not preceded by foreshocks.

Other changes. The fifth type of precursor is a class that does not fit readily into the above four categories. For example, over the centuries hundreds of reports have been made of unusual behavior of animals prior to earthquakes. Although no one report seems credible, the sum of the reports is compelling. There is also no clear evidence as to what the animals are detecting. More detailed research on this subject is required.

T. Rikitaki, among others, showed that the time between the onset of a precursory anomaly and the ensuing earthquake is, in most cases, related systematically to the magnitude of the earthquake (Fig. 6). In the remaining cases the precursors occurred just prior to the event irrespective of magnitude. There is a relative lack of short-term precursors, which is a prime reason why observations of abnormal animal behavior are being considered more seriously now.

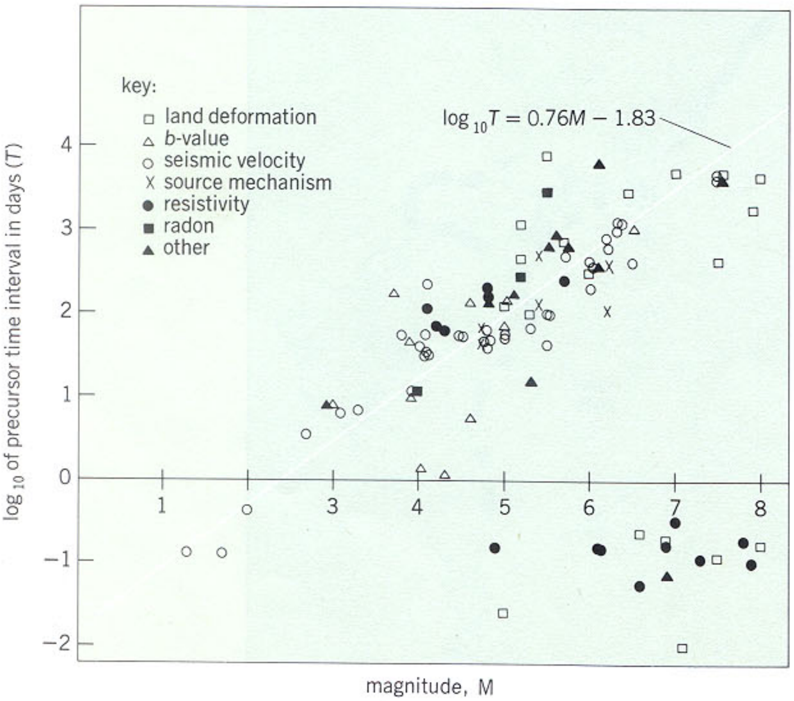

Fig. 5. Logarithmic plot of precursor time in days versus magnitude of ensuing earthquake. (*From T. Rikitaki, Earthquake Prediction, Elsevier, 1975*)

Earthquake source models. Physical processes occurring before and during earthquakes are being studied in the laboratory to aid in reliable interpretation of field observations of precursors and to aid in the design of field experiments to observe precursors. Intact rocks fracture when subjected to a wide variety of stresses, temperatures, and strain rates, releasing seismic energy in many small events prior to fracture as well as in the main fracturing event. Another seismic process, called stick-slip, is observed along existing faults or planar discontinuities such as saw cuts through the rock sample. Most earthquakes are thought to occur on such existing faults. Motion along the fault occurs in discrete events that closely resemble earthquakes. As motion continues on such faults, the rock surfaces are ground up into a powder called fault gouge which strongly influences the mechanical properties of the fault.

When rock is stressed in the laboratory, it is compressed for a while and then actually expands just prior to failure. This dilation process, called dilatancy, can explain many of the precursors observed in the field. However, detailed studies suggest that dilatancy cannot account for the large size of many precursory signals or for their time history. Another process observed in the laboratory is preseismic fault slip. During stick-slip events there is usually a slow propagation of slip along the fault, followed by a rapid stage of slip that becomes unstable after propagating some distance, and then the main slip event. Most precursors can also be explained by such preseismic slip. At this time the relative importance of dilatancy and preseismic slip before large earthquakes is unclear. See ROCK MECHANICS.

Societal response. When an earthquake prediction has been made, certain questions must be asked, such as how reliable is the prediction, what is the reputation of the predictor, and how many other scientists agree with the prediction.

Another question is how will the occurrence of the earthquake affect people. In a major metropolitan area such as Los Angeles or San Francisco, a very large earthquake is likely to kill 3,000 people if it occurs late at night and perhaps 12,000 people if it occurs in midafternoon. The specific hazards in an area can be determined by asking the local disaster office, city or county planning office, or a structural or geologic engineer. It is important to find out whether one lives or works near major faults or areas of potential landsliding and whether the buildings and dams in the area are designed according to modern earthquake codes. An appropriate response to a prediction in the United States rarely involves evacuation. It merely involves avoiding hazardous regions and structures, storing food, water, and medical supplies for emergency use, making contingency plans, and being sure there are no heavy objects around to fall. In many other areas such as China and Latin America, since most buildings either are not designed according to modern earthquake code or are made of unreenforced masonry, evacuation may be wise.

