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YIELDS OF UNDERGROUND NUCLEAR EXPLOSIONS AT AZGIR AND SHAGAN RIVER, USSR AND IMPLICATIONS FOR IDENTIFYING DECOUPLED NUCLEAR TESTING IN SALT

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Bodywave magnitudes, m_b, are recomputed using station corrections for all known Soviet underground nuclear explosions at Shagan River and Azgir. The m_b values for explosions of announced yield, Y, in various parts of the world in either hard rock or below the water table were normalized to the SW part of the Shagan River testing area using previously published values of t* and m_b bias. The resulting relationship, $m_b = 4.48 + 0.79 \log Y$, which includes yields published by Bocharov et al. (1989) for Shagan River, differs very little from a regression that does not include those data. Using magnitudes determined from Lg at NORSAR as a standard, the Shagan River site is divided into three subareas. Yields calculated from these revised m_b values and from m(Lg) are much more consistent for the same explosion; each agrees closely with the yields published by Bocharov et al. for large explosions in 1971 and 1972 in the NE and SW parts of the testing area. Yields calculated by averaging determinations from Lg and body waves for 66 explosions have a high precision at 95% confidence (mean value 1.14) for Y > 10 kt. The explosion of 23 July1973 of Y = 193 kt is clearly the largest underground explosion at Shagan River. The newly calculated values provide strong evidence of clustering in the distribution of yields of Soviet tests. In a special study

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made for the Azgir explosion of 1.1 kt of 1966, m_b was measured at 16 stations for which seismograms were available, giving $m_b = 4.52 \pm .06$. For purposes of appreciating the detection capability of a given seismic network, it is important to recognize that a fully-coupled explosion of 1 kt in salt in high-Q areas of the U.S.S.R. has an m_b of 4.46; fully decoupled events of 1 and 10 kt have m_b's of 2.61 and 3.40 respectively. Yields are recalculated for past Soviet nuclear explosions at Azgir and in other areas of thick salt deposits through 1986. The yields of fully decoupled and nearly fully decoupled (Sterling conditions) nuclear explosions that could be detonated in the cavities produced by those events are calculated. Most of the "opportunities" for decoupled testing of those types are concentrated in the area to the north of the Caspian Sea. The "oppontunities" for the largest tests, up to a maximum of 7 to 8 kt, are largely confined to Azgir itself. Possibilities for decoupled testing are more restricted in the area of bedded salt to the northwest of lake Baikal.

CONTENTS

INTRODUCTION

The detonation of nuclear explosions by the Soviet Union in large underground cavities under either a Low-Yield threshold test ban treaty (LYTTBT) or a comprehensive test ban treaty (CTBT) would constitute the greatest challenge to U.S. verification efforts.That evasion scenario sets the limit on how low a yield can be verified effectively. The recent OTA Report *Seismic Verification of Nuclear Testing Treaties* found that between 1 to 2 and 10 kilotons (kt) the only plausible method of evasion is that of nuclear testing in large cavities in salt domes. It concluded that no method of evading a good monitoring network is credible above 10 kt and that several evasion scenarios, including testing in cavities in bedded salt and in hard rocks, are possible below 1 to 2 kt.

Our work address a number of aspects of the problem of clandestine nuclear testing in large cavities in salt domes, bedded salt and hard rock--what types of evasion scenarios are plausable based on geological and engineering constraints, which ones are likely to escape detection by the U.S. and which ones are likely to be identified. We devote particular attention to the Soviet Union and to the critical yield regime from 1 to 10 kt, where scientific research over the next few years seems most likely to have a major impact on the verifiability of a LYTTBT and on what threshold can be verified effectively. Several important aspects of decoupling have received little study for more than 20 years. Since then a great deal of experience has been obtained by the U.S. and several European countries on the rheological properties of salt in conjunction with research on radioactive waste disposal in salt deposits and by industry on the construction and stability of large cavities in salt for petroleum storage and waste disposal. Experience with very large cavities in salt domes is available from the U.S. Strategic Petroleum Reserve and from the U.S.S.R. and U.S. on cavities in salt for gas storage.

Our major research objectives during the first year were:

1) Derive revised m_b values for Soviet underground nuclear explosions in salt and for small explosions at the main Soviet test sites; determine improved magnitude-yield relationships, especially for explosions of small yield;

2) Study numbers, magnitudes and spectral character of small earthquakes and large chemical explosions in and near areas of thick salt deposits in the U.S.S.R.;

3) Evaluate and synthesize data from engineering, rock mechanics and geological sources on the properties of salt, stability of large underground cavities in salt, and the use of cavities in salt for possible clandestine nuclear testing, especially in the yield range 1 to 10 kt;

4) Start work on maps of the U.S.S.R. showing locations suitable for possible decoupled testing of explosions of various yields in salt. Identify areas that have known salt

deposits, those that are not known to but conceivably could be such sites, and areas that do not and cannot contain salt deposits of any appreciable thickness (such as old cratonic regions and young volcanic areas).

During the past year work has been done on all four of the above areas. The first topic has been completed and a paper on that work is being finished for journal submission. Most of this report is devoted to that topic and to the implications for detecting and identifying decoupled nuclear testing in the Soviet Union in the Azgir region and in adjacent areas to the north of the Caspian Sea where the world's most numerous salt domes are found.

There has been a long debate going back before the signing of the TTBT in 1974 about the yields of Soviet underground nuclear explosions at their various test sites and about the correct methodology for calculating explosion yield from the amplitudes of various seismic waves. The establishment of a threshold in terms of yield by the TTBT put a premium on accurate yield determination. After 1974 the debate in the United States focused upon the Shagan River portion of the Soviet testing area in Central Asia (eastern Kazakhstan) since the largest underground nuclear tests by the U.S.S.R. after the start date for that treaty (April 1, 1976) were conducted there. (The Shagan River area is called the Balapan testing area by Soviet workers.) Until three years ago when Bocharov et al. (1989) published yields of a number of underground explosions at the Central Asian test site for the period 1961 through 1972, an approximate yield had only been published or released by the Soviet Union for a single explosion in that area. The use of that data point for calibrating yields of fully contained underground nuclear explosions was difficult since that event, which occurred in January 1965, produced a large crater. Its m_b was probably smaller than that of a fully contained explosion of the same yield.

Underground nuclear explosions at the main Soviet test sites in Central Asia and Novaya Zemlya generate larger P waves at large (teleseismic) distances that U.S. explosions of the same yield at the Nevada Test Site (NTS). The difference in magnitude, often called the m_b bias, is + 0.3 to +0.4 magnitude units for either of those Soviet weapons testing sites with respect to NTS, providing the explosions are in the same rock type (Office of Technology Assessment, 1988). In practice, most U.S. underground explosions have been conducted in softer, less competent rocks than those at Shagan River, leading to an overall bias of about 0.4 to 0.5 with respect to NTS.

In 1988 the United States and the U.S.S.R. conducted nuclear explosions at NTS and Shagan River, respectively, that were stipulated by bi-lateral agreement to be in the yield range from 100 to 150 kt. Each country permitted the other to make on-site measurements of yield by hydrodynamic (Corrtex-type) and seismic methods. It is unfortunate that yield estimates and other pertinent data for those two Joint Verification Experiments (JVEs), as well as yield determinations for five previous nuclear tests at each site that were communicated to the other country, remain classified and have not been announced publically. Nevertheless, a detailed technical report on the two JVEs in the New York Times for October 30, 1988 stated that the American and Soviet on-site measurements by the hydrodynamic method gave yields of 115 and 122 kt, respectively for the Soviet JVE of September 14, 1988.

In previous work my colleagues and I determined yields for Soviet explosions at Shagan River and Novaya Zemlya by using calibration curves for P waves that were based on underground explosions of announced yield for which their P-wave magnitudes were corrected for m_b bias between the actual test site of the explosion and the Soviet site in question. Sykes and Ekstrom (1989) showed that the reported hydrodynamic yields of 115 and 122 kt for the Soviet JVE were consistent with those m_b-yield relationships for Shagan River. They also obtained a maximum value of 145 kt for the yield of that explosion using surface waves.

In the last few years much progress has been made in using magnitudes derived from the short-period seismic phase Lg for precise determinations of yield of explosions at Shagan River (Ringdahl and Fyen, 1988; Ringdahl, 1989; Ringdahl and Marshall, 1989; Hansen et al., 1990). The precision of a single determination of magnitude from Lg waves is often comparable to that obtained after averaging values of m_b from 50 to 100 worldwide stations. Magnitudes determined from Lg waves, m(Lg), will probably become the single method of choice in the future as more data become available from digitally-recording stations in the Soviet Union at regional distances. Lg waves studied by Ringdahl and his co-workers were recorded digitally at Norsar and Graftenberg at distances of about 4000 km from Shagan River. Events of m_b less than about 5.5 (Hansen et al., 1990), that is for yields smaller than about 40 kt, typically have a small signal-to-noise ratio at those large distances. It appears possible to use data from high-quality stations in the U.S.S.R. to determined yield from Lg waves for tamped (well-coupled) explosions as small as 1 kt (Hansen et al., 1990).

Nevertheless, accurate determinations of yield from m_b continue to be essential for most past explosions of small to moderate yield at Shagan River and at other Soviet testing areas, explosions detonated in the 1960s before digital data of high quality became available from either Norsar or Graftenberg, Peaceful Nuclear Explostions (PNEs) in areas of the U.S.S.R. more distant from those arrays, and explosions in regions like Azgir where the propagation of Lg is poor to many stations. Yields determined from m_b become a valuable check on calculations from Lg and can be used to measure the precision of yield determinations by the two methods. I show later that more precise yields for Shagan River explosions can be obtained by suitably averaging determinations from m_b and m(Lg) than can be obtained from either of those wave types alone.

A major problem exists in converting relative yields from Lg into absolute yields, i.

e. in calibrating a given test site in an absolute sense. While yields for several explosions at Shagan River prior to 1973 have recently been published by Soviet workers (Bocharov et al., 1989) and yields of five other Soviet explosions have been turned over to the U. S. Government, the Soviet JVE of 1988 is the only event for which yield has been determined independently on-site by experts from outside the Soviet Union. As mentioned above, the yields measured on-site for the JVE and those five events have not been formally released or published by either the U. S. or Soviet governments. Thus, calibration of absolute yields for Shagan River from Lg alone must be based on either the single data point for the Soviet JVE or the unverified yields reported by Bocharov et al. (1989).

Body wave-yield relationships, however, have the advantage that data from many explosions of announced yield in other parts of the world can "transported" to the Shagan River site via relative bias values for m_b, such as those determined from attenuation. This has the advantage of relying on more than a single m_b-yield pair of values in constructing a magnitude-yield relationship for explosions at Shagan River. Ringdahl and Marshall (1989) calibrated a m_b-yield relationship for that site using the m_b value and approximate yield (111 kt) of the cratering explosion of January 15, 1965 and then making a correction (addition) to its m_b to account for its very shallow depth of burial, i. e. for the fact that, unlike almost other Shagan River explosions, it was not contained. Since Lg measurement were not available for that event from Norsar or Graftenberg, Ringdahl and Marshall (1989) regressed data on m(Lg) with those on m_b for many contained explosions to obtain a m(Lg)-yield relationship and thence to computed yields of other events from that expression. Their absolute values of yield are, of course, sensitive to the uncertainties in the values of m_b, yield and the m_b correction term for the 1965 event.

