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Peaceful Uses of Nuclear Explosives

Review Paper No. 4

Monitoring Yields of Underground (PNE) Explosions from Normalised Amplitudes of Seismic Signals

H I S Thirlaway

FOREWORD

This Review is one of a series on topics relevant to the Peaceful Uses of Nuclear Explosives (PNE) prepared by AWRE under contract to the United Kingdom Atomic Energy Authority.

The aim of the series is to provide a reasonably comprehensive review and some assessment of published work, to indicate areas of uncertainty and to provide answers to some of the questions likely to arise during the initial consideration of possible PNE projects.

The series comprises:-

Review Number	Title	Author	AWRE Report Number
1	Radioactivity and PNE	Editor: Ruth Lapage	011/74
2	Ground motion and seismic damage	P J Atkins F H Grover K Parker H I S Thirlaway	020/74
3	Air blast from underground nuclear explosions. An introductory guide	T Whiteside	010/74
4	Monitoring yields of underground (PNE) explosions from normalised amplitudes of seismic signals	H I S Thirlaway	017/74
5	Semi-empirical predictions of configurations produced by contained nuclear explosions	L Gatfield	021/74
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1. INTRODUCTION

The International Atomic Energy Agency (IAEA) is currently considering the role which it might play in the international observation of peaceful nuclear explosions called for by Article V of the Non-Proliferation Treaty (NPT). In November 1970 the Director General of the Agency convened a group of experts to advise him on this question and in their report (GOV/1433 Annex II) they recommend that "the international observers should, inter alia, be enabled to employ simple but adequate instrumentation to ascertain that the nuclear device was exploded, for instance instrumentation for an approximate yield determination". Paragraph 14 of "Guidelines for International Observation of Peaceful Nuclear Explosions" prepared by the Director General for the Board of Governors (GOV/1540, 1972) suggests that "At the time of the detonation and immediately thereafter, as described in the observation agreement, the Agency observers shall employ simple but adequate methods to ascertain that the nuclear explosive device or devices have been detonated. For a completely contained underground explosion this requirement might be satisfied by ground motion instrumentation to determine approximate explosive yield".

The purpose of this report is to examine how close-in and distant seismic signals might be used to determine the yield of PNE devices fired underground and to assess the advantages and disadvantages of the alternative methods in terms of feasibility, accuracy, acceptability and cost. It is assumed that yield determinations by sampling, or by ground motion measurements within several hundred metres of the explosion point, are ruled out since their implementation could lead to the international observers (and possibly others) securing information relevant to nuclear weapon design.

2. YIELD ESTIMATES FROM DILATIONAL (P) WAVES

In principle the motion of the ground resulting from the radiation of seismic waves generated by an underground explosion should be uniquely related to the size of the explosion. Empirical results on vertical ground motion measured from the amplitude of the seismic P-wave (the first to arrive at a recording station) show that this is not so in practice. For distances up to 1000 km, where the signal propagates through relatively shallow upper layers [1], as well as for distances of several thousand kilometres when deeper paths are traversed [2,3], variations in the P-wave amplitudes of nearly 100 have been observed for a given yield. This uncertainty is unlikely to be acceptable for PNE projects. The effect is due partly to the time histories of explosion sources being dependent on the source medium [4] and partly to large variations of the absorption, diffraction and scattering characteristics of rock material forming transmission paths for the propagating P-wave.

It is true that the preliminary estimates of yields at the Nevada Test Site (NTS) are much more consistent. Four seismographs are operated there at fixed sites 200 to 300 km from the test area, and a relationship providing good estimates of yield between seismic amplitude and yield has been derived from observations of several explosions of known yield. For example, the Joint Congressional Committee on Atomic Energy (JCAE) revealed that the regionally normalised seismic amplitudes are related to yields of explosions from the Pahute Mesa area of the NTS with a precision of 15 to 20% [5].

This result is possible only because the propagation paths are fixed and have been calibrated with many sources of known yield, whereas explosions for PNE projects may take place in uncalibrated areas in any part of the world. The calibration of unknown areas by means of small chemical explosions has not been tried systematically; the calibration shots must be emplaced at the PNE-designed depth, and the scaling factor for chemical to nuclear explosions has yet to be established. Furthermore, the inconsistencies in the seismic amplitude (P-wave)-yield relationship in different areas is at the root of the divergence of international views on the subject. For these reasons it is thought to be unprofitable, for the time being, to consider the use of P-waves to estimate PNE yields; to be adequate for IAEA purposes, the procedure would not be simple, as advocated in GOV/1540, 1972.

3. YIELD ESTIMATES FROM RAYLEIGH (R) WAVES

Variations in the geological transmission paths, which contribute to the observational scatter, approximate dimensionally to the wavelengths of the propagating dilational (P) signal. Although the signal is best detected at the high frequency (> 1 Hz) end of the seismic spectrum, greater attention has been devoted recently to the use of low frequency signals for the measurement of yield since they are less affected by geological variations which are dimensionally small compared with the signal wavelength. In particular, surface (Rayleigh) waves are seen to be well dispersed into sinusoidal wave groups with wavelengths of 30 km or more when the source to receiver distance is greater than about 1000 km, the frequencies being approximately the same at different stations for groups whose group velocity u is distance (Δ)/travel time (t).

