Chapter 5

Identifying Seismic Events

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Identifying Seismic Events

Once a seismic event has been detected, the next step is to determine whether it was created by an underground nuclear explosion.

INTRODUCTION

Once the signals from a seismic event have been detected, and the event located, the next step in seismic monitoring is that of identification. Was the event definitely, or possibly, an underground nuclear explosion, or can the signals be identified unambiguously as having another cause? As discussed in the previous chapter, seismic signals are generated by natural earthquakes and by natural rockbursts in mines, as well as by chemical and nuclear explosions. The identification problem in seismic monitoring, called the discrimination problem, is to distinguish underground nuclear explosions from other seismic sources.

In the case of a located seismic event for which signals are large, that is, larger than could be ascribed to a chemical explosion or a rockburst, the only candidates for the source of the signals are an earthquake or a nuclear explosion. Physical differences between earthquakes and nuclear explosions cause their seismic signals to differ, and these differences can be used to identify the events.

Identification becomes more complicated, however, for small events. When identifying small events (comparable in size to an explosion of less than 10 kilotons), the identification procedures encounter four types of difficulty that do not arise for larger events:

1. the quality of available signals is typically lower;
2. the number of natural events that must be discriminated against is larger;
3. the possibilities now include chemical explosions and rockbursts;
4. the event, if nuclear, is of a size where attempts may be made to muffle or hide the seismic signal.

Each of these difficulties becomes more severe at **lower yields.**

The last difficulty listed above brings up the subject of evasion which is discussed in the next chapter. For the purposes of understanding this chapter, however, the reader should recognize that identification capabilities must always be considered against the feasibility of various evasion scenarios. The successful *use* of a muffling or decoupling evasion technique could cause a 1-10 kt decoupled nuclear explosion to produce seismic signals comparable to either a chemical explosion of 10-100 tons respectively, or an earthquake ranging from magnitude 2-3 respectively. The similarity in size and, in some cases, the properties of the signals for these three types of events pose the most serious monitoring challenges. The monitoring system must be able to demonstrate a capability to identify with high confidence seismic events whose signals might be intentionally reduced or hidden through credible evasion techniques. It is the need to demonstrate such a capability, as signals become smaller, that ultimately sets the threshold for seismic identification.

The present chapter describes the different kinds of seismic sources and the basis for solving the identification problem. It then describes capabilities of current seismic networks, and how these capabilities might be improved by the addition of new seismic stations, including stations within the U.S.S.R.

BASIS FOR SEISMIC IDENTIFICATION

The seismic signals from a nuclear explosion must be distinguished from seismic signals created by other events, particularly earthquakes, chemical explosions, and rockbursts. Most seismic signals from located events are caused by earthquakes, although chemical explosions are also present in large numbers. Significant rockbursts and other sources of seismic signals are rare. A monitoring network, however, will encounter seismic signals created by all of these sources and must be able to identify them. Consequently, the burden on any monitoring network will be to demonstrate a capability to detect and **identify** with high confidence a clandestine nuclear test against the background of large numbers of earthquakes and industrial explosions and infrequent rockbursts. This section reviews basic properties of these other seismic sources and discusses the physical basis for discriminating them from nuclear explosions.

Earthquakes

Earthquake activity is a global phenomenon, though most of the larger earthquakes are concentrated inactive tectonic regions along edges of the Earth's continental and oceanic plates (figure 5-l). In the U. S. S. R., most large earthquakes are located in a few active regions along the southern and eastern borders of the country (figure 5-2). For the many earthquakes occurring along the Kurile Islands region on the Pacific border of the Soviet Union, the shallow earthquakes generally occur on the ocean side of the islands, while the deeper earthquakes occur beneath the islands and toward the U.S.S.R. landmass (figure 5-3). Elsewhere, earthquakes can occur as deep as 700 kilometers in the Earth's mantle.

In figure 5-2, large areas of the U.S.S.R. are shown for which there is no significant earthquake activity. Given presently available information, such areas are referred to as *aseismic;* although some activity may occur in these regions at magnitudes below m_b 3.0.

As table 1 illustrates, there are about 7,500 earthquakes that occur with m_b 4.0 or above each year, and about 7 percent of these occur in the Soviet Union. However, approximately two-thirds of the Soviet seismicity occurs in oceanic areas, mainly off the Kurile-Kamchatka coast. Seismicity in oceanic areas does not raise an identification problem because acoustic sensors provide excellent identification capability for nuclear explosions in water. Consequently, it is earthquakes on Soviet land areas from which nuclear explosions need to be differentiated. For example, at the magnitude level of m_b 4.0 and above, where there are 7,500 earthquakes each year, approximately 183 occur on Soviet land areas and would need to be identified. The number of such earthquakes that occur each year above various magnitudes is shown in the third column of table 1. The smaller the magnitude, the more earthquakes there are.

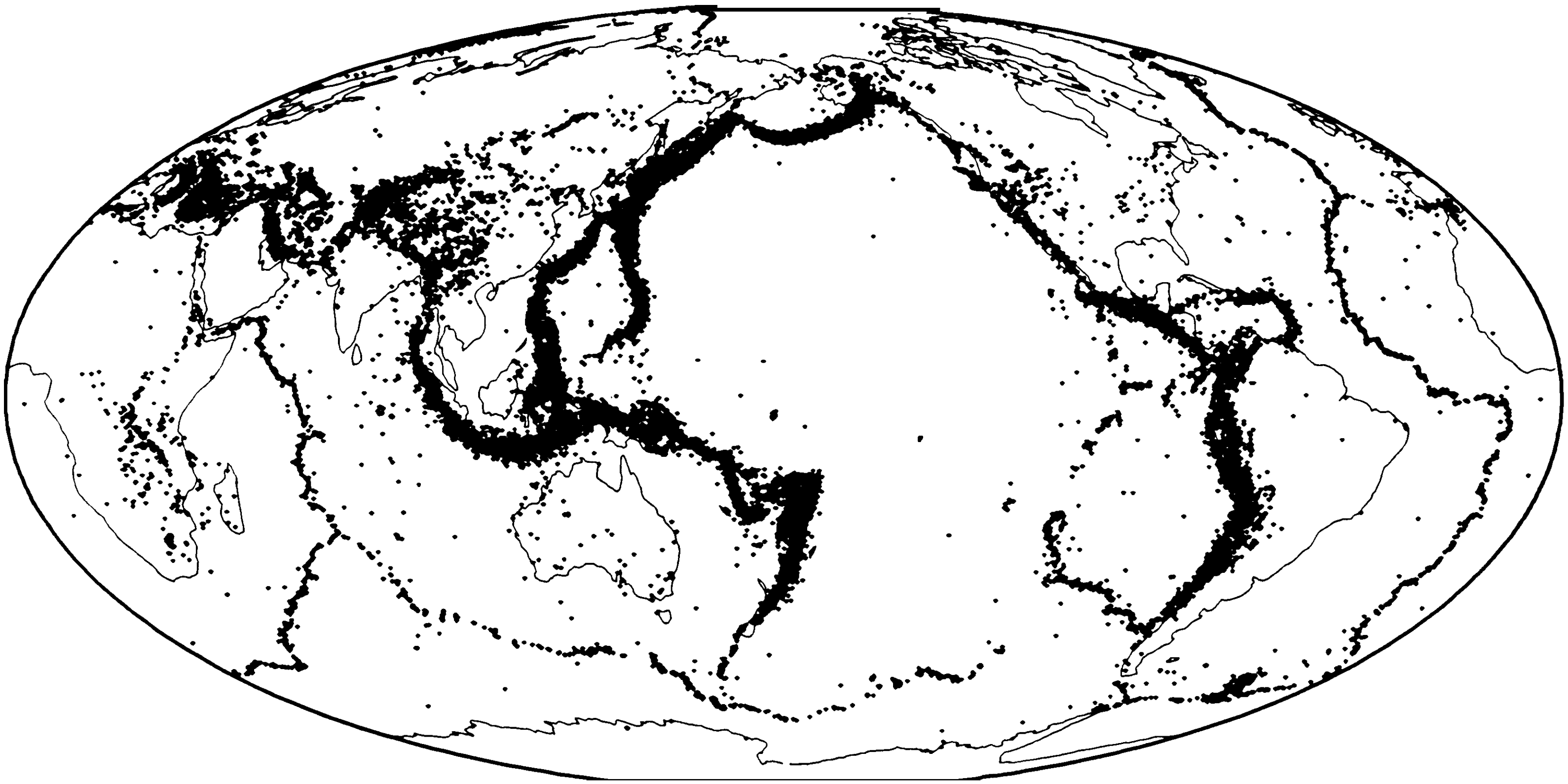
Earthquakes and their associated seismograms have been studied on a quantitative basis for about 100 years. Since 1959, seismologists have engaged in a substantial research effort to discriminate between earthquakes and explosions by analyzing seismic signals. Thousands of studies have been conducted and reports written. As will be discussed in the following section, this identification problem is now considered to be solved for events above a certain magnitude.