Conclusion. Some predictions have been issued as well as some false alarms, and it may be a decade or many decades before a proved prediction system exists. Unlike many scientific methods, earthquake prediction cannot be developed in a laboratory. Nevertheless, a credible prediction could be issued at any moment. Scientists in the field must consider observed evidence and provide a responsible interpretation immediately to the public, with the realization that there is a finite chance of issuing a false alarm. Furthermore, in the worst case, a credible prediction could cause more social and economic disruption than the ensuing earthquake

[PETER L. WARD]

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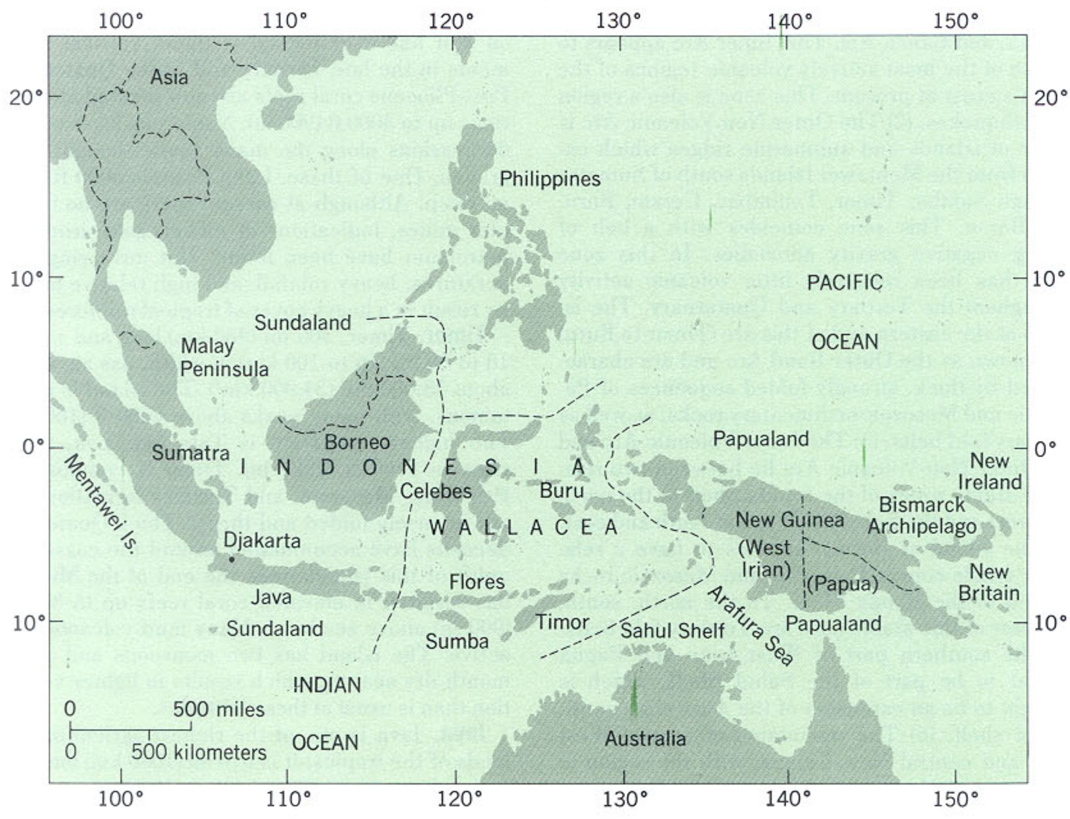
East Indies

The Indonesian islands and, for convenience of presentation, New Guinea and the Bismarck Archipelago, lying between Asia and Australia. They make up the territory of Indonesia, Brunei, part of Malaysia, and regions formerly under Australian trusteeship. Together with the intervening seas, the East Indies form a region of great relief and of geological diversity. The islands extend from western Sumatra to eastern New Guinea, a distance of about 4000 mi or 6400 km (see illustration).

Geographically, three basic divisions are recognized: (1) Sundaland, or the islands west of Macassar and the Lombok Straits; (2) Papualand, or the islands east of the Aru Islands and New Guinea; and (3) Wallacea, or the islands between Sundaland and Papualand and south of the Philippines. Each division is an important biological and geomorphological region.

During the Quaternary, a lowering of the general level of the world's oceans is thought to have resulted in the emergence of dry land between the western edge of Wallacea and Asia, and on the east in exposed portions of the Sahul Shelf beneath the Arafura Sea. The islands of Wallacea, however, remained separated by deep water,



The East Indies. Dashed lines in water areas represent boundaries of Sundaland, Wallacea, and Papualand.