

Chapter 3

The Role of Seismology

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The Role of Seismology

Seismology provides a technical means for monitoring underground nuclear testing

INTRODUCTION

Verifying a ban on nuclear testing requires global monitoring systems capable of detecting explosions in the atmosphere, underwater, and below ground. Tests in the atmosphere and under water can be readily detected with high degrees of confidence. The atmosphere is monitored effectively with satellites containing sensors that can detect the visible and near-infrared light emitted by a nuclear explosion. The oceans can also be monitored very effectively because water transmits acoustic waves

efficiently. Underwater explosions would be detected by the acoustic sensors already in place as part of anti-submarine warfare systems. The most uncertain part of the global verification system is the monitoring of underground nuclear explosions that might be conducted within the Soviet Union. The main technical tools for monitoring underground nuclear explosions come from the field of seismology, which is the study of earthquakes and related phenomena.

THE CREATION OF SEISMIC WAVES

A nuclear explosion releases its energy in less than 1/1,000,000 of a second (a microsecond). The explosion initially produces a gas bubble containing vaporized rock and explosive material. Within a microsecond, the temperature within the bubble reaches about 1 million degrees and the pressure increases to several million atmospheres. A spherical shock wave expands outward from the bubble into the surrounding rock, crushing the rock as it travels. As the hot gases expand, rock is vaporized near the point of the explosion and a cavity is created.

While the cavity is forming, the shockwave continues to travel outward into the surround-

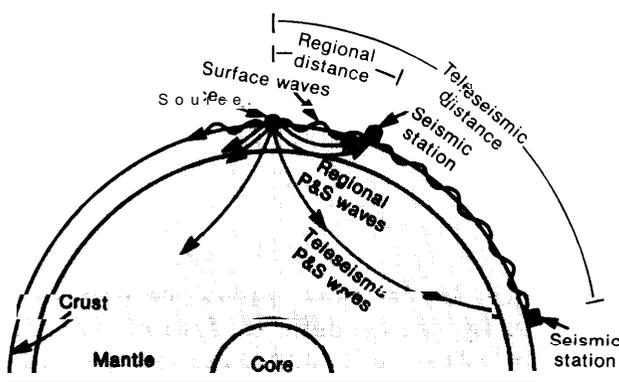
ing medium. Eventually, the shock wave weakens to the point where the rock is no longer crushed, but is merely compressed and then returns (after a few oscillations) to its original state. These cycles of compression and relaxation become seismic waves that travel through the Earth and are recorded by seismometers. By looking at seismic records (seismograms) and knowing the general properties of the travel paths of various waves, seismologists are able to calculate the distance to the seismic event and what type of motion caused the wave.

TYPES OF SEISMIC WAVES

As with earthquakes, seismic waves resulting from an explosion radiate outward in all directions (figure 3-1). These waves travel long distances either by passing deep through the body of the Earth (body waves), or else by trav-

eling along the Earth's surface (surface waves). The body and surface waves that can be recorded at a considerable distance (over 2,000 km) from the earthquake or explosion that created them are referred to by seismologists as

Figure 3-1.—Seismic Waves Propagating Through the Earth



An earthquake or underground explosion generates seismic waves that propagate through the Earth.

SOURCE: Office of Technology Assessment, 1988.

teleseismic waves. Teleseismic body and surface waves are important to monitoring because to be recorded they do not usually require a network of seismometers near the source. This allows for seismometers to be located outside the region that is being monitored.

TELESEISMIC WAVES

The various types of teleseismic waves are differentiated by both the paths along which they travel and the type of motion that enables them to propagate. The two main subdivisions (body waves and surface waves) are distinguished by the areas through which they travel.

Body Waves

The waves traveling through the body of the Earth are of two main types: *compressional waves* (also called *P waves*) and *shear waves* (also called *S waves*). The designations P and S are abbreviations originally referring to primary and secondary arrivals; compressional waves travel faster than shear waves and, consequently, arrive first at a recording station. Apart from their different speeds, P waves and S waves also have different characteristics.