Table 5-1.—Approximate Numbers of Earthquakes Each Year, Above Different Magnitude Levels

m_b	Globally[a]	Soviet Union[b]	Soviet land areas[c]
5.0	950	70	23
4.5	2,700	200	67
4.0	7,500	550	183
	21,000	1,500	500
3.0	59,000	4,200	1,400
2.5	170,000	12,000	4,000

[a] Based on F. Ringdal's global study of a 10-year period, for which he finds the statistical fit log N = 7.47-O.9m . F. Ringdal, "Study of Magnitudes, Seismicity, and Earthquake Detectability Using a Global Network," in The Vela Program, Ann U. Kerr, (cd.), Defense Advanced Research Projects Agency, 1985.
[b] Based on 7 percent of global earthquakes with numbers rounded up slightly.
[c] Based on removing two-thirds of Soviet Union earthquakes. Two-thirds of the earthquakes in the Soviet Union occur in oceanic areas, e.g., off the Kurile-Kamchatka coast and, therefore, do not present an identification problem.

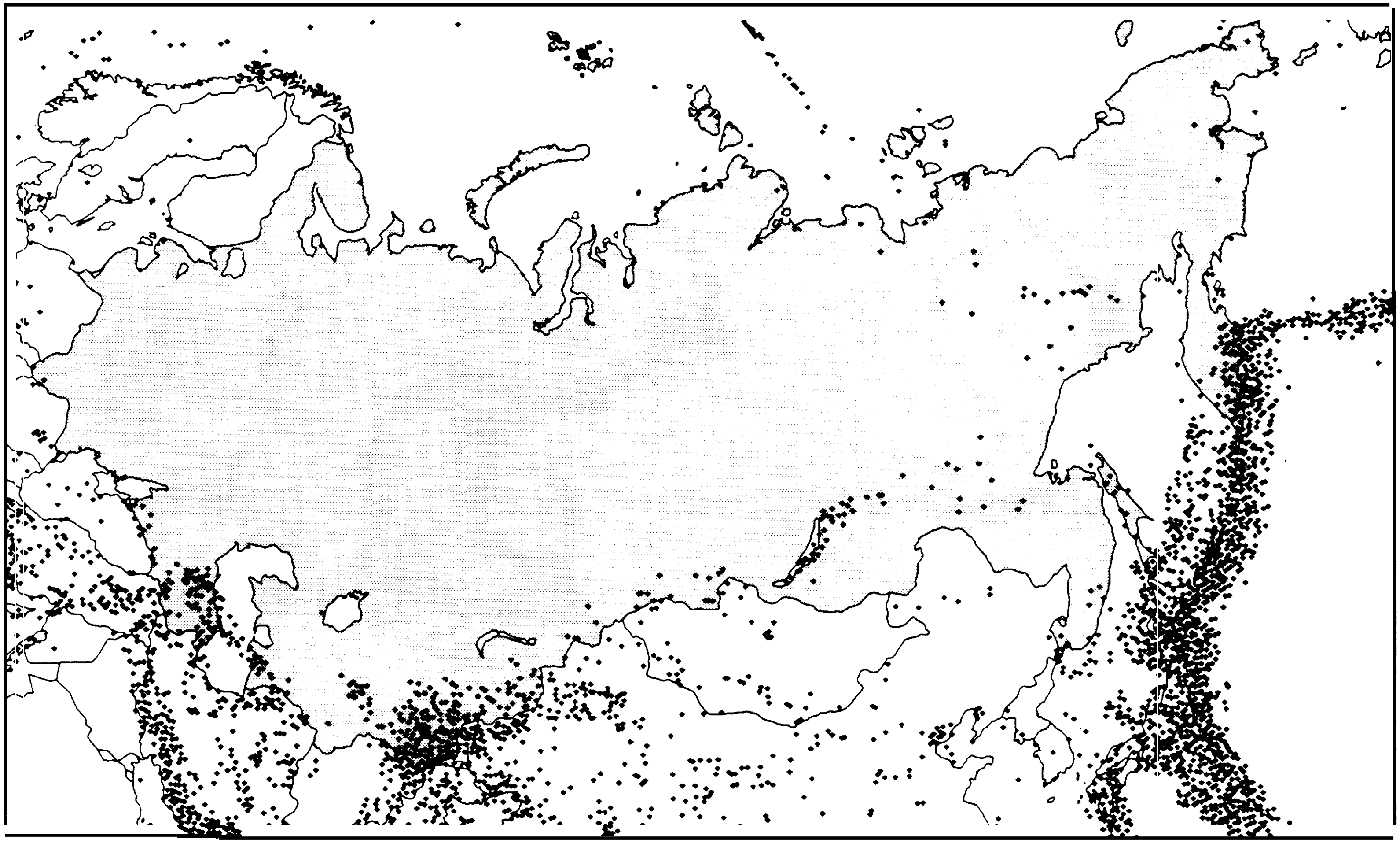
Figure 5-1.—Seismicity of the World, 197 -1986



Distribution of earthquakes with magnitudes ≥ m_b 4.0.

SOURCE: U.S. Survey.

