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Yields of Soviet underground nuclear explosions from seismic surface waves: Compliance with the Threshold Test Ban Treaty

(arms control/verification of test ban treaties/seismic magnitudes)

LYNN R. SYKES AND INÉS L. CIFUENTES

Lamont-Doherty Geological Observatory and Department of Geological Sciences of Columbia University, Palisades, NY 10964

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ABSTRACT Magnitudes of the larger Soviet underground nuclear weapons tests from the start of the Threshold Test Ban Treaty in 1976 through 1982 are determined for short- and long-period seismic waves. Yields are calculated from the surface wave magnitude for those explosions at the eastern Kazakh test site that triggered a small-to-negligible component of tectonic stress and are used to calibrate body wave magnitude–yield relationship that can be used to determine the sizes of other explosions at that test site. The results confirm that a large bias, related to differential attenuation of P waves, exists between Nevada and Central Asia. The yields of the seven largest Soviet explosions are nearly identical and are close to 150 kilotons, the limit set by the Threshold Treaty.

The Threshold Test Ban Treaty (TTBT), which took effect on March 31, 1976, sets an upper limit of 150 kilotons (kt) on the sizes of underground nuclear weapons tests by the two signatories, the United States and the Soviet Union. While the treaty has not been ratified by the U.S. Senate, both governments have announced that they will abide by its terms. Several officials and publications of the U.S. government state that there is reason to doubt that the Soviet Union is limiting its tests to 150 kt (1, 2). This allegation has been cited as one of the main reasons for not continuing the negotiations toward a Comprehensive Test Ban Treaty, which have been in recess since 1980.

Verifying compliance with the terms of the TTBT makes accurate determinations of the yields of underground tests imperative. Yields of Soviet explosions are estimated from seismic wave amplitudes using empirically derived amplitude–yield relationships for explosions, most of which occurred outside that country. The Soviet Union has released yields for only a few peaceful nuclear explosions.

Most arguments about the yields of U.S.S.R. explosions arise not from uncertainties about the amplitudes of seismic waves but from questions about the sizes of systematic errors or biases in converting amplitudes of seismic waves into yield. Amplitudes of P waves with periods near 1 s [and the derived body wave magnitude (m_b)] are known to be strongly affected by differences in attenuation in the upper mantle beneath explosion sources (3). The difference is primarily due to the presence or absence of recent tectonism near test sites. Most Soviet explosions (all of the large ones since 1976) have been detonated in regions with no appreciable tectonic activity in the last several hundred million years. In contrast, the majority of U.S. explosions are set off in Nevada, a region of recent tectonism. If the m_b data from Soviet explosions are converted to yield by applying the Nevada m_b–yield (Y) curve, the yields are overestimated. Several recent estimates (3–7) of the bias in m_b between the eastern Kazakh and Nevada test sites are between 0.3 and 0.45 units, equivalent to a bias in yield amounting to a factor of 2 to 3. When m_b is corrected by those amounts, the largest Soviet tests from 1976 to 1982 are found to have yields close to 150 kt. Surface wave magnitudes (M_s) show less regional variation than m_b; we obtain independent estimates of yield from M_s. The yields of the largest Soviet tests from 1976 to 1982 as estimated from M_s are also close to the 150-kt limit.

MATERIALS AND METHODS

We used both m_b and M_s to estimate the yields of 31 U.S.S.R. explosions reported to have $m_b \geq 5.8$, from 1976 to 1982 at the eastern Kazakh testing area in Central Asia near Semipalatinsk. The largest Soviet explosions during that period were conducted at that site. The individual m_b readings of 8 of the larger events recorded by 119 stations, as reported by the U.S. Geological Survey and the International Seismological Center, were used to derive station corrections, such that the sum of the corrections is zero. These corrections were then applied to the m_b values of the remaining 23 explosions. The large number of stations used per event and the use of station corrections results in average m_b values with very small SEM values (Table 1).

Surface Waves. Rayleigh wave amplitudes (LR) with periods from 18 to 22 s were measured on vertical component records for explosions at eastern Kazakh. Love wave amplitudes (LQ) were measured from transverse components. The measurements were restricted to stations with digital recording, good signal-to-noise ratio, and continental propagation paths. Since data of that type became readily available only after late 1978, the analysis is restricted to the period Aug. 1978 to Dec. 1982. The largest U.S.S.R. explosions since 1976 occurred during that period. M_s was computed from our measurements of LR by applying the distance and period corrections of ref. 8. Fig. 1 shows M_s values determined by the methods of ref. 3 for a different set of explosions with known yields using the same correction factors. We use those M_s–Y data to calibrate yields from M_s for explosions at eastern Kazakh.

