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The Seismic Signal Strength of Chemical Explosions

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Abstract We have compared the seismic magnitude of a wide variety of chemical explosions of known yield, to the magnitude expected for explosions set off in hard rock under conditions most favorable for generating strong seismic signals. Our results are based on numerous chemical explosions that include several different broad groups, mostly taken from practical experience with explosions carried out on territory of the former Soviet Union. To quantify these observations, we define the *deficit* of an explosion as the expected signal strength if that charge size, or yield, were fired under the most favorable conditions in hard rock, minus the actual strength. We document the size of the deficit using two different measures of signal strength: the energy class K and the seismic magnitude (which may be the teleseismic m_b or a regional magnitude).

In general, for ripple-fired chemical explosions carried out in the mining and construction industries, the magnitude deficit is around 1.5 to 2. The type of blasting that comes close to the maximum coupling efficiency (zero deficit) is now rare except for small-yield single-fired explosions that are specially designed to maximize signal strength (such as explosions for seismic refraction surveys). There are a small number of locations where the deficit is small (~0.5 magnitude units) for quite large chemical yields (several hundred tons). Such explosions, which appear to be uncommon and declining as blasting practices are modernized, may require special attention in the context of verification of the Comprehensive Test Ban Treaty.

Introduction

For more than 15 years following negotiation of the Threshold Test Ban Treaty in 1974, intensive study was made of the relationship between the seismic magnitude and the yield of underground nuclear explosions (UNEs). For conditions typified by the Soviet Union's main test site (closed in 1991), near Semipalatinsk, Kazakhstan, much work has been summarized by Ringdal et al. (1992) as the relationship

$$m_b = 4.45 + 0.75 * \log Y \quad \text{for yield } Y \text{ in kilotons.} \tag{1}$$

Their result is thought to apply to shield regions that include much of North America and Eurasia but can be different in tectonically active regions. For example, for well-tamped contained explosions below the water table at the Nevada Test Site in the western United States, the corresponding relation is given by Murphy (1981) as

$$m_b = 3.92 + 0.81 * \log Y. \tag{2}$$

These two equations indicate that a UNE at Semipalatinsk has seismic magnitude about 0.5 units larger than a UNE of the same yield at the Nevada Test Site (if both explosions are in hard rock, below the water table).

When estimates began to be made, in the early 1990s, of the numbers of chemical explosions set off routinely in industrialized countries, there was concern that the seismic signals from such explosions would be so numerous and would appear so similar to the signals expected from a small UNE that they would swamp efforts at CTBT monitoring based on seismological methods. The reasoning behind such pessimism was that the United States, Russia, China, and numerous non-nuclear-weapon states such as Australia, Canada, Kazakhstan, and countries of South America use a total of about 5 mt of chemical explosive per year. This overall total is distributed across numerous blasts of total charge size ranging above 1 kt (on the order of a few hundred per year), between 100 and 1000 tons (thousands per year), and between 10 and 100 tons (many thousands per year). These estimates are based upon Richards *et al.* (1992) for the United States, Khalturin *et al.* (1996) for territory of the former USSR, and technical reports by W. Leith and his colleagues (1996, 1997) for other countries. If these charge sizes were interpreted via equation (1), then one would expect chemical explosions to generate hundreds of events each year with magnitude greater than 4.5, thousands of events per year in the magnitude range 3.5 to 4.5, and several events per hour in the range 3 to 3.5 (a magnitude range that includes the source strength predicted for a fully decoupled UNE of around 5 kt).

This expectation, however, turns out to be far from the facts, because it is clear from seismicity bulletins (global and regional), published by numerous organizations, that the actual numbers of seismically detectable chemical explosions are on the order of a hundred times smaller than the foregoing predictions (Rivière-Barbier, 1993; Richards, 1995; USGS mining seismicity bulletin for the U.S. for the period May to October 1997).

A natural way to try to improve estimates of the numbers of chemical explosions observed at given magnitude levels would be to find the coefficients a and b in magnitude–yield relationships of the form $m_b = a + b * \log Y$ derived for chemical explosions in different regions and then to predict the number of events at different magnitudes from knowledge of the distribution of explosive between blasts of different size. But such an approach fails because chemical explosions do not exhibit a good fit to a linear relationship between magnitude and log yield, even when restricted to a particular mining region.

Instead, we have approached the issue quantitatively, but at a less detailed level. Our approach has been to determine the upper limit $M(Y)_{max}$ for the magnitude of an explosion (chemical or nuclear) at given yield Y for numerous different explosions carried out under different conditions in hard rock and in different tectonic provinces and then to compare the magnitude of an explosion of interest (of known charge size or yield) with the upper magnitude limit for that yield. We find that typical chemical explosions carried out by the mining and construction industries are highly inefficient at generating seismic signals—as compared to this upper limit. For quantitative purposes, we propose that the observed inefficiency of seismic signal generation can usefully be described by the *deficit,* defined as the difference in source strength for a given explosion with a particular charge size, between that *predicted* for a well-coupled explosion at that charge size (yield) and under conditions of efficient signal propagation, and the *actual* source strength. (Signal strengths here are based on logarithmic scales, so the deficit implies not a difference but an extra factor, if a linear strength scale were used.) We find that this deficit, which is subject to considerable scatter, can nevertheless be roughly estimated for different broad groups of chemical explosions. The deficit is commonly around 1.5 to 2 magnitude units for chemical explosions carried out in the mining and construction industries—which is why the great majority of blasts that would be counted as large in terms of charge size are not detected seismically. For many very large commercial blasts, the deficit can be larger—around 3 magnitude units. Below, we comment on an apparent lack of any systematic difference in maximum coupling efficiency between chemical and nuclear explosions.

Given the number of factors that contribute to the deficit, we were gratified to find that it was indeed possible to obtain useful summary information. The three principal factors contributing to the deficit are details of blasting practice, such as shot depth, how many individual charges were fired, and the pattern of delays; the local geological conditions; and the efficiency of propagation of seismic signals, once they have been excited at the source.

The following sections report our available data and methods of analysis. We present evidence that the upper limit in magnitude for explosions of known yield in hard rock, under favorable propagation conditions, is given by the relation

$$M(Y)_{max} = 2.45 + 0.73 * \log Y \text{ (tons)}$$
$$= 4.64 + 0.73 \log Y \text{ (kt)},$$

and the upper limit in energy class, again for hard rock, is

$$K(Y)_{max} = 7.0 + 1.55 \log Y \ (Y \text{ in tons}).$$

To obtain the coefficients in these equations with acceptable confidence, the observational data must be studied over as wide a range of yields as possible, including well-coupled explosions at both high and low yields. Once the upper limits have been obtained, we are able to comment upon the magnitude deficit for explosions that are not well coupled into seismic energy propagating with maximal efficiency. We briefly discuss the properties of explosions underwater or in soft saturated rock such as clay—which couple into seismic energy even more efficiently than the upper limit for hard rock. For such super-efficiently coupled events, it is natural to speak of their magnitude *excess.* Finally, we comment on possible implications for the verification regime of the Comprehensive Test Ban Treaty opened for signature in 1996.

Available Data

We have acquired data on charge size, or yield, of a wide variety of chemical and nuclear explosions, together with data on seismic source strength. Our emphasis has been on the former Soviet Union, for which we have data on chemical explosions from about 30 regions (Khalturin *et al.,* 1996). We also report data from Israel, Germany, China, and North America. Our data on source strength in some cases come from measurements of the energy class K, and in other cases, the data come from a seismic magnitude—teleseismic m_b for large events, otherwise a regional magnitude based upon P_n or L_g waves or upon a coda measurement.

It was important to include the use of energy class K in our study, because this is the only measurement of seismic source strength reported for many explosions (and earthquakes) on territory of the former Soviet Union (FSU). The K scale (Rautian, 1960) has been in use since the late 1950s up to the present time to characterize the size of locally and regionally recorded events at distances from a few kilometers up to 2000 km. It is based upon the sum of amplitudes A_p and A_s of both *P* and *S* (or *Lg*) waves on short-period instruments. *K* is called a measure of the energy class because it is equal to the value of log *E*, where *E* is an estimate in joules of the radiated seismic energy. *K* is still the standard measure of source strength as reported in regional catalogs of the FSU. An increment of *K* by one unit corresponds to an increment of $\log(A_p + A_s)$ by 0.56 units.