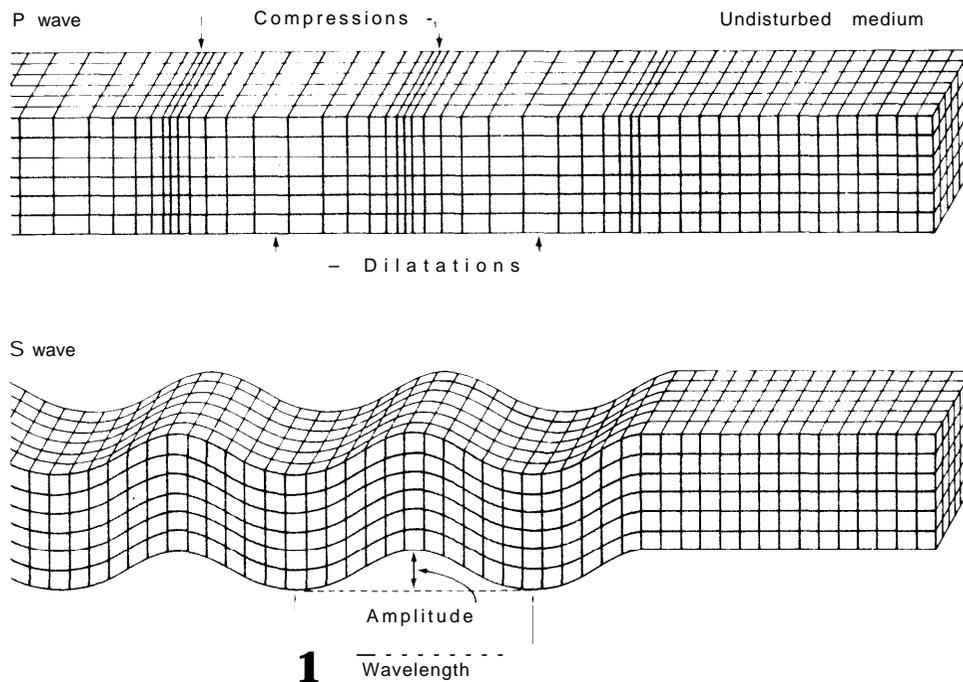
Teleseismic waves contrast with what seismologists call *regional waves*. Regional waves are seismic waves that travel at relatively high frequencies within the Earth's crust or outer layers and typically are observed only at distances of less than 2,000 km. Regional waves are therefore recorded at seismic stations that, for application to monitoring Soviet nuclear explosions, would have to be located within the territory of the Soviet Union. Such stations are called *in-country* or *internal* stations.

When seismic waves reach a seismic station, the motion of the ground that they cause is recorded by seismometers. Plots of the wave forms are called *seismograms*. Because the different waves travel at different speeds and along different routes, they arrive at seismic stations at different times. The farther away the seismic station is from the source of the waves, in general, the more dispersed in time the different arrivals will be. By studying seismograms, seismologists are able to recognize the various types of waves produced by events such as earthquakes and nuclear explosions.

P waves travel in a manner similar to sound waves, that is, by molecules "bumping" into each other resulting in compression and dilation of the material in which they propagate. A cycle of compression moves through the Earth followed by expansion. If one imagined a particle within the wave, its motion would be one of shaking back and forth in the direction of propagation in response to the alternating compressions and expansions as the wave trains move through. The particle motion is in the direction of travel and the wave can propagate through both solids and liquids. A sudden push or pull in the direction of wave propagation will create P waves (figure 3-2a).

In contrast, S waves propagate by molecules trying to "slide" past each other much as happens when one shakes a rope from side to side and the disturbance passes down the rope. The

Figure 3-2.—Body Waves



Waves traveling through the body of the Earth are of two main types: compressional waves (P waves) and shear waves (S waves).

SOURCE B A Bolt, *Nuclear Explosions and Earthquakes*, W H Freeman & Co., 1976

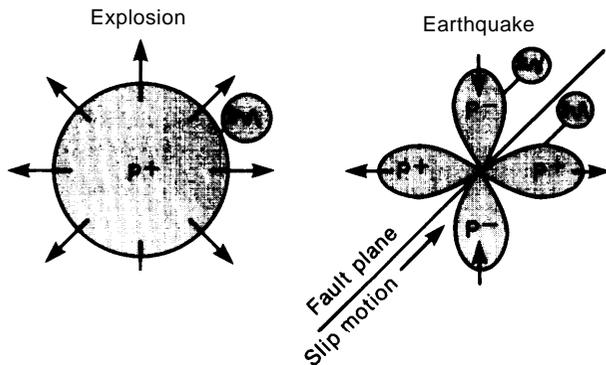
wave motion is at right angles to the direction of travel. Any particle affected by the wave would experience a shearing motion as the wave passed through. Because liquids have little resistance to shearing motion, S waves can only pass through solid materials. (Liquids can be compressed, which is why P waves can travel through both solids and liquids.) A sudden shearing motion of a solid will result in S waves that will travel at right angles to the direction of propagation (figure 3-2 b).

In a P wave, particle motion is longitudinal in the direction of propagation, thus there can be no polarization of a P wave. S waves, however, being transverse, are polarized and can be distinguished as either horizontal or vertical. Particle motion in an SH wave is horizontal. In an SV wave, particles oscillate in a vertical plane perpendicular to the path.

An underground explosion creates a uniform pressure outward in all directions. Therefore,

explosions should be a source of nearly pure P waves. In practice, however, some S waves are also observed. These waves are usually due to asymmetries of the cavity or the pressure within the cavity created by the explosion, structural inconsistencies in the surrounding rock, or the presence of pre-existing stresses in the host rock that are released by the explosion. An earthquake, on the other hand, is generally thought of in terms of blocks of the Earth's crust breaking or slipping past one another along a fault region. Because of the shearing motion, an earthquake creates mostly S waves. P waves are also generated from an earthquake, but only in a four-lobed pattern that reflects the opposite areas of compression and expansion caused by the shearing motion (figure 3-3). As discussed in chapter 5, this difference in source geometry can be used as a means of distinguishing the seismic signals caused by explosions from the seismic signals generated by earthquakes.