Underground tests have long been known to trigger the release of various amounts of natural stress (tectonic release) near the shot point. LQ is generated by the tectonic component alone whereas LR is generated by it and the pure explosion (4). F' is the ratio of the seismic moments of the tectonic and explosion components. The calibration explosions in Fig. 1 are characterized mainly by a tectonic component of the strike-slip type, which does not significantly bias the average M_s of the pure explosion for $F' < 0.7$. Eq. 1 in Fig. 1 is a least-squares fit to data (9) with $F' \leq 0.4$. Eq. 1 is statistically indistinguishable from Eq. 2, a best fit to all of the data. The calibration data in Fig. 1 are fit well by linear relationships between M_s and log Y over a 1000-fold variation in Y.

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Abbreviations: kt, kiloton(s); LQ, Love wave amplitude; LR, Rayleigh wave amplitude; m_b, body wave magnitude(s); M_s, surface wave magnitude(s); TTBT, Threshold Test Ban Treaty; Y, yield.

Table 1. Parameters of nuclear explosions at eastern Kazakh

Date	m_b	n_b*	M_s†	LQ/LR	F'	M_s(max)‡	n_s§
Aug. 29, 1978	5.967 ± 0.012	50	3.637 ± 0.107	0.57	0.38	3.73	2
Sep. 15, 1978	5.963 ± 0.015	62	3.831 ± 0.032	0.40	0.26	3.95	3
Nov. 4, 1978	5.576 ± 0.018	76	3.582 ± 0.024	0.60	0.79	3.99	4
Nov. 29, 1978	5.996 ± 0.017	48	Data tape not available				
Jun. 23, 1979	6.215 ± 0.013	89	3.991 ± 0.022	0.51	0.34	4.26	5
Jul. 7, 1979	5.839 ± 0.020	76	4.027 ± 0.232	1.59	2.0		5
Aug. 4, 1979	6.161 ± 0.013	97	4.052 ± 0.036	0.34	0.35	4.29	6
Aug. 18, 1979	6.170 ± 0.015	93	3.743 ± 0.072	0.99			7
Oct. 28, 1979	5.990 ± 0.016	91	3.974 ± 0.058	0.63	0.34	4.21	4
Dec. 2, 1979	5.998 ± 0.013	78	4.080 ± 0.022	0.26	0.22	4.17	5
Dec. 23, 1979	6.170 ± 0.017	81	3.772 ± 0.016	0.46	0.32	3.87	3
Jun. 29, 1980	5.707 ± 0.019	69	3.400 ± 0.087	0.91			2
Sep. 14, 1980	6.213 ± 0.030	62	4.043 ± 0.019	0.83			6
Oct. 12, 1980	5.918 ± 0.019	80	4.094 ± 0.015	0.22	0.20	4.20	5
Dec. 14, 1980	5.953 ± 0.019	64	3.934 ± 0.038	0.35	0.27	4.07	6
Dec. 27, 1980	5.872 ± 0.023	58	3.758 ± 0.144	0.72			5
Apr. 22, 1981	5.954 ± 0.015	78	4.070 ± 0.020	0.34	0.26	4.21	5
Sep. 13, 1981	6.064 ± 0.017	72	4.206 ± 0.026	0.31	0.25	4.33	3
Oct. 18, 1981	6.033 ± 0.019	54	4.094 ± 0.020	0.25	0.21	4.20	3
Dec. 27, 1981	6.242 ± 0.028	72	4.106 ± 0.030	0.40	0.30	4.26	4
Apr. 25, 1982	6.089 ± 0.021	70	4.026 ± 0.009	0.37	0.28	4.15	5
Jul. 4, 1982	6.222 ± 0.026	62	Surface waves masked by earthquake				

*Number of P readings used for m_b determination.
†Not corrected for tectonic release (see Fig. 3).
‡Value of M_s as corrected for pure thrust faulting (see Fig. 4).
§Number of surface wave observations for M_s determination.