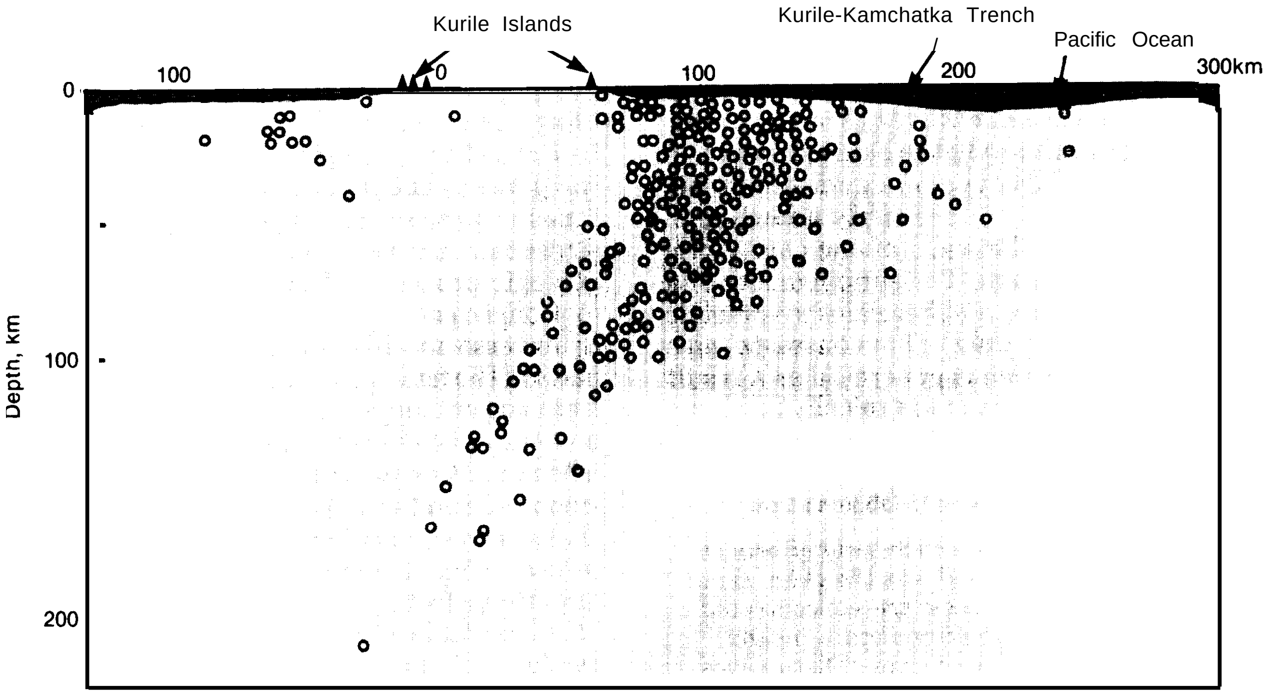
Figure 5-2.—Seismicity of the U.S.S.R. and the Surrounding Areas, 1971-1986



Seismicity for a 15-year period. Many of the earthquakes shown are located outside the U.S.S.R. to the south or n the Pacific Ocean region.

SOURCE: U.S. Geological Survey.

Figure 5-3.—Cross-Sectional View of Seismicity Along the Kurile-Kamchatka Coast



Two-thirds of Soviet seismicity at magnitudes greater than m_b 3.5 **is** off the Kurile-Kamchatka coast. This sectional view shows that almost all these events are deep, below land or shallow, below ocean. Neither case is a candidate explosion location.

SOURCE: L.R. Sykes, J.F. Evernden, I.L. Cifuentes, American Institute of Physics, *Conference Proceed/r@* 704, pp. 85-133, 1983.

From these studies, a number of identification methods have evolved. These methods all have as their basis a few fundamental differences between nuclear explosions and earthquakes. These differences are in:

- location,
- geometrical differences between the point source of an explosion and the much larger rupture surface of an earthquake, and
- the relative efficiencies of seismic wave generation at different wavelengths.

With regard to the first difference, many earthquakes occur deeper than 10 km, whereas the deepest underground nuclear explosions to date have been around 2.5 km and routine weapons tests under the 150 kt threshold appear all to be conducted at depths less than 1 km. Almost no holes, for any purpose, have been drilled to more than 10 km deep. The exceptions are few, well known, and of a scale that would be difficult to hide. Because nuclear explosions are restricted to shallow depths (less than 2.5 km), discrimination between many earthquakes and explosions on the basis of depth is possible in principle. In practice, the uncertainty in depth determination makes the division less clear. To compensate for the possibility of very deep emplacement of an explosion, the depth must be determined to be below 15 km with high confidence before the event is to be identified unequivocality as an earthquake. Events with shallower depths that show large uncertainties in depth determination might be considered as unidentified on the basis of depth.

With regard to source geometry, the fundamental differences are due to how the seismic signals are generated (see box 5-A). As discussed in chapter 3, an underground nuclear explosion is a highly concentrated source of compressional seismic waves (P waves), sent out with approximately the same strength in all directions. This type of signal occurs because the explosion forces apply a fairly uniform pressure to the walls of the cavity created by the explosion. The simple model of a nuclear explosion is a spherically symmetric source of P waves only. This contrasts with an earthquake, which is generated as a result of massive rock failure that typically produces a net shearing motion. It is common here to think in terms of two blocks of material (within the crust, for shallow events) on opposite sides of a fault. The stress release of an earthquake is expressed in part by the two blocks moving rapidly (on a time scale of seconds) with respect to each other, sliding in frictional contact over the plane of the fault as a result of the spontaneous process of stress release of rock—stress that has accumulated over time through geologic processes. Because of this shearing motion, an earthquake radiates predominantly transverse motions–i.e., S waves, from all parts of the fault that rupture. Though P waves from an earthquake are generated at about 20 percent of the S-wave level, they have a four-lobed radiation pattern of alternating compressions and rarefactions in the radiated first motions, rather than the relatively uniform pattern of P-wave compressions radiated in all directions from an explosion source. These idealized radiation patterns,. P waves from an earthquake and an explosion, are shown schematically at the top of figure 5-4. These two types of source geometries result in the following differences:

1. **Energy partitioning.** The energy of a seismic event is partitioned into compressional, shear, and surface waves. Earthquakes tend to emit more energy in the form of shear waves and surface waves than explosions with comparable compressional waves (figure 5-4). At lower magnitudes, however, differences of this type may be difficult to distinguish if the surface waves from either source become too small to detect.
2. Dimensions of the source. Earthquakes tend to have larger source dimensions than explosions because they involve a larger volume of rock. The bigger the source volume, the longer the wavelength of seismic waves setup by the source. As a result, earthquakes usually emit seismic waves with longer wavelengths than explosions. Instead of describing the signal in terms of wavelength, an equivalent description can be given in terms of seismic wave frequency. Explosions, which

