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Yields of US and Soviet nuclear tests

Failure to account properly for geological and seismological differences between the US and Soviet test sites has led to overestimates of the yields of Soviet tests and to incorrect claims of Soviet cheating on the treaty limit of 150 kilotons.

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The likelihood that the United States will negotiate a comprehensive or low-threshold test ban treaty with the Soviet Union in the relatively near future depends not only on the ability of the US to monitor such an agreement but also on US perception of past Soviet compliance with treaties that limit nuclear testing. Of particular importance is the 1974 Threshold Test Ban Treaty, which prohibits tests of nuclear weapons exceeding 150 kilotons in yield. This treaty is unratified, but both the United States and the Soviet Union have avowed their compliance since 1976, when the treaty was scheduled to go into effect. (For an annotated list of treaties, see Herbert York's article in PHYSICS TODAY, March 1983, page 24.)

The US needs an accurate method for estimating the yields of Soviet nuclear tests, not only to assess compliance with existing or future treaties but also to estimate the effectiveness of Soviet strategic forces. Although several systems employing a variety of methods are currently available for detecting Soviet tests, only signals recorded by seismic networks give accurate estimates of the yields of individual underground explosions. Other techniques give estimates of the yields only of sets of Soviet tests.

We begin this article by reviewing the several seismological procedures for estimating the yields of Soviet explosions, our purpose being to demonstrate that yield estimates made by direct seismological measurements are accurate and do imply that the Soviets have abided by the 150-kiloton limit of the Threshold Test Ban Treaty.

Test of a nuclear device with an energy yield equal to that of 10 kilotons of TNT. The test, code-named Baneberry, took place at the Nevada test site, 110 miles north of Las Vegas, on 18 December 1970. The venting of radioactive dust was accidental. Releases of radioactive material in underground explosions at the site since this test have been limited to minor seepage. Figure 1

Seismic magnitudes

The discussion centers on two seismic "magnitudes," m_b and M_S. The magnitude m_b is calculated from measurements of P waves, which are compressional seismic waves in the body of the Earth. The magnitude M_S is calculated from measurements of Rayleigh waves, which are surface seismic waves. These magnitudes are simple logarithmic functions of the amplitudes of the pertinent seismic waves. The amplitudes are normalized for distance from the epicenter and for path of propagation, so that magnitude estimates made at arbitrary distances and locations are internally consistent. The normalizations for distance and propagation path are based upon extensive empirical data obtained over decades by many seismologists.

A seismic event does not have a single magnitude—it has several. When one uses different seismic waves and frequencies to estimate the magnitude of an event, one gets markedly different numerical values for the magnitude. For instrumental and seismological reasons, routine magnitude estimates are based on P waves of 1-second period and Rayleigh waves of 20-second period. The magnitudes m_b and M_S assigned a seismic event are averages of the magnitudes determined at many seismological stations. By applying empirically observed corrections based on data from many earthquakes and explosions, one can reduce the standard deviation of the magnitude estimates for any given event to 0.20–0.25 units of magnitude. The standard deviation of the mean depends on the number of stations used to determine the magnitude. The relationships between the magnitudes and the yields of nuclear explosions are also derived empirically: Yields of an adequate number of US explosions have been declassified and published to allow accurate estimates of the relationship between magnitude and yield at the Nevada test site.[1]

Magnitude bias. Because of geological

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variations within the crust and upper mantle of the Earth, an explosion at the Soviet test site at Semipalatinsk or Novaya Zemlya produces seismic P waves of much greater amplitude at distances than does an explosion of the same yield at the US test site in Nevada, shown in figure 1. The difference is determinable quantitatively; to obtain it one solves the so-called P-wave magnitude bias or m_b bias problem. The large regional variations in the properties of the Earth's crust and upper mantle lead to different attenuations of body waves, thus causing amplitude differences and magnitude bias along different paths between epicenters and seismic stations.