In this paper I compare my recalculated values of m_b with values of m(Lg) reported by Ringdahl and Fyen (1988) and Ringdahl (1989) for large numbers of explosions at Shagan River. The difference between those two magnitudes is shown to vary systematically from southwest to northeast across that testing area. That variation is attributed to systematic differences in m_b (and hence in m_b bias with respect to NTS), with Lg being generated uniformly throughout the entire Shagan River area. Subdividing the Shagan River area into three parts, corrections to m_b are then made as a function of location on the test site to form a corrected body wave magnitude, m_b' The values are normalized to the southwestern part of the Shagan River area where $m_b = m_b'$.

I then use m_b values for explosions of announced yield, Y, in various parts of the world and correct them to the southwestern part of the Shagan River testing area using the bias values determined from the relative attenuation of P waves by Der et al. (1985) for various testing areas. A regression of m_b upon log Y is obtained for those data but omitting the yields of Bocharov et al. (1989). Fortunately, the explosions with the three largest yields in Bocharov et al. were located in the three different subareas of the test site that I define. When their m_b values are corrected for position on the testing area, the corrected values, m_b', and their published yields fall very close to the m_b-yield relationship determined without recourse to those data points. This indicates that the Bocharov et al. yields must be nearly correct and that they are neither seriously biased nor unrepresentative. It also indicates that it is, in fact, m_b and not m(Lg) that varies systematically with position on the test site. (Consistent yields are not obtained if m_b is taken to be constant and m(Lg) varies over the testing area).

Thus, to obtain yield estimates for Shagan River explosions from m_b that are more accurate than a factor of 1.4 , it is necessary to use somewhat different m_b-yield calibration curves for various parts of that test site. Values of m(Lg) are then regressed against m_b' so that a new magnitude m_b(Lg) can be calculated from Lg. In that way the m_b-yield relationship that was obtained for the southwest part of Shagan River (Fig. 1) can be used to obtain very accurate yield estimates of explosions at Shagan River from either m_b', m_b(Lg) or a weighted average of those two magnitudes. An advantage of this calibration procedure is that it does not rely on the magnitude or yield of a single event like the Soviet JVE or the 1965 cratering explosion; it also permits the yields published by Bocharov et al. (1989) to be verified.

The yields obtained herein by an equal weighting of data from P and Lg waves agree very closely, i. e. within about 15%, with those calculated by Ringdahl and Marshall (1989) using the 1965 cratering event for calibration. Seismology appears to be clearly capable of providing yields for large Shagan River explosions that are at least as good as and often better than those attributed to the Corrtex method (Office of Technology Assessment, 1988). For small explosions at that site, seismic methods have a clear advantage for yield determination compared to Corrtex (Office of Technology Assessment, 1988). For other less well calibrated test sites, like Novaya Zemlya, one to a few Corrtex measurements can be used to calibrate the site such that seismic waves can be used to estimate yields more accurately for past and possibly future explosions in that area.

RESEARCH ACCOMPLISHED

Improved Bodywave Magnitudes

Revised m_b values were recomputed using station corrections for all known Soviet underground nuclear explosions at the Shagan River testing area in Central Asia and in the Azgir region to the north of the Caspian Sea for which data were available from the International Seismological Center (ISC) and the United States Geological Survey

(USGS) for the period January 1961 through May 1988. Station corrections for Shagan River events were derived for 9 large explosions and applied to all undergroud events for which data were available for that testing area. Similar previous work on magnitude and yield determination are described in Sykes and Cifuentes (1984), Sykes and Ruggi (1986, 1989), Sykes and Davis (1987) and Sykes and Ekstrom (1989). Stations used in the recalculations were confined to the distance range 25^{o} to 95^{o}.

A major object in our work has been to reduce the standard error of the mean for m_b to values as small as 0.015 to 0.03 by using large numbers of stations (80 to 100 for larger events) and by applying station corrections. Since individual stations typically record explosions from a given test site with amplitudes that are consistently either higher or lower than the mean for many stations, the application of station corrections considerably reduces the standard deviation of a single reading and avoids biases related to the inclusion or exclusion of individual readings from one event to another. It is particularly important to use station corrections since data from the many stations of countries like Canada or France were not available for some explosions but were available for many others. Similarly, station corrections were derived for the seven largest underground explosions at Azgir, where the testing medium is salt, and applied to other events at Azgir, including the PNE explosions of 1966 and 1968 for which the Soviet Union long ago announced yields of 1.1 and 25 kt respectively. Recomputed magnitudes for Azgir and Shagan River explosions, their standard errors of the mean, and other pertinent data are listed in Tables 1 and 2.

Small Azgir Explosions

In a special study made for the Azgir explosion of 1.1 kt of 1966, m_b was measured at 16 stations for which seismograms were openly available, giving $m_b = 4.524 \pm .056$. Although small in amplitude, P waves could be readily identified at many of the better WWSSN stations of higher gain and good signal-to-noise ratio. The ability to detect such a small event 25 years ago using analog records from mainly simple (non-array) stations reflects the high coupling of a tamped underground explosion in salt and the efficent propagation (high Q) for P waves from the Azgir area to stations worldwide A similar study for the 1968 Azgir PNE event gave $m_b = 5.529 \pm .027$.

Magnitude-Yield Relationships for Shagan River and Azgir

The m_b values for explosions of announced yield, Y, in various parts of the world in either hard rock or below the water table were normalized to the southwestern part of the Shagan River testing area and to Azgir using the published values of relative attenuation and m_b bias of Der et al. (1985). For example, a bias of 0.351 m_b units between the southwest part of the Shagan River testing area and NTS was used. Values of m_b in Fig. 1 for Soviet explosions are from Tables 1 and 2; those for other events are from Marshall et al. (1979).

An aim here has been to use as few Soviet announced yields as possible so as to permit the yields of Bocharov et al. (1989) and other yields recently turned over by the U.S.S.R to the U.S. to be verified. The resulting m_b-yield regression (dotted line in Fig. 1) for the southwest part of the Shagan River area,

$$m_b = 4.483 + 0.787 \log Y \quad (1)$$

which includes yields published by Bocharov et al. (1989) for Shagan River , in fact, differs very little from the other regression in Fig. 1 (solid line) that does not include those data but does include the yields of PNE explosions at Azgir in 1966 (1.1 kt) and 1968 (25 kt), which were made public many years ago as part of an exchange of data on peaceful uses of nuclear explosions. The inclusion or exclusion of the two Azgir events mainly affects the slope of the m_b-log Y relation and not the computed magnitudes for yields from 100 to 150 kt. A similar relationship,

$$m_b = 4.456 + 0.787 \log Y \quad (2)$$

was obtained for Azgir using a bias of 0.324 with respect to NTS (Der et al., 1985). It can be seen that the two explosions in salt at Azgir couple as well as those in hard rock at Shagan River as do the three in granite in Nevada.

<u>Subdivision of Shagan River Testing Area for Yield Determination</u>

Magnitudes determined from Lg at Norsar, m(Lg), and our recalculated values of m_b are now available for large numbers of events at Shagan River. Fig. 2 shows that the difference between m(Lg) and m_b varies systematically across the Shagan testing area from low values in the southwest to high values in the northeastern part, much like that found previously by Ringdahl and Marshall (1989). In constructing Fig. 2 I used the locations of Marshall et al. (1984) as well as Marshall, written communication, for more recent events. Using m(Lg) as a standard, the Shagan River test site is divided into three subareas. The straight line boundaries between the subareas were drawn such as to minimize the number of misfitting data points and to be approximately parallel to structural features on and near the test site. A new magnitude m_b' is defined equal to m_b for the southwestern area, $m_b + 0.145$ for the northeastern area, and $m_b + 0.067$ for the transitional zone between them. Much less scatter is evident for the subregions and for the entire Shagan River area (Figs. 3 and 4) when m(Lg) is compared with m_b' rather than with m_b.

Yields for Shagan River Events from Lg and Bodywaves

A new magnitude,

$$m_b(Lg) = 1.090\ m(Lg) - 0.440 \quad (3)$$

is defined from the regression of m_b' and m(Lg) that is shown in Fig. 4. This permits yields for Shagan River events to be calculated from either m(Lg) or m_b' using (1). This permits Lg observations to be used for yield determination using the much larger collection of m_b values that are available for explosions of announced yield on a worldwide basis. Its use also avoids using mainly unverified Soviet yields when calculating yield directly from observations of Lg. Yields calculated from those two magnitudes are much more consistent for the same explosion than those calculated from Lg and uncorrected body wave magnitudes. The same is true for the yields of the three largest explosions published by Bocharov et al. (1989)--125, 140 and 165 kt, which occurred at Shagan River in 1969 and 1972 in each of the subregions defined in Fig. 2.

The quantities m_b', m_b(Lg) and the average of those two magnitudes were each regressed against logY using the published yields for those three explosions and the average yield, 119 kt, determined from hydrodynamic measurements for the Soviet JVE as published in the New York Times (Sykes and Ekstrom, 1989). The slope of each magnitude-log Y relationship was held constant at 0.8 since the yields cover a very narrow range. Each of those magnitudes had the following standard deviations: m_b', 0.046; m_b(Lg), 0.035; average magnitude, 0.018 magnitude units. While a slightly better weighted average of the two computed values of log Y could be calculated, only a simple average seemed warranted at this time. Nevertheless, it is clear for these four events that the precision of yield estimates can be improved by using an average based on the magnitude determined from Lg and the corrected magnitude m_b' rather than relying on yield estimates based on either of those magnitudes alone.

Close agreement is found between the yields published by Bocharov et al. (1989) and those calculated from the relationship in Fig. 1 that does not include those data or any other recently released Soviet data. Thus, the published of yields Bocharov et al. for Shagan River must be equal to or close to the actual yields. The inclusion of the four yields of Bocharov et al. for Shagan River explosions, in fact, leads to slightly larger computed yields than those obtained in Fig. 1 without those data. The yield computations based on m_b' in Table 1 utilize the relationship that includes those data. Nevertheless, they do not differ significantly from those computed with the other relationship in Fig. 1. The close agreement between yields computed from m_b' and m_b(Lg) and those published by Bocharov et al. also argues that m_b, in fact, and not m(Lg) varies with position from southwest to northeast across the Shagan River testing area.

Precision and Accuracy of Yield Determinations for Shagan River Explosions

The values of log Y obtained by taking a simple average of the magnitudes obtained from Lg and bodywaves for 66 Shagan River explosions of $Y \geq 10$ kt (Table 1) have standard errors of the mean (SEM) between 0.00 and 0.08 and an average SEM of .029. These translate into yield determinations based on those two wave types with a precision at 95% confidence (R value) of a factor of 1.0 to 1.45 (mean value of 1.14) (Fig. 5). Only one explosion of yield greater than 62 kt, an event in 1969, has an R value greater than 1.28. The decrease in precision, i. e. increase in R values, for events smaller than about 60 kt probably mainly reflects the smaller signal-to-noise ratios of the Lg waves that were used to determine m(Lg) at large distances.

These uncertainties in yield estimation, of course, pertain to precision and not necessarily to accuracy. Nevertheless, it seems unlikely that the calibration curves used in Fig. 1 are more uncertain than either 0.07 in magnitude, 0.08 in log Y or a factor of 1.2 in yield. The greatest contribution to the uncertainty of the yields determined by averaging magnitudes from Lg and P waves for explosions with yields larger than about 60 kt comes from the uncertainty in the magnitude-yield calibration curve. Nonetheless, yields determined in this way for explosions larger than about 60 kt appear to have an accuracy at 95% confidence that is comparable to and perhaps better than the factor of 1.3 attributed to the Corrtex method for Shagan River explosions (Office of Technology Assessment, 1988). The published yield of 16 kt (Bocharov et al., 1989) for the explosion at Shagan River of February 10, 1972 agrees well with the yield of 18 kt (Table 1) obtained from m_b'. This indicates that the calibration relationship and yield estimates for that test site near 20 kt from P wave magnitudes probably are of comparable accuracy to those obtained from P waves alone for yields between 100 and 150 kt. At the present time the Corrtex method could not be used with confidence to determine yield for explosions smaller than several tens of kilotons (Office of Technology Assessment, 1988). Thus, seismic methods offer a clear advantage in monitoring compliance under a Low-Yield Threshold Test Ban Treaty. The availability of digital recordings of Lg from regional stations in the Soviet Union, such as stations operated in conjunction with the IRIS program, should result in greater precision in determining yield for tamped explosions as small as about 1 kt.

