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An Analysis of Seismic Waves from Earthquakes and Explosions in the Sino-Soviet Area during 1966

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CONTENTS

SUMMARY

Discrimination criteria are applied to a suite of seismic waveforms originating from seismic disturbances in the Sino-Soviet area. Explosions are identified and attention is drawn to special circumstances in which the $m_b:M_s$ criterion is shown not to work.

ABBREVIATIONS

m_b	Body wave magnitude.
M_s	Surface wave magnitude.
SIPRI	Swedish International Peace Research Institute.
WWSSN	World Wide Standard Seismograph Network.
SNR	Signal to noise ratio.
ER	Energy ratio.
USCGS	United States Coast and Geodetic Survey.
ISC	International Seismological Centre, Edinburgh.
PDE	Preliminary determination of epicentre.
SP	Short period.
LP	Long period.
h	Depth of focus in kilometres.
NOS	National Ocean Survey (formerly USCGS).
EDR	Earthquake Data Report.

1. INTRODUCTION

At the SIPRI meeting on seismic discrimination between earthquakes and explosions (SIPRI, 1968) data from the four UKAEA type arrays and the World Wide Standard Seismograph Network (WWSSN) were presented by Dr H I S Thirlaway. A summary is contained in the SIPRI report but no detailed account has been published. It is the purpose of this report to present the main details behind the analysis. At the same time, it models the kind of national verification procedures (which may be required under a Comprehensive Test Ban (CTB)), using as a data centre the United States Coast and Geodetic Survey (USCGS) seismograms and epicentre source, together with the four arrays sponsored by the United Kingdom.

The four arrays are well located for monitoring seismic activity in the Sino-Soviet areas, which are of prime importance in this context. The seismic data are therefore collected from twelve months of recordings of events in these areas; a total of 348 seismic disturbances, detected by the WWSSN and arrays, was located by the USCGS. These seismic events were analysed using the accepted source discrimination criteria of depth of source (focus), the body wave-surface wave ratio (m_b:M_s), direction of first motion and P wave signal complexity. A study of signal to noise ratio of the P waves at the four arrays was also completed. Emphasis is placed on the two most useful criteria, namely depth of focus and the m_b:M_s ratio.

Surface wave data were provided from the WWSSN long period seismographs by the USCGS microfilm source; no long period systems were operational at the array sites during 1966. The amplitudes of the surface waves used to derive M_s were measured in 1967 so the empirical relation due to Gutenberg [1] was employed. The Marshall and Basham [2] relation has been shown to be more effective in discrimination studies, but its use would have required re-reading the seismograms.

After analysing the data in terms of m_b:M_s a number of events remain unidentified and these are discussed in some detail. During the analysis of the seismograms, data relative to the complexity of P waves and signal to noise ratio at the four arrays were accumulated and these topics are considered in the appendices.

2. DISCRIMINATION CRITERIA

2.1 Depth of focus

In any discrimination study the depth of focus of a seismic source is an important parameter. If the source depth can be shown to be greater than, say, 10 km it can be reasonably assumed that the source is an earthquake and not an explosion. However, depth estimation is difficult and often not very accurate particularly for shallow sources, and in the absence of positive evidence (depth phases (pP, sP) or depth determination from P wave travel times) the source depth must, in discrimination studies, be assumed very shallow, then the source may be an earthquake or an explosion. Evidence of a large depth of focus can be used as a positive identifier of earthquakes.

2.2 m_b:M_s

For explosions, the ratio of high to low frequency energy in the seismic wave spectrum is greater than for shallow earthquakes. An estimate of the high frequency content of a source is made by measuring the short period P wave magnitude m_b; the low frequency content is estimated by measuring the surface wave (LR) magnitude M_s. By plotting m_b:M_s it is, in general, possible to separate the explosions from the earthquakes since for the same M_s values all the explosions have higher m_b values than the earthquakes. This technique is particularly successful when applied to a suite of events from which the deep-focus sources have been removed. (Surface wave amplitudes decrease with source depth.) Thus, m_b:M_s can be used as a positive identifier of explosions.

