damaged more than 90% of the houses. The prediction is said to have been based on precursors, including ground deformation, changes in the electromagnetic field and groundwater levels, anomalous animal behavior, and significant foreshocks. However, in the following year, the Tangshan earthquake occurred not too far away without precursors. In minutes, 250,000 people died, and another 500,000 people were injured. In the following month, an earthquake warning in the Kwangtung province caused people to sleep in tents for two months, but no earthquake occurred. Because foreign scientists have been yet been able to assess the Chinese data and the record of predictions, including both false positives (predictions without earthquakes) and false negatives (earthquakes without predictions), it is difficult to evaluate the program.

In summary, despite tantalizing suggestions, at present there is still an absence of reliable precursors. The frustrations of this search have led to the wry observation that "it is difficult to predict earthquakes, especially before they happen." Most researchers thus feel that although earthquake prediction would be seismology's greatest triumph, it is either far away or will never happen. However, because success would be of enormous societal benefit, the search for methods of earthquake prediction will likely continue.

1.2.7 *Real-time warnings*

Some recent efforts are directed to the tractable goal of real-time warnings, where seismometers trigger an immediate warning if a set of criteria is met. For tsunamis, the warning may be several hours in advance, which is enough time for preparations. This is because tsunamis travel more slowly than seismic waves. A P wave travels from Alaska to Hawaii in about 7 minutes, whereas a tsunami traveling at about 800 km/hr across the ocean takes 5.5 hours. After the damage done to Hilo by the 1946 Alaska earthquake, the Seismic Sea Wave Warning System was organized for countries that rim the Pacific Ocean. Information from seismometers and tide gauges was phoned to the Tsunami Warning Center in Honolulu, Hawaii, which issued tsunami alerts if necessary.[12] Tsunami warning systems have since become more automated, using real-time digital seismic data to locate large earthquakes and derive information about their magnitudes, depths, and focal mechanisms. An assessment can be made of the likelihood of a tsunami, which usually results from vertical motion at the sea floor.

The situation is much more complicated with seismic waves. Although local seismic networks can automatically and immediately locate an earthquake and assess if it is hazardous, the warning time is short. For example, a warning after a major earthquake on the New Madrid fault system instantly relayed via Internet or radio to St Louis would arrive about 40 seconds before the first seismic waves. Seismologists, engineers, and public authorities are thus discussing what might be done with such short warning times. Although such times would not permit evacuations, certain steps might be useful. For example, real-time warnings are used in Japan to stop high-speed trains, and it may be practical to have gas line shut-off valves or other automatic responses connected to such a system. The questions are whether the improved safety justifies the cost and whether the risk of false alarms is serious.

A related approach is to provide authorities with near-real-time information, including data on the distribution of shaking, immediately after major earthquakes. Seismic networks are working to provide emergency management services with information that can help direct the needed response to the most affected areas during the chaotic few hours after a large earthquake, when the location and extent of damage are often still unclear.

1.2.8 *Nuclear monitoring and treaty verification*

Another important societal application of seismology is the monitoring of nuclear testing. Although atomic physics destabilized world politics through the invention of the atomic bomb, seismology has partially restabilized it. Throughout the cold war between the USA and the Soviet Union, seismology helped verify that treaties were being observed.

The role of seismology in nuclear monitoring began in 1957 when the USA detonated RAINIER, the first underground nuclear explosion. By the early 1960s it became clear that radioactive elements produced by atmospheric nuclear testing posed significant health threats. In 1963, 116 nations signed the Limited Test Ban Treaty, which banned nuclear testing in the atmosphere, in the oceans, and in space, and required testing to occur underground. At about this time, the US Air Force helped fund the deployment of the World Wide Standardized Seismographic Network (WWSSN). WWSSN stations provided important information for monitoring nuclear testing and a wealth of data that played a major role in modern geophysical seismology.

In 1976, countries began to abide by the Threshold Test Ban Treaty, which limited the size of underground nuclear tests to 150 kt (equivalent to 150 kilotons of TNT). Before then, the largest atmospheric test had been 58 Mt, and the largest underground test had been 4.4 Mt. Figure 1.2-18 shows the yields estimated seismologically for underground nuclear tests carried out by the Soviet Union. Although it was initially thought that some of the post-1976 explosions were greater than 150 kt, this turned out to reflect the different geologies of the western USA and central Asia. The conversion of seismic body wave magnitude m_b values into TNT yields was calibrated using the Nevada test site, but the western US crust is more seismically attenuating than the more stable Soviet sites in Kazakhstan and Novaya Zemlya (see Section 3.7.10). The yields of explosions in kilotons, Y, can be related to the observed seismic magnitudes by

[12] Serious or older television viewers may recall the episode of *Hawaii 5-0* in which criminals force the center to issue a spurious tsunami warning to prompt evacuation of downtown Honolulu and facilitate a robbery.