Yields Determined from Surface Waves for Shagan River Explosions

Yields were also determined in Table 1 from surface waves for all moderate to large nuclear explosions at Shagan River for which digital data were available through the end of 1986. With one exception, data of that type were available only after late 1978. Rayleigh wave (LR) and Love wave (LQ) amplitudes with periods in the narrow band 18-21 s were measured on vertical and transverse component digital seismograms for long-period stations in Eurasia. Only data for pure or nearly pure continental paths were used so as to avoid complications resulting from surface wave propagation across continental margins. The method of analysis for computing the surface wave magnitude, Ms, and station corrections are described in Sykes and Cifuentes (1984) and Sykes and Ekstrom (1989).

It has been recognized for many years that many underground explosions at Shagan River trigger the release of natural tectonic stresses in the vicinity of the explosion shot point. Both the explosion source itself and the release of those stresses contribute to LR and Ms whereas only the latter contributes to LQ. Following our previous work on yield estimation from Ms, we sought to make a correction to Ms so as to largely remove the effect of tectonic release. This was done only for explosions with small to moderate tectonic release compared to the size of the pure explosion itself, i. e. for LQ / LR < 0.60, where that ratio was taken as an average over all stations used in the analysis. A full moment tensor solution is need for larger values of LQ/LR.

Yields were computed from

$$Ms + B(LR/LQ) = 2.16 + 0.97 \log Y \qquad (4)$$

using the measured values of Ms, where the second term is a linear correction to Ms for the effect of small to moderate tectonic release (Sykes and Cifuentes, 1984; Sykes and Ekstrom, 1989). The relationship Ms = 2.16 + 0.97 was determined by Sykes and Cifuentes (1984) using explosions of announced yield in various parts of the world for which either LQ/LR was small or the mechanism of the tectonic release was such as to not significantly affect Ms as averaged over a range to azimuths from the event. Values of B were obtained for each explosion at Shagan River of LQ/LR < 0.60 for which Ms was available and Y had been determined from m_b and/or m_b(Lg). The average value, B = 0.45, is close to the value 0.43 obtained by Sykes and Cifuentes (1984) for a much smaller number of events at Shagan River for which moment tensor solutions were available at the time in the literature. That value is in accord with the hypothesis that tectonic release at that site involves predominantly thrust faulting and,hence, that the correction to Ms is positive. Also, the argument can be turned around taking B = 0.43 from those moment tensor events to derive yields from surface waves that differ only slightly from those in Table 1. Those yields can then be used along with values of m_b' for those explosions to calculate the constant in the m_b-yield relationship for Shagan River. That constant is nearly identical to the two values obtained in Fig. 1 using a bias value of 0.35 m_b units for the southwestern part of the Shagan River area with respect to NTS.

The individual values of log Y calculated from Ms (Table 1), however, scatter much more when plotted against log Y determined from either m_b' or m_b(Lg) than is the case when the latter two quantities are plotted against one another. Thus, surface wave estimates of yield are less precise and, hence, are not used in this paper to calculate average yields. They can be used, however, as a less accurate additional constraint on yield if an estimate from Lg waves is not available or the average yield from P and Lg is near or above the 150 kt threshold of the TTBT.

Yields of Weapons Deployed on Soviet Strategic Delivery Systems and Tested at Shagan River

In November and December 1972 and in July 1973 the Soviet Union detonated three nuclear explosions at Shagan River with yields between 140 and 200 kt. Those events occurred well before either the negotiations for the TTBT in July 1974 or the start date for that treaty in 1976. The U.S.S.R. did not test again in the yield range above 120 kt at Shagan River until June 1979. A number of much larger explosions with yields of 500 kt or greater were detonated at the two remote sites in Novaya Zemlya in the 20 months between the signing of the TTBT and its start date. Those three events at Shagan River were the only nuclear explosions detonated by the U.S.S.R. at any of their test sites in the yield range 120 to 400 kt from 1970 to June 1979, a period of a several years both before and after the signing of the TTBT (Sykes and Davis, 1987; Sykes and Ruggi, 1989).

The occurrence of three explosions at Shagan River in that yield range within 9 months of one another in 1972 and 1973 suggests that they represent the full yield or nearly full yield testing of important and distinct Soviet nuclear weapons. The use of precise methods of yield estimation from P and Lg waves permits an assessment to be made of the yields of those three events and to compare them with the published yields for the two events in 1972. The yields determined as an average of the log Y values from m_b' and m_b(Lg) are 154, 138 and 193 kt with associated R values (95% confidence on precision) of 1.14, 1.22 and 1.22 kt respectively (Tables 1 and 3). The calculated yields of the first two events agree closely with the announced yields (Bocharov et al., 1989) of 165 and 140 kt (Table 3). The explosion of July 23, 1973 of Y = 193 kt, for which the yield has not been released by the U.S.S.R., is clearly the largest underground explosion at Shagan River.

Those three explosions occurred a few years before the initial deployment (Table 4) by the Soviet Union of their first MIRVed (multiple independently targetable re-entry vehicles) intermediate-range ballistic missiles (IRBMs) and MIRVed submarine launched ballistic missiles (SLBMs) according to Sykes and Davis (1987). The throw-weights of the SS-20, (the IRBM), and SS-N-18 mod 1, (the SLBM), and the number of re-entry vehicles (three per missile) are consistent with warhead yields between 140 and 200 kt (Sykes and Davis, 1987). SS-20 missiles have been destroyed under the terms of the Intermediate Nuclear Forces treaty; a number of SS-N-18 systems are still operational as of late 1991. Thus, one or more of the three largest nuclear tests at Shagan River in 1972 and 1973 appears to have been for the weapons to be carried by these two important additions to the Soviet arsenal of strategic nuclear weapons.

Clustering of Yields of Shagan River Explosions

The newly calculated yields in Table 1 provide strong evidence of clustering in the distribution of yields of Soviet tests at Shagan River from the start of the TTBT in 1976 to mid 1988. The cumulative number of events at Shagan River during that interval with yields less than Y are plotted in Fig. 6 as a function of Y. The yield ranges centered on 40, 88 and 138 kt, where the slope is greatest in Fig. 6, are associated with the most frequent testing at Shagan River. Additional tests with yields between 30 and 100 kt during that period occurred at Novaya Zemlya as did a few others at the Degelen Mountain site in Central Asia. Most tests smaller than about 30 kt during that time interval took place at the Degelen Mountain portion of the Central Asian test site (Sykes and Ruggi, 1989).

The clustering of yields near 138 kt in Fig. 6 undoubtedly mainly reflects the artificial cutoff set by the 150 kt limit of the Threshold Treaty. Kidder (1985) shows a peak in testing by the United States from 1980 through 1984 at yields somewhat smaller than 150 kt that is quite similar to the Soviet peak near 138 kt. He states that the "accumulation of [U.S.] tests near 150 kt is partly the result of testing, at reduced yield, strategic weapons whose yield would otherwise exceed the TTBT limit." Presumably, a similar logic holds for at least some Soviet tests near 138 kt as well.

Soviet Compliance with the Threshold Test Ban Treaty

As yield estimates for Shagan River explosions have become more precise, the number of events since 1976 with a yield determined from either P waves, Lg or their average (Table 1) that exceeds 150 kt has become smaller. The maximum calculated yields of any of those explosions has decreased as well. For example, five events from 1976 through mid-1988 have average yields in excess of 150 kt: 157, 158, 162, 169 and 170 kt (Table 1). Each of those values is within a factor of 1.13 times 150 kt. Only the event of July 1973, which occurred before the TTBT became effective, has a yield that is greater than 150 kt at a high level of confidence. For two of those five explosions the average yield was based on m_b' alone since Lg magnitudes were not available. A more common situation in Table 1 is for one of the two yield estimates to be above 150 kt, another below and the average somewhat below 150 kt. For example, the event of December 10, 1972 had an announced yield of 140 kt, a yield from m_b of 125 kt, that from $m_b(Lg)$ of 153 kt, and an average calculated yield of 138 kt.

Thus, all of the explosions at Shagan River from the start date of the TTBT through mid-1988 are consistent with Soviet compliance with that treaty. A similar conclusion was reached by the Office of Technology Assessment (1988). Nevertheless, the new estimates are still not accurate enough to ascertain a 10% or smaller exceedance of the threshold with high confidence. For example, the event of November 2, 1972 with an announced yield of 165 kt has an average yield of 154 kt and yields from P and Lg waves of 144 and 165 kt. If any events since 1976 were in excess of the threshold by small amounts, the most likely candidates are 169 kt on August 18, 1979 and 170 kt on October 27, 1984. The explosion of July 1973, on the other hand, is a good example of present capability to identify a past or future event with a yield in excess of about 190 kt as being significantly larger than 150 kt at a high level of confidence.

Cavities Formed by Nuclear Explosions in Thick Salt Deposits that Might be Usable for Future Clandestine Nuclear Testing

The U.S.S.R. has carried a number of nuclear explosions in salt near Azgir as well as conducting several other PNEs in regions known to contain salt. Cavities produced by nuclear explosions in salt, such as Salmon and Gnome in the United States, have remained standing for many years whereas cavities produced in other rock types usually collapse within short periods of time. Many investigators working on decoupled nuclear testing that might be conducted under either a CTBT or a LYTTBT have paid considerable attention to the possible use of cavities produced by nuclear explosions. I will show, however, that monitoring of the relative few areas of the Soviet Union in which cavities of that type could exist that could be used in the future for either the full or nearly full decoupling of explosions with yields larger than 1 kt is a tractable problem. Instead, more attention needs to be devoted to the feasibility of decoupled testing in the yield range from 1 to 10 kt in large cavities produced by solution mining. Many more potential sites are available in the U.S.S.R. for creating large cavities by solution mining than are available from past nuclear explosions in salt.

Table 2 lists Soviet underground nuclear explosions that were detonated through 1986 either in or in the general vicinity of thick salt deposits. As mentioned in earlier sections, yields for explosions at Azgir were determined using recalculated m_b values that included station corrections derived for that site. Applying those station corrections to events more than 100 km from Azgir, howe\ :, did not reduce the standard error of the mean of m_b values for those events. Hence, .ation corrections were not used in recomputing m_b for the other events in Table 2. The yields of all of the events in Table 2 were calculated from (2).

Nine of the explosions at Azgir have yields between 25 and 110 kt. All of those events occurred between July 1, 1968 and October 24, 1979 in the area of numerous salt domes to the north of the Caspian Sea, what Soviet workers call the Pri-Caspian region. I will now make estimates of the sizes of decoupled nuclear explosions that could be detonated in cavities created by those and other Soviet nuclear explosions located either in or in the general vicinity of thick salt deposits. The conservative assumption will be made that cavities, in fact, remain standing for all of those events and that they could be used for conducting small decoupled nuclear tests at some time in the future. First, information about the depths and dimensions of the cavities created by the U.S. explosion Salmon and two explosions at Azgir is used to calculate yields of nearly decoupled (Sterling conditions) and fully decoupled nuclear explosions that could be conducted in the cavities assumed to have been created by the Soviet events in Table 2.

