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Seismic Verification of a Comprehensive Test Ban

W. J. Hannon

A Comprehensive Test Ban Treaty (CTBT) prohibiting all testing of nuclear weapons has been discussed for more than 20 years. In 1977 the United States, the Soviet Union, and the United Kingdom reentered formal CTBT negotiations. Although these negotiations have been in recess since 1980, public interest in such a test ban is widespread.

Summary. The capabilities of in-country seismic monitoring systems for verifying the absence of underground nuclear explosions are compared against challenges posed by possible clandestine testing schemes. Although analyses indicate that extensive networks of in-country seismic arrays are needed to verify a Comprehensive Test Ban Treaty, such networks cannot ensure that all underground nuclear explosions will be identified. Political and military judgments will determine the level of risk acceptable to each nation.

Adequate verification measures are central to both formal and informal CTBT discussions. Because the Limited Test Ban Treaty of 1963 prohibits testing in the atmosphere, oceans, and space, verification concerns introduced by a CTBT focus on testing underground. However, a CTBT may change the relative importance of verification issues under other treaties.

This article discusses the goals of verification for a test ban treaty and evaluates networks of seismic stations with characteristics similar to those proposed for a CTBT verification system (*1*). The performance of these networks is compared with the challenges posed by credible clandestine testing schemes.

The author is program manager of the Seismic Monitoring Research Program, Lawrence Livermore National Laboratory, Livermore, California 94550.

Goals and Costs

In general, three goals of adequate verification systems can be identified: (i) to deter militarily significant testing programs (*2*); (ii) to ensure that significant attempts to continue underground testing and evade detection are identified in time to respond appropriately (*3*); and (iii) to build confidence by minimizing the number of natural or man-made nonnuclear events that are misidentified as nuclear explosions or remain unidentified.

By definition, a CTBT prohibits all testing; however, the limitations of realistic monitoring systems prevent 100 percent verification of compliance. Therefore, realistic performance measures must be established. Political, military, and weapons design considerations will help define such performance measures (*4*) by balancing judgments about the relative importance of each goal with estimates of the technical capabilities of the monitoring systems, definitions of what constitute militarily significant testing programs, and broad national policy issues (for example, linkage to compliance in other arms control areas). If deterrence is emphasized, the perception of the verification system and cost-versus-benefit evaluation of clandestine tests by the nation considering them must be estimated by other nations. If assurance that a treaty violation will be identified is emphasized, political responses to incomplete evidence of clandestine testing are important.

In some cases, measures to meet one goal are sufficient to meet another; for example, requirements to ensure that clandestine testing or treaty evasion attempts will be identified are, themselves, significant deterrents. However, a balance must be struck. If the requirements for showing that a treaty violation has occurred include a low detection threshold, many small earthquakes and nonnuclear explosions will be detected but not identified, and this could decrease confidence that the treaty is being honored.

In discussions on adequate verification some hold the position that any testing by the other side significantly threatens national security (*2, 4*). Further, some speculate that the probability of evasion attempts, given the right circumstances, is high irrespective of potential political costs. Proponents of these views suggest that the probability of identifying a single clandestine test should approach 90 percent. Others argue that only repeated testing has military significance (*5*) and suggest that the costs of being caught are so high that even a small possibility of detection would be a deterrent. Proponents of this position suggest that our verification provisions need only a 30 percent probability of detecting a single test. In effect, they equate a high (but unspecified) degree of confidence in deterrence capability with a low probability of detecting a single violation. The two approaches can be compared quantitatively: given a 30 percent probability of detecting a single event, seven tests would have to be conducted before the probability of identifying at least one violation in the series exceeds 90 percent.

The costs of negotiating, deploying, and operating verification systems also help determine their specifications. Considerations include money and manpower and such intangibles as the presence of foreign personnel near sensitive locations, technology transfer, efforts to resolve false alarms in one's own and other countries, and concessions to negotiate verification provisions not desired by other treaty participants. Ultimately, each nation evaluates these costs in light of its security goals.

Verification Systems

Verification systems include components that are under differing degrees of national control. Some, called national technical means (NTM), are controlled by the monitoring nation—satellites and seismic stations operated outside the monitored country are examples. Others are negotiated as part of the treaty and involve interactions between treaty participants; for example, provisions for in-country local seismic networks and hydrodynamic measurements of yield are part of the Peaceful Nuclear Explosion Treaty. Finally, the openness of the society and the availability of information are factors.

Significant differences exist between NTM and negotiated elements. Although the NTM's precise properties are known by only one side or party to a treaty, many properties of and data from the negotiated provisions are known by both sides. The only aspects of the negotiated provisions that will not be known by all parties are the processing to be applied to the data and the decision-making steps that follow. Even these aspects can be partially determined through repeated exchanges about possible treaty violations, allowing potential evaders to calibrate the overall system.