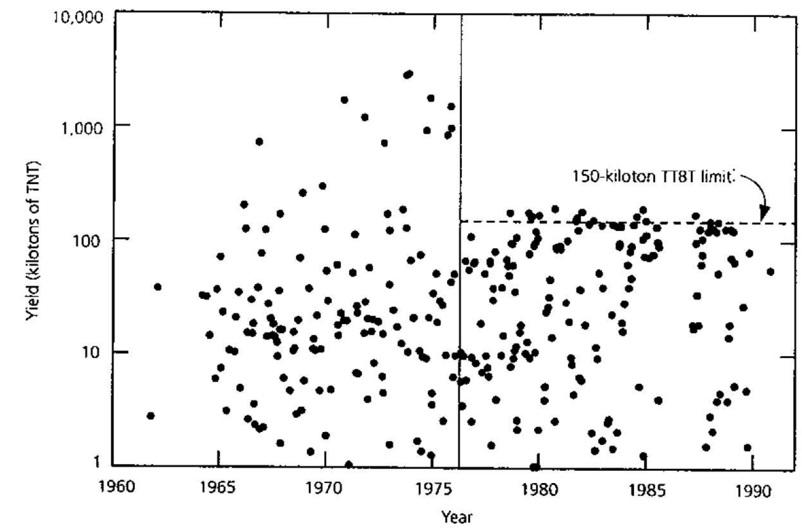

Fig. 1.2-18 Yields of underground nuclear tests carried out by the Soviet Union, determined through seismically observed m_b magnitudes. After the Threshold Test Ban Treaty (TTBT), seismology verified that the Soviet Union was in general compliance with the 150-kiloton limit. Data courtesy of P. Richards (personal communication).

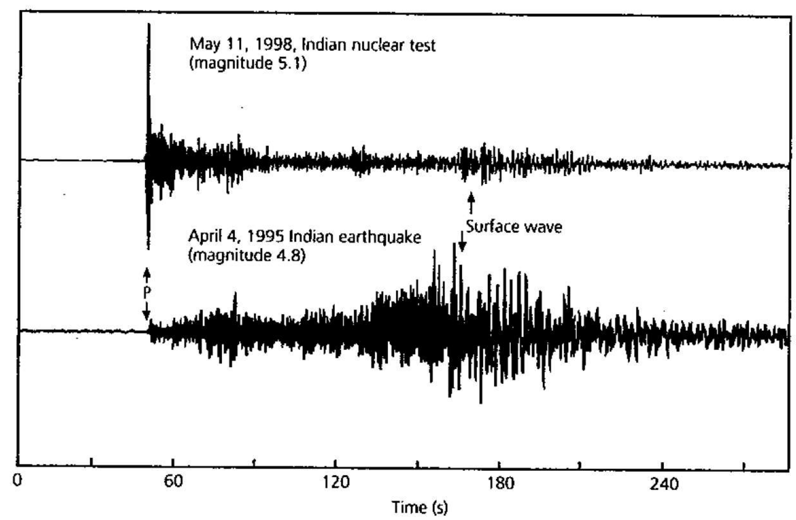

Fig. 1.2-19 Seismograms showing the differences between an earthquake and an explosion. For shallow earthquakes, in this case an m_b 4.8 shock in India, the P wave is much smaller than the surface waves. By contrast, the initial P wave is the largest arrival for explosions like this Indian nuclear test. Data recorded at Nilore, Pakistan. (Courtesy of the Incorporated Research Institutions for Seismology.)

$$m_b = C + 0.75 \log Y, \qquad (2)$$

but the constant differs for Nevada ($C = 3.95$) and Kazakhstan ($C = 4.45$). With these corrections, it appears that the Soviet Union complied with the treaty.

Monitoring nuclear tests requires distinguishing them from earthquakes. Examples of the differences are shown in Fig. 1.2-19 for an earthquake and an explosion in India. Earthquakes occur by slip across a fault, generating large amounts of shear wave energy and hence large surface waves. By contrast, explosions involve motions away from the source, and so produce far less shear wave energy. Hence, for bombs the surface waves are dwarfed by the initial P wave. This difference is the basis for discrimination between earthquakes and explosions. A plot of M_s vs m_b (Fig. 1.2-20) separates earthquakes, which generate more surface wave energy (M_s), from the explosions, which generate more body (P) wave energy (m_b).

The challenge of seismic monitoring has increased in recent years. Since 1996 the USA has abided by the Comprehensive Test Ban Treaty (CTBT), which bans all nuclear testing, preventing the development of new nuclear weapons. Thus the focus of US monitoring efforts has expanded to include smaller countries around the world.[13] There is also the need to identify possible smaller nuclear tests, including those by terrorists. Hence seismic monitoring must identify explosions less than 1 kt, which have a magnitude of 4–4.5 (Eqn 2). This requires locating and identifying more than 200,000 earthquakes and additional mining explosions every year.

[13] A strategy described as "In God we trust, all others we verify."