Salmon, a fully-tamped explosion of 5.3 kt, was detonated in a salt dome in the state of Mississippi at a depth of 828 m in 1964. The Sterling nuclear explosion was a decoupled event of 0.38 kt detonated in the Salmon cavity at the same depth in 1966 (Denny and Goodman, 1990). The Salmon cavity, like that produced by the Gnome explosion in bedded salt in New Mexico and that produced by the tamped Soviet explosions of 1966 and 1968 in salt domes, was not perfectly spherical in shape. In each case a significant amount of rubble and molten salt accumulated at the bottom of the initially nearly spherical cavity. The cavity volume for the Sterling event was 19,400 m^3, giving a mean radius 16.7 m (Denny and Goodman, 1990). The 1968 Azgir event of 25 kt was detonated at a depth of 590 m and produced a cavity with a volume of 140,000 m^3, giving a mean radius of 32.2 m (Kedrovskiy, 1970). The 1966 Azgir explosion of 1.1 kt was detonated at a depth of about 165 m and generated a cavity with a volume of 10,000 m^3 (mean radius of 13.4 m). Since that cavity filled with water (Kedrovskiy, 1970), it obviously could not be used for detonating decoupled explosions unless the water could be removed. The Soviet explosion at Orenburg of October 22, 1971 of 15 kt in bedded salt was used to produce a cavity for storing gas condensates at an unspecified depth. Its volume was 50,000 m^3, giving a mean radius of 22.9 m (Izrael' and Grechushkina, 1978).

The requirement that a clandestine nuclear test in a large underground cavity in salt not produce a crater or other disturbance at the surface and that it be fully contained so as not to leak radioactive products to the surface set limits on the minimum depth of such a cavity. For a very weak material like salt, Latter et al. (1961) conclude that the pressure on the cavity wall for full decoupling must be less than or equal to one half the overburden pressure (i.e. the vertical stress, ρgh) so as to prevent failure in tension of the surrounding salt material and, hence, to prevent leakage of radioactive gases from the cavity. The relationship between a step in cavity pressure, P, produced by an explosion of yield, Y, in a cavity of volume, V, and the requirement for containment that P be less than some constant, k, times the vertical stress can be written

$$P = (\gamma-1)Y/V \leq k\,\rho gh \tag{5}$$

where γ is the ratio of heat capacities taken to be 1.2 under the conditions of interest (Latter et al., 1961), ρ is the average density of the material from the surface down to depth, h, and g is the gravitational acceleration at the earth's surface. The average density in the following applications is taken to be that of salt at the Salmon site, 2200 kg / m^3. For the Latter criterion mentioned above, k = 0.5.

Taking k = 0.5 and the relevant parameters for the cavities created by the Salmon and the1966 and 1968 Azgir explosions, the maximum yields of fully decoupled explosions according to the Latter criterion that could be detonated in those cavities (after converting the energy in Joules, J, to kilotons, where 1 kt = 4.184 x 10^{12} J) are 0.21, 0.02 and 1.1 kt respectively. The ratios of the size of the tamped nuclear explosion that was used to create each of those cavities to the size of the largest fully decoupled event that could be detonated in them under the Latter criterion are 25, 55 and 23 for the Salmon, 1966 and 1968 events.

Sterling was almost, but not fully decoupled; P was a factor of 1.8 = 0.38 / 0.21 times larger than that calculated by way of the Latter criterion. The value k = 0.90 calculated for that event indicates that P still did not exceed the vertical stress (k = 1). Experience with cavities in salt used for gas storage indicates that leakage of the storage product may occur when the internal pressure in the cavity exceeds the vertical stress. If Sterling conditions, i. e. k = 0.90, apply rather than the Latter criterion to the 1966 and 1968 cavities at Azgir, maximum yields for explosions that could be detonated in those cavities are 0.04 and 2.0 kt. The ratio of the size of the tamped nuclear explosion that was used to create a cavity to the size of the largest decoupled event that could be detonated in them under what I will term Sterling conditions is 13.9 = 5.3 / 0.38 for the Salmon / Sterling pair and 27 and 12.5 for the 1966 and 1968 explosions at Azgir.

Thus, much larger (12 to 55 times larger) tamped explosions are needed to create cavities than the maximum sizes of either fully decoupled or nearly fully decoupled explosions that can be detonated in them. This is important since, even at the unclassified level, the United States knows of all past Soviet underground explosions down to a small yield that have been detonated either in or possibly in areas of thick salt deposits. The yields of fully decoupled and nearly fully decoupled explosions that could be detonated in cavities that may remain standing from those events is at least an order of magnitude smaller than the yields of the explosions that generated those cavities.

While the cavity volume produced by a tamped explosion undoubtedly varies with the depth of the event, it should be appreciated that fully decoupled and nearly fully decoupled nuclear explosions larger than 1 kt would have to be conducted in a fairly narrow range of depths. An air filled cavity in salt is likely to deform significantly at depths greater than 1000 m whereas an evader determined not to be caught testing at such yields, would use only cavities that are at least several hundred meters deep to insure that bomb-produced products did not escape from the cavity. There is a tradeoff between the fact that a shallower tamped explosion produces a larger cavity than a deeper one in the same material and the fact that a larger cavity at a shallower depth is needed to satisfy inequality (5) for a decoupled event of a given yield.

Since the depths of most of the explosions in Table 2 are not known, two estimates of the yields of fully decoupled and nearly fully decoupled nuclear explosions that could be detonated in cavities created by those events have been made in the last column of Table 2. The smaller value is derived by dividing the computed yield of each event in Table 2 by the yield ratio 5.3 / 0.21 = 25, where 5.3 is the yield of Salmon and 0.22 is the computed yield by the Latter criterion of the largest fully decoupled yield that could be tested in the Salmon cavity. The larger yield in the last column is computed by dividing the calculated yields of each event in the table by the yield ratio for the Salmon / Sterling pair = 5.3 / 0.38 = 13.9. Those simple calculations--1.0 and 1.8 kt--for the cavity produced by 1968 Azgir event of 25 kt are very close to the values obtained above using the published depth and volume for that cavity--1.1 and 2.0 kt. The simple calculations for the much smaller 1966 event overestimate the yields calculated above from the depth and volume of that cavity.

The yields of the various events in Table 2 divided by 13.9 (larger numbers in last column) are taken as a measure of the yields of nearly fully decoupled explosions that could be detonated in the cavities produced by those events. This, of course, assumes Salmon / Sterling conditions. Uncertainties in the yields of the events that produced those cavities and their depths can lead to uncertainties in the estimates of decoupled yields by a factor of 1.5. Our main concern here, however, is what are the "opportunities" that may be available to test weapons *clandestinely* of certain approximate sizes and not that exact size.

Table 5 summarizes the yields of nearly fully decoupled (Sterling conditions) nuclear explosions that could by detonated in the cavities of events in Table 2 both by area and yield range. Most of the "opportunities" for such testing are concentrated in the area to the north of the Caspian Sea. The "oppontunities" for the larger tests, up to a maximum of 7 to 8 kt, are mostly confined to Azgir itself. Possibilities for such decoupled testing are more restricted in the area of bedded salt to the northwest of lake Baikal. Some and perhaps all of those events may not have been conducted in salt but in other rocks in the strategraphic sequence or in rocks just outside the area of salt deposits. Once again, this list attempts to be conservative in its cataloguing of potential areas and sites for decoupled testing in the range 1 to 10 kt. For example, the single Bukhara event (Tables 2 and 5) was used to put out a fire in an oil well that had encountered an unanticipated fault that had provided pathways for escaping petroleum. It was also detonated at such a great depth (2.5 km) that closure of the salt cavity undoubtedly occurred soon after it was detonated. Thus, on both of those grounds it appears to be a poor and risky candidate site for conducting a clandestine decoupled nuclear explosion.

Thus, the number of cavities produced by past nucler explosions that potentially could be used for clandestine testing of nearly fully decoupled nuclear explosions under either a CTBT or a LYTTBT is limited. Those sites are confined to a few areas of the

U.S.S.R. The question of using those cavities instead for partially decoupled events as described by Stevens et al. (1991) will be dealt with in a separate paper along with the feasibility of constructing and using cavities in hard rock for either the full or the partial decoupling of explosions with yields from 1 to 10 kt. Possibilities of clandestine testing in large cavities created by solution mining also will be dealt with in a separate paper.

CONCLUSIONS AND RECOMMENDATIONS

Implications for Identifying Small Decoupled Nuclear Explosions in Salt

For purposes of appreciating the detection capability of a given seismic network, it is important to recognize, using data from Azgir, that a fully-coupled (tamped) explosion of 1 kt in salt in high-Q areas of the U.S.S.R. has an m_b of 4.46; fully decoupled events of 1 and 10 kt have m_b's of 2.61 and 3.40 respectively (assuming a decoupling factor of 70). These magnitudes are higher than has generally been thought previously. For example, chemical explosions of $m_b < 2.6$ in high Q areas containing salt need not be considered in monitoring a 1 kt threshold treaty. Most areas of thick salt deposits in the U.S.S.R. are typified by high Q (efficient transmission) for P waves and low natural seismic activity.

Past nuclear explosions conducted in salt by the Soviet Union for which cavities may remain standing that are large enough for the full decoupling of explosions larger than 1 kt are concentrated in only a few areas of that country. The existence of all cavities of that size or larger that have been created by past nuclear explosions is known (Table 3) since the explosions that created those cavities must be about 25 times larger in yield than the size of the fully decoupled event that can be detonated in them. (That ratio is 13.9 for the Salmon/Sterling pair where the yield of Sterling was about 1.8 times larger than that of a fully decoupled explosion in the Salmon cavity).

Hence, the monitoring of cavities of that size that may remain standing that were created by past nuclear explosions should be relatively easy under a Low-Yield Threshold Test Ban Treaty with a threshold of 1 kt, providing U.S. stations are allowed to operate under the treaty near the epicenters of those past explosions. Probably the greatest difficulty in monitoring such a LYTTBT involves cavities created, not by nuclear explosions, but by solution mining in other areas of thick salt deposits of the U.S.S.R.

Precise Yield Estimates for Explosions at Shagan River

Yield determinations for Shagan River explosions can be improved by subdividing that testing area into three parts with different m_b-yield relationships and by combining those results with yields calculated from Lg. The calculated yields of many of those explosions since 1976 are clustered in a few specific ranges of yield.

REFERENCES

Bocharov, V.S., S.A. Zelentsov and V.N. Mikhailov (1989). The characteristics of 96 underground nuclear detonations at the Semipalatinsk test range, Atomic Energy **67**, 210-214.

Denny, M.D. and D.M. Goodman (1990). A case study of the seismic source function: Salmon and Sterling reevaluated, J. Geophys. Res. **95**, 19, 705-19, 723.

Der, Z., T. McElfresh, R. Wagner and J. Burnetti (1985). Spectral characteristics of P waves from nuclear explosions and yield estimation, Bull. Seismol. Soc. Amer. **75**, 379-390, 1222.

Hanson, R.A., F. Ringdahl and P. G. Richards (1990). The stability of RMS Lg measurements and their potential for accurate estimation of the yields of Soviet underground nuclear explosions, Bull. Seismol. Soc. Amer. **80**, 2106-2126.

Izraehl, Yu. A. and M.P. Grechushkina (1978). The use of peaceful underground nuclear explosions with minimum radioactive contamination of the environment, Peaceful Nuclear Explosions **V**, International Atomic Energy Agency, Vienna, document IAEA-TC-81-5/7, pp. 167.

Kedrovshiy, O.L. (1970). Prospective applications of underground nuclear explosions in the national economy of the USSR, UCRL-Trans-10477, (Translation from Russian), Lawrence Radiation Laboratory, University of California, Livermore, CA, 1-47.