RESULTS

As shown in Fig. 2, there are three pronounced peaks in the sizes of tests at eastern Kazakh. The peak near 6.20 consists of seven explosions with a small range of m_b values, 6.16 to 6.24, all of which have occurred since June 1979. Explosions from March 1976 to June 1979 there and at other Soviet test sites were smaller. Hence, we focus on the yields of those seven. About half of the variance of the seven m_b values with respect to their mean of 6.20 is associated with uncertainties in individual m_b values. The rest must be related to very small variations in either yield or geological properties near the shot points. Variations in yield about the mean for the seven, however, cannot be >6% at 1 SD. Thus, the yields of those seven explosions are nearly identical.

Station corrections for M_s were calculated for seven explosions characterized by low tectonic release (small LQ/LR) and were applied to the other events studied (Fig. 3). For all events with LQ/LR < 0.4, the SEM values (Table 1) are similar to those for m_b even though the number of stations used was seven or less. None of the M_s values in Fig. 3, where no correction was made for tectonic release, correspond to yields by either Eq. 1 or 2 of Fig. 1 that are as large as 150 kt.

Helle (10) and North and Fitch (11) obtained nearly identical values of F' by different methods for several of the explosions in Table 1. Their values correlate well with LQ/LR. We calculated F' from LQ/LR for the remaining explosions of Table 1 with LQ/LR ≤ 0.7. Corrections to M_s for tectonic release can be calculated for each station if the orientation of the double couple describing that release and F' are known (11). Azimuthal variations in LR for several explosions (10, 11), a major fault near the test site (11), and the mechanism of a nearby earthquake (12) give consistent values of the strike of the double couple (303–336°). They also indicate components of thrust and strike-slip faulting. Correcting the M_s values in Fig. 3 for pure strike-slip faulting reduces the calculated yields somewhat. Pure thrust faulting results in

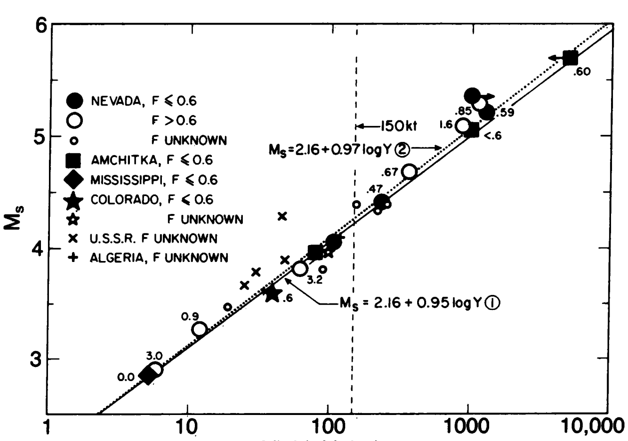

FIG. 1. Underground explosions in granite, salt, or below water table. M_s values from ref. 3 as functions of announced yield in kt. The numbers beside the data points are F values ($F = 3/2\ F'$) from ref. 9. Horizontal arrows attached to two data points indicate that yields are maximum or minimum values.

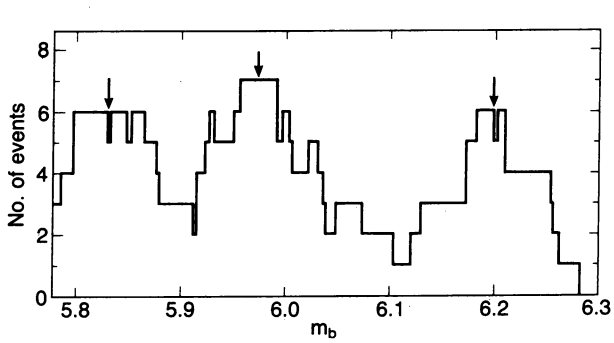

FIG. 2. Moving window analysis of 31 Soviet underground explosions (eastern Kazakh test site; Apr. 1976–Dec. 1982) of m_b ≥ 5.8. In plotting the histogram, each event was taken to have a width of ±0.04 m_b units about its mean value. Underground tests are concentrated near magnitudes indicated by arrows.