Another difference is that countries may be unwilling to present evidence from NTM in international forums even though it indicates that a violation has occurred. Such decisions are made to protect some NTM capability for future use or because the credibility of the NTM has not been established internationally. Generally, neither consideration constrains negotiated provisions.

Verifying CTBT compliance requires both NTM and negotiated elements. NTM could include external seismic stations and satellites. Negotiated elements could include networks of seismic stations within the countries to be monitored, providing data to all treaty participants (*1*), and "voluntary" on-site inspection privileges to resolve ambiguous events (*4*).

In-Country Networks

There are significant differences between data recorded by external and in-country seismic stations. External stations, distant from potential test sites, record the motion of only a few useful waves (for example, compressional and surface waves) from larger events—that is with seismic magnitudes (m_b) greater than ~4. Frequencies greater than ~5 hertz in the data have generally been reduced by attenuation and scattering within the earth. In-country stations, being closer to the sources, record multiple useful waves with large amplitudes, broad spectra ($0.02 < f < 10$ hertz) (*6*), and, in some cases, even higher frequencies from both large and small events (Fig. 1) (*6a*).

These differences give in-country stations advantages for detecting seismic waves and identifying their sources. The large amplitudes increase the probability of detection. The multiple phases observed by in-country stations leave the source at different angles and provide more samples of the source radiation pattern. The broad spectra and high-frequency content increase opportunities for using spectral differences to distinguish between explosions and earthquakes (*7*). The proximity of source and receiver (<800 kilometers) helps locate the source more accurately.

To use these advantages, data acquisition equipment must have a large dynamic range and good resolution over a broad range of frequencies. Triaxial seismometers or small seismic arrays are needed to determine the direction from which the waves approach.

The data must be transmitted and checked to ensure faithful recording. Then they must be processed and analyzed in three interdependent steps: (i) initial data processing, including seismic signal detection, association with a common source, measurement of properties, and wave identification (compressional, shear, and so on); (ii) characterization of source properties, including origin time, epicenter, and azimuthal variation in the energy radiation pattern as a function of time and frequency; and (iii) identification and discrimination among sources (for example, nuclear versus chemical explosions or earthquakes) for events in regions of interest.

Well-defined signals from a few stations are used to determine a trial location and origin time. If a structural model has been determined from initial in-country studies, the arrival times and amplitudes of waves arriving at other stations are predicted and the seismic data at all stations reexamined for additional signals. Then the trial location is redetermined and the process repeated. The final location forms the basis for an initial decision about the signal source, the focusing of other NTM, and more intensive efforts to identify the source.

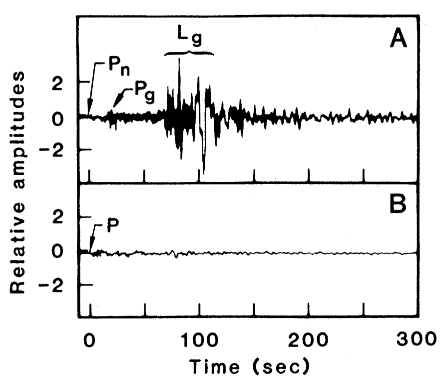


Fig. 1. First 300 seconds of vertical-component traces from two comparable earthquakes recorded on the same instrument. (A) "Regional" magnitude 5.6 event, 480 km from the station. (B) "Teleseismic" magnitude 6.4 event at 2990 km. The regional signal has larger amplitudes, more high-frequency information, and multiple identifiable phases to help detect, characterize, and identify the source. P_n and P_g are compressional waves that propagate in the upper mantle and crust, respectively. L_g is a complex wave composed of higher mode surface waves propagating in the crust. P_g and L_g are strongly dependent on the crustal structure and propagate to limited distances.