Kidder, R.E. (1985). Militarily significant nuclear explosive yields, F.A.S. Public Interest Report, (Journal of Federation of American Scientists)**38**, no. 7, pp 1-3.

Latter, A.L., R.E. LeLevier, E.A. Martinelli and W.G. McMillan (1961). A method of concealing underground nuclear explosions, J. Geophys. Res.**66**, 943-946.

Marshall, P.D., T.C. Bache and R.C. Lilwal (1984). Body wave magnitudes and locations of Soviet underground explosions at the Semipalatinsk test site, Atomic Weapons Research Establishment Report **0 16/84**, 1-87.

Marshall, P.D., D.L. Springer and H.C. Rodean (1979). Magnitude corrections for attenuation in the upper mantle, Geophys. J.R. Astr. Soc. **57**, 609-638.

Office of Technology Assessment, Congress of the United States (1988). Seismic Verification of Nuclear Testing Treaties, OTA-ISC-361, U.S. Government Printing Office, Washington, DC, 139 pp.

Ringdal, R. and P.D. Marshall (1989). Yield determination of soviet underground nuclear explosions at the Shagan River test site, Semiannual Tech. Summary 1 October 1988-31 March 1989, NORSAR Sci. Rpt 2-88/89, Kjeller, Norway, pp. 36-67.

Ringdal, F. (1989). NORSAR P-wave detection and yield estimation of selected Semipalatinsk explosions, Semmiannual Tech. Summary 1 April-30 September 1989, NORSAR Sci. Rpt. 1-89/90, Kjeller, Norway, pp. 54-61.

Ringdal, F. and J. Fyen (1988). Comparative analysis of NORSAR and Grafenberg Lg magnitudes for shagan River explosions, Semiannual Tech. Summary 1 April-30 September 1988, NORSAR Sci Rpt. 1-88-89, Kjeller, Norway, pp. 88-106.

Stevens, J.L., J.R. Murphy and N. Rimer (1991). Seismic source characteristics of cavity decoupled explosions in salt and tuff, Bull. Seismol. Soc. Amer. **81**, 1272-1291.

Sykes, L.R. and I.L. Cifuentes (1984). Yields of Soviet underground nuclear explosions from seismic surface waves: compliance with the Threshold Test Ban Treaty, Proc. Natl. Acad. Sci. USA, **81**, 1922-1925.

Sykes, L.R. and D.M. Davis (1987). The yields of Soviet strategic weapons, Sci. Amer., **256** 29-37.

Sykes, L.R. and G. Ekstrom (1989). Comparison of seismic and hydrodynamic yield determinations for the Soviet joint verification experiment of 1988, Proc. Natl. Acad. Sci. USA, **86**, 3456-3460.

Sykes, L.R. and S. Ruggi (1986). Soviet underground nuclear testing: inferences from seismic observations and historical perspective, Working Paper NWD **86-4**, Natural Resources Defense Council, Washington, DC, 88 pp.

Sykes, L.R. and S. Ruggi (1989). Soviet nuclear testing, in Soviet Nuclear Weapons, Nuclear Weapons Databook, **IV**, T.B. Cochran et al (editors), Ballanger, New York, 332-382.

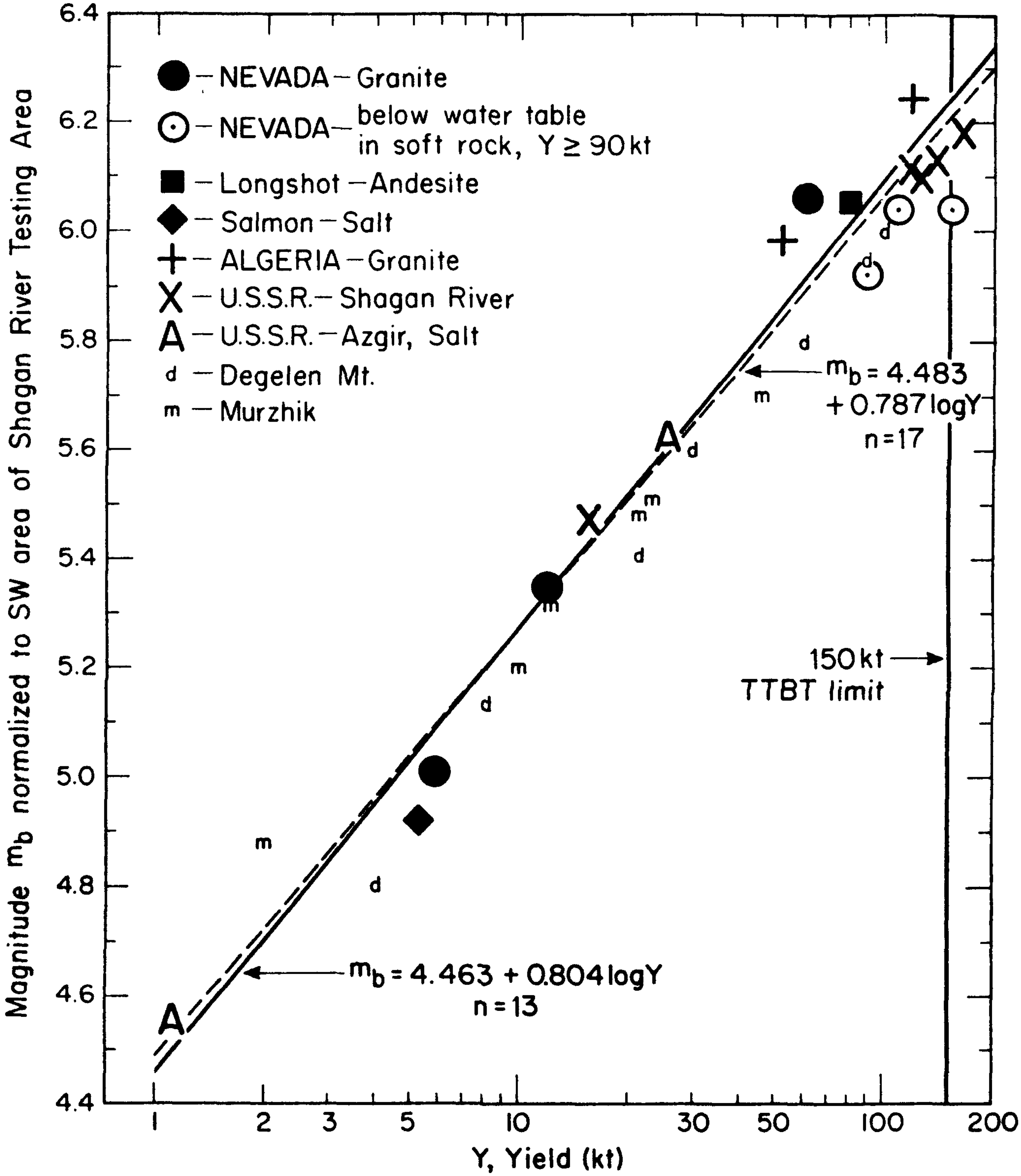

Fig. 1 Calibration curves used for yield estimation as normalized to southwestern portion of Shagan River testing area. Explosions at Degelen and Murzhik were not used in two regressions. Explosions used are those of published yield in either hard rock or below water table.

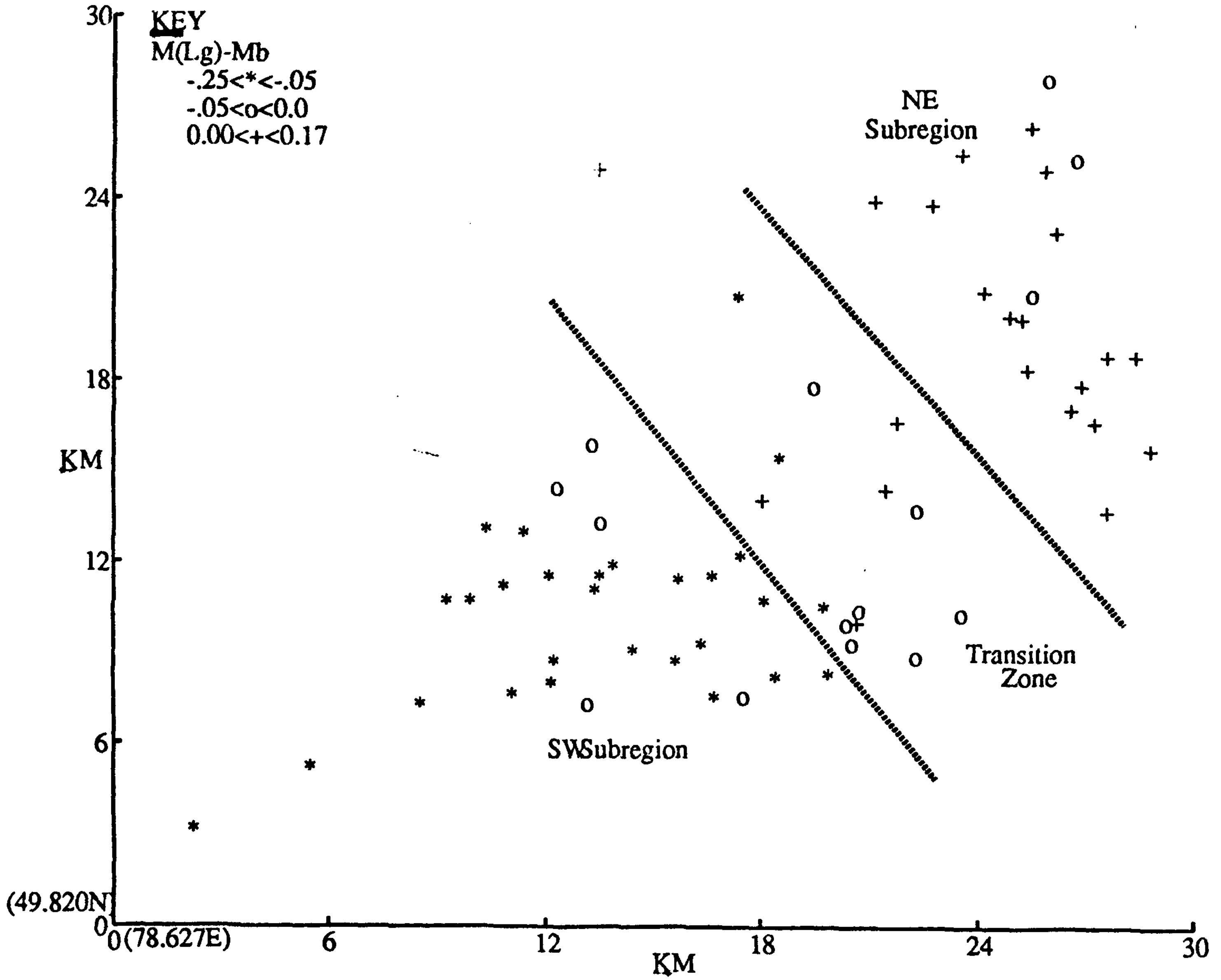

Fig. 2 L_g magnitude minus body wave magnitude as a function of location within Shagan River testing area. Testing area is divided into three parts for better estimates of yield from body waves.