The dispersion is due to the general increase with depth of the velocity of propagation of elastic waves within the earth. The upper curves in figure 1 illustrate typical cases of the variation of group velocity with period (T) for the wholly continental and oceanic paths of Rayleigh waves. The two curves reflect the differences in the average increase of velocity with depth within the two principal earth structures. The problem of correcting for any path over which Rayleigh waves are observed is more tractable than for P-waves, and was solved by Carpenter and Marshall [6]. Later, Marshall and Basham [7] evaluated average path corrections for Eurasian, North American, Oceanic and mixed continental-oceanic paths using group velocity-period observations of Rayleigh waves from earthquakes. The sizes of the corrections in terms of magnitude (M_s) units are shown in the lower sketch in figure 1. The differential effect on amplitude is small for wave groups of about 20 second period, and for distances greater than about 2500 km the maximum amplitudes of Rayleigh waves are developed in this period range. (The amplitude-distance function used for estimating the relative size of earthquakes was originally constructed using Rayleigh waves of this period.)

The lower sketch also shows that the maximum amplitudes of Rayleigh waves observed from explosion sources are developed at periods of 10 - 14 seconds. Because of the wavelength dependence on geological structures, they are more sensitive to changes in the propagation path in this band, but the amplitude corrections, though large, vary smoothly.

Following these recent studies, the relative size of explosions expressed in terms of normalised R-wave amplitudes (M_s) is estimated from

$$M_s = \log A + B'(\Delta) + P(T),$$

where A is the maximum amplitude (nm) in the Rayleigh wave train, $B'(\Delta)$ corrects for geometric spreading, dispersion and absorption (the amplitude-distance function), and P(T) is the path correction for the period measured. The latter may be applied from the average results already published, or for greater precision, from a special study of Rayleigh trains (from previous explosions or earthquakes) which have traversed the region of the PNE experiment. If the yields are to be 100 kton or more, Rayleigh waves will be detected at satisfactory signal levels at distances of 3000 km or so by the existing network of standard stations. For smaller yields it may be necessary to establish one temporary station (cost about $20000 for instrumentation) in a shallow emplacement at 1000 km or so from the PNE site to supplement the standard stations. This would be a relatively inexpensive and straightforward project using well-established equipment and methods and, by using a system which samples several parts of the seismic spectrum [8], the one emplacement would also discriminate between explosions and earthquakes - a useful facility for PNE projects in seismic areas.

The principal disadvantages of the R-wave amplitude method for estimating yields is that the signals are not so well developed from explosions as are the corresponding P-waves, and, because the propagation velocity of R-waves is less than half that of P-waves, they arrive later in a more disturbed part of the record. Reliable measurements may therefore be more difficult to make for yields less than about 10 kton.

4. THE M_s-YIELD RELATIONSHIP

The consistency and precision of the normalised R-wave amplitude (M_s)-yield relationship have been checked over a range of yields between 5 to 5000 kton [9]. The yield Y is expressed very nearly by

$$\log Y = M_s - 2$$

in agreement with the theoretical work of Hudson [10,11].

The scatter of observations above 100 kton is small enough to claim a precision of 50%. Below this level the scatter of observations is covered by a factor of two; the reason for the increase in error bands is the smaller signal to noise ratios and the uncertainties in P(T) at the higher frequencies. The data are much more consistent than those derived from P-wave amplitudes, and if greater precision is required for monitoring the yields of less than 100 kton for PNE projects, a temporary recording station at a distance of about 1000 km, as recommended above, would provide a precision of about 50% along properly evaluated paths, P(T). There are few regions where P(T) cannot be estimated from existing earthquake data, and computer codes are available for rapidly estimating specific paths.

In contrast to the P-wave case, another advantage is almost exact coincidence between conventional M_s values currently estimated by Soviet, European and North American data centres. The modifications with respect to B for distances 1000 - 2500 km and for path effects P(T), which have been proposed by Marshall and Basham [7], are now being considered by the International Association for Seismology's Commission on Practice. The recommendations of this body may be advantageous if PNE yields are to be verified internationally by means of seismic observations.

It is therefore recommended that the yields of peaceful nuclear explosions be estimated from the quantity M_s calculated from the amplitudes of Rayleigh waves recorded by existing observatories and, if necessary, by seismographs specially deployed for the purpose.

The two papers appended present a sample of the experimental evidence on which this recommendation is based.