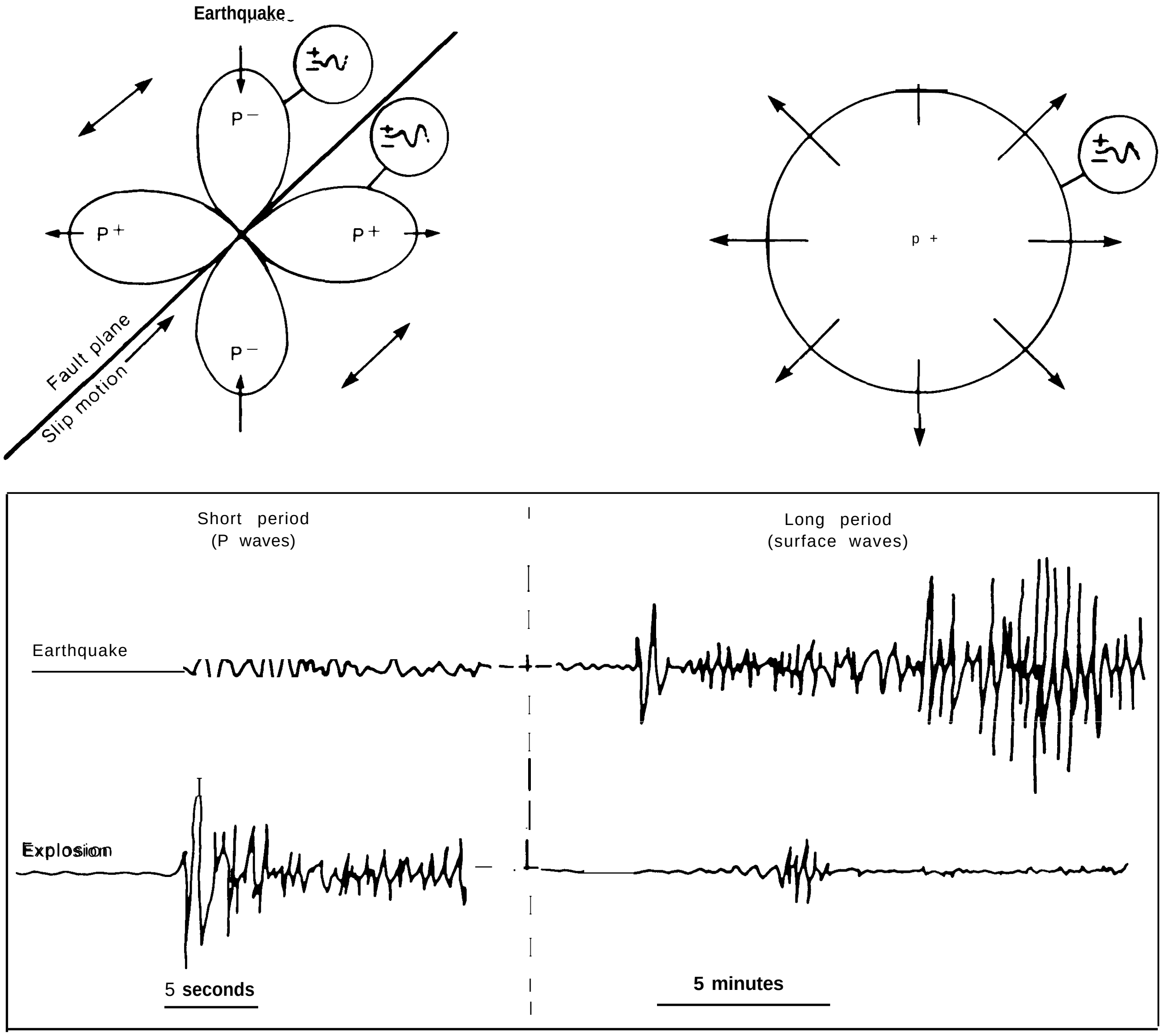
Box 5-A.—Theory and Observation

One of the points on which early efforts at discrimination stumbled was the claim that explosions, because they are concentrated pressure sources, would generate insignificant SH waves and Love waves. (These waves entail types of shearing motion, in which the ground moves in a horizontal direction.) But it was soon found, in the early 1960s, that some explosions generated quite strong SH and Love waves, so this discriminant came to be seen as unreliable.

A salutary further effect was that discriminants based purely on theoretical predictions came to carry little weight until they had passed stringent tests with actual data from explosion and earthquake sources. Occasionally, some useful discriminants are discovered empirically and a theoretical understanding is not immediately available. A recent example of this is the observation that regional phases P_n, P_g, and L_g for small earthquakes in the western U.S. typically exhibit more high-frequency energy (at 6-8 Hz) than do small NTS nuclear explosions of comparable seismic magnitude.* However, in the symbiotic relation between theory and observation, there is generally a framework of understanding in which progress in one field guides workers to new results in the other.

*J-R. Murphy and T.J. "A Discrimination Analysis of Short-Period Regional Seismic Data Recorded at Tonto Forest Observatory," *Bulletin of the Seismological Society of America*, vol. 72, No. 4, August 1982, pp. 1351-1366.

Figure 5-4.—Earthquakes v. Explosions



(Upper) Different radiation patterns for earthquakes and explosions. Earthquakes involve shear motion along a fault plane. Explosions are compressional sources of energy and radiate P waves in all directions.
(Lower) Recorded signals (i.e., seismograms) of earthquakes and explosions generally have different characteristic features. Note the much stronger P-wave: surface-wave ratio, for explosions as compared to the earthquake.

SOURCE: F. Ringdal, "Seismological Verification of Comprehensive Test Ban Treaty," paper presented *in* "Workshop on Seismological Verification of a Comprehensive Test Ban Treaty," June 4-7, 1985, Oslo, Norway.

are small, intense sources, send out stronger signals at high frequencies; and earthquakes generally have more low-frequency (long-wavelength) energy than explosions (figure 5-4). However, exceptions have been observed and the distinction may diminish for small events. The difference in frequency content of the respective signals, particularly at high frequencies, is a topic of active research.

These basic differences in seismic signal are understood on theoretical grounds; and this theoretical framework guides the search for new empirical methods of identification. As new types of seismic data become available (for example, data from within the Soviet Union), it maybe expected that methods of identification will be found that work at smaller magnitude levels. At low magnitudes, however, we have not only the problem of distinguishing nuclear explosions from earthquakes, but also of distinguishing nuclear explosions from the large chemical explosions that are commonly used for industrial purposes such as mining. This is a much more difficult problem because in theory the two source types should produce similar signals.

Chemical Explosions

Chemical explosions are used routinely in the mining and construction industries, and they occur also in military programs and on nuclear test sites. In general, from the seismic monitoring perspective, a chemical explosion is a small spherical source of energy very similar to a nuclear explosion. The magnitudes caused by chemical explosions are generally below m_b 4.0, although events with magnitudes up to m_b 4.5 occasionally occur. The fact that large numbers of chemical explosions in the yield range from 0.001 to 0.01 kt are detected and located seismically is a testament to the capability of local and regional seismic networks to work with signals below m_b 3.0.

There is little summary information available on the number and location of chemical explosions in the U. S. S. R., though it appears that useful summaries could be prepared from currently available seismic data. In the United States, chemical explosions around 0.2 kt are common at about 20 mines. At each of these special locations, tens of such explosions may occur each year. Presuming that similar operations are mounted in the U. S. S. R., this activity is clearly a challenge when monitoring nuclear explosions with yields below about 1 kt. It is also a challenge when considering the possibility that a nuclear testing nation may seek to muffle a larger nuclear explosion (say, around 5 kt), so that its seismic signals resemble those of a much smaller (say, around 0.1 kt) chemical explosion.

The problem of identifying industrial explosions can be partially constrained in three ways:

1. In the United States, almost all chemical explosions detonated with yields 0.1 kt or greater for industrial purposes are in fact a series of more than a hundred small explosions spaced a few meters apart and fired at shallow depth with smalltime delays between individual detonations. One effect of such "ripple-firing" is to generate seismic signals rather like that of a small earthquake, in that both these types of sources (ripple-fired chemical explosions, and small earthquakes) occur over a large area and thus lose some of the characteristics of a highly concentrated source such as a nuclear explosion. If individual salvos are large enough, however, they might be able to mask the signals from a sub-kiloton nuclear explosion. Recent research on this problem has shown the importance of acquiring seismic data at high frequencies (30-50 Hz); and indeed, such data suggest the existence of a distinctive signature for ripple-fired explosions.[1 2 3]
2. Many of the rare chemical explosions above about 0.5 kt that are not ripple fired can be expected to result in substantial ground deformation (e.g., cratering).[4] Such surface effects, together with absence of a radiochemical signal, would indicate a chemical rather than a nuclear explosion source. The basis for this discriminant is

[1] **A.T.** Smith and **R.D.** Grose, "High-Frequency Observations of Signals and Noise Near **RSON:** Implications for Discrimination of Ripple-fired Mining Blasts," **LLNL** UCID-20945, 1987.

[2] **A.T.** Smith, "Seismic Site Selection at High Frequencies: A Case Study, " **LLNL** UCID-21047, 1987.