2.3 Direction of first motion

An explosive source is in theory a radially symmetric compressional source; the P waves recorded at distant stations should have compressional first motions. Earthquakes are dipolar sources radiating quadripole patterns which are dependent upon the nature of the source function and orientation of the fault. Generally P waves recorded at distant stations will exhibit compressional (positive) first motion in some directions but rarefractional (negative) in others. However, some earthquake fault planes may be orientated in a way that the cone of rays which leave the source to be recorded at teleseismic distances may all be compressional and hence appear explosion like. Thus, the rarefractional first motion implies an earthquake source, while a compressional first motion could originate from an explosion or an earthquake.

A good signal to noise ratio of the order of 10 is essential to detect the smaller first motion so the criterion is applied only to relatively large events ($m_b > 5\frac{1}{2}$). It also requires that the seismograph is well calibrated and the direction of ground motion is clearly indicated on the seismogram.

2.4 Complexity

An explosive source is a sudden release of compressional energy with, in theory, little or no shear motion produced. The teleseismic seismograms should be simple in character with most of the energy arriving within the first few seconds of the P arrival. With little or no S wave energy the record should stay fairly simple since there will be no S to P conversions close to the source giving rise to late arrivals in the seismogram. On the other hand, earthquakes generate considerable amounts of S wave energy which in turn may be converted, close to the source, into P waves and be recorded at a teleseismic station some seconds after the P wave. This will give rise to complex seismograms from earthquakes relative to explosions. That explosion signals are simple and earthquakes complex is generally true. There are, however, notable exceptions to both and for this reason complexity is used as a "diagnostic aid" and not as a discriminant. Measurements of complexity at each array as a function of magnitude are presented in appendix F.

3. MEASUREMENTS MADE ON DATA

m_b. The unified magnitude defined by Gutenberg and Richter [3].

$$m_b = \log_{10} A/T + B(\Delta,h),$$

where A is the amplitude of the P wave in millimicrons (A is normally measured within the first few cycles), T is the period of the measured wave A, and $B(\Delta,h)$ is a distance normalising term with corrections for source depth. In this study h is assumed to be zero.

M_s. The surface wave magnitude defined by Gutenberg [1].

$$M_s = \log_{10} A + B(\Delta),$$

where A is the amplitude of the 20 second period wave and $B(\Delta)$ is a distance normalising term (see appendix C).

SNR. Signal to Noise Ratio. This is measured on short period processed records and is defined here as the maximum peak to peak signal divided by the maximum peak to peak noise with the same apparent frequency in the 30 seconds preceding the arrival of the P wave signal. The measurements are made on the summed array output measured on the seismogram filtered in the pass band $\frac{1}{2}$ - 4 Hz.

Complexity:Energy Ratio. As part of the routine processing of array seismograms one of the displays is the smoothed product of the two summed outputs of each array arm. This channel gives an indication of the rate of arrival of coherent energy at the array and a typical example is shown in figure 3. It is this channel which is used to determine the complexity of an event. The complexity is defined by the energy ratio ER.

$$ER = \frac{A_{(0-5)} - \frac{1}{6}A_{(-30-0)}}{A_{(5-35)} - A_{(-30-0)}},$$

where $A_{(0-5)}$ is the area under the curve in the first 5 seconds after the initial P wave onset, $A_{(30-0)}$ is the area beneath the curve in the 30 seconds of noise preceding the P wave onset and $A_{(5-35)}$ is the area under the curve 5 seconds after the P wave and up to 35 seconds. The ER as defined here is really a measure of the simplicity of a signal rather than complexity since a high value of ER indicates a simple seismogram.

4. DATA ANALYSIS

A total of 348 events was located within the area of interest during the period of time covered by the analysis presented here. This total represents all the events located by the USCGS (now known as NOS) and reported in their Earthquake Data Reports (EDR) plus three events, not located by the USCGS, but detected whilst processing the arrays. Two other events were added to this list, one on the 30 September and the other on the 20 October 1966. The former was taken from the International Seismological Centre (ISC) Bulletins for 1966, the latter from a Russian publication [4] and as will be seen later these were significant additions. When the initial suite of data was selected the earlier published epicentral parameters of the USCGS were used. These were replaced by the later, but more accurate, ISC epicentral data since the ISC uses data from a larger number of seismic stations.

4.1 Depth of focus

The first stage in the analysis was to remove all events from the list that could be assumed to be earthquakes by their depth of focus. In this study it was decided that all events of 40 km or less were genuine shallow sources and could be explosions. The accuracy of ISC depth determination claimed is of the order of ± 25 km. So a cut-off at 40 km depth should include all events that have occurred at a depth of less than 15 km. All explosions should be retained in the suite of data subjected to further analysis. By removing all events greater than 40 km the initial list of 348 events was reduced to 179.