We obtained the relationship between magnitude and *K* for several sets of earthquakes and explosions, using magnitudes reported by the International Seismological Centre (ISC), the British Atomic Weapons Establishment (AWE), and by NORSAR. In Figure 1 are shown examples of m_b versus *K* for underground nuclear explosions in the Degelen subarea of the Semipalatinsk Test Site and for chemical explosions at the same test site. Both cases are well fit by the relation

$$m_b = 0.46K - 0.64 \quad (\text{or } K = 1.39 + 2.17m_b). \quad (3)$$

Note that m_b 3.0 corresponds to a *K* value close to 8, and m_b 3.5, to a *K* value close to 9.

Table 1 names the regions, types, and numbers of explosions on which we report here. These sets of explosions were taken to cover as wide a range of yield and magnitude as possible, paying special attention to explosions for which the chemical energy was well coupled into energy of seismic waves. We have used chemical explosions with charge size ranging from 0.08 tons up to 11,120 tons. Our data come from more than 30 regions of the FSU and elsewhere and include 476 chemical explosions with known *K* (5.0 to 15.0) and known *Y* and 311 chemical explosions with known magnitude (0.3 to 6.25) and known *Y*. We also used magnitude data for 26 nuclear explosions at the Semipalatinsk Test Site with yield from 230 tons up to 165,000 tons. Note that there

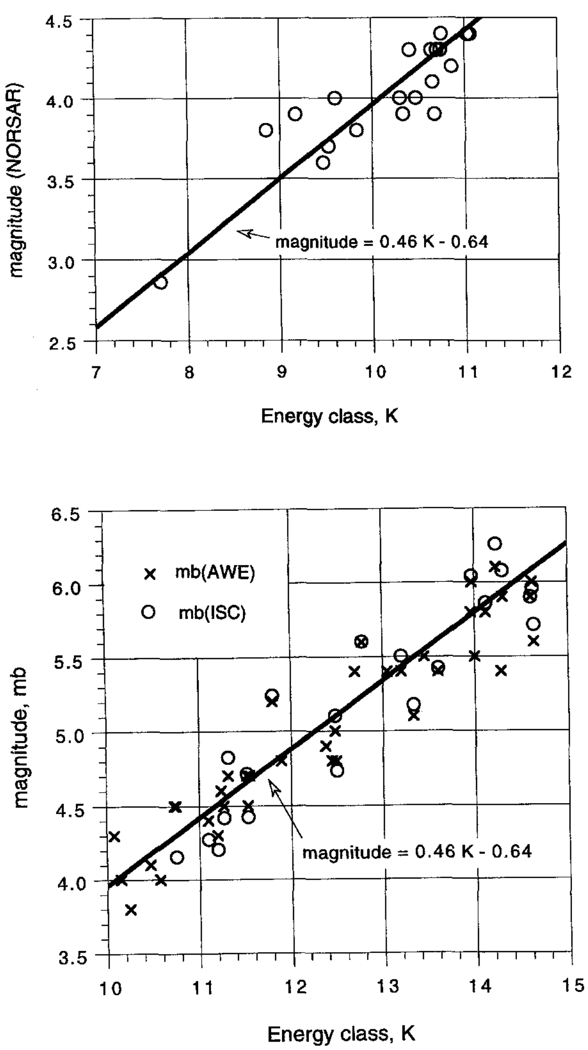


Figure 1. Relation between m_b and *K* for chemical (top) and underground nuclear (bottom) explosions at the Semipalatinsk Test Site. The solid line in both cases corresponds to the relationship $m_b = 0.46K - 0.64$. Consequently, $\Delta m = 0.46\Delta K$.

Table 1
Region, Type, and Number of Explosions with Known Yield *Y* and Energy Class K and Magnitude *M*, Which We Use for Estimation of Seismic Efficiency

Region	Type of Chemical Explosion	Number of Events with Known *K*	*M*
Central Asia	experimental:		
	underground	5	5
	surface	5	—
Central Asia, Caucasus	canal or dam construction	20	13
Apatity, Kola Peninsula	mining	188	117
Medeo, North Tien Shan	quarry	61	—
Tekeli, North Tien Shan	quarry	20	—
Kotur-Bulak, North Tien Shan	quarry	19	—
Tyrnauz, Caucasus	mining	39	—
Krivoy Rog, Ukraine	mining	5	4
Kuzbass, W. Siberia	coal mine	3	—
Semipalatinsk Test Site, East Kazakhstan	UNEs	24	26
Tadjikistan	underwater	87	—
Gold Mine, Nevada	mining	—	61
Israel	quarry blasts	—	50
	road construction	—	19
	underwater	—	3
Kursk Magnetic Anomaly, Russia	mining	—	9
New Mexico	experimental: on the surface	—	2
Nevada Test Site	experimental: NPE	—	1
Zhuhai, China	on the surface	—	1
Vogtland, Germany	mining	—	12
WW2 mine detonation, England	disposal		1
Offshore, United Kingdom	underwater		1
Total		476	325

is considerable overlap, in yield, between the sets of chemical and nuclear explosions. Besides K values and m_b for explosions with known Y, we collected local magnitudes (ML) and coda magnitudes (MC). We appreciate that work is needed to reconcile various regional magnitudes scales with the standard teleseismic scale, m_b, but available scales are still useful for preliminary estimates of the magnitude deficit of different explosions.

The theory and practical methods of employment of large chemical explosions was a well-advanced subject in the former Soviet Union, for example, in the construction of dams and canals. Many of these explosions were in the kiloton range and were detected teleseismically, as well as by special monitoring systems deployed from very close to the shot point out to local and regional distances of several hundred kilometers. Most interesting were a number of experimental well-contained single-fired underground explosions made under experimental conditions most favorable for generating seismic signals (for example, in the Kazakhstan platform). Such explosions, together with special sets of small industrial explosions in hard rock, indicate the upper limit of the magnitude–yield relation at fixed yield.

Table 2 gives basic information on 38 large well-documented chemical explosions whose parameters were used in our study. For some of these explosions, we have results of near-field observations, and for most of them, we have regional data that were used to assign the K value. Thus, the K values are assigned from regional data, and m_b values are taken from the ISC or NEIC (or the average of these if both are available). MLH is a Russian scale similar to M_s that is based on amplitude and period of surface waves; $MLH \sim M_s + 0.15$.

The shots of 1957 (in Uzbekistan), 1959, 1960 (in Tuya-Muyun, Kyrgyzstan), and 1961 (in the Degelen subarea of the Semipalatinsk Test Site, Kazakhstan) are of interest in the history of nuclear testing and CTBT negotiations. Technical details of the 1000 ton cratering shot Arys, of 1957, were quickly circulated and referred to in Geneva negotiations (see also Pasechnik *et al.,* 1960). The other three (190, 660, and 600 tons, respectively) were carried out underground as single-fired shots in order for the Soviet Union to acquire practical experience, for example, with containment, prior to carrying out a program of underground nuclear explosions—but few details on these shots emerged until the 1990s (Adushkin *et al.,* 1996). Large well-tamped chemical explosions that are single fired and at a depth permitting complete containment are very unusual. (In the United States, the only comparable example would appear to be the "chemical kiloton" Non-Proliferation Experiment of 22 September 1993). The 660 ton shot of 1960 was reported by the Soviet delegation in early negotiations as the seismic equivalent of 5 kt fired "under RAINIER conditions" (referring to the first contained underground nuclear explosion, carried out by the United States at the Nevada Test Site in September 1957—the first Soviet underground nuclear explosion was in October 1961, also at Degelen). The early Soviet report is understandable today in the context of what we now know about the magnitude bias between the Nevada and Semipalatinsk Test Sites. But in October 1960, Albert Latter, coauthor of the original article on decoupling, wrote that "I personally do not accept the Russian statement because they have not given any confirmatory details" (Latter, 1960).

Method of Analysis

Essentially, our approach began with plotting values of K, or magnitude, against log Y for numerous chemical and nuclear explosions in hard rock. The next step was to obtain the position of a straight line that could serve as the upper limit on K, or magnitude, at different values of log Y. The position of this line, $K = K(Y)_{\max}$ or $M = M(Y)_{\max}$, was taken to pass through or above almost all the data points, the exceptions being a small number of points whose position above the line could be ascribed to uncertainty in assigning the magnitude value.