Figure 3.3.—Seismic Radiation Patterns



The pattern of seismic body waves generated by a given source becomes complicated when the waves interact with the structures of the Earth. In general, when a wave hits a boundary within the Earth, such as where two different rock types meet, both reflected and transmitted P and S waves are generated at several different angles. (figure 3-4)

Because of all these possibilities, P waves and S waves break into many types as they travel through the Earth. At a depth of 30 to 60 kilometers in the Earth, the velocity with which sound passes through the Earth increases markedly. This discontinuity, called the Mohorovicic Discontinuity (Moho), serves as a wave guide to trap seismic energy in the upper crust of the Earth.

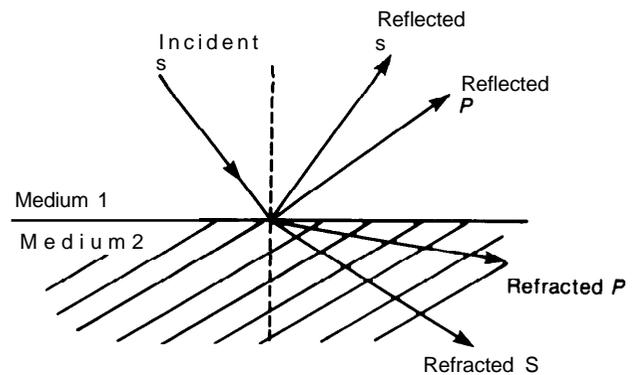
Surface Waves

At the Earth's surface, two additional seismic wave types are found. These surface waves, called *Rayleigh waves* and *Love waves*,¹ are produced by constructive interference of body wave energy in the upper layers of the crust.

The particle motion of Rayleigh waves is somewhat analogous to that of ripples spreading over the surface of a lake. The analogy is not exact, however, because unlike a water wave, the orbital motion of a particle in a Ray-

¹These waves are named after the mathematicians who first developed the theory to describe their motion (Lord Rayleigh and A.E.H. Love).

Figure 3-4.—Reflected and Refracted Waves



When a wave hits a boundary within the Earth both reflected and refracted waves can be generated.

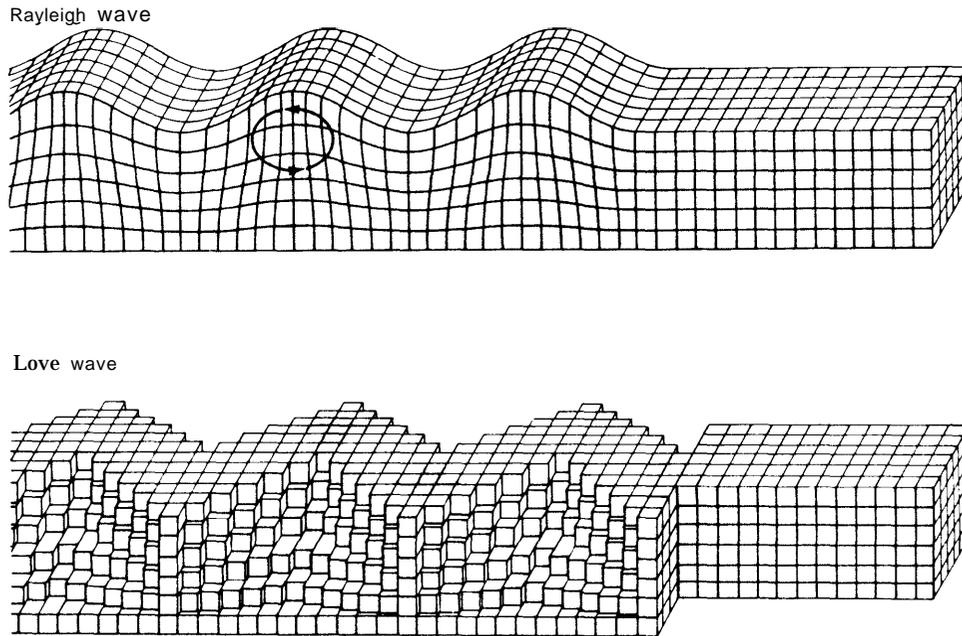
leigh wave is retrograde to the path of wave propagation (figure 3-5a). The energy of the Rayleigh wave is trapped near the ground surface, so as depth increases, the rock particle displacements decrease until, ultimately, no motion occurs.

The second type of surface wave which travels around the Earth is called a Love wave. Love waves have a horizontal motion that is shear, or transverse, to the direction of propagation (figure 3-5b). It is built up of trapped SH waves and has no vertical motion.

While Rayleigh waves can be detected by seismometers sensitive either to vertical or horizontal motion of the Earth's surface, Love waves are only detected by seismometers sensing horizontal motions.