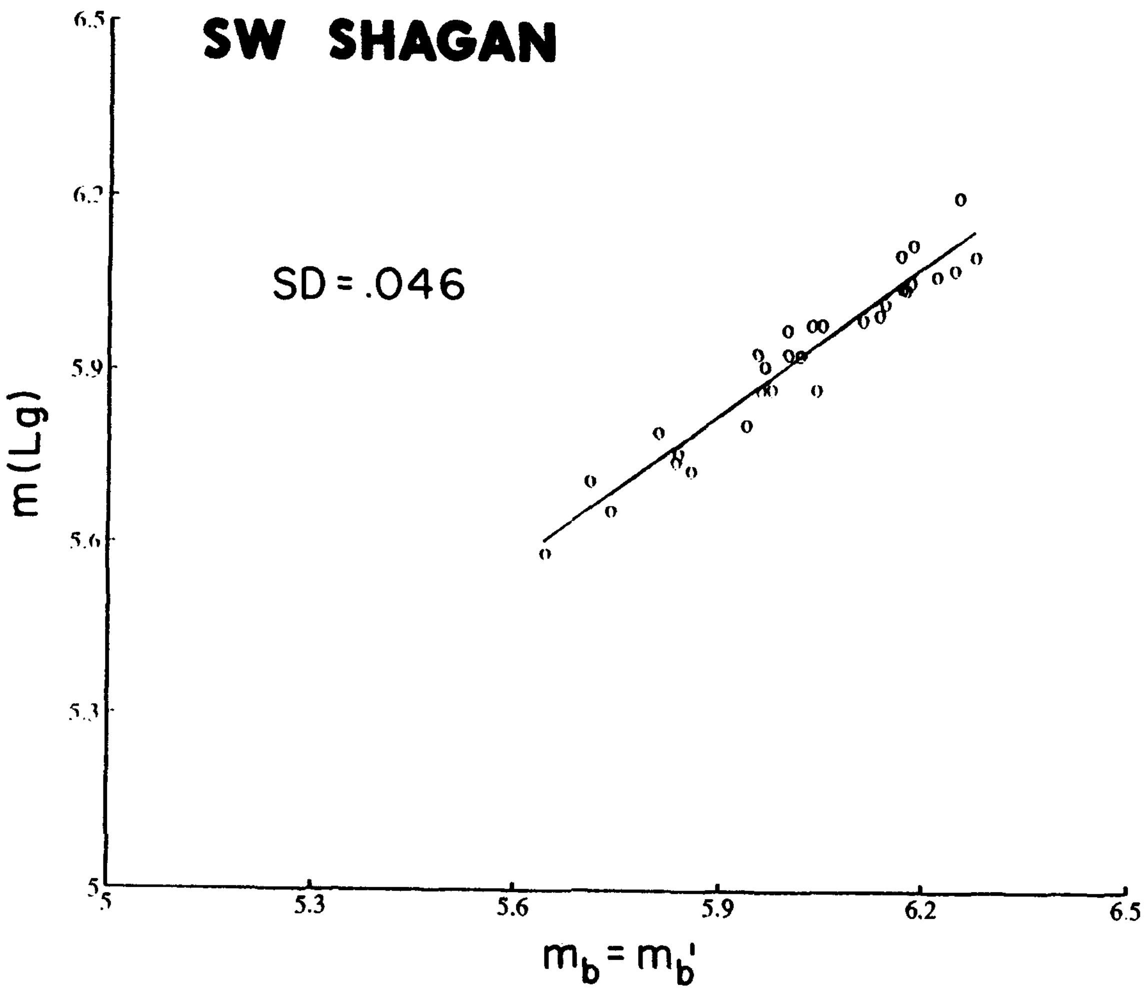

Fig. 3 L_g magnitude as a function of body wave magnitude for southwestern portion of Shagan River testing area. SD = standard deviation.

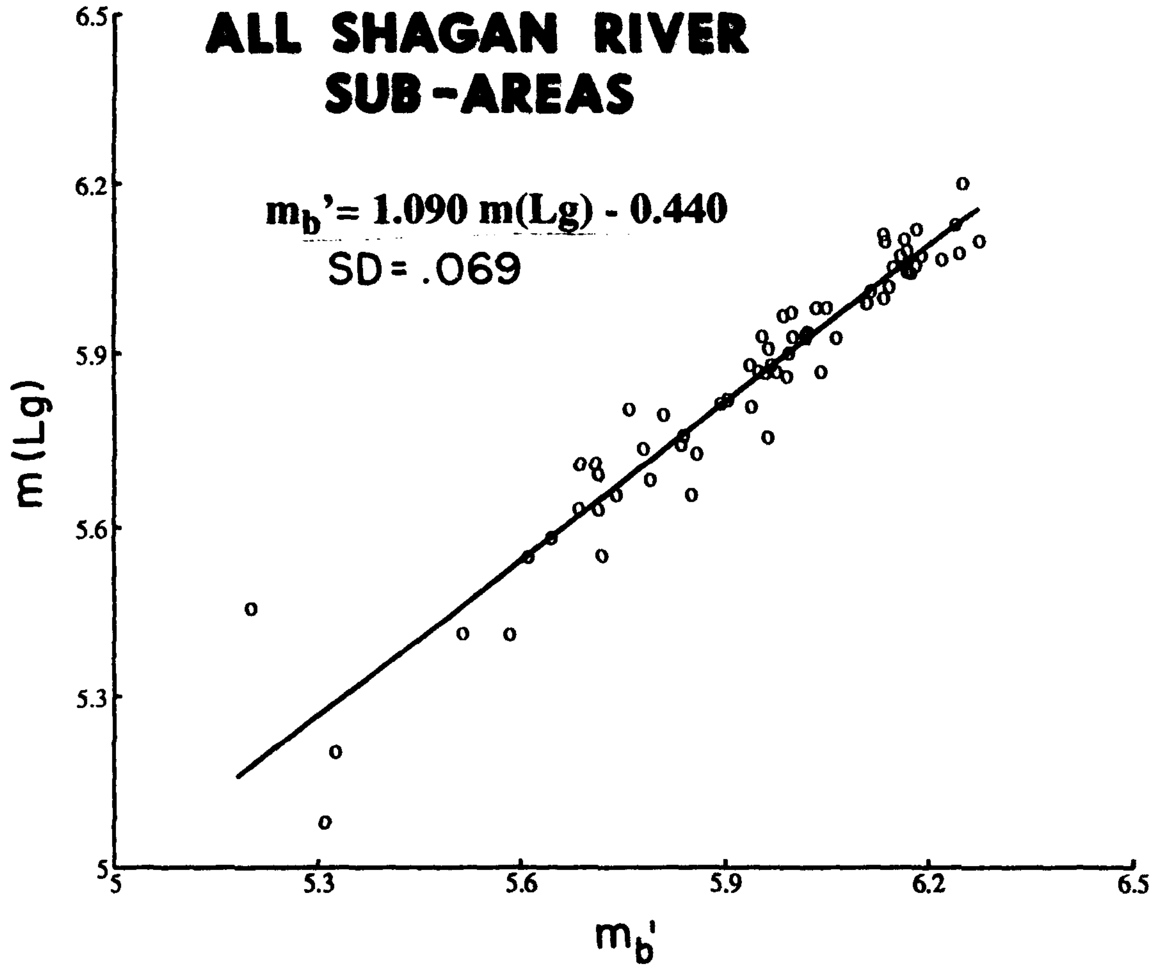

Fig. 4 L_g magnitude as a function of revised body wave magnitude, m_b'. SD = standard deviation.

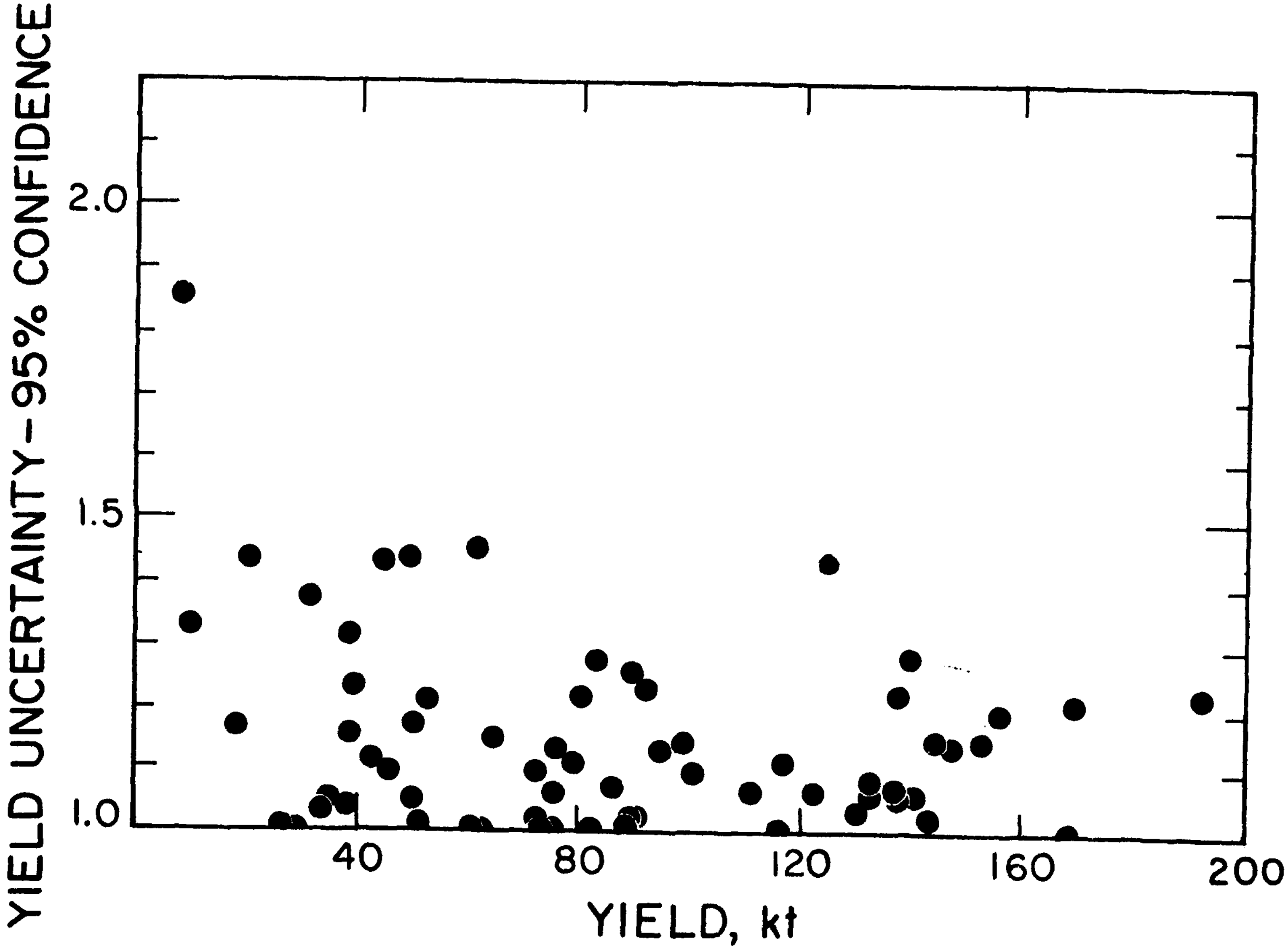

Fig. 5 95% confidence limits on average yield determined from body waves and L_g for Shagan River explosions as a function of calculated yield.