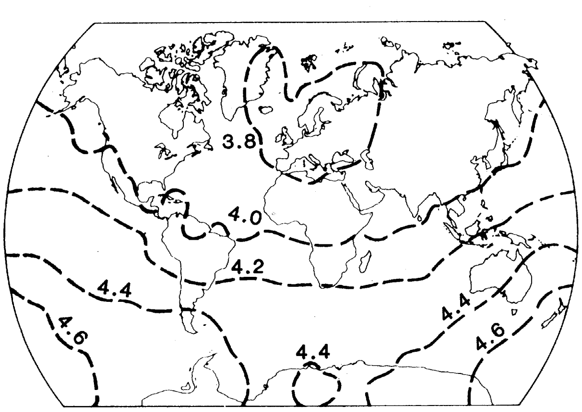
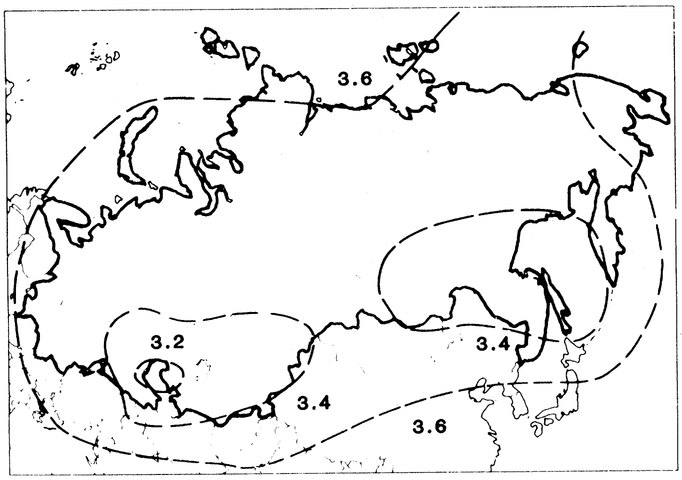


Fig. 2. Estimated short-period detection capability for hypothetical network of 50 stations distributed worldwide (*9*). The network represents existing stations, including five in the Soviet Union. Contours represent the m_b of the seismic event estimated to be detected with 90 percent confidence by a network of four or more stations.



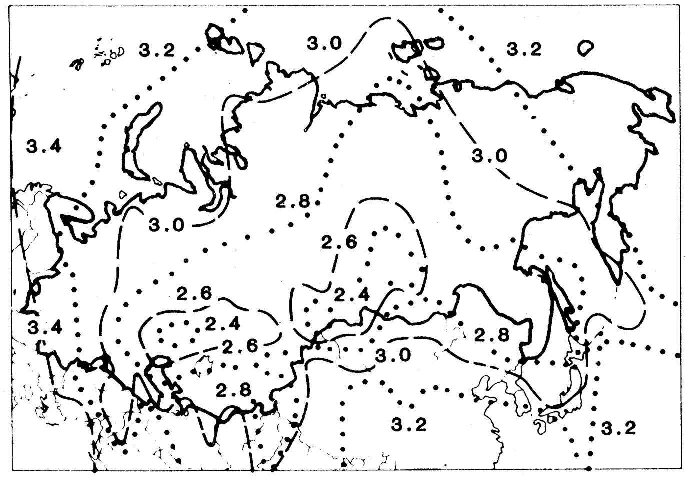


Fig. 3 (left). Estimated short-period detection capability at 90 percent confidence level for a network of 30 stations, including 15 within the Soviet Union (*5, 10*). Fig. 4 (right). Estimated short-period detection capability at 90 percent confidence level for a network with stations at the same sites as in Fig. 3 but with small arrays instead of single instruments at internal stations.

The information needed by the United States for these functions will be based on empirical and theoretical knowledge from studies of U.S. explosions and earthquakes and initial experience with in-country systems in the Soviet Union. Information about waveforms recorded at in-country stations from Soviet nuclear weapons tests or nuclear and chemical explosions in their civil applications program (*8*) is limited. This lack of in-country Soviet explosion data seriously limits U.S. confidence in its ability to identify small seismic events. The Soviets labor under no such limitation. U.S. seismic data and nuclear test information, including many explosion yields, are widely available.

Network Capabilities

At a given location, the detection capability of a seismic network is defined as the seismic magnitude of the source that will be detected there with a specified degree of confidence. Detection capability is estimated from the probability that the signal from a source at the given location will be sufficiently greater than the noise at a receiver site to be noticed by an analyst. Individual probabilities for distant stations, which contribute only a single short-period signal to the detection process, are combined to determine the probability that four or more stations will detect the event. (Four independent measurements are needed to determine the three spatial coordinates and the origin time of the source.) Figure 2 shows the calculational results for a hypothetical network of 50 stations distributed worldwide, including five in the Soviet Union (*9*).

Although nations could attempt clandestine testing outside their borders, and nuclear proliferation is a concern, the focus in this article is on monitoring within the Soviet Union. The size of the Soviet Union (almost 2.5 times larger than the contiguous United States) and operational and security considerations provide many possible sites for clandestine testing. Evernden (*10–12*) and Sykes and Evernden (*5*) describe a 30-station network for monitoring the Soviet Union. It includes 15 high-quality stations surrounding the Soviet Union and 15 simple stations, each with a single triaxial seismometer, within the Soviet Union. Figure 3 illustrates their estimates of this system's detection capabilities. Although their estimates do not make full use of regional phases to enhance detection capability, they predict significantly better capability than shown in Fig. 2.