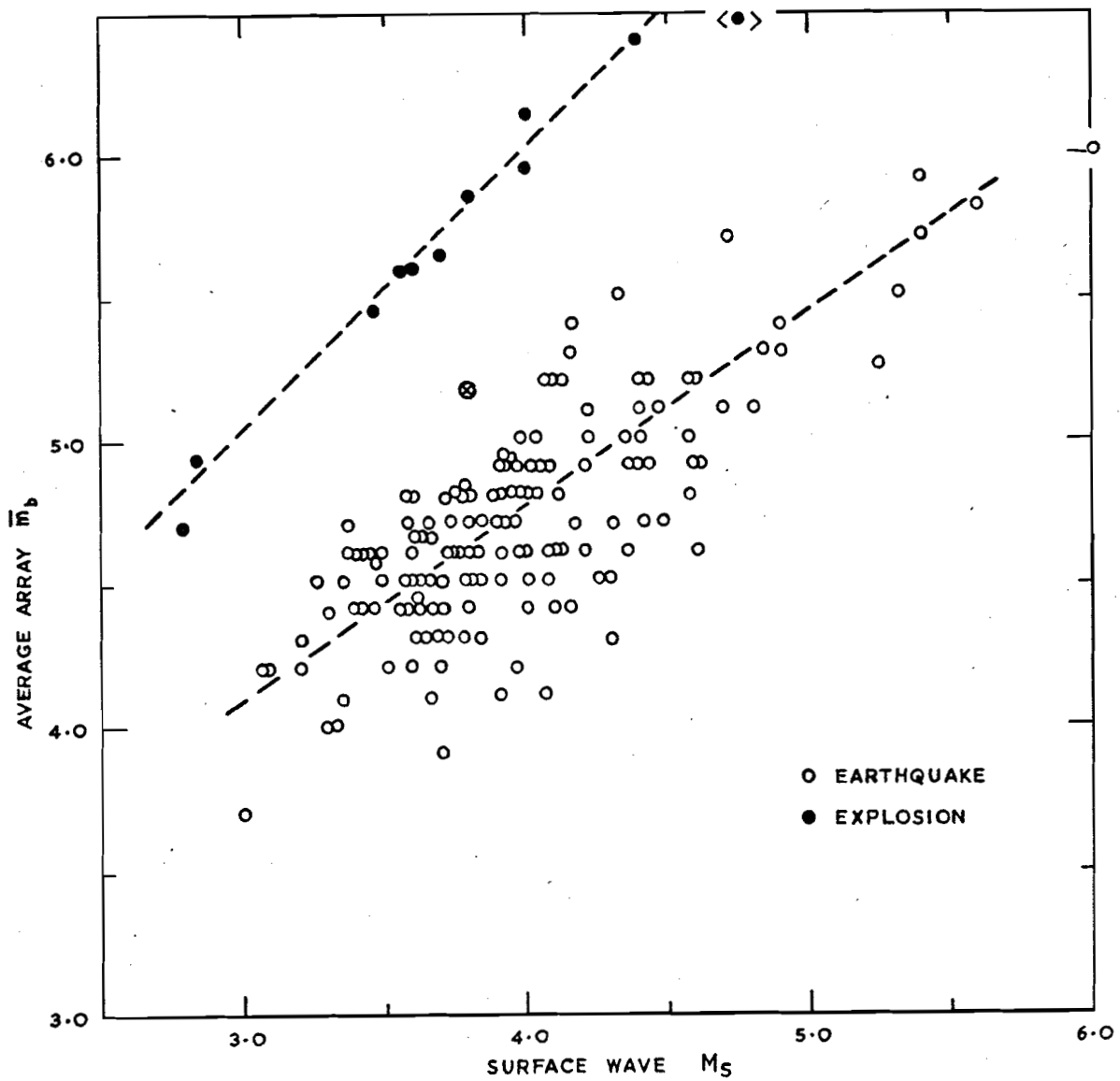

FIGURE 1. AVERAGE ARRAY MAGNITUDE m_b VERSUS AVERAGE M_s FOR ALL SHALLOW EVENTS

Mention should be made here of the value of ISC Bulletins, particularly in discrimination studies. In depth locations the ISC often reports events "... depth from P waves excessively negative"; this is a clear indication of the shallowness of the source. It was noted that this often applies to events later identified as explosions, in particular for explosions fired in a shield region where the upper mantle structure is very different from earthquake areas. Using travel times from earthquake studies and applying the travel time observations to explosions in shield regions characterised by high upper mantle velocities, the explosions will be located at either 0 km depth with an earlier origin time, or, if the true origin time is restrained, the event will be assigned a negative depth! This information is of particular interest in any discrimination study as it highlights the very shallow, and hence suspicious, sources immediately.

4.2 $m_b:M_s$

The residual 179 events were then considered using the $m_b:M_s$ discriminant. m_b is the average of the individual array measurements and M_s is the average WWSSN long period seismograph analysis. This may be an average of from 1 to 10 observations; the LP stations used in this study are listed in appendix D.

Of the 179 events, assumed to be shallow, 10 events (about 6%) were obscured by interfering surface wave trains from other events and M_s could not be measured. This is somewhat less than observed by a later study [2]. Five events could not be analysed in terms of $m_b:M_s$ as the WWSSN LP film chips were not available at the time the analysis was performed, but of these, one (22 April 1966) was located in the aseismic portion of the USSR and by definition was classed as suspicious. Eleven events were reported for which surface waves were not observed. The remaining 153 events, for which both m_b and M_s are available, are plotted in figure 1. Two distinct populations emerge; the upper solid circles are believed to be explosions and the remainder to be earthquakes. Special note is, however, taken later of the "earthquake" indicated by the crossed open circle. The 11 events unidentified by depth of focus or $m_b:M_s$, together with the one event in aseismic USSR, are now discussed in more detail.

5. UNIDENTIFIED EVENTS

5.1 30 June 1966; 09 25 40.8; m_b 4.9; Kuriles region.