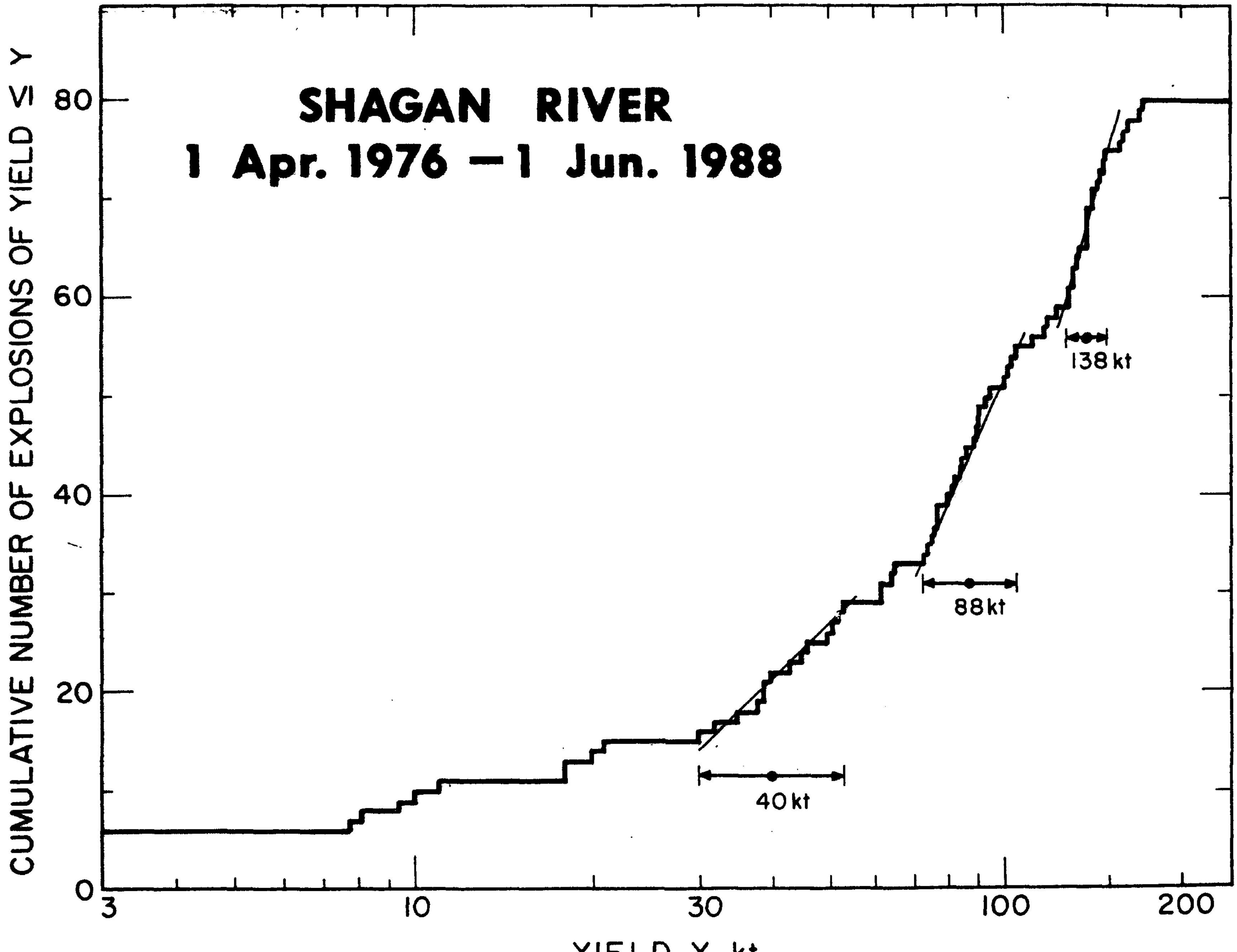

Fig. 6 Cumulative number of all known underground nuclear explosions at Shagan River for a time period indicated of calculated yield ≤ Y. Explosions tend to be clustered at a few specific ranges of yields as indicated by the thin lines of steeper slope.

Table 1. Calculation of Yield and Other Pertinent Data for Underground Nuclear Explosions at Shagan River Testing Area, U.S.S.R. through June 1, 1989

Year	Month	Day	mb	region	mb'	mb(Lg)	Ms	LQ/LR	Y(Ms)	Y(mb)	Y(mbLg)	R	Y(ave)	Y(ann)
1965	1	15	5.905	NE	6.050	.	.	.	(cratering shct- no yield determined)					100-150
1968	6	19	5.299	NE	5.444	.	.	.	.	17	.	.	17	< 20
1969	11	30	5.954	TZ	6.021	6.147	.	.	.	90	130	1.433	108	125
1971	6	30	5.483	NE(?)	5.628	.	.	.	.	28	.	.	28	< 20
1972	2	10	5.406	TZ(?)	5.473	.	.	.	.	18	.	.	18	16
1972	11	2	6.181	SW	6.181	6.228	3.922	0.20	81	144	165	1.145	154	165
1972	12	10	5.989	NE	6.134	6.203	.	.	.	125	153	1.220	138	140
1973	7	23	6.247	SW	6.247	6.317	.	.	.	174	213	1.221	193	.
1973	12	14	5.803	NE	5.948	5.956	.	.	.	73	74	1.023	73	.
1974	5	31	5.849	SW(?)	5.849	.	.	.	.	54	.	.	54	.
1974	10	16	5.444	TZ	5.511	5.458	.	.	.	20	17	1.165	19	.
1974	12	27	5.541	NE	5.686	5.781	.	.	.	34	45	1.315	39	.
1975	4	27	5.542	TZ	5.609	5.606	.	.	.	27	27	1.009	27	.
1975	10	29	5.616	TZ(?)	5.683	5.695	.	.	.	33	35	1.036	34	.
1975	12	25	5.690	TZ	5.757	5.883	.	.	.	42	60	1.434	50	.
1976	4	21	5.181	SW	5.181	.	.	.	.	7.7	.	.	7.7	.
1976	6	9	5.180	NE	5.325	5.227	.	.	.	12	8.8	1.326	10	.
1976	7	4	5.825	TZ(?)	5.892	5.893	.	.	.	62	62	1.002	62	.
1976	8	28	5.710	TZ(?)	5.777	5.809	.	.	.	44	48	1.095	46	.
1976	11	23	5.757	NE	5.902	5.902	.	.	.	63	64	1.001	64	.
1976	12	7	5.834	SW	5.834	5.817	.	.	.	52	50	1.049	51	.
1977	5	29	5.737	SW	5.737	5.724	.	.	.	39	38	1.039	38	.
1977	6	29	5.241	TZ	5.308	5.094	.	.	.	11	6	1.848	8.2	.
1977	9	5	5.790	NE	5.935	5.968	.	.	.	70	77	1.099	73	.
1977	10	29	5.588	NE	5.733	.	.	.	.	39	.	.	38	.
1977	11	30	5.893	TZ	5.960	5.830	.	.	.	75	51	1.450	62	.
1978	6	11	5.837	SW	5.837	5.833	.	.	.	52	52	1.013	52	.
1978	7	5	5.808	SW	5.808	5.875	.	.	.	48	59	1.213	53	.
1978	8	29	5.967	NE	6.112	6.111	3.637	0.57	62	117	117	1.004	117	.
1978	9	15	5.963	SW(?)	5.963	5.999	3.831	0.38	80	76	84	1.110	80	.
1978	11	4	5.576	NE	5.711	5.762	3.582	0.59	55	36	42	1.157	39	.
1978	11	29	5.996	SW	5.996	6.068	.	.	.	84	103	1.230	93	.
1979	2	1	5.326	NE(?)	5.471	.	.	.	.	18	.	.	18	.
1979	6	23	6.215	SW	6.215	6.169	3.991	0.56	141	159	139	1.139	148	.
1979	7	7	5.839	NE	5.984	6.063	4.027	1.73	.	81	102	1.253	91	.
1979	8	4	6.161	SW(?)	6.161	6.209	4.052	0.37	133	135	156	1.146	145	.
1979	8	18	6.170	TZ	6.237	6.237	3.743	1.08	.	169	169	1.000	169	.
1979	10	28	5.990	NE	6.135	6.155	3.974	0.74	.	125	133	1.067	129	.
1979	12	2	5.998	SW	5.998	6.022	4.080	0.38	144	84	90	1.073	87	.
1979	12	23	6.170	SW	6.170	6.142	3.772	0.51	80	139	128	1.083	133	.
1980	4	25	5.468	SW	5.468	.	.	.	.	18	.	.	18	.
1980	6	12	5.566	NE	5.711	5.693	3.154	0.63	.	36	34	1.052	35	.
1980	6	29	5.707	SW	5.707	5.779	3.400	1.03	.	36	44	1.230	40	.
1980	9	14	6.213	SW	6.213	.	4.043	0.86	.	158	.	.	158	.
1980	10	12	5.918	NE	6.063	6.020	4.094	0.22	125	102	90	1.131	95	.

Year	Month	Day	mb	region	mb'	mb (Lg)	Ms	LO/LR	Y(Ms)	Y(mb)	Y(mbLg)	R	Y(ave)	Y(ann)
1980	12	14	5.953	TZ	6.020	6.030	3.934	0.35	98	90	92	1.029	91	.
1980	12	27	5.872	NE	6.017	6.027	3.758	0.70	.	89	91	1.028	90	.
1981	3	29	5.573	NE	5.718	5.607	3.266	1.37	.	37	26	1.374	32	.
1981	4	22	5.954	SW	5.954	6.022	4.070	0.36	137	74	90	1.216	82	.
1981	5	27	5.354	NE	5.499	5.507	.	.	.	19	20	1.042	20	.
1981	9	13	6.064	TZ(?)	6.131	6.217	4.206	0.32	182	124	160	1.281	141	.
1981	10	18	6.033	SW	6.033	6.079	4.094	0.28	133	93	107	1.141	100	.
1981	11	29	5.643	SW	5.643	5.642	3.555	0.46	45	30	30	1.003	30	.
1981	12	27	6.242	SW	6.242	6.181	4.106	0.41	158	172	144	1.190	157	.
1982	4	25	6.089	TZ(?)	6.156	6.178	4.026	0.38	126	133	142	1.066	138	.
1982	7	4	6.222	SW	6.222	.	.	.	.	162	.	.	162	.
1982	8	31	5.289	SW	5.289	.	.	.	.	11	.	.	11	.
1982	12	5	6.132	SW	6.132	6.095	3.929	0.34	96	124	112	1.111	118	.
1982	12	26	5.703	NE	5.848	5.724	.	.	.	54	38	1.428	45	.
1983	6	12	6.119	TZ(?)	6.186	6.178	3.978	0.33	107	146	142	1.023	144	.
1983	10	6	6.040	SW	6.040	5.956	3.904	0.43	100	95	74	1.273	84	.
1983	10	26	6.139	SW	6.139	6.117	4.045	0.32	124	127	119	1.065	123	.
1983	11	20	5.436	NE	5.581	5.456	.	.	.	25	17	1.433	21	.
1984	2	19	5.855	SW	5.855	5.800	3.734	0.29	57	55	47	1.171	51	.
1984	3	7	5.644	NE	5.789	5.751	3.350	0.58	32	46	41	1.115	43	.
1984	3	29	5.926	TZ	5.993	5.993	3.806	0.40	77	83	83	1.000	83	.
1984	4	25	5.975	SW(?)	5.975	5.955	3.929	0.28	90	79	74	1.060	76	.
1984	5	26	6.021	NE	6.166	6.186	.	.	.	137	146	1.058	141	.
1984	7	14	6.178	SW	6.178	6.159	4.035	0.50	147	142	134	1.057	138	.
1984	10	27	6.272	SW	6.272	6.207	4.031	0.52	149	187	155	1.206	170	.
1984	12	2	5.821	NE	5.966	5.969	3.525	2.28	.	77	77	1.008	77	.
1984	12	16	6.166	SW	6.166	6.147	3.988	0.51	133	137	130	1.057	134	.
1984	12	28	6.047	SW	6.047	6.078	3.769	0.37	68	97	106	1.093	101	.
1985	2	10	5.937	SW	5.937	5.888	3.986	0.33	109	70	61	1.150	65	.
1985	4	25	5.923	TZ(?)	5.990	5.946	3.724	0.47	68	82	72	1.134	77	.
1985	6	15	6.107	SW	6.107	6.086	3.735	0.36	62	116	109	1.063	112	.
1985	6	30	6.018	SW	6.018	6.021	3.763	0.48	76	89	90	1.009	90	.
1985	7	20	5.957	SW	5.957	5.953	3.748	0.39	66	75	74	1.013	74	.
1987	3	12	5.461	.	.	5.247	.	.	.	.	9.4	.	9.4	.
1987	4	3	6.238	.	.	6.168	.	.	.	.	138	.	138	.
1987	4	17	6.011	.	.	6.002	.	.	.	.	85	.	85	.
1987	6	20	6.123	.	.	6.068	.	.	.	.	103	.	103	.
1987	8	2	5.877	.	.	5.959	.	.	.	.	75	.	75	.
1987	11	15	6.062	.	.	6.072	.	.	.	.	105	.	105	.
1987	12	13	6.158	.	.	6.189	.	.	.	.	147	.	147	.
1987	12	27	6.089	.	.	6.150	.	.	.	.	131	.	131	.
1988	2	13	6.118	.	.	6.145	.	.	.	.	129	.	129	.
1988	4	3	6.027	.	.	6.168	.	.	.	.	138	.	138	.
1988	5	4	6.184	.	.	6.150	.	.	.	.	131	.	131	.
1988	6	14	4.900	.	.	.	.	.	.	.	.	.	.	.
1988	7	8	5.612	.	.	.	.	.	.	.	.	.	.	.
1988	9	14	6.115	.	6.115	6.066	4.106	0.36	149	118	102	1.151	110	119