Figure 4 indicates the detection capability predicted for the Sykes and Evernden network with 15 simple in-country stations replaced by small-aperture regional arrays. The improvements result from explicit use of multiple seismic waves and array stations in extensions of calculational procedures described by Evernden (*11*). The array stations were assumed to have an effective noise level 12 decibels lower than the simple stations and improved abilities to detect and use combinations of regional seismic waves (for example, P_n, P_g, and L_g in Fig. 1). These improvements may help locate seismic sources from signals detected at as few as two stations.

The network would be expected to have a 90 percent probability of detecting seismic events with magnitudes greater than 3.0 or 3.1 in about 90 percent of the Soviet Union (Fig. 4). This contrasts with detection capabilities of 3.8 to 3.9 for the network with distant stations only (*9*) and 3.4 to 3.5 for the Sykes and Evernden network (*5, 11*). The capabilities of networks with in-country arrays are as low as 2.4 in specific regions, but, because the properties of internal stations are known, these localized high capabilities may not represent conditions that are present when a clandestine test is attempted. Also, the networks include external stations of unknown political viability in Iran and Afghanistan.

Figure 5 indicates the dependence of detection capability estimates on the number of internal stations and contrasts the capabilities of simple stations with stations that are small-aperture regional arrays. These estimates involve assumptions about the regional properties of signals and noise in the Soviet Union because of the lack of information about seismic wave properties there.

Figure 6 shows the estimated effects of varying some parameters. Changes in the signal-to-noise ratio (SNR) and required confidence levels have significant effects. If the SNR at internal stations decreases 12 decibels, detection capability is degraded 0.4 magnitude units. Relaxing the degree of confidence from 90 to 30 percent produces an apparent increase in the network's detection capability of 0.25 magnitude units.

The sensitivity of the estimated capability to variations in SNR is particularly important because noise levels and wave-propagation properties in the Soviet Union are poorly known to the United States while the Soviets will know these properties and the real-time data from internal stations. Thus, explosion sites could be selected such that the paths attenuate signals to stations providing the greatest constraint on evasion, or explosions could be detonated during high noise, or both.

Characterization and Identification

If waves from an event have been detected, the source must be characterized and identified as a nuclear explosion, an earthquake, or a chemical explosion. This process has several elements. First, event depth is an initial discriminant since current drilling limits are less than approximately 15 kilometers. Therefore, we can eliminate from consideration with confidence events deeper than 25 kilometers.

Second, earthquakes of magnitude 4.5 and above occur in fairly well-defined areas in the Soviet Union (Fig. 7) (*13*). Events with magnitudes greater than 4 occurring outside these areas would be presumed explosions, and detection of such events is nearly equivalent to identification. Similar statements cannot be made for smaller magnitudes. For example, we recently supported a study of parts of Louisiana, Oklahoma, and Texas where only one earthquake with a magnitude greater than 4.5 occurred in 8 years. The study revealed almost one earthquake per day in the magnitude range of 2.0 to 3.9 (*14*). These results and the low-level seismicity observed in many areas with granite outcrops indicate that identification of small events will be a distinct operation throughout much of the Soviet Union.

One discriminant for large events that are not eliminated by depth or location is that surface-wave magnitudes for earthquakes are generally larger than those for explosions with the same body-wave magnitudes (*15, 16*). Although evidence is incomplete and contradictory, this separation may exist at low magnitudes in some regions (Fig. 8) (*17–19*).

Other promising discriminants based on variations in spectral content and radiation pattern (*7*) have received limited study for low-magnitude events. However, regional signal variations will cause the discriminants' effectiveness to vary significantly.

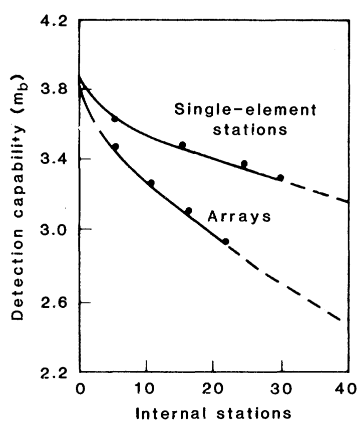
Characterization and identification typically involve spectral analyses and examination of seismic-wave particle motion, requiring a greater SNR than that for detection. Presumably most events of 0.5 magnitude units greater than the detection level will be characterized and identified (*11*).

The efficiencies of characterization and identification algorithms in this 0.5-magnitude-unit interval are not known for internal stations. We assume the algorithms are relatively efficient so that only 20 percent of the events in this interval will remain unidentified. Because small but potentially significant events (magnitudes 2 to 3) are poorly reported, their numbers must be estimated from larger events (Fig. 9) (*20*). Figure 9 shows estimates indicating that 100 to 1500 events per year may remain unidentified at magnitudes of 2 to 3. These magnitudes correspond to cavity-fired explosions with yields of a few kilotons (that is, equivalent to a few thousand tons of chemical explosives), and the events pose a significant problem to treaty verification. These estimates do not include contributions from earthquake swarms or aftershock sequences. These can contribute significant numbers of (often similar) events in limited time periods.