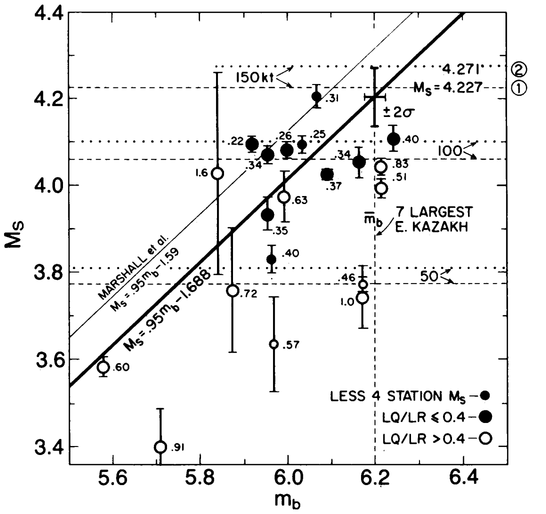

FIG. 3. Station corrections for m_b and M_s but not for tectonic release; M_s as a function of m_b for underground explosions at the eastern Kazakh test site. The heavy line is the least-squares fit to solid symbols assuming that the slope of 0.95 derived for Eurasian underground tests in ref. 3 is applicable; σ = SEM appropriate for m_b = 6.20. M_s values derived by Eqs. 1 and 2 of Fig. 1 for various yields are shown by horizontal dashes and dots. The procedure probably underestimates yields.

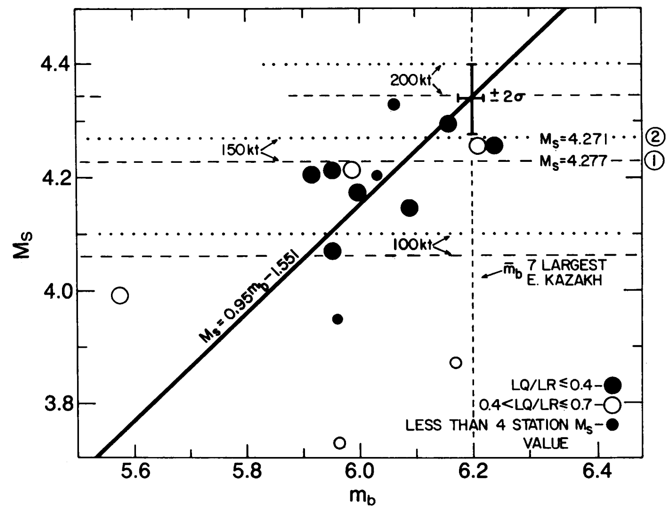

FIG. 4. M_s and m_b data for the eastern Kazakh site with M_s corrected for tectonic release assuming pure thrust faulting with strike of 326° and dip of 45°. Explosions with LQ/LR ≥ 0.7 are omitted. Other comments are as in Fig. 3. The procedure probably overestimates yields.

the largest M_s corrections and therefore the largest estimates of yield.

The existence of polarity reversals in LR for large F' (11) demands a sizable component of thrust faulting whereas several values of LQ/LR for azimuths near the strike of the double couple require a moderate component of strike-slip motion. Yields inferred by assuming either pure strike-slip faulting or no tectonic correction (Fig. 3) are likely to be underestimated whereas those calculated assuming pure thrust faulting (Fig. 4) probably are overestimates. The computations of Y in Figs. 3 and 4 both assume that the M_s–Y relationships of Fig. 1 can be applied without systematic error to paths in Eurasia. The data for those Soviet peaceful explosions for which the yields are known (× symbols in Fig. 1) suggest that yields estimated in Figs. 3 and 4 are slightly high. Path corrections could be determined to address this question. Systematic errors in M_s of ±0.05 to ±0.10 may result from this approximation. The overall uncertainty in Y deduced from M_s for explosions of low tectonic release is estimated to be about a factor of 1.3 at 1 SD when allowance is made for uncertainties in the calibration curve, measuring M_s, dispersion, attenuation, and tectonic release.

DISCUSSION

The yields of the largest Soviet explosions determined by four methods are listed in Table 2. Methods 1b, 2b, and 4 probably lead to overestimates; 1a, 2a, and 3, to underestimates. Of the seven largest explosions with nearly identical m_b values, four are characterized by relatively small tectonic release (LQ/LR < 0.51; F' < 0.35). Uncertainties in the M_s of the pure explosion are smallest when that perturbing factor is least. Methods 1a and 1b use three of those four explosions to give maximum yields of 89–98 kt with no correction for tectonic release and 149–166 kt when that factor is corrected for assuming pure thrust faulting. The most realistic correction for tectonic release would give a yield somewhat lower than the latter range. The inclusion of M_s for the explosion of Dec. 23, 1979, which is an average of only three stations, would result in lower yields. A maximum yield of 106–117 kt is obtained from five explosions of small LQ/LR that make up the central peak in Fig. 2.