Surface waves of either type, with a period of 10 seconds, travel with a velocity of about 3 kilometers per second. This corresponds to a wavelength of about 60 kilometers. Because of this long wavelength, surface waves are much less likely to be affected by small-scale variations in Earth structure than short period body waves. This makes the use of surface waves attractive for measuring yields of Soviet tests. Body waves (P waves and S waves) are faster than surface waves and therefore arrive first at a recording station. This is fortunate because the surface waves have larger am-

Figure 3-5.-Surface Waves



Waves traveling along the surface of the Earth are of two main types: Rayleigh waves and Love waves.

SOURCE: B.A Bolt, *Nuclear Explosions and Earthquakes*, W.H. Freeman & Co., 1976.

plitudes than the body waves. If they all arrived simultaneously, the smaller amplitude P waves would be hidden by the surface waves

unless the records were filtered to take advantage of the different frequency content of the two types of waves (figure 3-6).

REGIONAL WAVES

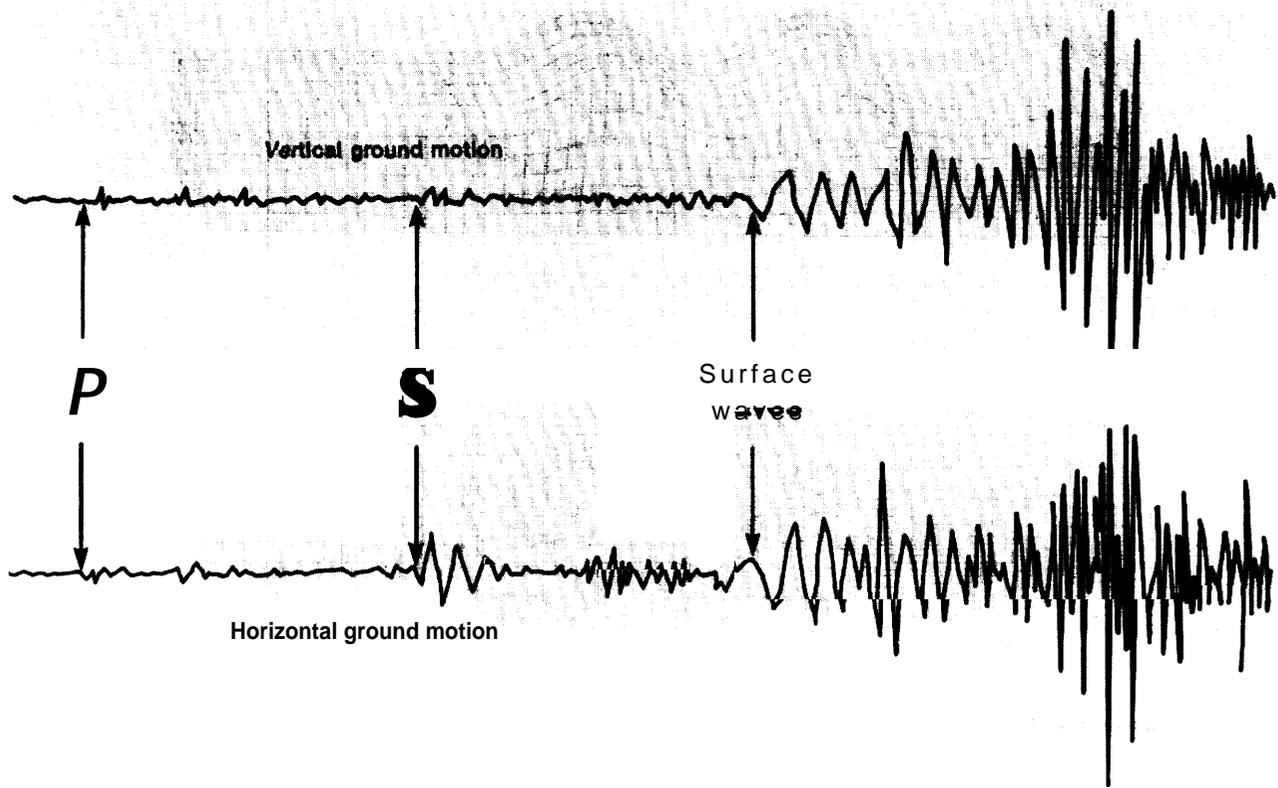
In contrast with the teleseismic waves described above, regional waves are usually observed only at distances of less than 2,000 km. In general they have larger amplitudes and higher frequency content than waves from the same source recorded at teleseismic distances. Depending on their propagation characteristics, such regional waves are denoted by P_n , P_g , S_n , and L_g . A comparison of teleseismic and regional seismic waves is illustrated in figure 3-7. Note the different time scales. The amplitude scales are also different.

At regional distances, P_n is usually the first wave to arrive at any given station. It is a wave

that goes down through the crust of the Earth, then travels mostly horizontally near the top of the upper mantle (in contrast to the usual body, which goes deeply within the mantle), and finally travels upward through the crust, where the receiver is located. This path is shown in the upper part of figure 3-8. In the lower part are shown some of the multiple bounces that also contribute to the P_n wave. The Moho marks the boundary between the crust and the upper mantle.