Quantitative determination of the P-wave magnitude bias has been a major issue in estimating the yields of Soviet underground explosions. Studies done in the early 1970s demonstrated the existence of the bias.[2,3] The US government, however, refused to accept the conclusions of those studies, even though they were conducted within the Defense Department and cleared by that department for publication in the open scientific literature. Finally in 1977 the government admitted that seismic amplitudes of P waves do vary with the sites of the sources and receivers, but chose for reasons never specified to apply correction factors that were too small. This choice formed the basis for claims by the Reagan Administration of Soviet noncompliance with the 150-kiloton test limit. Only now is the government moving toward acceptance of the proper correction factor, bringing its position into conformance with long demonstrated fact.

Something still not appreciated by many is that one can estimate the yields of large Soviet explosions through seismological procedures that do not require estimates of the magnitude bias between the US and Soviet test sites, and that these procedures confirm the validity of the method used to calibrate the P-wave magnitude bias estimates made by totally separate seismological procedures. One such technique is use of Rayleigh wave amplitudes, or magnitudes M_S.

Following our review of seismological procedures for estimating the yields of Soviet tests, we introduce a method for estimating the yields of US tests and show that this method gives estimates that agree with previously published yields of individual events and with recently declassified data on the US test pattern for 1980–84. We then investigate the Soviet testing program by placing the calculated pattern of Soviet tests within the constraints of physical law and military requirement—that is, to compare the US test program, a program with known logic, with that of the Soviet Union while assuming various values of P-wave magnitude bias. We also investigate the differences in the two test programs as a function of time. We show that if US and Soviet nuclear weapons are similar in basic design, meaning that most are two-stage thermonuclear weapons having primaries of comparable yields (we believe that military requirements and the physics of nuclear weapons demand this), then we would expect the testing programs of the two countries to show similar distributions of yields for a given level of weapons sophistication. We show that the level of the P-wave magnitude bias needed for this to be the case is consistent with that determined from seismological considerations. Conversely, if we accept the magnitude bias as determined by seismology, a comparison of the two test programs shows them to be strikingly similar. The comparison we make of the complete test programs of the two countries is the first to appear in the unclassified literature.

Explosion seismology

An underground explosion creates a radially symmetric shock wave that propagates outward with a velocity that depends on the yield. If the rock containing the explosion has little or no initial stress and if the properties of the volume of rock experiencing the shock wave are uniform, then the shock wave will consist almost completely of P waves and Rayleigh waves. The former are compressional body waves that propagate throughout the entire volume of the Earth, while the latter are surface waves whose amplitudes decrease exponentially with depth. Two types of surface waves are possible: Rayleigh waves and Love waves. Rayleigh waves are the elastic analog of waves on the surface of water; in addition to vertical motion, particles undergo horizontal motion in the plane of propagation, resulting in elliptical particle motion. Love waves are shear surface waves displaying horizontal particle motion perpendicular to the direction of propagation.

Simple conditions of very low initial stress, or pre-stress, are not general throughout the shallow zones of the Earth in which explosions occur. There is very little or no pre-stress in rocks overlying some subduction zones (the Aleutian Islands, for example), salt deposits and unconsolidated alluvium, but most other rock is under some pre-stress (10–100 bars in seismic areas), which arises from the never ending deformational processes going on within the Earth. An explosion produces a sphere of shattered rock of zero strength, allowing a readjustment of stress in the surrounding rock. This readjustment produces radiation of the full complement of possible types of elastic waves—shear body waves and Love surface waves in addition to the P body waves and Rayleigh surface waves. The waves resulting from this tectonic release can complicate identification criteria and can require calibration of Rayleigh-wave amplitudes when those amplitudes are used to estimate yields. However, the contribution of stress release to P-wave amplitudes has never been sufficient to alter the P-wave magnitude bias.

Estimating the bias

Figure 2a is a plot of the P-wave magnitudes m_b of Soviet nuclear tests as a function of time. The points of immediate interest are the cessation of high-magnitude tests by the Soviets in 1976 because of the 150-kt limit, and the rise in magnitude from 5.8 to 6.2 in the years following 1976. All the large Soviet tests before 1976 were at Novaya Zemlya, although most Soviet tests have been at Semipalatinsk.