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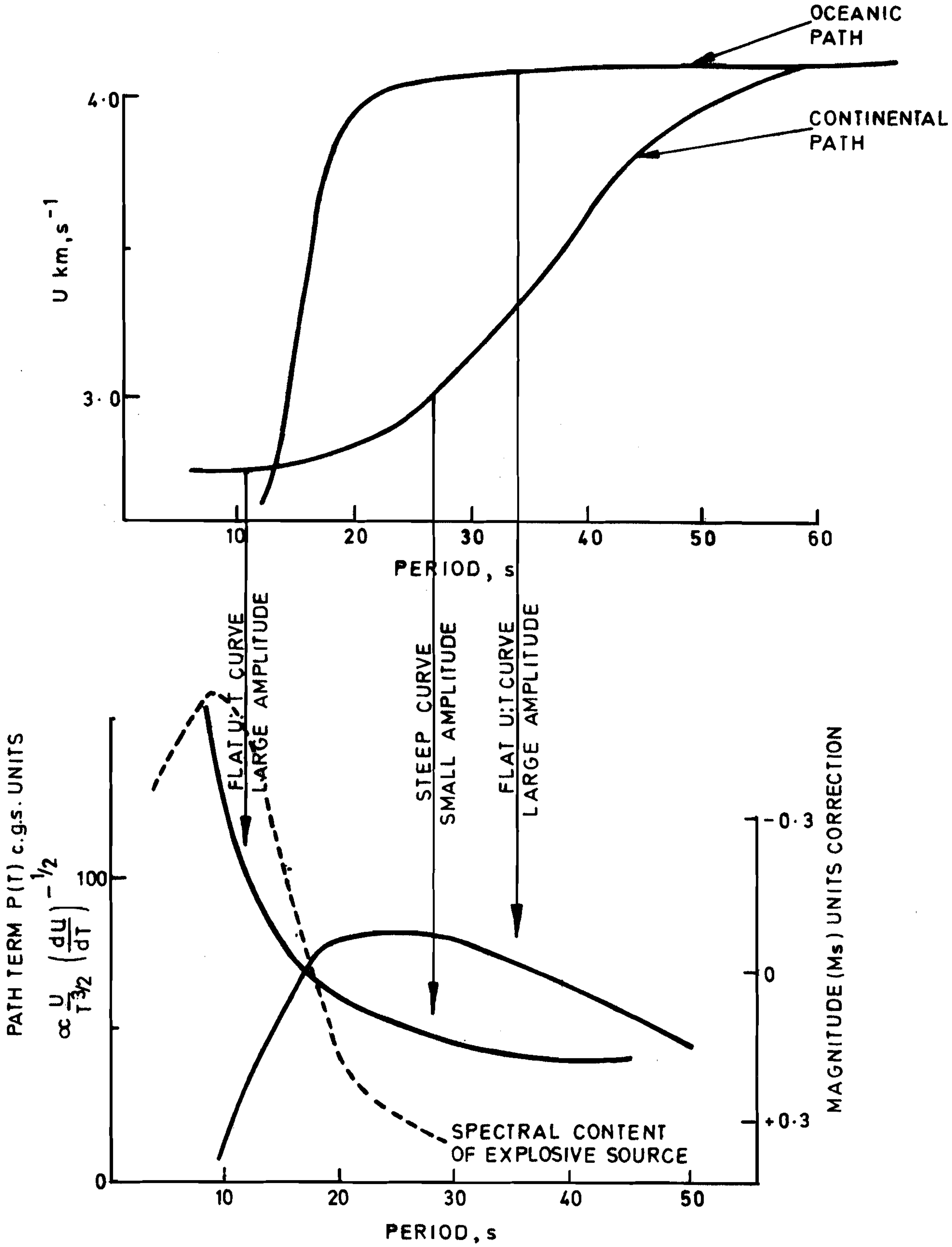

FIGURE 1. GROUP VELOCITY CURVES AND PATH CORRECTIONS FOR OCEANIC AND CONTINENTAL PATHS

APPENDIX A

UNITED KINGDOM WORKING PAPER ON SEISMIC YIELDS OF UNDERGROUND EXPLOSIONS - ESTIMATING YIELDS OF UNDERGROUND EXPLOSIONS FROM AMPLITUDES OF SEISMIC SIGNALS

(Adopted from the Conference of the Committee on Disarmament, 25 April 1972, CCD/363)

A1. DEFINITION OF YIELD AND MAGNITUDE

By making seismic measurements close to an explosion in a previously calibrated area, the energy release (size) of the explosion can be estimated. Such estimates of explosion size are generally referred to as the "seismic" yield of the explosion and are expressed in terms of kilotons. Recent testimony before the United States Joint Committee of the AEC suggests that yields of nuclear explosions in the Nevada Test Site can be estimated from such measurements to within 15 to 20% of the yields estimated from radiochemical measurements.

In the context of the comprehensive nuclear test ban (CTB) discussions, the Conference of the Committee on Disarmament (CCD) has been concerned with the more difficult problem of estimating yields of nuclear explosions from seismic waves which have traversed uncalibrated paths of much greater length. A brief recapitulation of the principles involved may be convenient. A small part of the energy released by underground explosions is converted to elastic energy and transmitted to distant parts of the earth as seismic waves. From the amplitudes of these waves, seismologists can determine a "seismic magnitude" for the explosion using magnitude scales devised to measure the relative size of earthquakes. The amplitudes of the seismic waves cannot be used directly as a measure of the size of a seismic event because the recorded amplitude depends on the distance of the recording station from the explosion; in general, the greater the distance the smaller the recorded signal. In computing the magnitude, a factor is applied to the recorded amplitude to correct for the effects of distance, after which all recording stations ideally give the same magnitude for a given event regardless of distance from the source of the event.

In this appendix we discuss the relationship between the seismic magnitude scales and explosion yields and demonstrate some of the difficulties in arriving at a consistent relationship, and hence in relating the detection and identification thresholds, expressed as magnitudes, of a given recording system to explosion yields.

When the CTB discussions began in 1958 the problem of estimating the relative sizes of earthquakes from recordings at distant stations already had a long history of careful experimental work. The principal objective of the research was the provision of universal distance factors and the following section summarizes the development of this work.

A2. THE SEISMIC MAGNITUDE SCALES

A scale for measuring the relative sizes of earthquakes was initiated by Dr Charles Richter at the California Institute of

Technology some 40 years ago. A local scale was developed for use with events within 600 km of recording stations, particularly in California, in order to eliminate subjective assessments of size by affected populations. The seismic magnitude scale is logarithmic, that is, differences in amplitudes of 10 at a given station from events at similar distances represent differences of one magnitude unit in the size of the events; the larger the number the greater is the size of the event.