P_g is a wave that comes in later than P_n , and travels the path between source and receiver wholly within the Earth's crust. As shown in

Figure 3-6.—Seismograph Recording of P, S, and Surface Waves From a Distant Earthquake



SOURCE: Modified from F. Press and R. Seiver, *Earth*, W.H. Freeman & Co., San Francisco, 1974.

figure 3-9, P_g is thought to be guided by a boundary layer within the crust. It does not propagate to as great a distance as P_n .

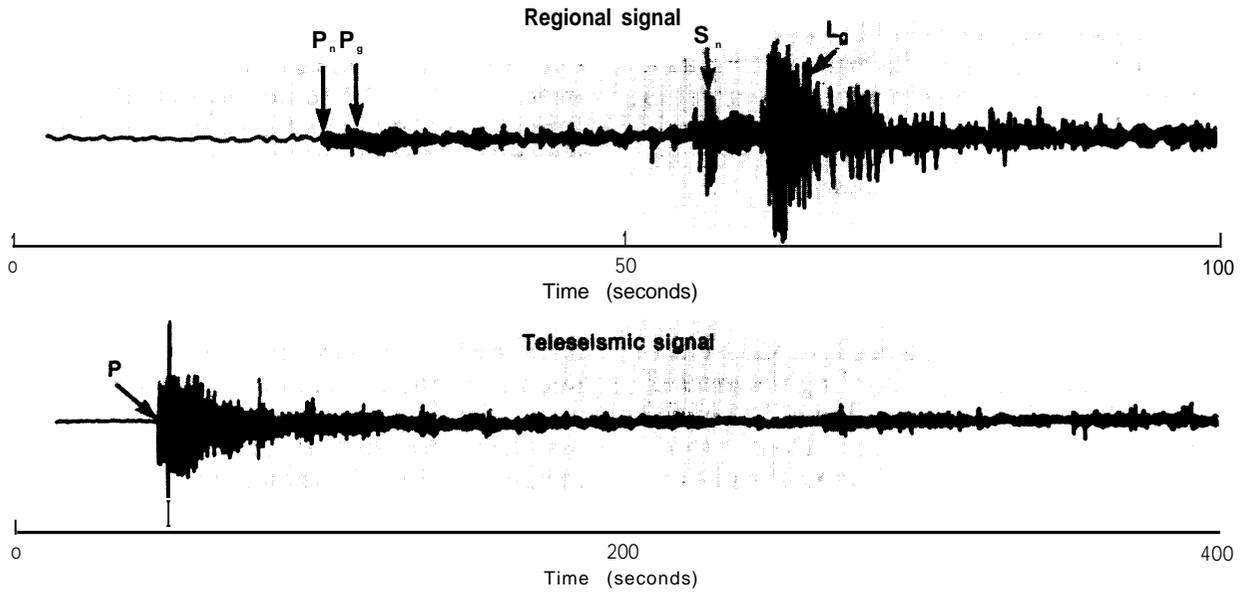
S_n is a shear wave that travels a path very similar to that of P_n , but arrives later. S_n arrives later because it is composed of shear waves, which propagate slower than the P waves that make up P_n .

For purposes of explosion monitoring, L can be the most important of the regional waves because it is typically the largest wave observed on a seismogram at regional distances. L_g is a type of guided shear wave that has most of its energy trapped in the Earth's crust. In fact, this wave can be so strong that (contrary to what is implied by its inclusion in the class of "regional waves") L for a large explosion can be observed even at teleseismic distances, i.e. well in excess of 2,000 km. The

observation of L_g out to teleseismic distances, however, can only occur across continents. Beneath an ocean, where the crust is much thinner, L_g fails to propagate even short distances.

Figure 3-10 illustrates how the L_g wave propagates. At the top is shown a seismic source within the Earth's crust. Energy departing downward is partially reflected in the crust and partially transmitted down into the mantle. However, for waves that travel in the more horizontal direction, as shown in the middle part of the figure, energy cannot get into the mantle and is wholly reflected back into the crust. The type of reflection occurring here is the total internal reflection that is similar to that occurring within the prisms of a pair of binoculars. For a fixed source and receiver, there may be many reflection paths, all totally

Figure 3-7.—Regional and Teleseismic Signals



Upper seismogram is of a "regional distance" from the source. Signals here are associated with waves that propagate in the crust and upper most mantle. Lower seismogram is of a "teleseismic distance." This wave has propagated through the deep interior of the Earth.

SOURCE: Modified from Defense Advanced Research Projects Agency.