After the upper limit lines have been determined, we define the *energy class deficit* ΔK of a given explosion with known charge size or yield, and whose K value has been measured, as

$$\Delta K = K(Y)_{\max} - K_{\text{measured}}. \qquad (4)$$

Similarly for the *magnitude deficit* Δm, we have the definition

$$\Delta m = M(Y)_{\max} - m_{\text{measured}}, \qquad (5)$$

where the measured magnitude may be m_b or a regional magnitude. In accordance with (3), the relation between Δm and ΔK is

$$\Delta K = 2.17\Delta M \quad \text{or} \quad \Delta M = 0.46\Delta K. \qquad (6)$$

The lower the seismic efficiency of the explosion, the greater the magnitude deficit. We shall find that the deficit can range up to about 3 magnitude units, part of which may be due to the magnitude bias associated with an attenuating propagation path. For very efficient seismic coupling in a region with low attenuation paths to the stations reporting magnitude values, the deficit is low, in the range about 0 to 0.3. The deficit can be found for individual explosions, or averaged for a set of explosions from the same region, over a range of yields.

In the case of explosions under water or in water-saturated clay, rather than the hard rock environment for which our upper limit relationships are derived, the ΔK and Δm values defined by (4) and (5) can be negative, and it is natural to reverse their sign and to speak of the magnitude excess rather than the deficit. We give examples below.

Within the framework of an upper limit on magnitude for an explosion at given yield in hard rock, and a definition of the deficit, we are interested in seeing if chemical and

Table 2
Large and Well-Documented Industrial or Experimental Chemical Explosions on Territory of the Former Soviet Union

Region	Date	GMT	Yield	*K*	m_b	MLH	Lat. N	Long. E	Purpose
Arys Uzbekistan	19 Dec 57	09:00:00	1000	10.5	—	3.1	42.204	69.000	science
Pokrovsky Urals (shots fired at shallow depth over a line more than 3 km in length)	25 Mar 59	09:00:00	3100	—	4.8	4.0	60.2	59.9	canal
Tuya-Muyun Kyrgyzstan	31 Dec 59	09:00:00	190	9.9	—	3.3	40.353	72.588	science, military
Tuya-Muyun Kyrgyzstan	03 Mar 60	09:00:00	660	10.6	—	—	40.354	72.588	science, military
Degelen Semipalatinsk Test Site	05 Jun 61	03:50:00	600	10.9	4.42	—	49.773	77.983	military
Dzhezkazgan Kazakhstan, on the surface	20 Nov 65	07:00:00	1152	9.5	—	—	48	67	military
Medeo Almaty	21 Oct 66	04:59:59	1689	11.4	—	—	43.154	77.061	dam
Medeo Almaty	21 Oct 66	05:00:03	3604	11.8	—	3.7	43.154	77.061	dam
Medeo Almaty	14 Apr 67	05:00:09	3940	11.0	—	—	43.154	77.061	dam
Baypazy Tadjikistan	29 Mar 68	06:48:42	1944	10.4	—	—	38.24	69.15	dam
Akh-Su Dagestan	26 Dec 72	04:08:57	552	9.4	—	—	43.0	47.1	dam
Tyrnyauz Caucasus	31 Dec 77	12:00:00	833	9.4	4.0	—	43.36	42.83	mining
Degelen Semipalatinsk Test Site, on the surface	31 July 78	08:00:00	5000	10.2	—	—	50.42	77.87	military
Kazakhstan Near Almaty, on the surface,	28 Nov 81	02:31:00	251	8.22	—	—	43.8	76.85	science
Tyrnauz Caucasus	27 Dec 81	07:44:21	1075	10.2	4.0	—	43.36	42.83	mining
Urgench Turkmenistan	26 Dec 82	05:29:00	2550	12.4	4.8	—	40.98	61.68	reservoir
Burkhara-1 Uzbekistan	23 Mar 83	11:07:57	1960	11.3	4.6	—	39.24	64.34	canal
Bukhara-2 Uzbekistan	22 Apr 83	03:56:22	2426	11.37	4.8	3.9	39.34	64.24	canal
Bukhara-3 Uzbekistan	16 May 83	12:07:51	1690	11.3	4.7	—	39.31	64.33	canal
Bukhara-4 Uzbekistan	26 May 83	12:46:22	3830	10.65	4.5	3.8	39.23	64.27	canal
Bukhara-5 Uzbekistan	15 Jun 83	13:34:03	4140	12.0	4.8	—	39.31	64.36	canal
Kosh-Bulak Turkmenistan	25 Jun 83	20:35:14	2550	11.9	4.5	—	40.860	61.653	dam
Bukhara-6 Uzbekistan	02 Jul 83	11:42:21	2560	11.5	4.8	4.2	39.22	64.36	canal
Bukhara-7 Uzbekistan	11 Jul 83	14:47:56	3460	11.1	4.6	—	39.23	64.38	canal
Bukhara-8 Uzbekistan	27 Aug 83	05:04:42	2280	11.15	4.55	4.1	39.24	64.47	canal
Alinjachai Caucasus	04 Sep 84	09:00:00	689	10.4	—	—	39.146	45.427	dam
Balapan Semipalatinsk Test Site	15 Sep 84	06:15:09.7	?	10.80	4.7	—	49.992	78.881	military
Quisa Caucasus	16 Dec 84	11:00:36	437	10.0	—	—	42.312	43.385	dam
Degelen Semipalatinsk Test Site, at the surface	27 Jun 85	12:57:00	500	8.5	—	—	49.73	78.10	military
Degelen Semipalatinsk Test Site, in the crater of 27 June 1985	29 Jun 87	05:55:00	500	8.5	—	—	49.73	78.10	military

(*continued*)

Table 2 (*Continued*)
Large and Well-Documented Industrial or Experimental Chemical Explosions on Territory of the Former Soviet Union

Region	Date	GMT	Yield	K	m_b	MLH	Lat. N	Long. E	Purpose
Novaya Zemlya On the surface	25 Aug 87	15:00:00	1000	—	—	—	73.38	54.78	military
Karaganda Central Kazakhstan, Joint US-USSR Experiment. "Chemex-1"	2 Sep 87	07:00:00	9	—	3.05	—	50.28	72.17	science
Degelen Semipalatinsk Test Site, Joint US-USSR Experiment. "Chemex-2", blowout	2 Sep 87	09:27:05	20	—	2.7	—	50.00	70.34	science
Karaganda Central Kazakhstan, Joint US-USSR Experiment "Chemex-3"	3 Sep 87	07:00:00	9	—	3.1	—	50.28	72.17	science
Uch-Terek Kyrgyzstan	11 Jun 89	06:59:47.5	827	—	—	—	41.644	73.289	dam
Uch-Terek Kyrgyzstan	11 Jun 89	06:59:52	1088	11.1	4.8	4.3	41.644	73.289	dam
Arkhangelsk North Russia	27 Feb 91	11:25:18	1000	—	4.5	—	62.95	41.88	military

nuclear explosions have the same upper limit and if the upper limit is valid and useful for sets of data other than those we present in this article. We argue that all these questions are answered affirmatively.

Upper Limit of Energy Class K versus Yield

To get the relationship between maximum values of K and log Y, we used data as summarized in Figure 2 that span the range from about 80 kgm to 165 kt—more than a factor of a million. The straight line is

$$\begin{aligned} K(Y)_{\max} &= 7.0 + 1.55 \log Y \ (Y \text{ in tons}) \\ &= 11.65 + 1.55 \log Y \ (\text{kt}), \end{aligned} \tag{7}$$

which divides the region of the graph that is filled with data points from a region that has almost none. Only six points lie above the line, and they do so by amounts on the order of 0.1 to 0.2 K units, which is about the error of K determination. All nuclear explosions shown in Figure 2 took place at the Semipalatinsk Test Site. They lie in a narrow band about the line, with K deficit typically from 0 to 0.8. The level of the line (7) is controlled at high yield by UNEs and some large chemical explosions. At low yields, it is controlled by small chemical explosions from three quarries in North Tien Shan (including the small Medeo explosions).

Table 3 shows the yield range, the energy class, and the K deficit for each main data set shown in Figure 2. The last two columns indicate average values of the deficit ΔK and of the corresponding Δm, obtained from ΔK via (6).