Constraints on Evasion

Successful evasion of the verification process can occur if any step in the process is prevented. Evasion is unnecessary if detected signals are attributed to natural seismic events or chemical explosions. Here, the focus is on evasion techniques that affect the detection of a nuclear explosion.

The probability of detection may be decreased by reducing the explosive energy that is transmitted (or coupled) into



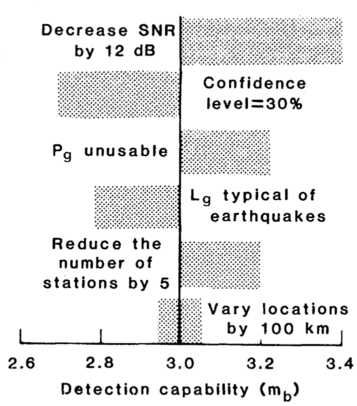


Fig. 5 (left). Overall detection capability as a function of number and type of internal stations. Above this magnitude, explosions at any point in 90 percent of the Soviet Union would be detected with 90 percent confidence. In specific areas, capability is up to 0.6 magnitude units better than overall network capability (see Figs. 2 to 4). Fig. 6 (right). Sensitivity of overall detection capability to variations in assumptions made in calculating network capability in Fig. 4. Calculations were carried out for a 90 percent degree of confidence.

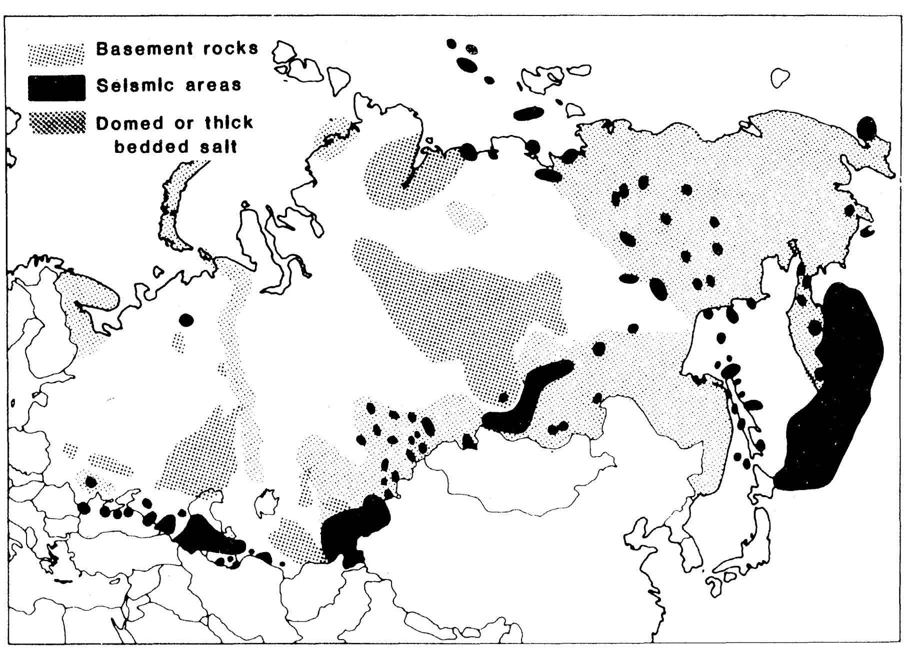


Fig. 7. Regions in the Soviet Union where earthquakes larger than magnitude 4.5 occurred between 1911 and 1967 (*13*) and regions of salt deposits and rock suitable for cavity decoupling (*27*). The distribution of smaller earthquakes is not known, but earthquakes in the range 2 to 2.5 are thought to be widespread (*14*).

the earth at the source or by choosing source-to-receiver paths that absorb significant seismic energy. Clandestine testing schemes that rely on decoupling appear to determine the numbers and types of in-country stations that are required for adequate verification. Schemes that rely on raising background noise, such as hiding explosion signals in earthquake coda or in natural or man-made noise, are also important but place less stringent constraints on the monitoring network.

To interpret network detection capabilities in terms of yield, the relations between magnitude and yield from the Nevada Test Site (NTS) are used (Fig. 10). Their applicability to the Soviet Union is under study. Various investigators (*21–23*) have shown that certain explosions at the main Soviet test site register several tenths of a magnitude unit higher than the same explosions at NTS, thus demonstrating a bias between the sites. The relation between magnitude and yield at low yields is uncertain.