Figure 3-8.—P_n Wave

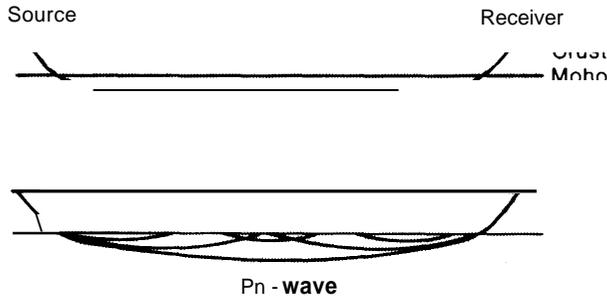


Figure 3-9.—P_g Wave

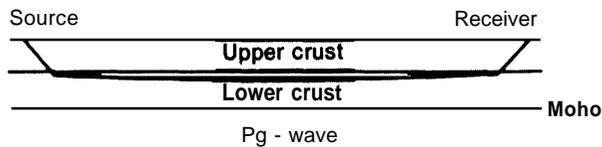
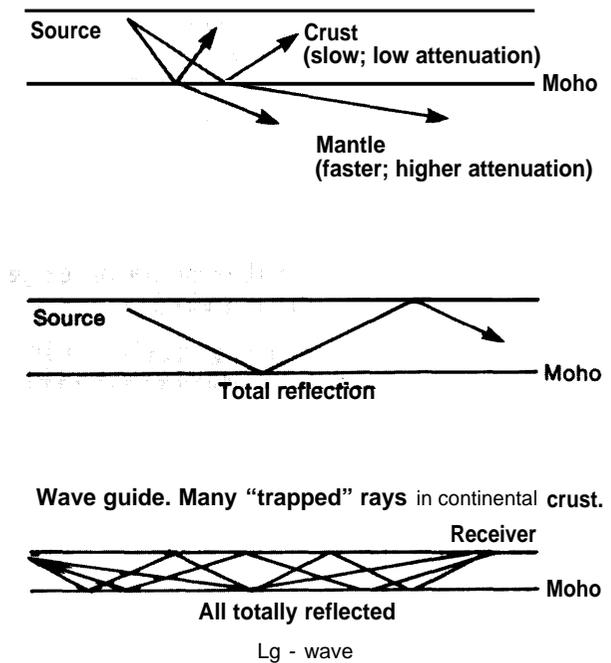


Figure 3-10.—L_g Wave



reflected and thus trapped within the crust. This is illustrated in the bottom of the figure. The L_g wave is composed of the entire family of trapped waves, with the crest acting as a wave guide. For regions in which the crust is composed of material that transmits seismic waves efficiently, L_g may be recorded at distances of thousands of kilometers.

For most of the last 30 years, regional waves have been thought of mainly in the context of monitoring small explosions which may not be detected teleseismically. In recent years, however, L_g has come to be recognized as useful for estimating yields for large explosions, independent of the more conventional body wave and surface wave measurements (see ch. 7).

RECORDING SEISMIC WAVES

Seismic waves are measured at observatories around the world by recording the ground motion. Most observatories have "triaxial" seismometers, meaning that they record ground motion in three directions at right angles to each other. Typically they are oriented north-south, east-west, and vertical. By having all three components, seismologists can reconstruct the complete three-dimensional ground motion from the seismograms.

The principle by which the seismometers work can be thought of as a heavy mass freely supported by a spring from a frame fixed to the Earth. When an earthquake or explosion occurs, seismic waves traveling through the Earth reach the seismometer. The frame is shaken in response to the motion of the wave. Although the frame is displaced by the ground motion, the heavy mass tends to remain stationary because of its inertia. The displacement of the grounded frame relative to the stationary mass is therefore a measure of the ground motion. This movement is then electronically magnified so that displacements as small as 0.0000001 centimeters (the same order as atomic spacings) can be detected.

If the Earth were perfectly still, recording small earthquakes and underground explosions would be easy. However, processes such as the winds, ocean waves, tides, man's activity, and seismic waves generated by earthquakes in other regions continually cause motions of the Earth. All of this motion is sensed

by seismometers and recorded. Although seismic instruments are sensitive enough to detect seismic waves generated by even the smallest explosion, it will be seen in the following chapters that naturally occurring background noise levels are the limiting factor in detecting small earthquakes and explosions.

To reduce the background noise caused by wind and other surface effects, seismometers have been designed to fit into torpedo-shaped casings and placed in narrow boreholes at a depth of about 100 meters. These types of stations are currently being used as part of the Regional Seismic Test Network (RSTN). The RSTN is a prototype system designed to evaluate the utility of in-country stations that could be placed within the Soviet Union to monitor a low-yield or comprehensive test ban treaty. A typical high quality installation contains three primary seismometers mounted in mutually perpendicular orientations along with three back-up seismometers (figure 3-11).

The seismometer installation is protected against tampering both electronically and through the inherent ability of the instrument to sense disturbances in the ground. The borehole package sends data to a surface station that contains transmitting and receiving equipment and in some cases to an antenna for satellite communications. Also contained in surface stations that might be used for monitoring are power sources, environmental con-