[3] **D.R. Baumgardt**, "Spectral Evidence for Source Differences between Earthquakes and Mining Explosions in Norway," ***Seismological Research*** *Letters*, vol. 38, January-March 1987, p. 17.

[4] 1t is also relevant that chemical explosions in the 0.1 -0.5 kt range are commonly observed to be quite efficient in generating seismic waves. For example, 0.5 kt chemical explosions are known to have m_b around 4.5 for shield regions.

that chemical explosions are typically very shallow.

3. To the extent that remote methods of monitoring chemical explosions are deemed inadequate (for example, in a low yield threshold or comprehensive test ban regime), solutions could besought by requiring such constraints as prior announcement of certain types of chemical explosions, inspections, shot-time monitoring, and in-country radiochemical monitoring. Note that in the United States (and so perhaps also in the U. S. S. R.) chemical explosions above 0.1 kt occur routinely at only a limited number of sites.

Rockbursts

In underground mining involving tunneling activities, the rock face in the deeper tunnels may occasionally rupture suddenly into the tunnel. This is referred to as a rockburst and results from the difference between the low pressure existing within the tunnel and the great pressure that exists within the surrounding rock. To prevent such mine rockbursts, bracing structures are used in the deeper tunnels.

In terms of magnitude, rockbursts are all small. They occur over very restricted regions of the Earth and generally have a seismic magnitude of less than 4.0 m_b.

The source mechanisms of rockbursts are very similar to those of small earthquakes. In particular, the direction of the first seismic motion from a rockburst will have a pattern similar to that for earthquakes. Therefore, for the seismic identification problem, rockbursts can be considered small earthquakes which occur at very shallow depths.

METHODS OF IDENTIFICATION

Over the years, a number of identification methods have been shown to be fairly robust. Some of these methods perform the identification process by identifying certain earthquakes as being earthquakes (but not identifying explosions as being explosions). Other identification methods identify certain earthquakes as being earthquakes and certain explosions as being explosions. The identification process is therefore a winnowing process.

Location

The principal identification method is based on the location of a detected seismic source. If the epicenter (the point on the Earth's surface above the location) is determined to be in an oceanic area, but no hydroacoustic signals were recorded, then the event is identified as an earthquake. Large numbers of seismic events can *routinely* be identified in this way, because so much of the Earth's seismic activity occurs beneath the ocean. If the location is determined to be land, then in certain cases the event can still be identified as an earthquake on the basis of location alone, e.g. if the site is clearly not suitable for nuclear explosions (such as near population centers) or if there is no evidence of human activity in the area.

Depth

With the exception of epicenter locations, seismic source depth is the most useful discriminant for identifying large numbers of earthquakes. A seismic event can be identified with high confidence as an earthquake if its depth is determined to be below 15 kilometers.

The procedure for determining source depth is part of finding the event location using the arrival time of four or more P-wave signals. Also, certain seismic signals, caused by energy that has traveled upward from the source, reflected off the Earth's surface above the source region, and then traveled down into the Earth, are similar to the P wave out to great distances. A depth estimate can be obtained by measuring the time-difference between the first arriving P-wave energy and the arrival time of these reflected signals. The analysis of broadband data through wave-form modeling is particularly useful for detecting these reflected signals. Empirical methods can also be used, based on comparison with previously interpreted seismic events in the same general region as the event under study.

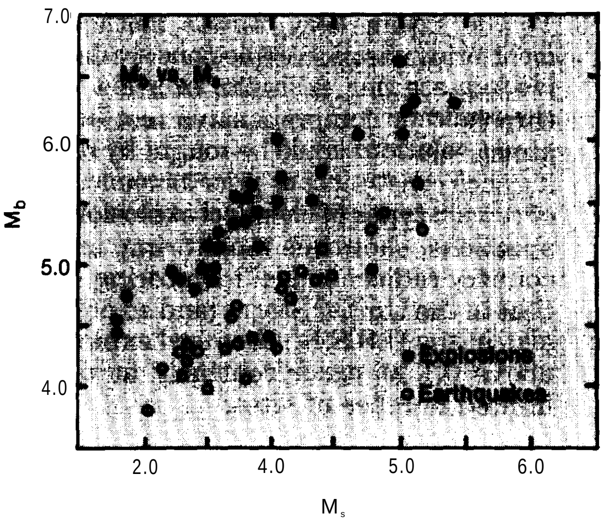
In principle, an advantage of depth as an identification method is that it is not dependent on magnitude: it will work for small events as well as large ones, provided the basic data are of adequate signal quality and the signals are detected at a sufficient number of stations. It will not alone, however, distinguish between chemical and nuclear explosions unless the nuclear explosion is relatively large and deep; or between underground nuclear explosions and earthquakes unless the earthquakes are sufficiently deep.

M_s:m_b

Underground nuclear explosions generate signals which tend to have surface wave magnitude (M_s) and body wave magnitudes (rob) that differ from those of earthquake signals. This is basically a result of explosions emitting more energy in the form of body waves (high-frequency seismic radiation), and earthquakes emitting more energy in the form of surface waves (low frequency seismic radiation). The phenomenon is often apparent in the original seismograms (figure 5-4), and examples are shown in terms of M_s:m_b diagrams in figures 5-5, 5-6, and 5-7. These diagrams can be thought of as separating the population of explosions from that of earthquakes. For any event which is clearly in one population or another, the event is identified. For any event which is between the two populations (as occasionally happens for explosions at the Nevada Test Site), this method does not provide reliable identification. The method, therefore, has the potential of identifying certain earthquakes as being earthquakes and certain explosions as being explosions.

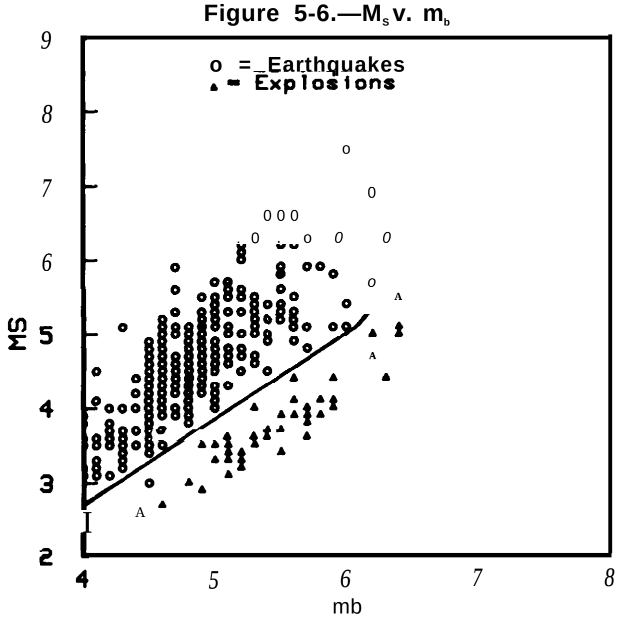
To use this identification method, both m_b and M_s values are required for the event. This is no problem for the larger events, but for smaller events (below m_b 4.5) it can be very difficult to detect low-frequency surface waves using external stations alone.[5] This difficulty is present particularly for explosions, with the

Figure 5-5.—M_s v. m_b for a Suite of Earthquakes and Explosions



SOURCE: P.D. Marshall and P.W. Basham, Geophysical Journal of the Royal As. tronomical Society, vol. 28, pp. 431-458, 1972.