Richter's scale turned out to be more successful than had been expected, and attempts were made to extend its usefulness beyond the local seismic problems of California. With Dr B Gutenberg, Richter attempted the task using the combined surface waves recorded by two horizontal components. (In those days, sensitive vertical component seismographs could not be built because of technical problems concerned with the length and stability of springs.) This still left out deep focus earthquakes which do not generate such large surface waves, so Gutenberg went a step further and created a magnitude scale based on the amplitudes of long period (low frequency) body waves, including, of course, the first arriving P-waves. The results of this work were published in 1945. Finally, in 1956, Gutenberg and Richter published what is called the unified scale which makes use of data from all sources, including short period P-waves. The authors used the term m_b to identify unified magnitudes, and it is this scale which has been in common use for CTB discussions since 1958 because for distant events more data for short period than for long period P-waves have been available from the Benioff and Willmore vertical component seismographs. In recent years, however, surface (Rayleigh) wave data have been provided by more sensitive long period vertical component seismographs. The value of magnitudes (M_s) derived from them for discriminating between explosions and earthquakes is well known. This appendix demonstrates that surface waves are also useful for estimating the yield of explosions.

Data from small events located at great distances were not numerous in the early days of CTB discussions and the various problems arising in these discussions focussed attention much more than before on the relative sizes and numbers of small seismic events. The problem of relating the original magnitude scale for local events (which included a sufficient number of small earthquakes) to the unified scale (which did not) proved difficult to solve during the lifetime of Technical Working Group II at Geneva in 1959. Long period instruments sensitive enough to record surface waves of such small events had not been developed at the time, and the Kirnos instruments of the Soviet Union, though technically ideal for resolving inconsistencies in the body wave magnitude scales, detect only the larger distant events above the seismic noise which is also well recorded by these seismographs. Some of the early difficulties enocuntered in applying the unified, or as it is now called, the m_b scale, to the detailed seismological problems of a CTB remain unresolved insofar as international agreement is concerned, and an appendix is devoted to the problem in the report of the Conference on Seismic Methods for Monitoring Underground Explosions, SIPRI Stockholm, 1968.

Specific examples of the problem insofar as it relates to estimating seismic yield of explosions are provided below. They are selected (a) from the United Kingdom studies on the well-documented explosions codenamed Gasbuggy, Rulison and Medeo, which were circulated by the United Kingdom Delegation to the CCD in August 1970, and (b) from the explosions on Amchitka Island in the Aleutians, two of which are equally well documented (for example, in references [A1] and [A2]) and which provide a useful frame of reference over a wider range of yields. No attempt is made to summarize the whole of the m_b-yield data which have accumulated since 1958; this is the subject of a detailed analysis which is being prepared for publication.

Figure A1 does, however, summarize the more consistent surface wave magnitude (M_s)-yield data. The M_s values plotted on this curve have been measured in accordance with the recommendations outlined in the Canadian Working Paper CCD/327 of June 1971, and detailed in a technical paper published in the Geophysical Journal of the Royal Astronomical Society, London [A5]. Some of the data on which the M_s-yield curve is based are presented at appendix B.

A3. m_b-YIELD

Commonsense would suggest that m_b values should increase with increasing explosion yield. This idea can be demonstrated experimentally when source to receiver paths are identical, or nearly so, for successive explosions. Take, for example, the three explosions on Amchitka Island in the Aleutians as recorded at Eskdalemuir in Scotland. (Yield and magnitude values are rounded off to the nearest significant figure in all the following tables.)

TABLE A1

Yields and Magnitudes for Explosions On Amchitka Island Recorded at Eskdalemuir

Explosion	Yield, kton	Yield Ratio	Relative Size from Seismic Amplitudes at Eskdalemuir	Seismic Magnitude at Eskdalemuir (m_b)
Longshot	100	1	1	6.2
Milrow	1000	10	2½	6.6
Cannikin	5000	50	5	6.9

It might also be expected that the seismic amplitudes would increase in the same ratio as the yields, but this is manifestly not true for the Amchitka to Eskdalemuir path for the observed range of yields.

Nevertheless, the result fulfils expectations more closely than the following example of two explosions separated by 300 km on the same continent, which were also recorded at Eskdalemuir.

TABLE A2

Yields and Magnitudes for Gasbuggy and Rulison Recorded at Eskdalemuir

Explosion	Yield, kton	Yield Ratio	Relative Size from Seismic Amplitudes at Eskdalemuir (Corrected for Distance)	Seismic Magnitude at Eskdalemuir (m_b)
Gasbuggy (New Mexico)	26	1	1 (4)	5.3
Rulison (Colorado)	40	1½	0.25 (1)	4.7

On the face of it, the smaller explosion has given the larger seismic signal. A special study by the United Kingdom of the signal amplitudes recorded by distant (teleseismic) stations, and omitting the close-in stations of North America, confirms that the result is not a peculiarity of Eskdalemuir; the average figures are for Gasbuggy, m_b 5.0 and for Rulison m_b 4.9.

The next example is even more remarkable. It compares readings at Eskdalemuir of Rulison in the United States with two chemical explosions (Medeo) in the Alma Ata region of the Soviet Union.

TABLE A3

Yields and Magnitudes for Rulison and Medeo Recorded at Eskdalemuir

Explosion	Yield, kton	Yield Ratio	Relative Size from Seismic Amplitudes at Eskdalemuir (Corrected for Distance)	Seismic Magnitude at Eskdalemuir (m_b)
Rulison	40	24	1	4.7
Medeo (1) (Chemical)	1.7	1	2	5.0
Medeo (2)	3.6	2	3	5.2

The relative size of Medeo (1) as estimated from seismic amplitudes was double that of the explosion which was 24 times more powerful.

These are well documented and accurately made observations which cannot be disputed. Since they were made in the real world, the observations must have rational explanations. The explanations, however, are in dispute and have been the subject of much debate in recent years. Some possible explanations are listed in the following paragraphs, but no attempt is made to arrive at degrees of plausibility or priority, nor to make detailed quantitative assessments. These topics are being dealt with at length in the detailed study referred to earlier.