The range of Y values from 230 to 4000 tons is covered in our data by big chemical explosions as well as by small nuclear explosions. For chemical explosions, it appears that the K deficit may be a little larger. The chemical explosions used to create dams or canals were not fired as single charges but were distributed in space in order to move large amounts of rock, and such sources are not as compact as UNEs. But typically, the total charge of each of these blasts was fired within a very short period of time, like a single-fired explosion. Their energy class deficit is seen to be small, varying between 0 and 1.5 to 2.0, and is about 1.0 on average.

Five events that were single-fired explosions on the surface, without any covering materials, have larger deficit, amounting to about 2 to 3 K units.

There is a "gap" in the values of K, for Y about 100 tons. This is probably due to an important difference in seismic coupling efficiency, between big single-fired and big ripple-fired industrial explosions in quarries. The term "ripple-firing" refers to the practice called "delay firing" by the mining community. This type of explosion occurs in Apatity (Kola Peninsula, Russia), Krivoi Rog (Ukraine), and Tyrnauz, (South Caucasus, Russia). Taking the ripple-fired explosion data together, we get the impression that over a wide range of Y values, from 0.5 to 500 tons, the energy class K has only a weak dependence on Y. For all these events, K is about the same, about 6.5 on average, and is scattered between 5 and 8, with deficit reaching 4 to 6 units.

Five explosions were available from Krivoi Rog, Ukraine, with both yield and K information. They are of nearly the same Y value, about 600 to 800 tons. Their K value is as small as 6.5 to 8, with deficit 2.5 to 3.5.

The left side of Figure 2 is dominated by data from small industrial explosions, many with small deficit, that took place at Almaty and Kotur-Bulak (Kazakhstan) and Medeo (North Tien Shan). These explosions strongly limit the position of the upper limit line in the low-yield range.

The Medeo explosions, to the south of Almaty, provided rock used to increase the elevation of a dam. The Medeo region is composed of hard granitic rocks. The K deficit for these Medeo explosions, with yield from a few tenths of a ton up to a few tens of tons, is never more than 2, and some of them have deficit close to 0. These explosions were single fired.

Further detail on the relationship between K and yield is given in Figure 3, showing sets of data from separate

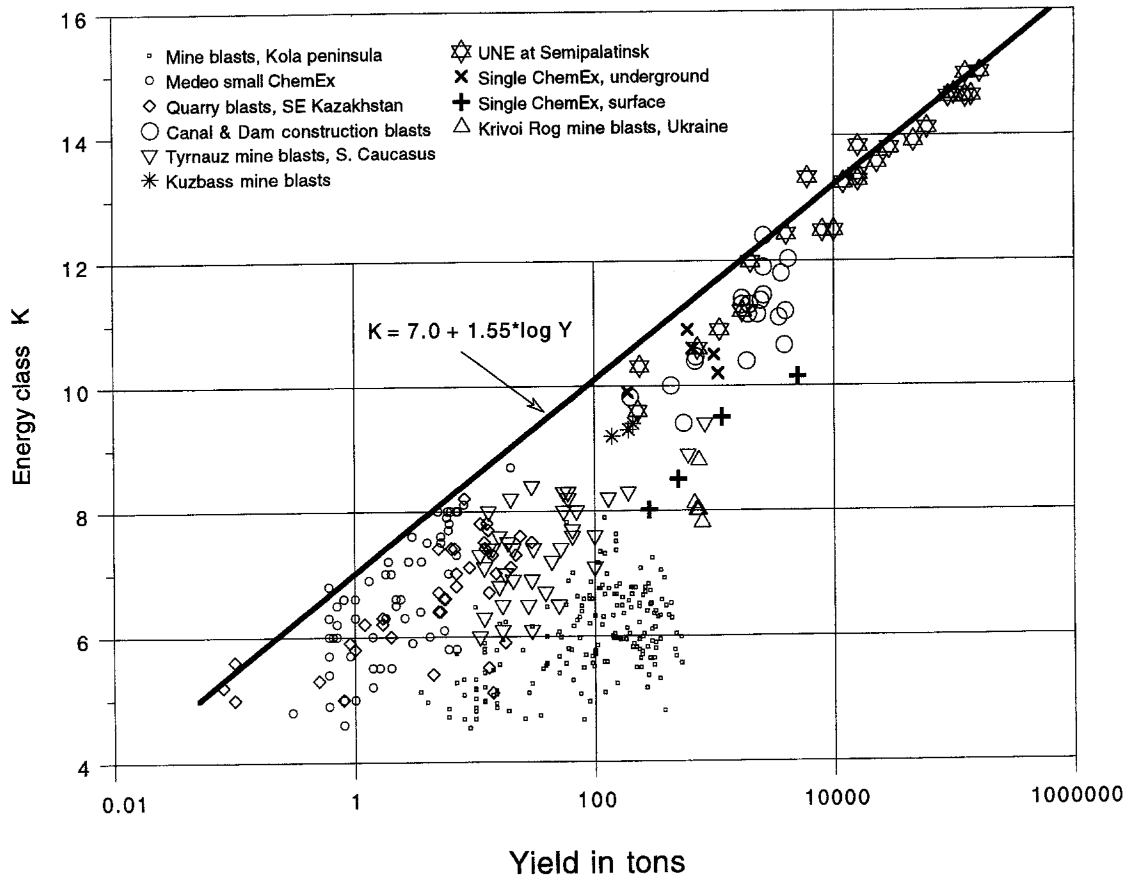


Figure 2. Energy class K versus Y (in tons) for several sets of explosions. The dotted line, $K(Y)_{max} = 7.0 + 1.55 \log Y$ (tons), is the upper limit for all observed K versus Y data. In the kiloton range, this line is controlled by underground nuclear explosions at the Semipalatinsk Test Site and in the low-energy range by chemical explosions from the North Tien Shan. Further details given in Figure 3.

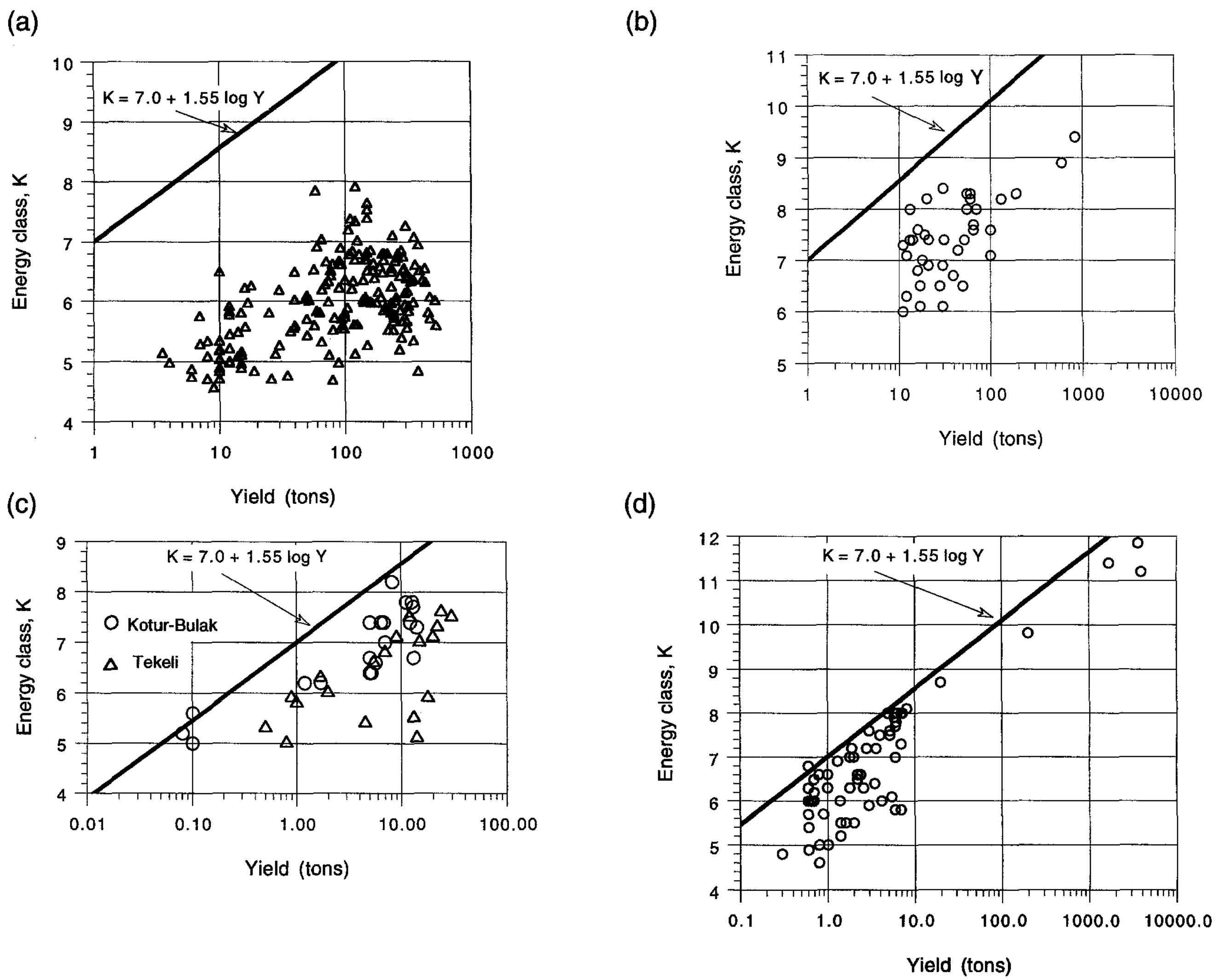
Table 3
The Energy Class Deficit ΔK for Different Sets of Explosions