Figure 3-11.—Seismic Instrumentation

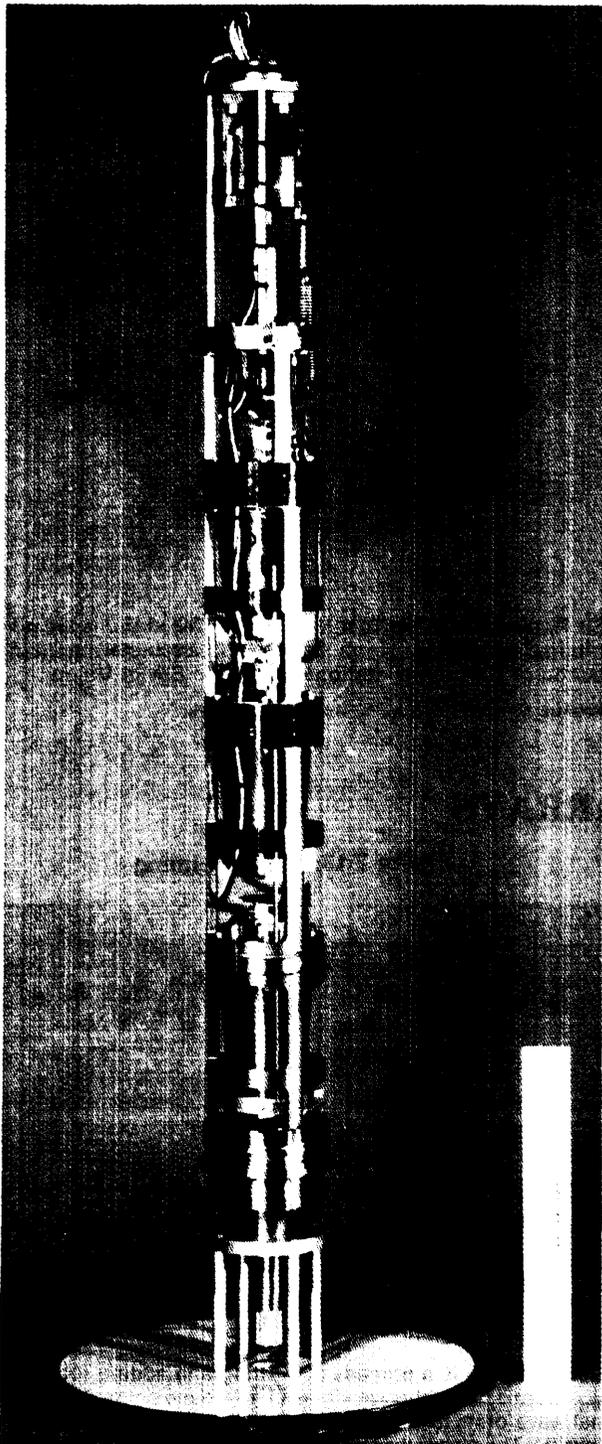
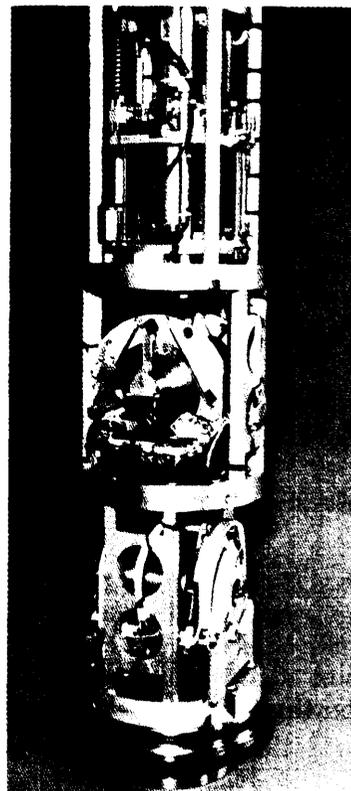
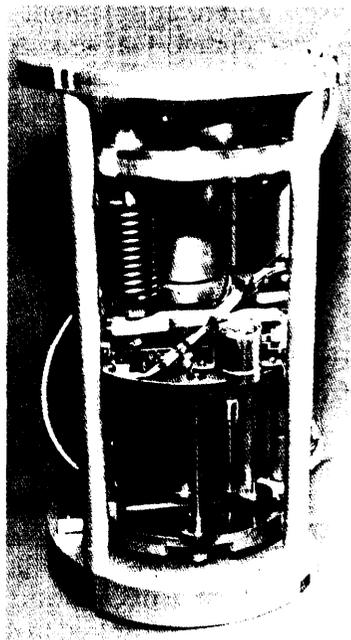


Photo credits: Sandia National Laboratories

Seismic station downhole package containing seismometers, authentication circuits, and processing electronics