A P wave from this event was detected at all arrays. WRA showed a clear pP phase (WRA generally shows a clear depth phase from events in the Kurile-Kamchatka region) with a less positive identification of pP and sP at the EKA, GBA and YKA. The depth estimated from pP is 34 km, in agreement with the ISC depth of 34 ± 7 km. A clear negative first motion was observed on the YKA seismogram, together with the evidence of its depth. This event is diagnosed to be an earthquake.

5.2 5 July 1966; 10 01 21.5; m_b 4.6; China-India border region.

The P waves were detected by the four arrays. YKA and EKA gave simple records and both showed positive first motions, whilst GBA and WRA

gave complex signals of undetermined first motion, but pP and sP were detected and used to produce a depth estimate of 15 km compared with the ISC estimate of 33 km. This event is, less positively, diagnosed to be an earthquake by its depth.

5.3 26 September 1966; 05 43 00; estimated m_b 4.5; China-India border region.

5.4 26 September 1966; 05 58 48; estimated m_b 4.5; China-India border region.

The two events above are discussed together. They were not reported by the USCGS but were found while processing the arrays for two other events around 0600 hours on the same day. They were detected on the array output beamed at the China-India border region. These events were detected only at EKA and WRA; the P waves were very similar to the P waves from the USCGS listed events. The similarity between the P waves suggests that they were located at a depth of about 20 km and are believed to be earthquakes. The two events detected by USCGS, which are close to the above events, were identified as earthquakes on the basis of m_b:M_s.

5.5 5 August 1966; 17 47 42.9; m_b 4.3; Yugoslavia

This event was detected at EKA only. The P wave record was very complex and no clear depth phases were observed. However, the ISC depth estimate was given as 35 ± 6 km and on this evidence this event is less positively classed as an earthquake.

5.6 17 March 1966; 22 25 17.9; m_b 4.0; Kamchatka

P waves were recorded at YKA and WRA and contained no depth phase information; the SNR was too small at WRA to use first motion information, but at YKA negative first motion was observed. The ISC depth estimation was given as 33 km (an arbitrarily selected depth when the solution does not converge), so this event remains unidentified.

5.7 19 June 1966; 04 12 12.5; m_b 3.7; Yugoslavia

This was detected only at EKA and gave a very complex, low SNR seismogram. The ISC gave this event a depth of 11 km. In view of its very low magnitude it is not surprising that surface waves were not recorded from this event. Little more can be said of this event and it remains unidentified.