The top band in Fig. 10 illustrates seismic magnitudes generated by explosions well coupled to hard rock in a region like NTS (*24, 25*). A well-coupled 1-kiloton (kt) explosion at the Soviet test site will have an average m_b of 3.8 to 4.2, depending on the NTS-Soviet bias.

Smaller m_b values can be generated for given yields by exploiting systematic reductions in the interaction between the explosion and surrounding material. The middle band in Fig. 10 shows the magnitude to yield relation expected for explosions detonated deep in dry alluvium like that in some NTS areas (*25*). Such material muffles explosions, and the depth prevents collapse craters common with shallow events.

Limited U.S. knowledge of Soviet geology indicates such material is rare in the Soviet Union. If it exists, 1-kt devices fired in it would have seismic magnitudes of 2.8 to 3.4, depending on the NTS-Soviet bias. Such events could remain undetected at the 90 percent confidence level by networks with 15 internal array stations (Fig. 4). Because characterization and identification capabilities require higher SNR's, the probability that networks would identify such explosions is significantly lower.

If cavities with explosion-produced wall stress below the elastic limit were constructed, further decoupling gains would be achieved. The lowest band in Fig. 10 shows the magnitude range predicted for explosions detonated in such cavities (*26*). If the variation in NTS-Soviet bias is combined with the spread in the decoupling factor and the magnitude-yield curves at low yields are known, cavity-detonated explosions with 1-kt yields would have seismic magnitudes in the range of 2.2 to 2.7. To approach the capability of detecting magnitude 2.6 events with 90 percent confidence in 90 percent of the Soviet Union, networks would need approximately 30 internal arrays (Fig. 5). Because the signals from decoupled explosions are small, the seismicity cannot be considered localized. Thus, additional array stations would be needed to achieve the same degree of confidence in characterization and identification. The negotiability of such networks is uncertain.

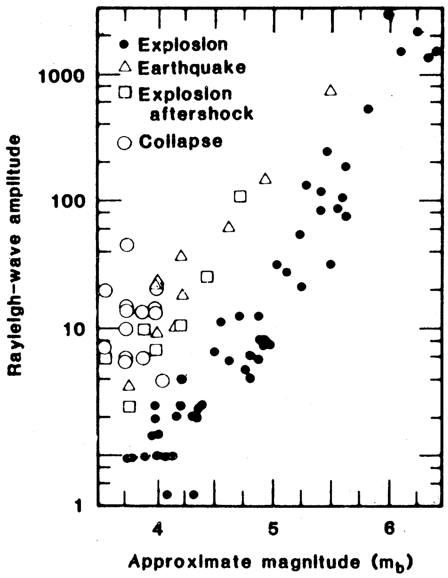
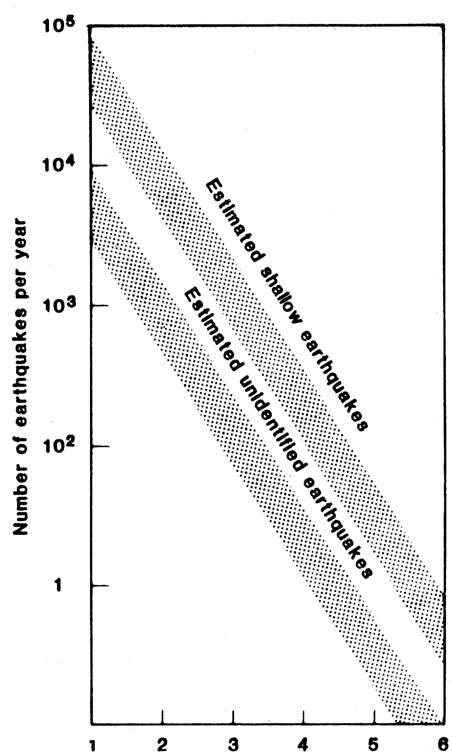


Fig. 8. Plot of Rayleigh-wave amplitude as a function of body-wave magnitude for small to medium seismic events in the western United States (*17*).

The estimate for networks with 15 array stations is that they could, with 90 percent confidence, detect cavity-decoupled events with yields of 3 to 10 kt [1 to 4 kt with 30 percent confidence (Figs. 5 and 9)], depending on the bias used. Some events in these ranges would not be identified, and the 90 percent confidence level for identification may include events twice as large. (However, it may be impossible to construct suitable, stable cavities for such large events.

Cavities sufficient to fully decouple 1-kt explosions would have volumes of 40,000 to 100,000 cubic meters, depending on the material in which they are constructed. Salt domes are especially attractive because of the volume of homogeneous, easily mined material that they contain. Assessments of the extent of salt domes and regions with thick, bedded salt (Fig. 7) indicate that opportunities for decoupling small events in salt cavities are widespread throughout the Soviet Union (*27*). To construct new cavities without suspicion would require suitable cover operations.