Explosions	Figure	Y, tons min–max	Class K min–max	Deficit min–max	ΔK aver.	Δm*
Experimental	3e	190–1000	9.9–10.9	0.6–1.4	1.0	0.45
Canal	3e	1700–5400	10.7–12.1	0.6–1.9	1.25	0.55
Dam	3e	200–4000	9.4–11.9	0.4–2.0	1.1	0.50
Surface	3e	290–5000	8.2–10.2	2.4–2.9	2.7	1.25
Apatity	3a	4–500	4.6–7.9	2.2–6.0	4.0	1.85
Medeo	3d	0.3–20	4.8–8.6	−0.08–2.2	0.8	0.35
Tekeli	3c	0.1–14	5.0–8.2	−0.2–1.8	0.9	0.40
Kotur-Bulak	3c	0.5–30	5.0–7.6	1.0–3.5	1.5	0.70
Tyrnauz	3b	10–1100	6.0–10.2	0.7–3.2	2.0	0.90
Krivoy Rog	2	680–820	7.8–8.8	2.8–3.8	3.3	1.50
Kuzbass	2	150–290	9.1–9.4	1.2–1.6	1.4	0.65
Underwater (Tajikistan)	2	1.28	7.1–8.1	−1.0–0	−0.75	−0.35
Underground (nuclear explosions, Semipalatinsk)	2	0.23–165 K	9.8–15.0	−0.3–1.0	0.45	0.20

*Δm calculated from ΔK using the relationship $\Delta m = 0.46\Delta K$ and rounding to nearest 0.05.

regions. These are arranged in order of decreasing deficit, from the lowest seismic efficiency (Apatity) to the highest (Medeo). Looking at Figures 3a to 3d, the difficulty of estimating the upper limit (7) from any single data set is apparent. Only for the Medeo region, where yield changes over a large range (more than a factor of 100,000) and the explosions were very well coupled, is the upper limit well indicated.

In Table 3, the K deficits (min, max, and average) are pointed out for various different groups of chemical explosions and for UNEs. Besides the question of how the shot was emplaced and whether it was ripple fired or single fired, there is also an effect from the geophysical nature of the region in which the explosion was carried out. The most efficient shots (lowest deficit) were chemical and nuclear explosions conducted in the Kazakhstan platform, namely, the UNEs and chemical explosions at the Semipalatinsk Test Site and chemical explosions in North Tien Shan. The well-tamped Tuya Muyun experimental explosions in Kyrgyzstan were less effective in generating seismic signals than north-



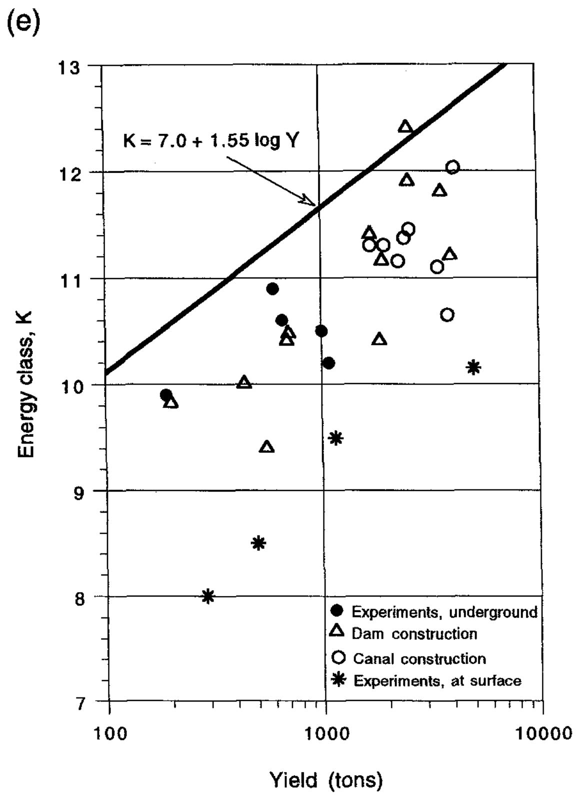


Figure 3. Details of the $K = K(Y)$ data shown for all our data in Figure 2. (a) Mining blasts in Apatity (Kola Peninsula). Energy class K calculated from Mykkeltveit (1992) data. Seismic efficiency of mining blasts in this region is very low: deficit $\Delta K = 3 - 5$ ($\Delta m = 1.4 - 2.3$). (b) Mining blasts in Tyrnauz (North Caucasus) quarries. Data from Godzikovskaya (1995). Seismic efficiency has intermediate value: deficit $\Delta K = 1.5 - 2.5$ ($\Delta m = 0.7 - 1.1$). (c) Quarry blasts from Kotur-Bulak and Tekeli quarries in the North Tien Shan. Data from Aptikaev (1969). Seismic efficiency is high: deficit $\Delta K = 0.5 - 1.5$ ($\Delta m = 0.2 - 0.7$). (d) Quarry and dam-construction explosions in the Medeo region (North Tien Shan, near Almaty). Observations cover a very wide range of yields from 300 kgm to 3900 tons. Explosions in the Medeo region are characterized by the highest efficiency: deficit $\Delta K = 0 - 1$ ($\Delta m = 0 - 0.45$). (e) Well-documented industrial and experimental underground and surface explosions mostly from Central Asia (see Table 2). Average deficit for surface explosions is $\Delta K = 2.5$ ($\Delta m = 1.1$), and for large industrial explosions $\Delta K = 1$ ($\Delta m = 0.45$).

ern Kazakhstan explosions. Dam explosions in the Caucasus region were less effective than similar explosions in Central Asia. Effects of regional variation, presumably due to regional wave propagation variability, are even more apparent in our magnitude—yield data than for energy class—yield, because of the wider range of geophysical regions for which magnitude data are available. This result is demonstrated in the following section.

Upper Limit of Magnitude versus Yield

Figure 4 shows our summary data on magnitude and log Y for numerous chemical and nuclear explosions. We found

$$M(Y)_{max} = 2.45 + 0.73 * \log Y \text{ (tons)} = 4.64 + 0.73 \log Y \text{ (kt)} \quad (8)$$

for the straight line representing the upper level of magnitude at given Y.