5.8 19 August 1966; 03 53 01.4; m_b 4.6; East Kazakh

This event was located within the known underground explosion test site at Kazakh.

The P waves were detected at the four array stations and were all very simple with positive first motion. By comparison with well recorded explosions in this area this event is classed as an explosion.

5.9 7 September 1966; 03 51 58.1; m_b 4.8; East Kazakh

This was located within the Kazakh test site region. The P waves were recorded at three arrays; GBA was non-operational at the time of this event. The direction of first motion is positive at the 3 arrays for which P wave data are available. By comparison with previous events from this area this event is classed as an explosion.

5.10 3 December 1966; 05 01 54.5; m_b 4.9; East Kazakh

This was recorded at all four arrays; the records were fairly simple but the SNR was not good, making it difficult to determine first motion. From its location within the test site region this event is again presumed to be an explosion.

5.11 21 October 1966; 04 59 59.1; m_b 4.7; Alma Ata

This event is known to be two large chemical explosions fired within 3 seconds of each other for earth moving in dam construction. Information concerning the source parameters are given in the paper by Aptikayev. These explosions are the subject of an AWRE Report [5].

5.12 22 April 1966; 02 58 03.6; m_b 4.4; Caspian Sea

This event was located in an aseismic area of the USSR. No LP film chips were available for this event but several features, eg, simple P, compressional first motion and frequency content, arouse suspicions that this was an explosion. By comparison with later explosions from this location this event is presumed to be an explosion.

5.13 Summary of unidentified events

Of the total of 12 events for which surface waves were not detected, 5 are classified as earthquakes and 5 as explosions; the remaining two events are unidentified. The classification expressed in these cases is not so much "identification" as a "guess" based on location, origin time and spectral content of the P wave train. These events are generally of small magnitude and highlight the fact that there is a significant difference between detection and identification levels, and that the lower the detection level the greater will be the chance of having a residual of unidentified events.

6. AN EXPLOSION OF SPECIAL INTEREST

With one exception, table 1 is a summary of all identified or presumed explosions found during this study. The explosion which took place on the 30 September 1966 in the Bukhara region of the USSR is not included, and this event is discussed in more detail.

In the last paragraph of section 4.2 it was stated that open circles in figure 1 are identified as earthquakes. There is one open circle with a cross in it which is known to be an explosion [6] but fails the m_b:M_s discrimination test; this is the event of 30 September 1966 in the Bukhara region of Turkmen USSR. This explosion was not included in the

TABLE 1

Explosions Identified on m_b:M_s Criterion

Date	Origin Time	Location	m_b	M_s
24.12.65	0500	RTS*	4.94	2.84
13. 2.66	0458	RTS	6.40	4.38
20. 3.66	0550	RTS	6.16	4.00
21. 4.66	0358	RTS	5.45	3.46
7. 5.66	0358	RTS	4.71	2.80
29. 6.66	0658	RTS	5.64	3.70
21. 7.66	0358	RTS	5.58	3.56
5. 8.66	0358	RTS	5.60	3.60
19.10.66	0358	RTS	5.85	3.80
27.10.66	0352	NZ*	(Ov)	4.76
17.12.66	0458	NZ	5.95	4.00
		Unidentified Events: Presumed Explosions		
22. 4.66	0258	Caspian Sea	4.4	-
19. 8.66	0353	RTS	4.55	-
3.12.66	0502	RTS	4.9	-
		Known Explosions in the USSR		
30. 9.66	0600	Bukhara	5.16	3.79
21.10.66	0500	Alma Ata	4.70	-

* RTS Russian Test Site - Kazakh

NZ Novaya Zemlya

results presented at SIPRI as it was not reported in the USCGS PDE cards or monthly summary list. However, it was reported in the USCGS Seismological Bulletin published in 1969 and in the ISC Bulletin.

The four array records of the event were processed and m_b measured; LP film chips were available. As seen in figure 1 this explosion falls on the edge of the earthquake population and could be classed as an earthquake. Further analyses of this event showed compressive first motions at all arrays, a Rayleigh wave spectrum having a large high frequency content and a negative depth of focus from P waves (therefore arbitrarily assigned a depth of 33 km by the ISC). The seismograms were also processed using the spike filter technique [7] which showed a compressive P pulse followed by pP giving a depth of focus of 1.5 km. Although discrimination on m_b:M_s failed for this explosion the other criteria indicate that in all probability this event was an explosion. Furthermore, if the Marshall and Basham [2] corrections are made to the Rayleigh wave amplitudes and plotted on their suite of m_b:M_s data, this event falls within the explosion m_b:M_s population.