The advance of cavity-construction technology in various media (*28, 29*) significantly increases the area suitable for cavity decoupling. Many cavities are



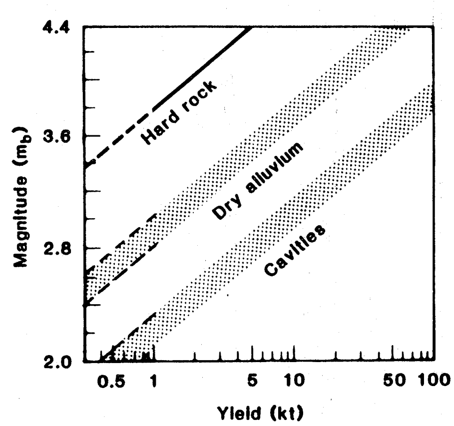


Fig. 9 (left). The annual number of shallow seismic events above a given magnitude varies with magnitude (upper band). We assume at least 20 percent of the detected events within 0.5 magnitude units of the overall detection threshold (especially those closest to the threshold) will not be identifiable (lower band). Fig. 10 (right). Seismic magnitude as a function of yield for different explosion environments. On the basis of data from the Nevada Test Site. Corresponding magnitudes for Soviet explosions could be several tenths higher. Values for yields of less than a few kilotons are extrapolated.

elongate, with widths narrower than the minimum desired for full decoupling. The overall volumes far exceed the total volume needed, however, and the asymmetry could generate radiation patterns that affect detection (*30*). Soviet regions underlain by suitable rock types for cavity construction are shown in Fig. 7.

It appears that cavity decoupling will significantly challenge CTBT verification of explosions near 1 kt, even with 30 in-country array stations. However, a possible decrease in the decoupling factor at higher frequencies (*31*), together with decreased noise levels at higher frequencies and good propagation of high-frequency seismic waves in some regions of the Soviet Union (*31, 32*), may make decoupling a less effective evasion tactic. These areas are being actively studied. Also, satellite surveillance may constrain the use of this evasion method in some areas.

Use of Increased Noise Levels

Earthquake signals could be used to mask explosion signals, although this approach lacks the flexibility of location or choice of firing time provided by cavity decoupling. Internal stations markedly decrease opportunities for such masked explosions, but the choice of the right test location could eventually allow detonations of explosions with yields of several kilotons. Choosing the location and detonation time is a significant technical challenge.

Accurate methods for predicting or exciting earthquakes could dramatically increase the usefulness of masking explosions in earthquake noise. At present, neither the United States nor the Soviet Union appears to have the requisite capabilities for large earthquakes, although both are actively involved in disaster prevention research. Periods of naturally occurring or man-made noise could also be used to mask explosion signals. This may seriously degrade the usefulness of low-noise sites for detecting and identifying clandestine explosions (*33*).

On-Site Inspection

The United States considers provisions for on-site inspections necessary for CTBT verification. Although the possibility of on-site inspections increases costs associated with clandestine testing and limits the data that can be collected from such tests, the efficiency of on-site inspections is unknown, and such inspections may not identify a violation identifiable by other means (*34*). Therefore, the role of on-site inspections in verification systems must be considered carefully. They may best be viewed as significant deterrents and a means of reducing false alarms and as providing sufficient but not necessary evidence for declaring a violation.

Conclusions

Seismic verification of a Comprehensive Test Ban Treaty will not ensure identification of all underground nuclear explosions. Political and military considerations must determine the degree of confidence desired of the verification system, what yields and number of tests constitute a militarily significant testing program, and the number of unidentified events that is acceptable, even if unresolved by on-site inspection.

Seismological analyses indicate that networks with 15 high-quality array stations in the Soviet Union could detect events with seismic magnitudes of 3.0 (and down to 2.4 localized regions). Such networks are thought to be capable of detecting cavity-decoupled explosions with 3- to 10-kt yields with 90 percent confidence.

Confident detection of lower-yield explosions would require networks of more than 30 high-quality in-country arrays. The negotiability of such networks is not known. With either the 15- or 30-station network, many events would remain unidentified and, if unresolved, significantly jeopardize continued acceptance of a CTBT.

In reaching these conclusions, enhanced internal station capabilities resulting from the use of multiple regional waves were explicitly invoked and the use of a greatly improved network of in-country seismic arrays capable of detecting and analyzing regional seismic waves was postulated. Three factors determined the conclusions: (i) decoupling cavities may be constructed throughout much of the Soviet Union; (ii) knowledge of signal and noise levels at in-country stations would allow calibration of the stations' ability to detect signals from various locations and the choice of a favorable detonation time—that is, when background noise is high—thus reducing network capability in specific areas; and (iii) because seismicity in the magnitude range 2 to 3 (appropriate for cavity decoupling 1- to 10-kt explosions) can occur in many areas, small unidentified events will pose significant verification problems.