Equation (8) runs quite closely through two small single-fired chemical explosions in Kazakhstan (these were calibration shots a few hundred kilometers from the Semipalatinsk Test Site, arranged in 1987 by the Natural Resources Defense Council and the USSR Academy of Sciences, executed in a way that maximized the seismic coupling—see Given *et al.*, 1990). The line is also close to the controlled detonation of a World War 2 mine (in England on 25 May 1994; ISC data). Unfortunately, at low yield, these were the only three well-tamped chemical explosions with known magnitude in high-Q regions. Other explosions such as the Apatiti and Israeli sets were ripple fired with low efficiency. The line runs just above most of the UNE data and close to most of the large single-fired chemical explosions. In choosing line (8), we had in mind, in addition to the values shown

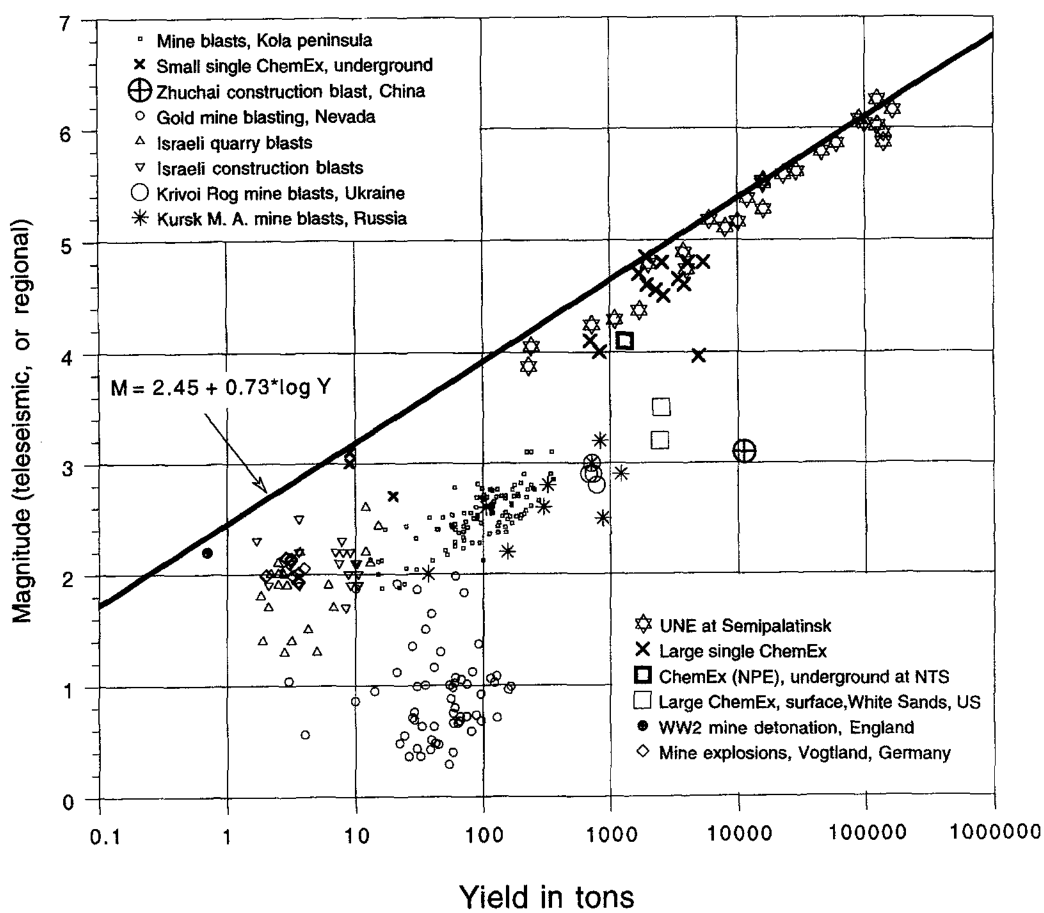


Figure 4. Magnitude versus yield (in tons) for several sets of data. The solid line, $M(Y) = 2.45 + 0.73 \log Y$ (tons) $= 4.64 + 0.73 \log Y$ (kt), is the upper limit of magnitude versus Y for our observed data. Further details are given in Figure 5. The level of this line is determined by underground nuclear explosions at the Semipalatinsk Test Site, by two well-coupled experimental chemical explosions in northern Kazakhstan, by a mine detonation in England, and also by inference from K values to m_b, for the small Medeo explosions shown in Figure 2. Teleseismic m_b values here are obtained from the International Seismological Centre (ISC) and the British Atomic Weapons Establishment (AWE). Other magnitudes are $m_b(Lg)$ from NORSAR, and regional versions of local magnitude ML and coda magnitude MC.

in Figure 4, the magnitude values that would be obtained via (3) from the K values shown in Figures 2 and 3d for the North Tien Shan quarries in southeast Kazakhstan and the small Medeo explosions. Such a conversion from K to m_b would give a magnitude around 2.58 for a 1-ton shot, and line (8) does go close to this value.

Some of the detailed features pointed out in Figure 2 are also present in Figure 4. For example, the increase in the magnitude deficit is substantial when going from well-coupled large single-fired explosions, to distributed ripple-fired explosions associated with a different practice of industrial blasting. The deficit increases abruptly by more than one magnitude unit near $Y = 1000$ tons. In Table 4, the magnitude deficit and magnitude and Y intervals are listed for several data sets.

The NPE in Nevada (using m_b from the ISC) has magnitude deficit about 0.6. But if we take into account the difference in attenuation between Nevada and the Kazakh Platform, intensively studied from UNEs at both test sites, a bias correction of about 0.5 magnitude units can be made. See, for example, the magnitude of a 1-kt explosion predicted by relationships (1) and (2). The component of the magnitude deficit for the NPE event that is solely due to seismic coupling is therefore quite small. In the same way, a part of the large-magnitude deficit for the gold mine explosions in Nevada (as reported by Jarpe *et al.,* 1996) is due to magnitude bias.

The explosion in Zhuhai, China, was made to level a hilltop for a new airport near Macow. Its magnitude deficit is 2.3, indicating that its huge charge was probably widely distributed. Though 11,200 tons of blasting agent were used, its seismic signals had the same magnitude as each of the 9-ton single-fired chemical explosions in northern Kazakhstan.

Figure 4 includes two single-fired surface explosions in the United States, both carried out at the White Sands missile range in New Mexico. Their deficit is around 1.5 magnitude units, due partly to the magnitude bias of the western United States and partly to the unconfined nature of these explosions, in which the blasting agent, ammonium nitrate and fuel oil (ANFO), was simply piled up on the ground surface and then detonated to make blast waves in the air.

Figure 5 shows some of our magnitude–yield data in more detail. The Apatiti explosions on the Russian Kola Peninsula had local magnitudes ML and coda magnitudes MC given by Kremenetskaya *et al.* (1995), shown in Figure 5c. The significant differences apparent between the two parts of this figure indicate that magnitudes from regional data for small events are sometimes assigned quite different values on different scales. A calibration explosion of 350 tons was carried out on 29 September 1996 in the Khibiny massif on the Kola Peninsula (see Ringdal *et al.,* 1997), and it had a local magnitude $ML = 2.9$ assigned by the regional Russian network. The explosion was in the same region and carried out with the same blasting technique (underground, ripple fired) as many similar explosions during 1988 to 1993. Their average ML was about 2.55 and yield about 150 tons, so for

Table 4
The Magnitude Deficit Δm for Different Sets of Explosions

Explosions	Figure	Y, tons min–max	Magnitude min–max	Deficit min–max	Δm aver.
Experimental	5d	9–600	2.7–4.4	−0.1–0.6	0.2
Canal and dam	5d	700–4100	3.7–4.9	0–0.5	0.3
Apatity	5b	10–360	1.0–3.0	0.9–2.2	1.5
Krivoy Rog	5d	680–820	2.8–3.0	1.5–1.7	1.6
Gold Mine, Nevada	5a	3–800	0.3–2.0	1.2–3.4	2.7
Israel	5c	0.8–16	0.8–2.6	0.3–2.0	1.0
Kursk	5d	37–1280	2.0–3.0	1.5–2.4	1.8
New Mexico	4	2000–2500	3.2–3.5	1.6	1.6
NPE, Nevada	4	1300	4.1	0.6	0.6
China, Zhuhai	4	11,120	3.1	2.3	2.3
German mines	4	2.0–4.0	1.9–2.2	0.6–0.8	0.7
UNEs	4	1.7–165 K	4.5–6.25	−0.2–0.5	0.2
(nuclear explosions at Semipalatinsk Test Site)					
Underwater:					
Tajikistan	5e	0.32–1.28	2.5–3.1	−0.45	−0.45
Israel	5e	0.024–0.30	2.0–3.1	−0.8	−0.8
Ocean	5e	5.5–12.7	4.1–4.4	−1.2	−1.2

the 350-ton explosion, we would expect ML of about 2.8 to 2.9, as was indeed obtained locally. The prototype International Data Center assigned ML 3.4 to this explosion, again indicating the need to improve agreement between different types of regional magnitude.