Linear best-fitting relationships for M_s and m_b were obtained for the solid data points in Figs. 3 and 4 assuming that the slope is 0.95, a value obtained (3) for a suite of Eurasian explosions. That slope, however, may vary appreciably for yields near 150 kt because an overestimate of m_b may result from a peak in the spectrum near 1 Hz generated by the phenomenon of overshoot for explosions in hard rock (13), the likely testing medium at eastern Kazakh (2).

Comparison of Figs. 1 and 5A shows that m_b varies much more than M_s for explosions of a given Y. The scatter in m_b is caused by at least two factors—different rates of attenuation beneath the test sites and varying seismic coupling related to different rock types near the shot points. Of the various test sites, attenuation beneath Amchitka in the Aleutian Islands is likely to be more similar to that of eastern Kazakh than is Nevada. Using the Amchitka data for calibration gives a yield of about 173 kt for the seven largest U.S.S.R. explosions. In Fig. 5B, m_3 was obtained from m_b (3) by mak-

Table 2. Estimates of yields of largest Soviet explosions, 1976–1982

Method	Yield, kt
1. M_s for three largest explosions of low tectonic release	
1. a. No correction for tectonic release (Fig. 3)	89–98*
1. b. Corrected for pure thrust faulting (Fig. 4)	149–166*
2. Best fitting M_s for m_b = 6.20 assuming slope = 0.95	
a. No correction for tectonic release (Fig. 3)	127–141*
b. Corrected for pure thrust faulting (Fig. 4)	176–196*
3. Average m_3 = 6.21 for seven largest explosions using equation given in Fig. 5B	113
4. Average m_b = 6.20 for seven largest explosions using Amchitka data of Fig. 5 for calibration	173

*From Eqs. 2 and 1 of Fig. 1, respectively.

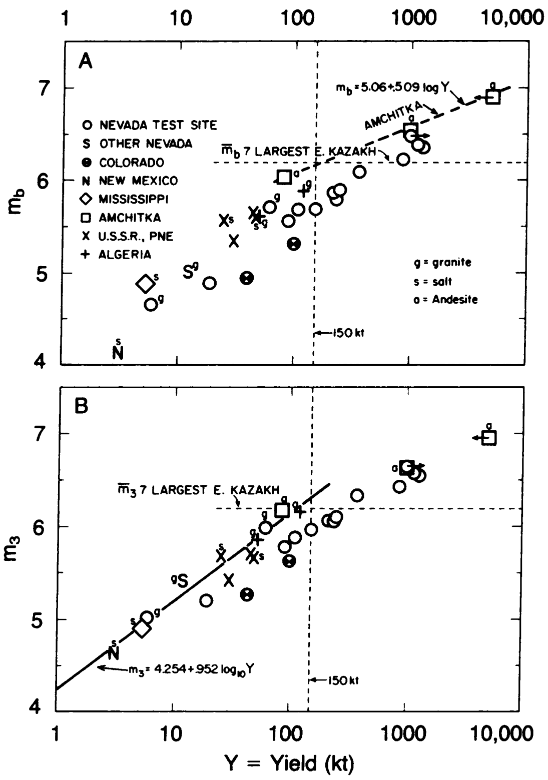

FIG. 5. Underground explosions in granite, salt, or below water table; short-period magnitudes m_b and m_3 as functions of announced yield in kt. (*A*) Data are from ref. 3. (*B*) Magnitude m_3 is corrected for differences in attenuation beneath various test sites (3). The equation at the lower left is a least-squares fit for explosions in granite, salt, and Andesite.

ing a correction for attenuation. The yields of the largest U.S.S.R. tests using the best fitting relationship for explosions in granite, salt, and Andesite are about 113 kt.

The various estimates (Table 2) of the yields of the seven largest Soviet explosions range from 89 to 196 kt. Considering that some determinations are maximum and others minimum estimates, the actual yields are likely to be somewhere near the middle of that range, close to the 150-kt limit of the TTBT. Given the uncertainties in the various methods, however, the actual yields of the seven could be 125 or 175 kt. Nonetheless, they cannot be 260 to 800 kt or larger as has been claimed (2, 14–16). Such large values appear to be the product of incorrect calibration of m_b for differential attenuation and the properties of the testing medium.

Since M_s is not very sensitive to variations in physical properties near the shot point, attenuation in the upper mantle, or overshoot, its use in yield estimation has several advantages. We do not, however, recommend its use for explosions of LQ/LR > 0.7 because the correction for tectonic release will be large and more uncertain. In that case, yield can be derived from m_b by using a m_b–Y relationship calibrated for that test site using surface waves from explosions of small LQ/LR.

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