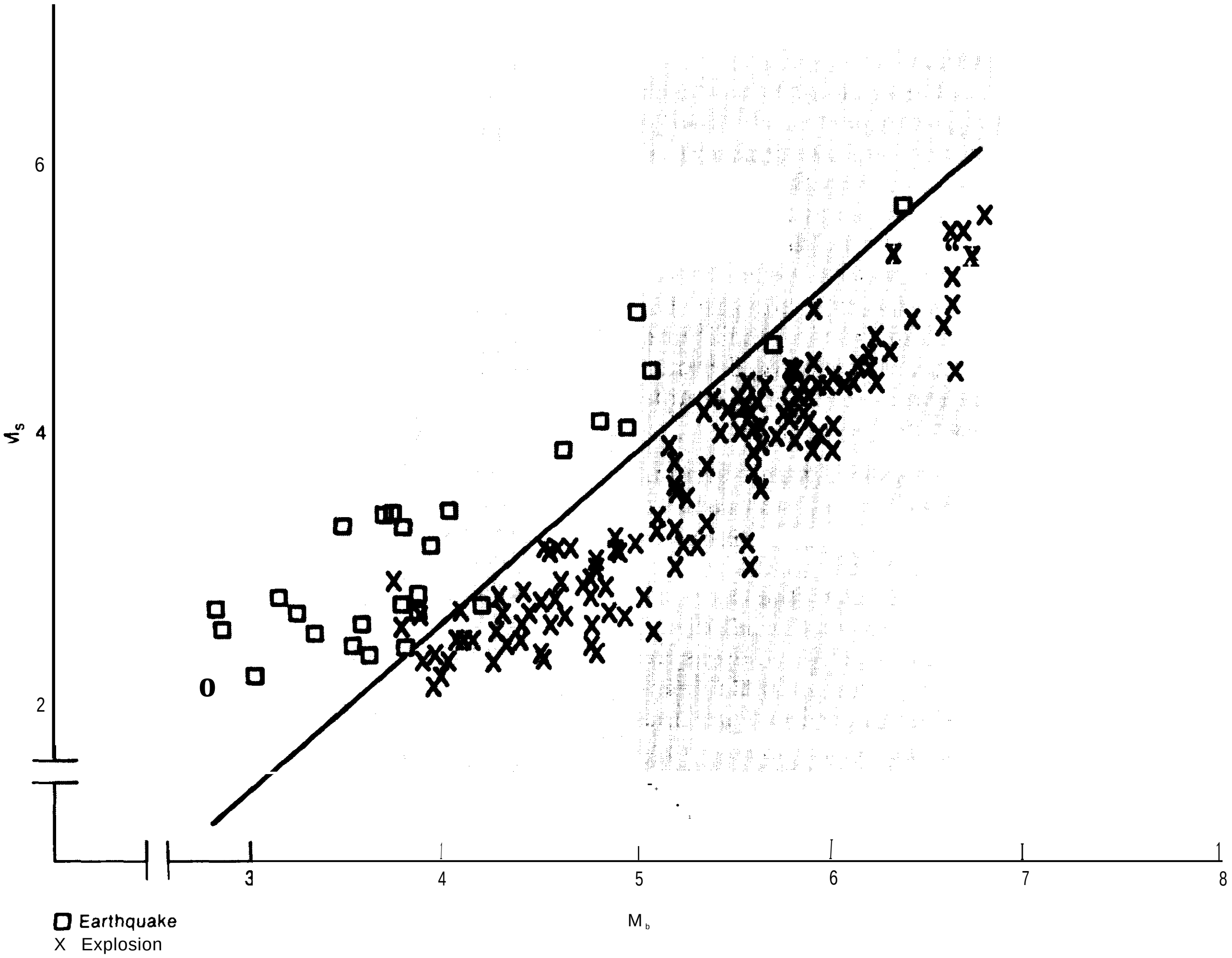
Figure 5-6.—M_s v. m_b



SOURCE: L.R. Sykes, J.F. Evernden, I.L. Cifuentes, American Institute of Physics, Conference *Proceeding 104,* pp. 85-133, 1983. (All of the events (both earthquakes and explosions) were corrected for bias.]

[5] In special studies of regional data that evaluate the M_s:m_b discriminant, it has been found that between 10 percent and 20 percent of the surface waves of small events are masked by signals caused by other events. This, however, has little net effect on the discrimination of events for which more than one station is close enough to receive surface waves.

Figure 5-7.—The m_b:M_s Discriminant for Populations of NTS Explosions and Western U.S. Earthquakes



SOURCE: Modified from S.R. Taylor, M.D. Denny, and E.S. Vergino, *Regional m_b:M_s Discrimination of NTS Explosions and Western United States Earthquakes A* Progress Report, Lawrence Livermore National Laboratory January 1986.

result that the M_s:m_b method works intrinsically better for identifying small earthquakes than it does for identifying small explosions. Internal stations would provide important additional capability for obtaining M_s values for events down to m_b 3.0 and perhaps below.

It is known that M_s:m_b diagrams, with their separate populations as shown in figures 5-5, 5-6, and 5-7, tend in detail to exhibit somewhat different properties for sources occurring in different geophysical provinces. That is, the best identification capabilities are obtained, for a particular event of interest, if there is already a data base and an associated M_s:m_b diagram tailored for the general region of the Earth in which that event occurred.

The M_s:m_b method has proven to be the most robust identification technique available for shallow events. For events below m_b 4.0, the separation between the two M_s:m_b populations has been found to decrease in some studies. In the opinion of many seismologists, however, a useful separation (at low magnitudes) may be possible if good quality data for such small events can be found. Again, in the context of monitoring for small underground explosions in the U. S. S. R., obtaining such data would require in-country stations and empirical confirmation.

Other Simple Methods

Several other methods, with applications in particular circumstances, are used to provide identification. Several are still in the research stage, and are having an impact on the design of new instruments and the development of new procedures in data analysis. Some of these methods, based on the whole spectrum of frequencies contained in a seismic signal, are described in the following section. Other methods have been used for decades, and are still occasionally important for use in identifying certain problem events. In order of decreasing importance, the remaining three simple methods can be listed as follows:

1. The use of “first motion.” By this term is meant an identification method based on differences in the direction of the initial motion of P waves. As illustrated in figure 5-4, an explosion is expected to create initial compressive motions in all directions away from the source, whereas an earthquake typically creates initial compressive motions in some directions and rarefactional motions in others. In a compressive wave, the ground first moves away from the source. In a rarefaction, the ground first moves toward the source. From a good seismometer recording, it is often possible to observe the direction of this initial motion (for example, from observation of whether the ground first moves up or down at the seismometer). This identification method can be powerful if the signal-to-noise ratio is large. But for small events in the presence of seismic noise (as discussed in chapter 4) it can be difficult or impossible to determine the direction of the first motion. Because it is never clear that rarefactional motions may not exist in directions for which network coverage is poor, the method at best identifies an earthquake as an earthquake, but cannot unequivocally identify an explosion as an explosion.
2. The observation of S waves. Because of the compressive nature of explosion sources, explosions typically generate less shear wave energy than do most earthquakes. Therefore, the observation of significant shear wave energy is indicative that the event is probably an earthquake.
3. Complexity. Many explosion-generated body wave signals tend to be relatively simple, consisting of just a few cycles. Many earthquake-generated body wave signals tend to be relatively complex, consisting of a long series (known as the coda) following the initial few P-wave cycles. The concept of complexity was developed in an attempt to quantify this difference in signal duration. Complexity is the comparison of amplitudes of the initial part of the short-period signal with those of the succeeding coda. There are cases, however, where an explosion signal is complex at some stations and an earthquake signal is simple. Therefore, the complexity method is regarded as not as reliable as M_s:m_b. In practice, whenever the complexity method works, other identification methods also work very well.