A4. DISCUSSION OF m_b-YIELD ANOMALIES

Along with most seismograph systems, Eskdalemuir was designed to detect the characteristic band of frequencies in which the seismic energy of small events is radiated. The centre point of this band moves towards lower frequencies as the size of explosions increases, and because for an explosion of 1 Mton the centre point of the radiated energy lies on a different part of the sensitivity curve than for one of 1 kton, the recorded amplitudes may be that much smaller. (The analogy of radiation from the sun is apposite; the human eye cannot perceive beyond the ultra-violet and infra-red ends of the light spectrum.) The importance of the effect for estimating magnitude (m_b) of explosions may be uncertain, but its effect in assessing the relative sizes of larger earthquakes is obvious when comparing the m_b values of "standard" (WWSSN) stations with those of the wide band Kirnos instruments of the Soviet Union. The Kirnos also records a great deal of earth noise and has consequently been held to be less useful since the CTB discussion stimulated efforts for the detection of ever smaller events and thereby pushed research teams into recording two narrow samples of the total seismic spectrum. Nowadays there is a much greater understanding of the structure of earth noise, and the means for reducing its effects, and a new look might with advantage be taken at the Kirnos type system, for discrimination problems as well as those of magnitude and yield.

Another source of the observed anomalies may be due to differences in coupling efficiency. The Committee is already aware that media in which nuclear explosives are emplaced can affect the size of the P-wave signals by factors of ten or more when comparing coupling efficiency in dry alluvium with that of a massive rock-like granite. In the case of Gasbuggy and Rulison the rocks are shale and sandstone [A3], which, although very different types of rock, are seismically not so different from each other as are dry alluvium and granite. The Medeo explosions were designed to move earth rather than generate seismic energy, and were therefore incompletely contained; although that gives the results an even more extraordinary aspect, it must be said that the more slowly reacting chemical explosions are more efficient generators of seismic energy than are nuclear explosions; only a factor of about 2 or 3 has ever been suggested, however.

The amplitude of short period P-waves is also sensitive to source depth. The depths at which Gasbuggy (1300 m) and Rulison (2574 m) were buried are unusually large for the yields involved because the experiments were designed for the purpose of improving the flow of natural gas in strata at those depths. (For weapon tests, it is necessary to bury the device only to a depth sufficient for containment of radioactive debris.) This depth would have the effect of increasing the seismic coupling efficiency, but would tend to separate the surface reflected signal away from the direct signal. This would be particularly true of Rulison, for which the surface reflection can be clearly observed arriving some 1½ seconds after the direct P-wave at Eskdalemuir (figures 2 and 3 of reference [A3]). In the case of Gasbuggy (and all nuclear weapon tests of similar size which were buried at shallower depths) the surface reflection adds to the direct signal and can thereby double the amplitude of the direct signal. The yields of weapons such as Milrow and Cannikin, however, are so large that the depths for full containment of the debris are sufficient to separate the reflected and direct signals, and the magnitudes of both these events may thereby be under-estimated relative to Longshot; factors nearer to 2 than to 10 are involved.

However, possibly the most important cause of m_b anomalies has been revealed in the last twelve months by studies in the United Kingdom, which indicate that there are deep-seated geological structures in areas which are associated with earthquake belts and with mountain ranges, having a greater capacity for absorbing high frequency seismic energy (short period P-waves) than the ocean floor and those ancient blocks in the interior of continents known as shields. Such structures may also cause the P-wave radiation to take two or more paths (multipathing) just different enough to cause the signals to interfere one with the other at the recording stations. By means of computers, models of these possible structures have been designed and the passage of seismic signals in them has been studied. The results do suggest that the geophysical causes of the more extraordinary anomalies may be found to underlie seismic and recently seismic areas. As explosion seismologists develop techniques for using larger chemical explosions for the study of earth structure, more evidence accumulates to illustrate the effects because the detonations are often in stable, aseismic areas. The most recent example, an explosion of 10 tons in the North Sea, was reported in the journal Nature as having been recorded as far away as Brasilia and Brisbane, and was given a seismic magnitude of m_b 4.8 at Uinta Basin in Utah. The United Kingdom studies predict that explosions in continental shield areas recorded by stations on shields will be assigned m_b magnitudes some two units greater than recordings of the same yield on seismic area to seismic area paths. When the Soviet Union releases more yields of explosions, great progress in this field of research will be possible because of the variety of geologic structures and seismicity in that country.

Whatever the explanation, the observations of m_b are a matter for concern since one conclusion to which they lead is that it is at present almost impossible to estimate the relative size of explosions from m_b unless they are fired at one site and compared at one station. This is a very serious constraint in the context of a CTB. Whether for counting numbers of earthquakes at a given yield equivalent, or for defining magnitude yield thresholds, a method for estimating the relative sizes of earthquakes and explosions, much less sensitive to source, path and receiver, and which provides for easily evaluated path corrections, is highly desirable.

In recent years the United Kingdom has therefore devoted some effort to the study of this problem. The successful development of sensitive long period vertical seismographs by the United States has made possible the accumulation of surface wave data of small events. The principal impact of these data has, of course, been on the m_b:M_s criterion for discriminating between earthquakes and explosions but the United Kingdom has taken another look at the use of surface wave magnitudes (M_s) for estimating yield, and the principal results of this study are reviewed in the final paragraphs of this appendix.