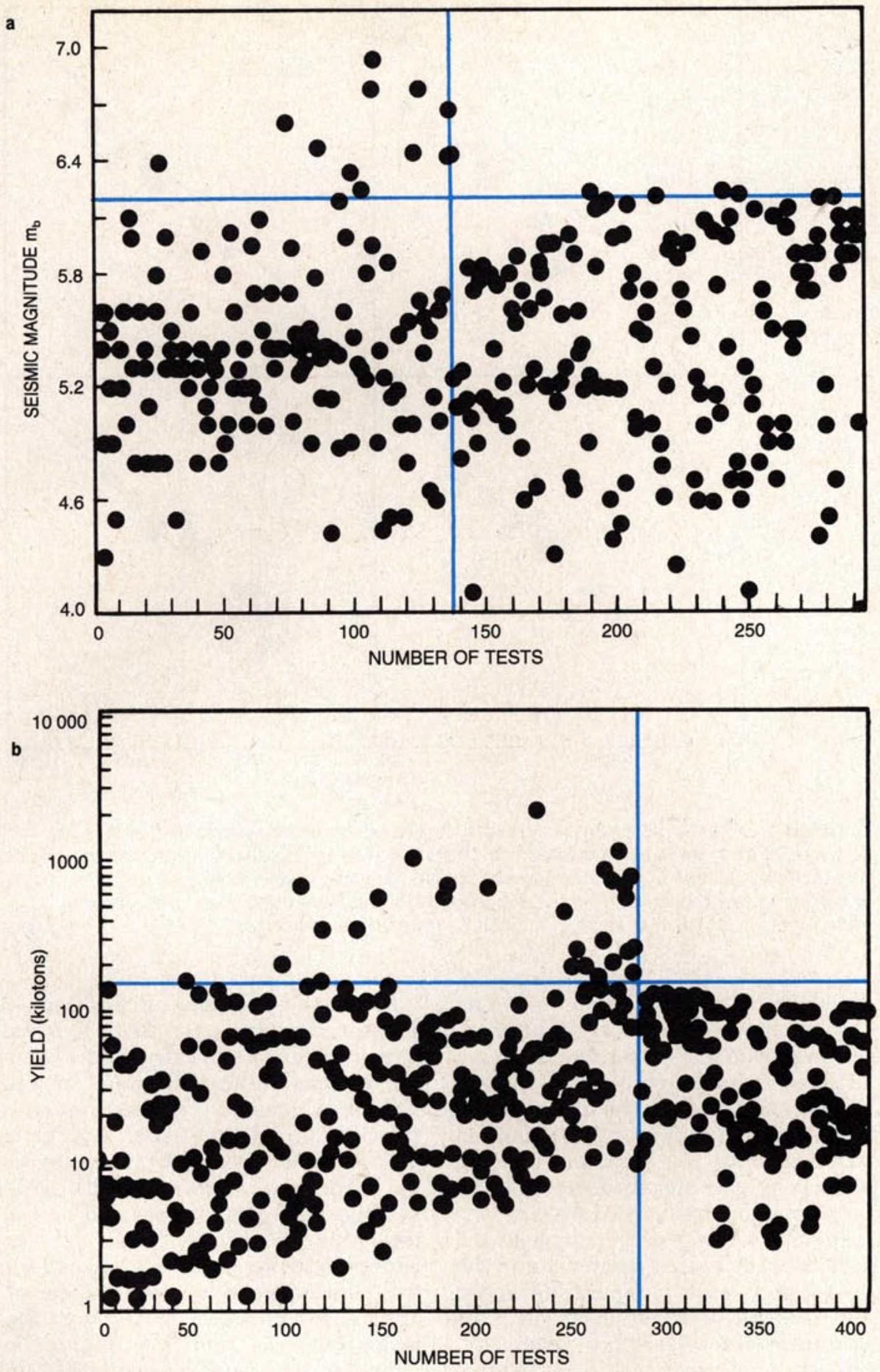
As we will see below, an explosion at the Nevada test site with a magnitude m_b of 6.2 would have a yield of 600–700 kilotons. However, there is a large P-wave magnitude bias between Semipalatinsk and the Nevada test site, and one must take this into account if one is to use yield-vs-magnitude curves based on the Nevada test site to make accurate estimates of the yields of Soviet tests of such magnitude. Let us review the seismological procedures that demonstrate the magnitude bias.