Spectral Methods

The basis of the success of M_s:m_b diagrams is, in part, the fact that the ratio of low frequency waves to high frequency waves is typically different for earthquakes and explosions. Thus, M_s is a measure of signal strength at around a frequency of 0.05 Hz, and m_b is a measure of signal strength at around a frequency of 1 Hz. As a way of exploiting such differences, M_s:m_b diagrams are quite crude compared to methods that use a more complete characterization of the frequency content of seismic signals. The analysis of earthquake and explosion signals across their entire spectrum of frequencies is an important component of the current research and development effort in seismic monitoring.

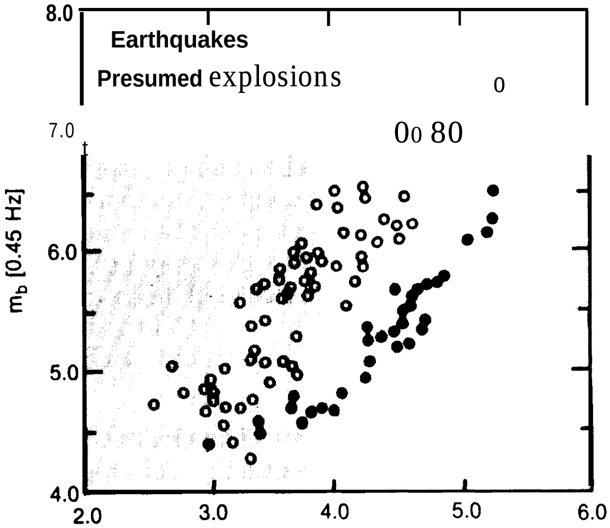
Because M_s:m_b diagrams work well when surface waves are large enough to be measured, the main contribution required of more sophisticated analysis is to make better use of the information contained in the P-wave signals and other large amplitude, high frequency signals. This offers the prospect of improved identification capabilities just where they are most needed, namely for smaller events. Thus, instead of boiling down the P-wave signals at all stations simply to a network m_b value, one can measure the amplitude at a variety of frequencies and seek a discriminant which works on systematic differences in the way earthquake and explosion signals vary with frequency. One such procedure is the variable *frequency-magnitude (VFM)* method, in which the short-period body wave signal strength is measured from seismograms filtered to pass energy at different frequencies, say, f_1 and f_2.[6] Discrimination based on a comparison of $m_b(f_1)$ and $m_b(f_2)$ in many cases shows a clear separation of earthquake and explosion populations (figure 5-8).[7,8,9]

An analogy for the VFM discriminant would be a person's ability to tell by ear the difference between a choir with loud sopranos and weak contraltos, and a choir with loud contraltos and weak sopranos. M_s:m_b is like comparing basses and contraltos. For small events, VFM is complementary to M_s:m_b in several ways: VFM is improved by interference of the main P wave with waves reflected from the surface above the explosion, while M_s:m_b is degraded; VFM is more effective for hard rock explosions, while M_s:m_b will preferentially discriminate explosions in low-velocity materials; and VFM is insensitive to fault orientation. Further, the M_s:m_b method requires averaging over observations from a network of stations surrounding the event, while the VFM method may be applied at a single station at any distance and direction from the source. It is found in practice, however, that the VFM method is most reliable when several high performance stations are used. (Obviously if several stations provide VFM data independently identifying an event, as an explosion for example, then assigning a numerical probability that the event observed was indeed an explosion can be accomplished with more reliability and confidence.) VFM is more sensitive to noise and regional attenuation differences than M_s:m_b, but *the main point is that simultaneous use of both methods should allow improved discrimination of small events.*

High-Frequency Signals

The use of high-frequency signals in seismic monitoring is strongly linked to the question of what can be learned from seismic stations in the U.S.S.R. whose data is made available to the United States. Such "in-country" or "internal" stations were considered in CTBT negotiations in the late 1950s and early 1960s, and the technical community concerned with monitoring in those years was well aware that seismic signals up to several tens of Hz could propagate from explosions out to distances of

Figure 5-8.—The VFM Method



The body-wave magnitude is determined at two different frequencies. Earthquakes and explosions fall into separate populations because explosions are relatively efficient at generating higher frequencies.

SOURCE: J.L. Stevens and S.M. Day, *Journal of Geophysical Research,* vol 90, pp. 3009-3020, 1985.

[6] C.B. Archambeau, D.G. Harkrider and D.V. Helmberger, U.S. Arms Control Agency Report, "Study of Multiple Seismic Events," California Institute of Technology, ACDA/ST-220, 1974.

[7] J.F. Evernden, "Spectral Characteristics of the P-codas of Eurasian Earthquakes and Explosions," *Bulletin of the Seismological Society of America,* vol. 67, 1977, pp. 1153-1171.

[8] J.M. Savino, C.B. Archambeau, and J.F. Masse, *Discrimination Results From a Ten Station Network,* DARPA Report SSS-CR-79-4566, S-CUBED, La Jolla, CA, 1980.

[9] J.L. Stevens and S.M. Day, "The Physical Basis for m_b:M_s and Variable Frequency Magnitude Methods for Earthquake/Explosion Discrimination," *Journal of Geophysical Research,* vol. 90, March 1985, pp. 3009-3020.

several hundred kilometers. The seismic waves most prominent at these so-called "regional distances" (by convention, this means distances less than about 2,000 km) are known as P_g, P_n, S_n, and L (see ch. 3 for a discussion of these regional waves). P_g propagates wholly within the crust; P_n and S_n travel at the top of the mantle just below the base of the crust; and L_g, guided largely by the crustal layer, is often the strongest signal and is sometimes observed across continents even at distances of several thousand kilometers.

However, this early interest in regional waves lessened once the Limited Test Ban Treaty of 1963 was signed and it was recognized that subsequent programs of large underground nuclear explosions could be monitored teleseismically (i.e., at distances beyond 2,000 km), so that internal stations were not needed. At teleseismic distances, seismic body wave signals are usually simpler and have indeed proved adequate for most purposes of current seismic monitoring, even under treaty restrictions on underground nuclear testing that have developed since 1963. Thus, it is in the context of considering further restraints on testing, such as a comprehensive or low-yield test ban, that the seismic monitoring community needs to evaluate high-frequency regional seismic signals. The basis for the role of high-frequency monitoring, in such a hypothetical new testing regime, is that the greatest challenge will come from decoupled nuclear explosions of a few kilotons, and for them the most favorable signal-to-noise ratios may beat high frequency. Internal stations, of high quality and at quiet sites, will be essential to address the monitoring issues associated with such events.

It is clear that a dedicated program to make optimal use of high-frequency seismic data from internal stations should lead to significant improvements in detection capability.[10] The daily recording of many very small seismic events, together with the possibilities for evasion at low-yields, focuses attention on the discrimination problem for events in the magnitude range m_b 2.0 to m_b 4.0.