A5. M_s-YIELD

What has always been attractive about using surface waves for estimating relative size is firstly, that the much larger wavelengths make them less sensitive to the vagaries of geologic structure, so that gross path corrections can be applied on a continent-wide basis (as was amply demonstrated in the Canadian Working Paper) and secondly, that the frequencies of the recorded signals fall within the usual recording band of frequencies of long period seismographs over a much greater range of yield than is the case for the P signals recorded by high gain short period seismographs. Surface wave magnitudes are also preferred because seismographs in the Soviet Union provide almost identical M_s values to those estimated elsewhere. The difficulty in the use of M_s has been that surface waves were recorded only from relatively large events.

Table A4 gives the surface wave magnitude-yield comparisons for the set of explosions which have been looked at earlier when considering the m_b-yield relationship. The Medeo explosions cannot be included because no surface waves from them have been detected outside the Soviet Union. The surface wave magnitudes have been determined in accordance with the recommendations of the Canadian Working Paper CCD/327.

TABLE A4

Yields and Magnitudes (M_s) for Underground Explosions in the United States

Explosion	Yield, kton	Yield Ratio	Relative Size from Seismic Amplitudes (Corrected for Distance and Path According to CCD/327)	Average Seismic Magnitude (M_s)
Gasbuggy	26	1	1	3.4
Rulison	40	1½	1.6	3.6
Longshot	100	4	5	4.1
Milrow	1000	40	60	5.2
Cannikin	5000	200	200	5.7

It is immediately obvious that the M_s values are much more consistent over the whole range of yields than any of the m_b values listed in the earlier tables, not only in relation to yield, but also from site to site. This very satisfactory result has been confirmed by detailed analysis of all the surface wave data available to the United Kingdom from explosions for which the yields have been announced by France, the Soviet Union and the United States.

Figure A1 summarizes the analysis. For completeness, the M_s-yield theoretical curve for atmospheric explosions is also summarized. The theoretical basis for the curve was published in reference [A4] and is of special interest at lower yields (less than 50 kton) because it applies also to underground explosions in dry alluvium or other unconsolidated rocks. The curve for underground explosions applies to containment in any consolidated rock in any part of the world. The dotted lines, which bracket the solid, show the maximum scatter of the observations used in the analysis. The release of more yield data, together with more refined path corrections, is expected to decrease the width of the error bands.

These curves are now used by the United Kingdom for obtaining the best estimates of seismic yield. Low yield explosions, for which surface waves are not detected, must still be estimated from m_b with all their inherent uncertainties, but explosions as small as 5 kton have provided surface wave records from the closer stations. As more surface wave data are released, and better long period stations are deployed, the limit of the method will be established, and this limit is also of interest as representing the technical threshold for discrimination by the $m_b:M_s$ criterion.

In using the curves, delegations may find it interesting to make estimates of yield from M_s values provided by their national stations or by world data centres. The path corrections will be found in the technical paper on which the Canadian Working Paper CCD/327 is based. As an example on which to conclude, the following estimates of the yields of some of the larger underground explosions, which have occurred at each of the world's principal nuclear test sites, are estimated from the path corrected world average M_s values, and the recommended M_s-yield relationship.

TABLE A5

Site	Explosion	Average Path Corrected M_s	Yield Estimates from Curve, or $\log Y = M_s - 2$, kton
Sahara	Saphir	4.1	125
Kazakh	13 February 1966	4.4	250
Nevada	Greeley	5.1	1250
Nevada	Benham	5.1	1250
Novaya Zemlya	14 October 1970	5.1	1250
Novaya Zemlya	27 September 1971	5.1	1250
Aleutian Island	Milrow	5.2	1600
Aleutian Island	Cannikin	5.7	5000

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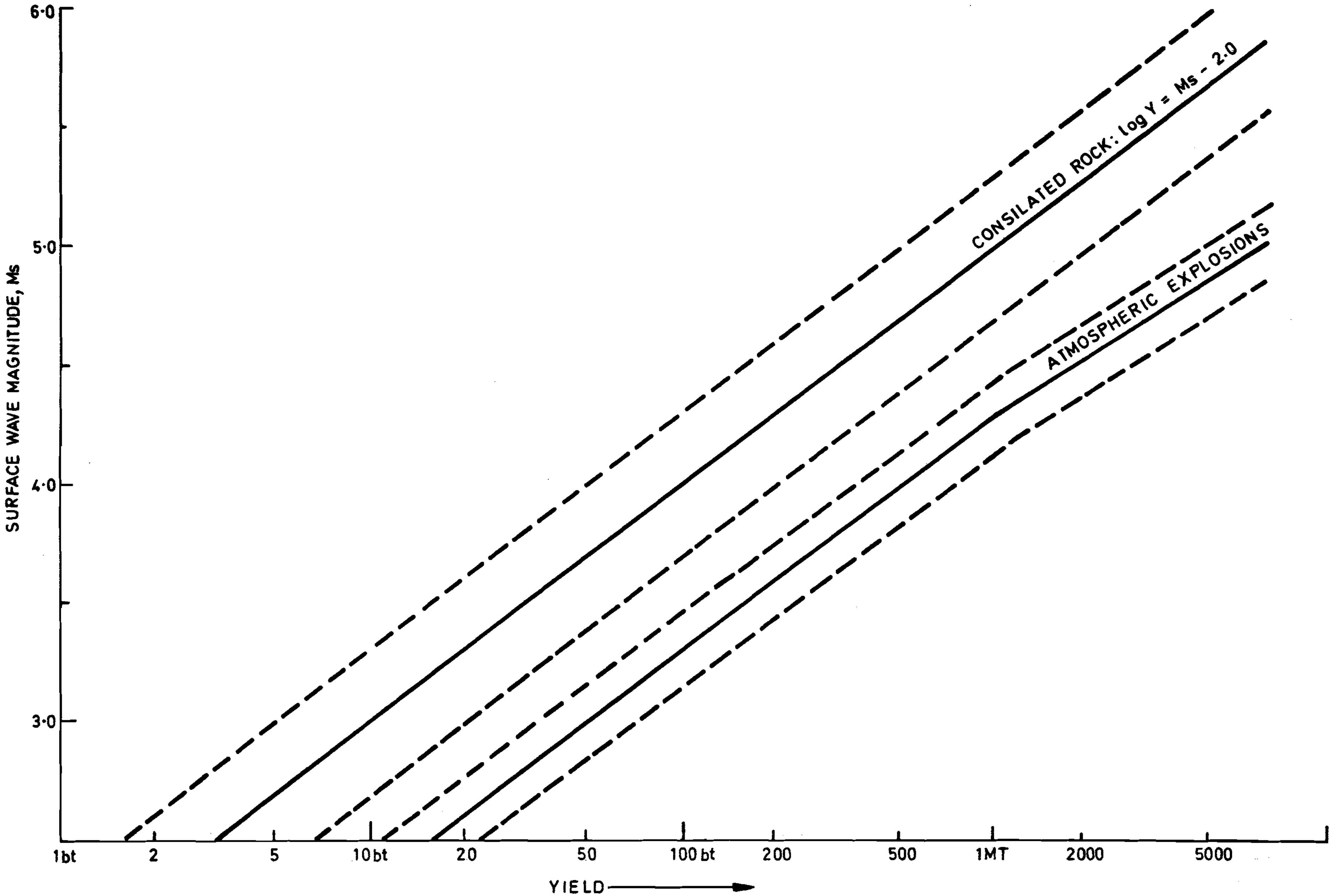