Nonetheless, this explosion was one of the first to illustrate the kind of problem which might face the m_b:M_s criterion. It also raised the question of whether or not conditions giving rise to the seismic effects could be employed as a method for giving an explosion the appearance of an earthquake for the purpose of evading a CTB.

One other interesting observation concerned with this explosion is that Soviet seismological observatories published its P wave arrival data. This is the only explosion in the USSR for which this has happened.

7. GENERAL OBSERVATIONS

The depth of focus is a particularly useful parameter in identifying earthquakes and reducing the amount of data which must be screened in discrimination studies.

Aside from the cautionary note sounded in section 6, the criterion based on surface wave:body wave energy ratios (m_b:M_s) is a successful discriminant.

There is difficulty in detecting surface waves from events in the Kurile-Kamchatka region. This is mainly due to station distribution and to low magnification of the wide band WWSSN LP seismographs determined by the oceanic microseisms. However, depth phases are recorded from almost all of the events from this area by the WRA array and most events can be classed as earthquakes by their depth. The greater than normal depth of these events is another reason why the surface waves are not easily detected.

An area which could present difficulties in discrimination is that surrounding the Himalayan Mountains - Tibet and Tadzhikstan for example. In Takzhikstan P waves propagating northwards travel away from the source beneath the undisturbed "shield" of the USSR and are detected at great distances with large amplitude, whereas the surface waves, for which the nearer stations to the south of the Himalayas are relied upon

for detections, are scattered and attenuated by the deep going structure of the mountain ranges. The effect is to give earthquakes the appearance of explosions perhaps leading to false identification of the nature of the source. However, use of first motion and depth phases observed from these events are particularly useful in classifying them as earthquakes. The seismic wave-forms from events in these areas have been studied by Douglas et al. [8] and criteria for their discrimination are presented.

8. ACKNOWLEDGMENTS

In the preparation of this report almost every member of the Seismological Research Group at AWRE has been involved in some way, either processing the data or analysing the processed seismograms. Data from the overseas arrays were provided through the co-operation of the Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa, Canada; the Bhabha Atomic Research Centre, Trombay, India; and the Department of Geophysics and Geochemistry, Research School of Physical Sciences, Australian National University, Canberra, Australia. We thank all concerned for making possible the data of high quality on which the analyses reported here have been based.

APPENDIX A

AVERAGE ARRAY MAGNITUDE COMPARED WITH m_b CGS

The magnitude of an event published by the USCGS is determined by averaging the reported magnitudes. The stations which report magnitudes are widely scattered and do not form a regular network. The four arrays comprise a small, but well sited, network and because the m_b measurements were made by one observer, they have been used to provide an average magnitude in preference to the USCGS data. A comparison is made between the average array magnitude and the USCGS magnitude for an event. Using a two error regression analysis and assuming a standard error of 0.25 in each determination the relationship between USCGS and array magnitudes is given by the equation

$$m_b = (0.94 \pm 0.05)m_{CGS} + (0.13 \pm 4.0).$$

This shows that at the higher magnitudes the four arrays give a slightly lower average m_b than the USCGS.

Only earthquakes were used to determine the above relationship but, as is seen in figure 2, the explosions tend to give slightly larger magnitudes at the arrays than the USCGS. This is probably caused by the differences in bandwidths of the recording systems.