For an explosion that is well-coupled to the ground, an m_b = 2.0 can be caused by only a few thousandths of a kiloton, that is, a few tons of TNT equivalent. At this level, a monitoring program would confront perhaps 1,000 to 10,000 chemical explosions per year. Given the difficulty of discriminating between chemical and nuclear explosions, it is clear that below some level events will still be detected but identification will not be possible with high confidence. However, recognizing that relatively few chemical explosions occur at the upper end of this m_b range (2.0 - 4.0), where many chemical explosions can be identified by characteristics of their signals over a broad frequency band (see the earlier discussion of ripple-fired chemical explosions), high frequency data recorded within the U.S.S.R. can clearly contribute substantially to an improved monitoring capability. It is difficult to reach precise but general conclusions on what future yield levels could be monitored, because much will depend on the degree of effort put into new seismic networks and data analysis. Conclusions would depend too on judgments about the level of effort that might be put into clandestine nuclear testing. The discussion of evasion scenarios is taken up in the next chapter, and high-frequency seismic data are clearly useful for defeating some attempts to hide small nuclear explosions.

[10] For a more complete discussion of the use of high-frequency data for detection, see ch. 4, "Detecting Seismic Events."

IDENTIFICATION CAPABILITY

By applying one or more of the methods discussed above, many seismic events can be identified with high confidence. Note, however, that no one method is completely reliable. It is the set of different identification methods, taken as a whole and applied in a systematic fashion, that must be assessed when giving summaries on capability.

Identification Capability Within the U.S.S.R. Using No Internal Stations

The identification capability of any network of seismic stations will always be poorer than the *detection* capability for that network. In general, a rough estimate of the 90 percent identification threshold will be about 0.5 m_b above the 90 percent detection threshold for magnitudes above m_b 3.5. Below a magnitude of about 3.5 m_b, this difference may be larer than 0.5 m_b.

In the previous chapter, a network consisting of a dozen or so arrays all *outside* the Soviet Union was discussed as a type example to convey a sense of what capabilities can be achieved. A cautious calculation of the *detection* capability for such a network was that it would have a 90 percent probability of detecting at four or more stations all seismic events within the Soviet Union with a magnitude (rob) of 3.5 or greater.” Therefore, for seismic events in the U. S. S. R., a cautious estimate of the *identification* capability of such a network external to the Soviet Union is that the 90 identification threshold will be m_b 4.0. From table 5-1, it can be seen that approximately 180 earthquakes occur at magnitude 4.0 or above each year on Soviet land areas. This would mean that approximately 18 of these earthquakes would not be identified with high confidence by routine seismic means alone. This, however, does not translate into an opportunity to cheat, because from the cheater's perspective there is only a one-in-ten chance that any given event above this magnitude will not be identified through seismic means.

Events larger than this will be identified seismically with even higher confidence. A larger percentage of the events that are smaller will not be identified, and the number of events will also increase with decreasing seismic magnitude.

“See ch. 4, “Detecting Seismic Events. ”

Identification Capability Within the U.S.S.R. Using Internal Stations

With a number of internal stations, it is clearly possible to attain a much improved detection and location capability within the Soviet Union. From estimates described in the previous chapter, there is consensus that detection capability (90 percent probability of detection at four or more stations) of m_b 2.() -2.5 can be realized, although the debate is not yet resolved on the number of internal stations that would be required, nor on whether the value is closer to m_b 2.0 or m_b 2.5.

A detection capability down to somewhere in the range m_b 2.0-2.5, however, cannot be easily translated into a statement about identification capability. Estimation of the capability of hypothetical networks, using regional seismic waves, is difficult because data on noise levels and signal propagation efficiency are not usually available and assumptions must be made that turn out to have a strong influence on conclusions. Although there is now general agreement on the *detection* capability of hypothetical networks, there are some significant differences in opinion on the identification capability such networks provide.

Discussion of identification capability for small events (m_b in the range 2.5- 4.0), using internal stations, is one of the main areas of technical debate in seismic monitoring. Internal stations will significantly improve the capability to identify many small earthquakes as earthquakes, because such stations extend the discriminants related to the M_s:m_b method down to lower magnitudes. (Internal stations will also permit more accurate determination of epicenters and source depths, thus supplying for small events the most basic information upon which most sources are identified.) But certain types of shallow earthquakes, below some observable magnitude level, are recognized as difficult if not impossible to identify. Also, preliminary use of high frequencies in the United States, to discriminate the explosion signals of small nuclear tests in Nevada from signals of small earthquakes in the western United States, has had some discouraging results. While some say that this is indicative merely of difficulties associated with high frequency seismic wave propagation in the western United States (and that high frequencies propagate with higher signal-to-noise ratios in the U. S. S. R.) or that the instrumentation used in the study prevented data of sufficiently high quality from being brought to bear on the problem, others claim that these preliminary results are valid and are indicative of a fundamental lack of capability in the seismic method, at very small magnitudes.

In the absence of access to extensive Soviet data (particularly, explosion data), some guidance in what might be possible is given by detailed studies of experience with U.S. explosions. Here, it is recognized that use of more than one discriminant results in improvement over use of the single best discriminant (which is usually M_s:m_b). In one multi-discriminant experiment for U.S. explosions and earthquakes which drew heavily on data such as that presented in the last diagram of figure 5-5 (in which m_b for some earthquakes is less than 3.0), seismic discrimination was achieved for all events that had both m_b and M_S values.[12 13] The discriminants tested were M_s:m_b, combined with a list that included relative excitation of short-period SH waves; relative signal amplitudes for P_n, P_g, L_g, and the largest part of the P wave; generation of higher mode surface waves; long-period surface wave energy density; relative amplitudes of crustal Love and Rayleigh waves; excitation of S_n; spectral ratios of P_n, P_g and L ; various other spectral methods; and a dept discriminant (see box 5-B). Not included, was what in practice in the U.S.S.R. would be a key but not definitive discriminant, namely an interpretation of the epicenter location.

From this body of experience, there appears to be agreement that, with internal stations that detect down tomb 2.0-2.5, identification can be accomplished in the U.S.S.R. down to at *least* as low as m_b 3.5. This cautious identification threshold is currently set by the uncertainty associated with identifying routine chemical explosions that occur below this level. Many experts claim that this identification threshold is too cautious and that with an internal network, identification could be done with high confidence down to m_b 3.0. At present, however, this has not been accepted as a consensus view, partly because some experts are on principle unwilling to extrapolate from experience with limited U.S. data to a hypothetical situation that relies on internal stations in the U.S.S.R. On the other hand, advocates of high-frequency monitoring maintain that identification can be routine at thresholds well below m_b 3.0. The acceptance of an identification capability below m_b 3.0, however, would probably require practical experience with data from a monitoring network throughout the Soviet Union.

Box 5-B.—Progress in Seismic Monitoring

Progress in seismic monitoring has been characterized by research results that, when first offered, seemed optimistic but which in several key areas have withstood detailed subsequent study and thus have become accepted. Occasionally there have been setbacks, as noted elsewhere in describing explosion-induced S-waves, and signal complexity.

The current situation is still one of active research, in that spectral discriminants have been proposed that (if corroborated by empirical data, which is now lacking) would permit monitoring down to fractions of a kiloton. A key problem in estimating what future capability is possible is that current research suggestions often entail data analysis significantly more sophisticated than that required for conventional discriminants. Database management would also have to be improved. The requirement, for operational purposes, that a discriminant be simple to apply, is thus in conflict with the requirement that the maximum amount of information be extracted from seismic signals.

[12] M.D. Denny, S.R. Taylor, and E.S. Vergino, "Investigations of m_b and M_s Formulas for the Western U.S. and Their Impact on the m_b:M_s Discriminant, " UCRL-95103 LLNL, August 1986.

[13] R.E. Glaser, S.R. Taylor, M.D. Denny, et.al., "Regional Discriminants of NTS Explosions and Western U.S. Earthquakes; Multivariate Discriminants, " UCID-20930 LLNL, November 1986.