FIGURE A1. SURFACE WAVE MAGNITUDE - YIELD CURIE

APPENDIX B

SURFACE WAVES FROM UNDERGROUND EXPLOSIONS

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Several authors [B1,B2] have published data on the surface wave magnitude (M_s) and yield (Y) for underground explosions at test sites in North America. Figure B1 shows the dependence of M_s on yield for all test sites for which we could obtain explosion yield data. The details of the explosions are given in table B1. From figure B1 it is clear that for explosions in consolidated rock (tuff, salt, granite, andesite and sandstone) all the observations lie close to the line

$$M_s = \log Y + 2.0$$

for yields from 4 to 1300 kton. Only for Discus Thrower and Duryea does the observed value of M_s deviate by more than 0.3 magnitude units from this line, so only for these explosions would the yield estimated from M_s differ by more than a factor of 2 from the published yield. For explosions in unconsolidated rock (alluvium) the curve of M_s against yield seems to be more like

$$M_s = \log Y + 1.0$$

at least for yields less than 100 kton, but more data are required to define this curve. The M_s values plotted in figure B1 are means of individual station determinations of M_s, each of which is corrected for deviations of the source to receiver path from an average path. After correction, the standard deviation (SD) of an observation for a given explosion is usually 0.25 magnitude units and the SD on the mean value of M_s is about 0.1. Corrections are applied for the effect of the path on the propagation of surface waves of different periods. Over short paths in North America, for example, the large amplitude pulse-like arrival observed on wide band long period instruments is made up of period components close to a minimum value in the group velocity curve. This apparent large amplitude is due to the path and not to the source; the path effect can be estimated as a function of frequency and a correction determined (P D Marshall and P Basham, to be published). It should be pointed out that path corrections are significant only for short transmission paths over which there is little dispersion. If these transmission path corrections are not applied, the data do not display a consistent relationship between M_s and yield when data from different test sites are combined.

Theoretical curves of M_s against yield computed using the theory described by Hudson [B3,B4] and using the explosion source functions of Haskell [B5] are also shown in figure B1. These theoretical computations have also been corrected to an average crust. For consolidated rocks, the fit of the computed curve with the observations is very good; for unconsolidated rocks the predicted value of M_s for a given yield seems to be rather low. (Theoretical predictions were only made up to 30 kton in unconsolidated rocks because this is approximately the maximum yield for containment in a surface layer of alluvium 0.5 km thick - the depth of the alluvium layer in the crustal model of the Nevada Test Site [B8].)

From the data presented in figure B1 we conclude that, provided one assumes that explosions at any location have been fired in consolidated rock, yields can usually be estimated to within a factor of two. This is a great improvement on routine calculations using body wave magnitude. For example, the body wave magnitudes (m_b) of the Medeo explosions (1.6 and 3.7 kton chemical explosions) were 5.0 and 5.2 respectively at Eskdalemuir (EKA) [B7], whereas the value of m_b for the 40 kton Rulison explosion in Colorado was found to be 4.7 at EKA [B8]. Figure B1 also shows that the use of the m_b:M_s criterion [B9] to identify explosions at the teleseismic detection limit of $M_s \sim 2.5$ implied yields of about 40 kton in dry alluvium and 3 kton in consolidated rock. Long period arrays on low noise sites are required to record such low magnitudes at distances greater than 15 degrees from the firing site.