Figure 3a is based on data for 33 Soviet explosions for which Lynn Sykes and Inés Cifuentes at Columbia University have published carefully calibrated mean magnitudes m_b and M_S calculated from data from many seismic stations.[4] Yields were calculated from magnitudes M_S using the following formula:[5]

$$\log_{10}(\text{yield in kt}) = 0.762M_s - 1 \quad (1)$$

This equation, which is based on explosions of known yield from numerous sites worldwide, applies to explosions in hard rock anywhere. The existence of a universally applicable relationship between magnitude M_S and yield for explosions in hard rock when Rayleigh waves are little affected by the release of tectonic stress was first shown[2] in 1971, and the bases for it were first summarized[6] in 1977.

In figure 3a, the yields based on the magnitudes m_b of the 33 Soviet explosions were calculated using the relationship that is correct for the Nevada test site (see figure 4b), only the high-



Soviet and US testing patterns. **a:** Seismic magnitudes m_b as a function of time for Soviet tests, 1964–85. The time axis is not uniform, as each tick mark indicates 10 tests. **b:** Yields of US tests as a function of time, 1963–84. The vertical lines mark the effective date of the Threshold Test Ban Treaty. Figure 2

yield portion of the relationship being needed:

$$\log_{10}(\text{yield in kt}) = 1.25m_b - 4.95 \quad (2)$$

Note that using equations 1 and 2 gives pairs of values for the Soviet explosions, that is, for log yield(M_S) and log yield(m_b), and that these pairs result in a distribution of points (figure 3a) that scatter around a straight line with a slope of essentially 1. This implies, as expected, that the fundamental physics controlling the slopes of equations 1 and 2 is identical at hard rock sites in the US and USSR. Note also that the yield-versus-magnitude curves appropriate to the Nevada test site give m_b-based estimates of yields of Soviet tests that are 3 to 4 times greater than the M_S-based estimates. Thus there is a problem of "magnitude bias" between the Soviet test sites and the US test site. To resolve this problem, one must determine whether the problem is with the magnitudes m_b or the magnitudes M_S.

Evernden and John Filson in the early 1970s were the first to demonstrate[2] the existence of this problem, and Evernden explained[6] it in the mid-1970s. Simply put, there are significant variations in anelastic processes and in the velocity structure of seismic waves at depths of 0–200 km in different regions of the Earth. Tectonically active terrains, such as that found at the Nevada test site, are characterized by high mean elevation, high heat flow, low P-wave velocities at the Mohorovičić discontinuity (the boundary between the Earth's crust and mantle), marked travel-time delays of both P and S body waves, and significant anelastic attenuation of all seismic body waves. The P-wave attenuation leads to lower measured amplitudes and thus to lower measured magnitudes m_b than in terrains such as Canada, the eastern United States and most of the Soviet Union. None of these Earth structures significantly perturb the amplitudes of 20-second Rayleigh waves, the waves used to determine the magnitudes M_S.

Several procedures

The contrast in properties between active and stable terrains leads to several distinct procedures for estimating the nature and size of the magnitude bias illustrated by figure 3a:

▶ Both empirical data and theoretical analysis establish that 20-second Rayleigh waves do not experience significantly different propagation effects in different terrains, and also establish the uniformity of explosion-generated low-frequency source amplitudes, and thus Rayleigh-wave amplitudes, for explosions of the same yield in a wide variety of "hard rock."[6] Therefore, if tectonic release does not perturb the magnitudes M_S, no correction need be applied to these magnitudes, and one can estimate[7] directly from figure 3a the bias in the magnitudes m_b.

▶ If it becomes necessary to correct the observed magnitudes M_S for the release of tectonic energy, one can use procedures for calculating both the explosion- and earthquakelike components of the 20-second Rayleigh waves from multi-azimuth multiperiod observations of both Rayleigh and Love waves. Use of the corrected magnitudes M_S then permits estimation of the bias in the magnitudes m_b. The assumptions required, the sensitivity of the calculations to the details of the earthquakelike energy release, the size of the necessary correction for some of the Semipalatinsk events and the limit-