Insufficient knowledge of signal and noise properties in the Soviet Union and the lack of regional discriminants and uncertainties in the magnitude-yield relation at low yields introduce uncertainties in all such calculations. Satellite surveillance may help in identifying cavity construction and high-frequency signals may improve detection capability significantly, but both are currently unproven.

The use of earthquakes to mask explosion signals has not been considered in detail because analysis indicated that cavity decoupling determines the critical properties of in-country seismic networks. However, explosions with yields of several kilotons or more can be hidden by earthquakes. (The long intervals between tests, however, raise questions about the military value of such schemes.) Their usefulness could increase dramatically if earthquake prediction or excitation technologies become available.

Defining and negotiating in-country seismic systems for CTBT verification requires interrelated political, military, and seismological analyses and decisions. Political and military considerations establish performance requirements, and seismology provides technical specifications for the seismic system needed to meet those requirements. The acceptability of specific systems or treaties ultimately is determined by each nation's view of its national security requirements.

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Interactions Between the Gonadal Steroids and the Immune System

Charles J. Grossman

Summary. The immune system is regulated by the gonadal steroids estrogen, androgen, and progesterone, but the circulating levels of these steroids can also be affected by immune system function. Such interactions appear to be mediated through the hypothalamic-pituitary-gonadal-thymic axis and depend on pituitary luteinizing hormone released by thymic factors under the control of the gonadal steroids.

Historically the fields of reproduction and immunology have been classified as separate biological disciplines. A connection between these fields was first reported in 1898 when Calzolari (*1*) observed that the thymus of rabbits castrated before sexual maturity was larger than that of the controls. At the time this report first appeared it was not considered of much importance. However, 70 years after Calzolari's publication, researchers have begun to place greater emphasis on the interactions between the reproductive and immune systems. These reproductive-immunological interactions appear to be hormonally regulated, and the hormones involved originate from the thymus, the hypothalamus-pituitary unit, and the gonads. In this article, the role of the gonadal steroids in regulation of the acquired immune system is emphasized.

In humans, the innate and acquired immune systems constitute the total immune system. The innate system (also known as the nonspecific system) encompasses all reactions that are not antigen dependent, such as phagocytosis and inflammation. The acquired system (also known as the specific system) involves the antigen-dependent reaction of classes of lymphocytes called T cells and B cells. T cells are regulators of the cell-mediated immune response, B-cell function, and phagocytosis, whereas B cells are involved in humoral immunity and produce immunoglobulins called antibodies (*2, 3*).

Both clinical and experimental evidence support the hypothesis that gonadal steroids regulate immune function. This conclusion is based on the following observations: (i) a sexual dimorphism exists in the immune response; (ii) the immune response is altered by gonadectomy and sex steroid hormone replacement; (iii) the immune response is altered during pregnancy when the amount of sex steroid hormone is increased; and (iv) the organs responsible for the immune response contain specific receptors for gonadal steroids.

The author is in the Research Service, VA Medical Center, Cincinnati, Ohio 45220; the Department of Physiology and Biophysics, College of Medicine, University of Cincinnati, Cincinnati, Ohio 45267; and the Department of Biology, Xavier University, Cincinnati, Ohio 45207. Address correspondence and requests for reprints to the VA Medical Center.

Sex Steroids and Humoral Immunity

Many studies have demonstrated that immunoglobin production is greater in females than in males. In mice, females show a greater and more sustained response than males to the antigens bovine serum albumin (*4*) and hemagglutinin (*5*), and females also generate higher titers of the immunoglobins IgG (*6*), IgG1 (*7*), IgM (*6*), and IgA (*8*) than do male controls. Female hamsters also generate larger amounts of immunoglobin as measured both in vitro (*9*) and in vivo (*9, 10*) than do males, and this lessening of antibody production in the male coincides with the increase in sex steroid hormones at sexual maturity (*10*).

The mechanism responsible for the greater concentrations of antibody in females than in males is not completely understood at present. However, estrogens enhance the antibody response in mice (*11*) and appear to regulate the synthesis of uterine IgA and IgG in rats (*12*). This suggests that the spontaneous increase of immunoglobin levels during the estrous cycle may result from the action of estradiol in the uterus (*12*).

One possible mechanism for the stimulation of antibody production by estrogen is found in a report by Paavonen *et al.* (*13*) suggesting that estradiol can inhibit suppressor T-cell activity. Since suppressor T cells prevent B cells from manufacturing antibody, it follows that inhibition of suppressor T-cell function will enhance B-cell maturation and in-