The magnitude deficit is from 1 to 2 for large explosions (fired almost simultaneously in long rows) in mines in the Kursk Magnetic Anomaly region (south of Moscow) and at Krivoi Rog (Ukraine). It reaches 2 to 3 for gold mine explosions in the western United States (Jarpe *et al.,* 1996) and is much less for small explosions in Israel, carried out in quarries and for road construction (Gitterman and Van Eck, 1993; Gitterman *et al.,* 1996). The magnitude deficit for the shots in Israel is 0.1 to 1.5.

Finally in this section, we point out the super-efficient seismic coupling of shots carried out underwater. Figure 5e shows several examples, with magnitude excesses in the range 0.5 to 2. Data for the shots in Israel are from Gitterman *et al.* (1996), the shots in the ocean (20 August 1970, 20 July 1971, 11 June 1972) are from the ISC (see also Jacob and Willmore, 1972), and the shots in Tadjikistan are from Gamburzev *et al.* (1996). The coupling efficiency of underwater explosions has long been exploited to provide sources for seismic refraction surveys, where the source is usually chosen to maximize signal strength using blasting practices that have minimal cost. Murphy (1996) has shown that peaceful nuclear explosions carried out by the Soviet Union in clay also have higher magnitudes than the same yield fired in hard rock.

Discussion

The size of a chemical explosion is expressed commonly in terms of its total charge. But it is important also to

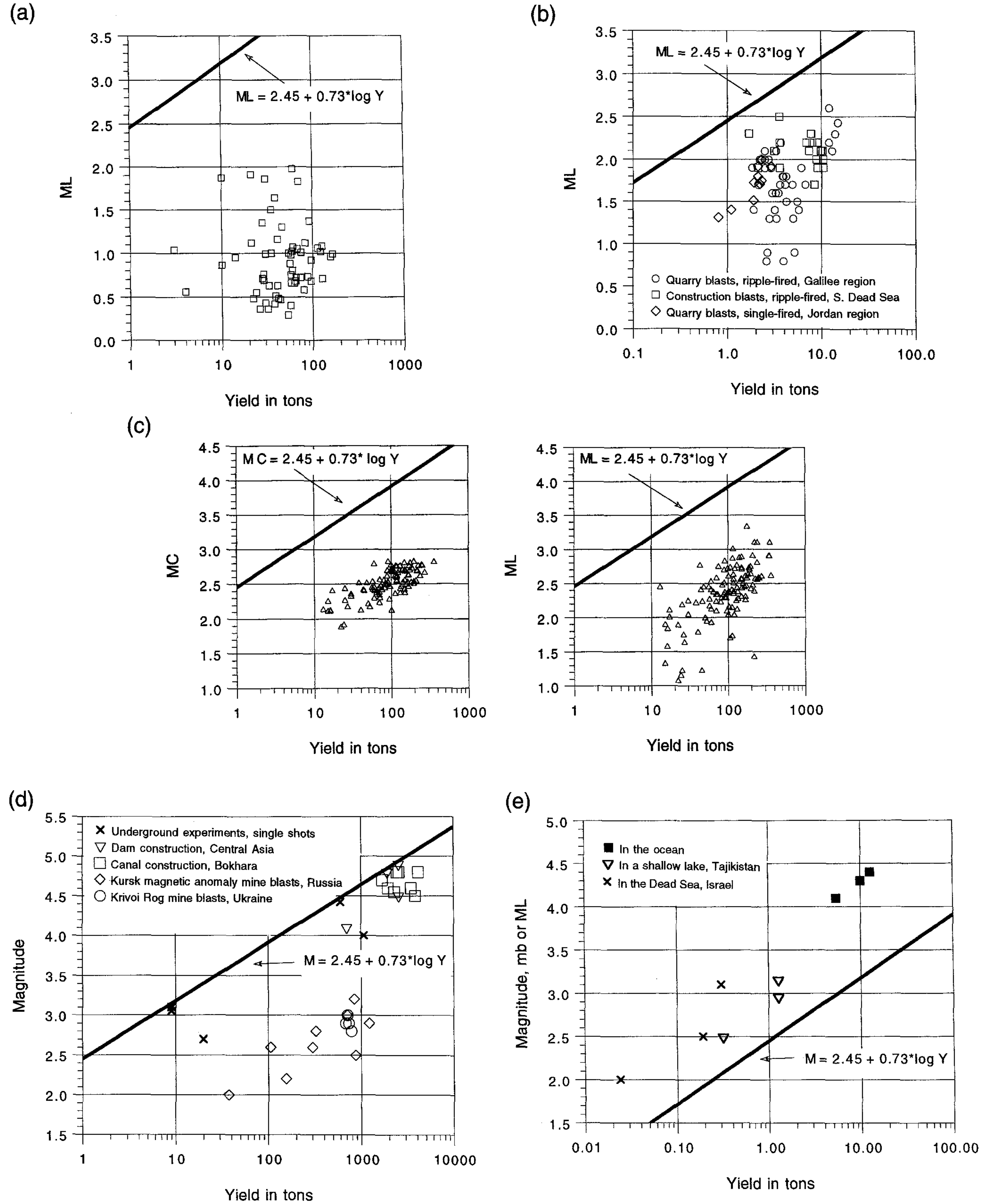


Figure 5. Details of the $M = M(Y)$ data shown for all our data in Figure 4. (a) Mining explosions in an open-pit gold mine, Nevada. Most of these explosions were ripple fired. Data from S. Jarpe *et al.* (1996). Explosions in this mine have the lowest seismic coupling efficiency: average $\Delta m = 2.7$. (b) Road construction and quarry explosions in Israel. Data from Gitterman *et al.* (1996). (c) Underground mining blasts in Apatity, Kola peninsula, Russia. For these explosions, two types of magnitude were reported: coda *MC* (left) and local magnitude *ML* (right). From Kremenetskaya *et al.* (1995). For *MC,* the magnitude deficit is 1.5, and for local magnitude, *ML* is 1.7. All three types of explosions have nearly the same seismic efficiency: average Δm is 0.8. (d) Large industrial and experimental chemical explosions. Experimental tamped explosions made in northern Kazakhstan have the highest efficiency (Δm is about zero). Mining explosions at the Kursk Magnetic Anomaly have very low coupling efficiency: average Δm is 1.8. (e) Underwater chemical explosions: in the ocean ($|\Delta m| = 1.2$); in shallow lakes (depth 9 to 25 m) in Tajikistan ($|\Delta m| = 0.5$); and in the Dead Sea, Israel, at the depth 70 m ($|\Delta m| = 0.8$). These explosions have magnitude excess, rather than a deficit, because of the super-efficient coupling in water.

investigate explosion size in terms of seismic magnitude, whether local, regional, or teleseismic, when the principal concern is with the observability of blasting activity. To this end, we have defined the concept of seismic magnitude deficit, being the amount by which signals are smaller than expected for maximum seismic coupling in hard rock, under conditions of efficient seismic wave propagation, and at the same yield as the explosion whose deficit we wish to estimate.

It is apparent from the data we have presented that the magnitude deficit of a chemical explosion is due to a number of contributing effects. We can write

$$\Delta m = \Delta m_{\text{blasting practice}} + \Delta m_{\text{geologic medium at the shot point}} + \Delta m_{\text{region}}. \quad (9)$$

Thus, blasting practice has an influence because it matters whether the shot is well tamped or not, whether it is deep or shallow or at the surface, and whether it is ripple fired or single fired. The geologic medium at the point of emplacement has an influence (see, e.g., Denny and Johnson, 1991). The effect of different regions is seen in the way that attenuation can vary for different paths of propagation to the reporting stations (Adushkin and An, 1990; Rautian and Khalturin, 1994). Each of these contributing factors has been studied extensively.

Of particular interest in the context of CTBT monitoring are any explosions in which large amounts of explosive or blasting agent are fired all at once in a contained environment. A few decades ago it was common practice in certain mines and quarries in the United States to drive a tunnel into a rock face, to fill the tunnel with chemical explosive, and to fire the whole charge at once. This practice is called *coyote blasting* in the United States. (The name arose because sometimes it was possible for blasters to find an existing tunnel, such as a coyote might be using.) The idea was to lift the body of rock upward and sideways above the tunnel, so that the rock was fragmented as it fell back down. This practice is known to produce strong seismic signals because, when carried out correctly, the explosion is substantially contained. But coyote blasting is a notoriously dangerous practice because of the possibilities for miscalculation: too much charge and the explosion will blow fragments far and wide; too little and the rock does not fragment as desired.