TABLE B1

Details of Some Underground Explosions

Event Number	Date	Name	Region	Medium	Yield, kton
1	14 April 1965	Palanquin	Nevada	Rhyolite	4.3(a)
2	15 February 1962	Hardhat	Nevada	Granite	4.8(a)
3	22 October 1964	Salmon	Mississippi	Salt	5.3(a)
4	26 October 1963	Shoal	Nevada	Granite	12.2(a)
5	5 November 1964	Handcar	Nevada	Dolomite	12 (a)
6	3 December 1961	Fisher	Nevada	Alluvium	13.5(a)
7	24 February 1966	Rex	Nevada	Tuff	16 (a)
8	30 September 1966	Bukhara I	Bukhara	Clay	30 (f)
9	27 May 1966	Discus Thrower	Nevada	Tuff	21 (d)
10	10 December 1967	Gasbuggy	New Mexico	Shale	29 (a)
11	9 October 1964	Par	Nevada	Alluvium	38 (a)
12	10 September 1969	Rulison	Colorado	Shale	40 (a)
13	27 June 1962	Haymaker	Nevada	Alluvium	45.5(a)
14	2 June 1966	Piledriver	Nevada	Granite	56 (a)
15	14 April 1966	Duryea	Nevada	Rhyolite	65 (a)
16	6 May 1966	Chartreuse	Nevada	Rhyolite	70 (a)
17	26 May 1967	Knicker Bocker	Nevada	Tuff	71 (a)
18	29 October 1965	Longshot	Aleutians	Andersite	85 (a)
19	6 July 1962	Sedan	Nevada	Alluvium	100 (b)
20	15 January 1965	Kazakh	Kazakh	Sandstone	125 (g)
21	27 February 1965	Saphir	Algeria	Granite	135 (d)
22	23 May 1967	Scotch	Nevada	Tuff	150 (a)
23	13 September 1963	Bilby	Nevada	Tuff	250 (a)
24	30 June 1966	Half Beak	Nevada	Rhyolite	300 (a)
25	20 December 1966	Greeley	Nevada	Tuff	825 (a)
26	19 December 1968	Benham	Nevada	Tuff	1100 (a)
27	26 April 1968	Box Car	Nevada	Tuff/Rhyolite	1200 (a)
28	2 October 1969	Milrow	Aleutians	Lava	1200 (e)
29	26 March 1970	Handley	Nevada	Mesa	1200 (e)
30	1 May 1962	Beryl	Algeria	Granite	52 (g)
31	21 May 1968	Bukhara II	Bukhara	Salt	47 (f)

(a) Reference B10; (b) Vela "Uniform" Information Digest, 2, No. 11; (c) inferred from New Scientist, 437 (May 1966) and reference B13; (d) reference B9; (e) press reports; (f) inferred from press reports and reference B11; (g) reference B12.

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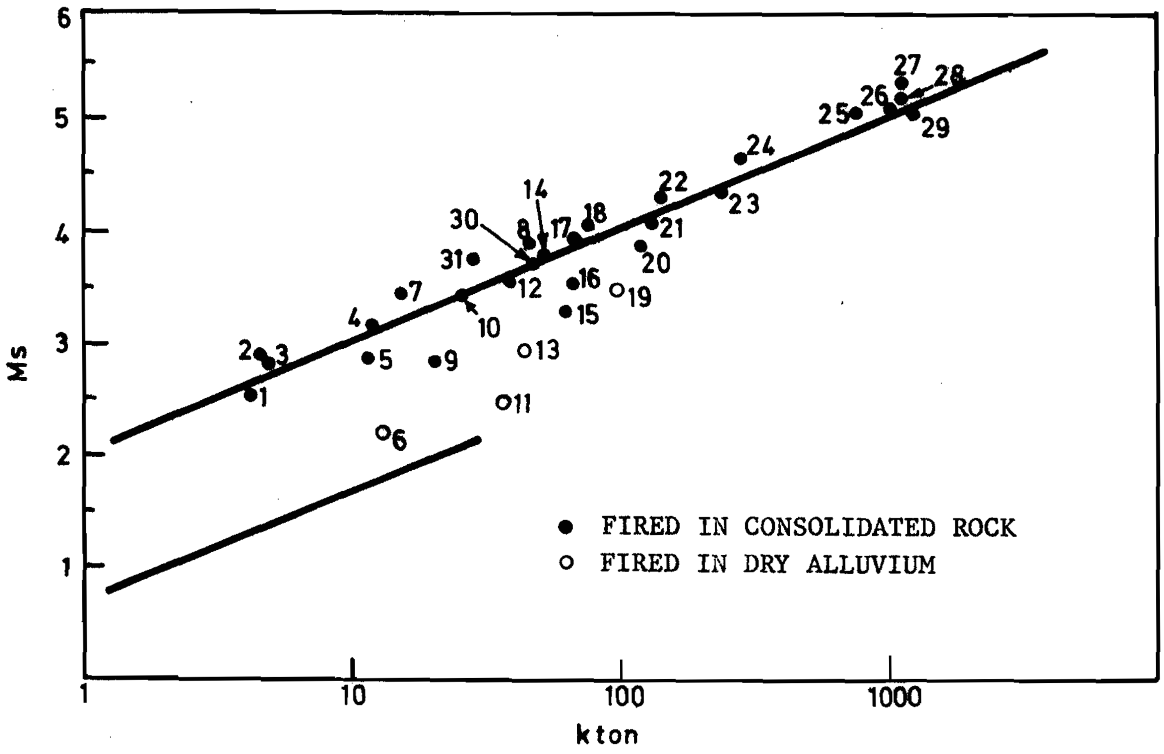

FIGURE B1. SURFACE WAVE MAGNITUDE (Ms) AGAINST YIELD (kton) FOR EXPLOSIONS IN VARIOUS PARTS OF THE WORLD

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Abstract

Seismological methods for estimating yields of underground nuclear explosions are reviewed in the light of peaceful applications. The use of surface (Rayleigh) waves for this purpose is advocated. Evidence on which this recommendation is made is appended.