Year	Month	Day	mb	region	mb'	mb(Lg)	Ms	LQ/LR	Y(Ms)	Y(mb)	Y(mbLg)	R	Y(ave)	Y(ann)
1988	11	12	5.288	.	.	.	.	.	.	.	.	.	.	.
1988	12	17	5.901	.	.	5.883	.	.	.	.	60	.	60	.
1989	1	22	6.108	.	.	.	.	.	.	.	.	.	.	.
1989	2	12	5.866	.	.	.	.	.	.	.	.	.	.	.

KEY:

m_b = body wave magnitude as re-calculated for this paper

region = subregion within the Shagan River test site:
SW = southwest; NE = northeast; TZ = transition zone between these two subregions

(?) = event is near the border of subregions

m_b' = m_b corrected by subregion as follows:
SW = +0.0; TZ = +0.067; NE = +0.145 using event locations of Marshall et al. (1984) and Marshall personal communication to determine subregion

$m_b(Lg)$ = m_b derived from m (Lg), using the equation $m_b (Lg) = 1.0899 (m(Lg)) - .4397$

Ms = Surface wave magnitude

LQ/LR = ratio of Love to Rayleigh wave amplitudes

Y(mb) and Y (mbLg) = yields determined using equation (1)

Y (Ms) = yields determined using equation (4)

Y (ave) = antilog of the average log (Y(mb)) and log (Y(mbLg))

R = the uncertainty factor (i.e., 95% confidence limits), equal to 1.96 times the antilog of the standard error of mean of logY (ave)

Y (ann) = announced yield of Bocharov et al. (1989), plus yield of JVE as discussed in the text

Table 2. Underground Nuclear Explosions in or Near Thick Salt Deposits of U.S.S.R.

Area	Date Day Mon. Year	Origin Time Hr. Mn. Sec.	Lat. (°N)	Long. (°E)	m_b	n	Y (mb) in kt	Y (announced) in kt	Y (decoupled) in kt
Azgir	22 Apr 1966	02 58 04.0	47.93	47.69	4.524 ± .056	16	1.2	1.1	.05-.08
Bukhara II (multiple explosion)	21 May 1968	03 59 10.0	38.89	65.10	5.4	135		40.	1.7-2.9
Azgir	01 July 1968	04 02 00.9	47.85	47.72	5.529 ± .027	20	23.	25.	1.0-1.8
Orenburg	22 Oct 1971	05 00 00.7	51.61	54.45	5.260 ± .043	23	11.	15.	0.6-1.1
Azgir (double explosion)	22 Dec 1971	06 59 56.5	47.90	48.07	6.064 ± .020	22	110.		4.6-7.9
Lake Aralsor	20 Aug 1972	02 59 57.8	49.40	48.06	5.750 ± .037	22	44.		1.8-3.2
Elista (in salt?)	03 Oct 1972	08 59 57.8	46.86	44.87	5.864 ± .050	21	62.		2.6-4.4
Orenburg	30 Sept 1973	04 59 57.8	51.66	54.54	5.213 ± .047	20	9.2		0.4-0.7
Ishinbay (in salt?)	14 Aug 1974	14 59 58.6	68.94	75.83	5.530 ± .031	30	23.		1.0-1.6
Azgir	25 Apr 1975	05 00 02.5	48.08	47.20	4.808 ± .088	5	2.8		0.1-0.2
Azgir	29 Jul 1976	04 59 58.0	47.81	48.10	5.884 ± .015	30	65.		2.7-4.7
Mirnyy	05 Nov 1976	03 59 56.9	61.52	112.73	5.100 ± .052	16	6.6		0.3-0.5
Azgir	30 Sept 1977	06 59 55.9	47.85	48.13	4.994 ± .029	25	4.8		0.2-0.3

Area	Date Day Mon. Year	Origin Time Hr. Mn. Sec.	Lat. (°N)	Long. (°E)	m_b	n	Y (mb) in kt	Y (announced) in kt	Y (decoupled) in kt
NW of Yakutsk (in salt?)	09 Aug 1978	17 59 58.1	63.65	125.34	5.629 ± .023		31.		1.3-2.2
South of Igarka (in salt?)	21 Sept 1978	14 59 57.6	66.53	86.26	5.124 ± .032	42	7.1		0.3-0.5
Mirnyy	08 Oct 1978	00 00 00.	61.53	112.87	5.249 ± .034	39	8.8		0.4-0.6
Azgir	17 Oct 1978	04 59 56.6	47.81	48.09	5.851 ± .014	63	59.		2.4-4.2
Azgir	18 Dec 1978	07 59 56.3	47.78	48.14	5.977 ± 012	65	86.		3.6-6 .2
Azgir	17 Jan 1979	07 59 55.8	47.87	48.06	6.027 ± .013	58	99.		4.1-7.1
Azgir	14 July 1979	04 59 55.2	47.81	48.07	5.620 ± .012	59	30.		1.2-2.2
Azgir	24 Oct 1979	05 59 56.7	47.79	48.11	5.762 ± .015	69	46.		1.9-3.3
Astrakhan	08 Oct 1980	05 59 57.3	46.79	48.29	5.184 ± .038	44	8.4		0.3-0.6
Kuyumba	01 Nov 1980	12 59 58.0	60.79	97.57	5.208 ± .034	40	9.0		0.4-0.6
Astrakhan	26 Sept 1981	04 59 57.4	46.82	48.28	5.146 ± .035	48	7.5		0.3-0.5
Astrakhan	26 Sept 1981	05 03 57.0	46.79	48.27	5.183 ± .034	36	8.4		0.3-0.6
W. Tura	25 Sept 1982	17 59 57.4	64.33	91.80	5.211 ± .034	41	9.1		0.4-0.7
Mirnyy	10 Oct 1982	04 59 56.9	61.53	112.86	5.323 ± .028	40	13.		0.5-0.9
Astrakhan	16 Oct 1982	05 59 57.4	46.77	48.22	5.230 ± .033	33	9.6		0.4-0.7

Area	Date Day Mon. Year	Origin Time Hr. Mn. Sec.	Lat. (°N)	Long. (°E)	m_b	n	Y (mb) in kt	Y (announced) in kt	Y (decoupled) in kt
Astrakhan	16 Oct 1982	06 04 57.4	46.77	48.24	5.272 ± .031	36	10.9		0.5-0.8
Astrakhan	16 Oct 1982	06 09 57.4	46.77	48.22	5.255 ± .035	35	10.4		0.4-0.7
Astrakhan	16 Oct 1982	06 14 57.5	46.75	48.20	5.381 ± .034	42	15.0		0.6-1.1
Karachaganak	10 July 1983	03 59 57.3	51.33	53.29	5.313 ± .029	48	12.		0.5-0.9
Karachaganak	10 July 1983	04 04 57.2	51.34	53.29	5.350 ± .031	48	14.		0.6-1.0
Karachaganak	10 July 1983	04 09 57.1	51.37	53.30	5.235 ± .027	44	9.8		0.4-0.7
Astrakhan	24 Sept 1983	04 59 57.1	46.82	48.29	5.159 ± .070	32	7.8		0.3-0.6
Astrakhan	24 Sept 1983	05 04 57.2	46.82	48.28	5.100 ± .046	31	6.6		0.3-0.5
Astrakhan	24 Sept 1983	05 09 57.5	46.86	48.27	4.996 ± .046	26	4.9		0.2-0.4
Astrakhan	24 Sept 1983	05 14 57.1	46.78	48.30	5.175 ± .040	24	8.2		0.3-0.6
Astrakhan	24 Sept 1983	05 19 57.1	46.80	48.30	5.342 ± .033	31	13.4		0.6-1.0
Astrakhan	24 Sept 1983	05 24 57.0	46.80	48.29	5.267 ± .044	29	10.7		0.4-0.8
Karachaganak	21 July 1984	02 59 57.1	51.36	53.25	5.331 ± .028	52	13.		0.5-0.9
Karachaganak	21 July 1984	03 04 57.0	51.37	53.26	5.264 ± .026	52	11.		0.5-0.8
Karachaganak	21 July 1984	03 09 57.0	51.35	53.27	5.323 ± .026	49	13.		0.5-0.9
Astrakhan	27 Oct 1984	05 59 57.1	46.86	48.10	5.018 ± .042	38	5.2		0.2-0.4
Astrakhan	27 Oct 1984	06 04 56.7	46.84	48.08	5.082 ± .046	38	6.2		0.3-0.4

Table 3: Largest Shagan River Underground Explosions prior toJune 1979 of Yield > 125 kt

Date	Yield (kt)	
	Announced	Calculated
02 Nov. 1972	165	154
10 Dec. 1972 II	140	138
23 July 1973	--	193

Table 4: Major Soviet Missile Systems with Throw-weights Appropriate to above Yields

System	First Deployment	#RVs	Comments
SS-20	1977	3	First Soviet MIRVed IRBM
SS-N-18 mod 1	1978	3	First Soviet MIRVed SLBM

Table 5. Number of cavities that may remain standing from Soviet Underground Nuclear Explosions form 1961 to 1986 within and near salt deposits that might be useful for conducting nearly fully decoupled nuclear explosions with yields greater than 0.5 kiloton. (Obtained from calculated yield of known explosion at site divided by yield ratio for Salmon/Sterling explosions = 5.3/0.38=13.9.)

Area of Known Salt Deposits	Maximum Nearly Fully Decoupled Yield (kt)							
	0.5-1	1-2	2-3	3-4	4-5	5-7	7-8	>8
1. North Caspian Region								
a. Azgir		1	1	1	2	1	2	
b. Astrakhan	9*	1						
c. Other	6	2		1	1			
2. a. Central Siberian Platform (northwest of Lake Baikal)	4							
b. Within a few hundred kilometers of layered salt deposits	1	1	1					
3. Bukhara II, Central Asia (explosion used to extinguish fire in oil well)			1					
Total	20	5	3	2	3	1	2	0

* Many small nuclear explosions at nearly the same location. Cavities conceivably could be interconnected to form a larger cavity

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