The following are Richards' notes of a January 1994 interview with an expert old-time blaster, who executed many coyote blasts in the 1950s and 1960s:

> "The Corona quarry in Southern California shot coyote blasts up to a million pounds in the 1950s . . . The Mapleton quarry, Pennsylvania, shot coyote blasts around 25–30,000 pounds until recently . . . The key is, to break the rock up small enough so it's easy to move. You could get a lot of rock for little money—but [coyote blasting] is a lawyer's delight today. The only place I know where it is still carried out regularly, is blasting in basalt in Oregon and Washington—maybe several thousand pounds at a time—to break rock used for logging roads."

Seismic data from the network operated by the University of Washington confirms that some of the seismicity observed in logging areas appears to be due to blasting (S. Malone, personal comm.).

The practical reason it has become possible to avoid the dangers of coyote blasting is that drilling technology has improved so much in recent years. For the typical large chemical explosions now carried out for commercial purposes, ripple firing with a sequence of preplanned delays is used exclusively. This conclusion is reached after interviews with numerous blasters, blast vibration consultants, and powder company executives.

The technology of blasting has become more and more sophisticated in recent years, with increasing reliance on accurate timing to achieve maximum desired fragmentation in a controlled blast. The mining industry now refers to high-tech ripple firing as "millisecond delay initiation."

The common purpose underlying almost all industrial blasting is to break or move rock. Often the goal is to break the rock into fragments of prespecified size.

The amount of ground vibration is found in practice to be related to the maximum size of charge fired in any hole, rather than to the total charge size (Devine and Duvall, 1963; Nicholls *et al.,* 1971). It appears that the seismic magnitude is also determined by the amount of charge detonated in one component blast, which for a large industrial explosion will be on the order of 1% of the total—contributing 2 magnitude units to the deficit, according to equation (9). Thus, blasts of over a kiloton in Wyoming surface coal mines are observed to have magnitude around 2 (L. Glenn, personal comm.), whereas they would be expected to have magnitude around 4 for a contained kiloton fired all at once.

Another type of blasting with effectively instantaneous detonations is presplit blasting, in which a single line of holes are lightly charged and all are fired together. The purpose of presplitting is to propagate a crack between holes to establish a fracture plane in the rock mass, for example, around the perimeter of a future excavation site, so that the finished face of the rock, left after the excavation has been completed, is smooth and undamaged. However, because the intent is not to fragment the rock, presplit blasts do not use large amounts of explosive.

Blasting practices in the United States in surface mining for coal underwent significant changes following 1986, when the Surface Mining Act prompted a series of regulations (30 CFR, paragraphs 816.61 to 816.67). These changes included rules governing how much explosive may be shot in any 8-msec period. As a result, the "maximum pounds per delay period" is now *defined* in U.S. industry to be the amount of explosives designed to be detonated within an 8-msec interval. Blasting is also highly regulated in West European countries. Even where there is little or no regulation, blasting in practice is carried out with ever-increasing attention to the smooth working of operations around the blast site. For example, in an open-pit copper mine or a strip-mining operation where millions of dollars of equipment must be used efficiently for commercial success, it is undesirable to stop operations for any length of time and pull equipment back from the vicinity of a blast site. The blasting industry in the United States (and presumably elsewhere) is still undergoing changes in professional practice, adopting more sophisticated techniques to minimize ground vibrations and maximize the intended function of the blast, which, again, is almost always to break rock safely and reliably into fragments of a chosen size. The outcome of these changing techniques in the United States has been a reduction, over a period of several years, in the magnitude of seismic motion associated with blasting activity.

To summarize the foregoing discussion of changes in blasting practice, almost all aspects of industrial blasting in the United States emphasize techniques that are different from that associated with execution of a deep, large (over 100 tons), single-fired chemical explosion, such as the Non-Proliferation experiment of September 1993 or the Soviet-era chemical explosions of the 1950s and 1960s. The latter type of underground explosion is an inefficient way to break rock and the most efficient way to make seismic signals.

Equation (9) has a regional term contributing to the deficit. Regional differences are often associated with the need for station magnitude corrections when interpreting teleseismic m_b. However, in practice, when all the major factors affecting the deficit are contributing together, we can use the deficit to characterize directly the cumulative outcome on chemical explosion magnitudes.

In some regions, the seismic efficiency of explosions can be high for local observations (*ML*) and low for teleseismic m_b. Such a disparity may apply to the Lake Baykal region, with a high Q crust and a low Q upper mantle. In this region, mining and quarrying are carried out extensively with many seismic observations of regional waves but without teleseismic detections.

At the beginning of our study, we were not sure whether the upper limit $M = M(Y)_{\max}$ for chemical and nuclear explosions would be the same. It is commonly thought that under the same conditions of containment, depth, and shotpoint geology, the seismic signals from a chemical kiloton are about twice those of a nuclear kiloton (see, for example, Denny *et al.*, 1996). Only after examination of available data in the region of yields where we had both chemical and nuclear explosions (230 to 4000 tons) did we conclude that the upper limit and hence the maximum seismic efficiency is essentially the same for both groups. The level of the upper limit curve has applicability beyond our own interests. For example, it can indicate the source size needed in a long-range refraction survey.

Mine blasts in the Kuzbass region, to the east of Novosibirsk in western Siberia, have a deficit amounting perhaps to about 0.65 magnitude units (see Table 3), but we are aware that explosions in this region (and in the Abakan region slightly further to the east) have often exceeded $K = 10$, which corresponds approximately to magnitude 4 via equation (3). These explosions are often detected by regional stations out to 1000 km in Central Asia (W.-Y. Kim, personal comm.) and possibly at teleseismic stations. The Kuzbass/Abakan region appears to contain some of the largest mine-blasting operations (in terms of seismic magnitude and frequency of signals) in Eurasia. As such, the region will be of interest to those who must interpret the Kuzbass blasting signals that will surely be recorded by seismographic networks used to monitor compliance with the Comprehensive Test Ban Treaty.

It is of interest that the magnitude–yield relation of Ringdal *et al.* (1992), derived for the underground nuclear explosions at the Semipalatinsk Test Site, differs very little from our relation between the maximum magnitude and yield (compare equations 1 and 8). In our terminology, the deficit of these nuclear explosions is only about 0.15 magnitude units.

Conclusions

We have found the upper limit on magnitude as a function of yield, for chemical and nuclear explosions in hard rock.

We have defined the deficit of an explosion as the amount by which its seismic signals are smaller than would be expected if the explosion were carried out under most favorable coupling conditions in hard rock and with most efficient propagation characteristics. The deficit is a quantitative measure of the inefficiency of generation of seismic signals. We find that the magnitude deficit is typically around 1.5 to 2 magnitude units for chemical explosions in the mining and construction industries. This is the reason that the great majority of blasts that would be counted as large in terms of charge size are in fact not detected seismically. The reason for the inefficiency of generating seismic signal is presumably because the usual commercial purpose of chemical explosions entails the need to fracture rock into small pieces, which necessitates firing practices (such as ripple firing) in which much of the explosive energy goes into rock fragmentation. A smaller fraction is then radiated seismically than would be the case for a well-tamped single-fired shot.

In the context of treaty monitoring, it is fortunate that the great majority of mining areas do not conduct blasts with seismic signals of magnitude above 3, and very few (on the order of 10 per year in the United States) are associated with signals above magnitude 3.5 (Khalturin *et al.*, 1998). Nevertheless, there are a limited number of regions in which mine blasting is seismically detectable over large distances. The Kuzbass mining region of W. Siberia, Russia, and the region near Abakan farther to the east, appears to be associated with explosions with magnitude greater than 3.5 that are likely to be detected a few times each month at considerable distances.

Also in the context of treaty monitoring and for general seismological studies of chemical explosions, it will be very helpful to improve upon current practices of assigning magnitude based upon regional signals and then to relate regional magnitudes for small earthquakes and explosions to magnitude values assigned on the teleseismic m_b scale.

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