Three seismometers mounted in mutually perpendicular orientations



Seismometer

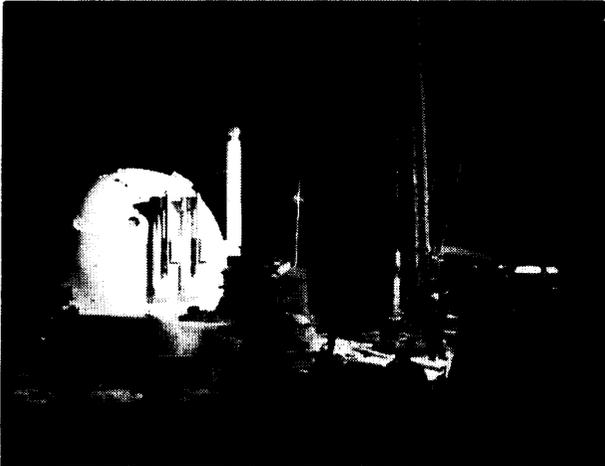
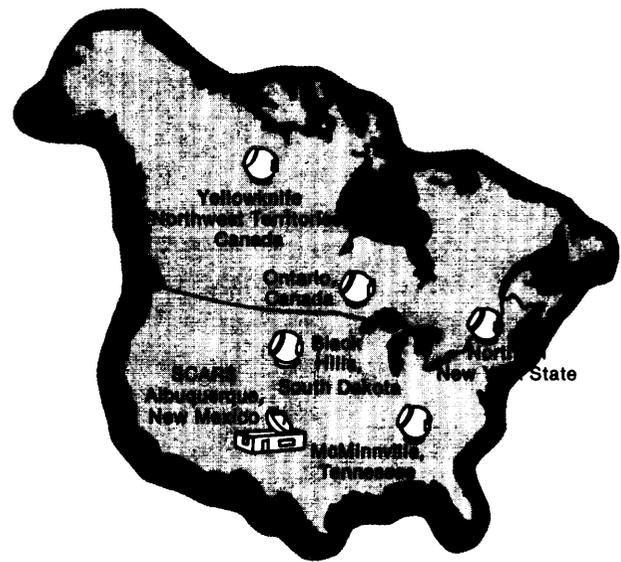


Photo credit: Sandia National Laboratories

An example of what an internal seismic station might look like.

control apparatus, and tamper-protection equipment. The distribution of six of these stations in North America is designed to simulate the distribution of 10 internal stations within the Soviet Union (figure 3-12).

Figure 3-12.—Distribution of RSTN Stations



Six Regional Seismic Test Network (RSTN) stations are distributed throughout North America to simulate the distribution of 10 internal stations within the Soviet Union.

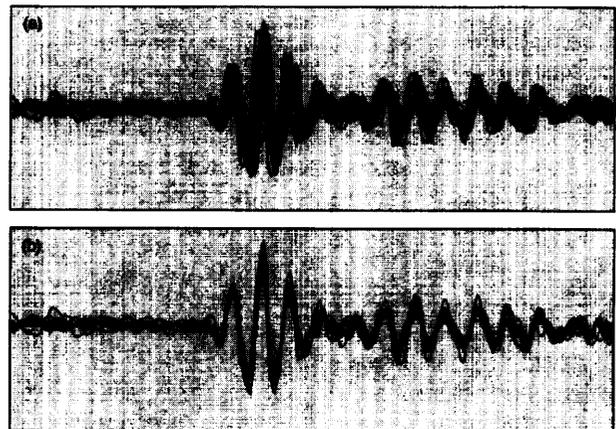
SOURCE: Modified from Sandia National Laboratories.

SEISMIC ARRAYS

The use of seismic arrays has been proposed as an alternative and/or supplement to single three-component seismic stations. A seismic array is a cluster of seismometers distributed over a fairly small area, usually on the order of a few kilometers. The signals from the various instruments are then combined to improve the detection and identification of any small or weak signals that maybe recorded. Seismic arrays can function like phased array radar receivers, sensitive to waves from a particular direction while excluding waves from other directions. By doing so, arrays can pull small signals out from the surrounding background noise.

To test the application of arrays for monitoring regional seismic events, the United States and Norway installed the Norwegian Regional Seismic Array (NORESS) in 1984. NORESS is located north of Oslo and consists of 25 individual sensors arranged in 4 concentric rings with a maximum diameter of 3 km.

Figure 3-13.—Beamforming



Beamforming is a process of shifting and adding recorded waveforms to emphasize signals and reduce noise. The original waveforms (a) can be shifted to remove propagation delays (b). The signal waveforms are now aligned but the noise is not. The average of the shifted waveforms in (b) would be the beam.

SOURCE: *Energy & Technology Review*, Lawrence Livermore National Laboratory, August 1986, p. 13.

To imagine how an array works, consider an example where a seismic wave is coming from a known location and with a known speed. The time it takes for the wave to travel to each sensor in the array can be predicted from the known direction and speed. In contrast, the seismic background noise will vary randomly from sensor to sensor. The recorded signals from each sensor in the array can then be shifted in time to allow for propagation across the array and combined (figure 3-13). The sensors are close enough so that the signal from the coherent source is nearly the same from each seismometer and remains unchanged. The background noise varies more rapidly and cancels out when the records are added together. Thus, it is possible to suppress the noise relative to the signal and make the signal easier

to detect. This process of shifting and adding the recorded waveforms is called *beamforming*. The combination of the shifted waveforms is called the beam.

Arrays do, however, have some drawbacks compared to three-component single stations:

1. they are more expensive because they require more hardware and higher installation costs;
2. they require access to a larger area; and
3. they have more sensors that, in turn, generate more data that must be transmitted, stored and processed.

A comparison of the advantages and disadvantages of arrays versus three-component single stations is presented in chapter 4.