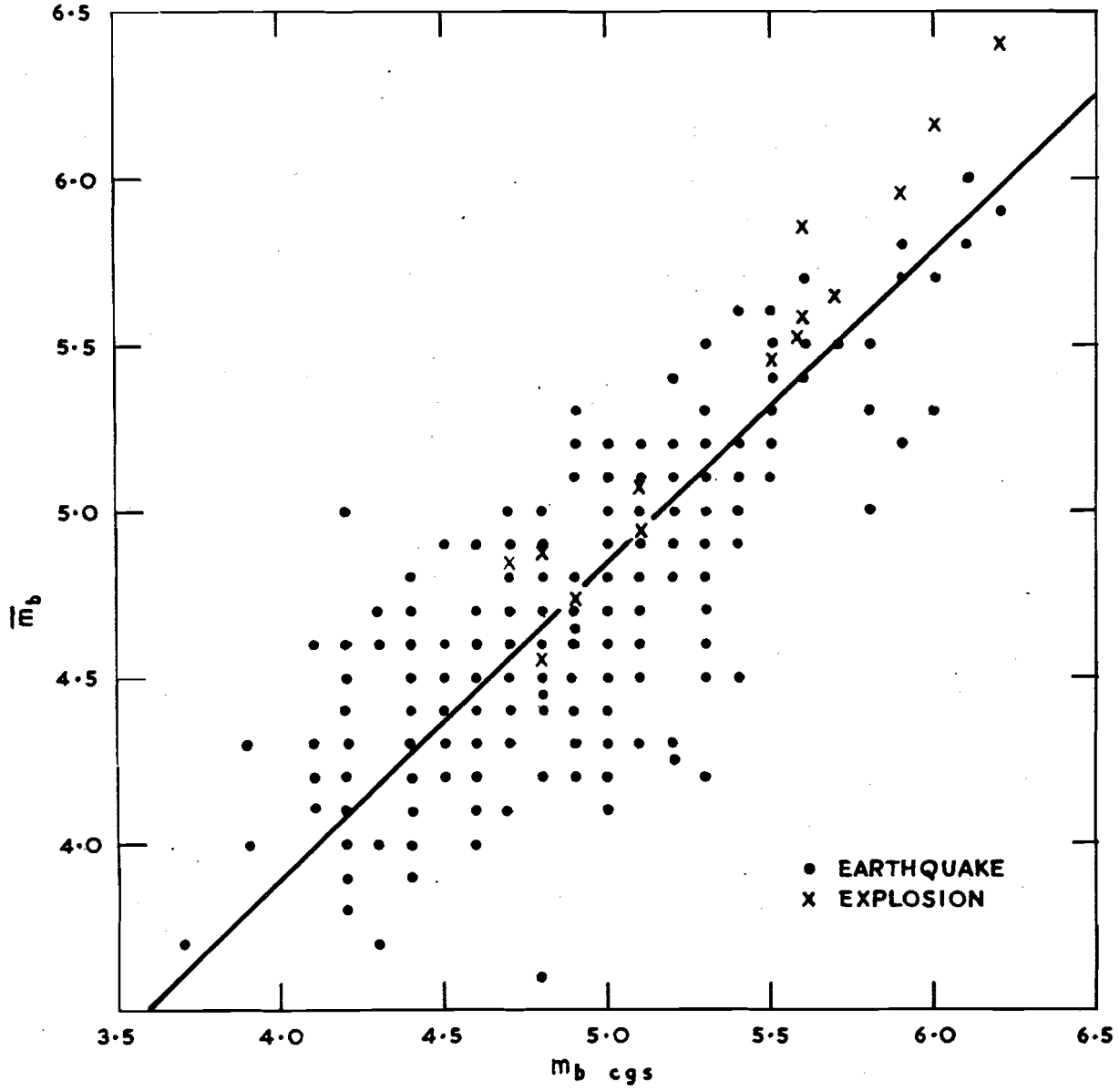

FIGURE 2. ARRAY $\overline{m}_b$ AGAINST m_b c.g.s.

APPENDIX B

SHORT PERIOD SEISMIC ARRAY

A description of the SP array recording system is given by Keen et al. [9]. A copy of every magnetic tape produced by an array is sent to UKAEA, Blacknest for processing and analysis. At the time the analysis described here was made the standard processing of the 20 element array data was displayed on an eight channel pen recorder. The description of each channel is given below.

Channel	Output
1	Single seismometer filtered 1 - 2 Hz.
2	ΣALL unfiltered. This is the delayed and summed output of the array; best beam.
3	As for channel 2 filtered ½ - 4 Hz broad band.
4	As for channel 2 filtered 1 - 2 Hz high frequency.
5	As for channel 2 filtered ½ - 1 Hz low frequency.
6	Summed red arm × summed blue arm. The cross product channel. Filtered 1 - 2 Hz.
7	As for channel 6 filtered ½ - 1 Hz.
8	Smoothed product channel 1 - 2 Hz.
Time	

An example of the array processing described above is given in figure 3.

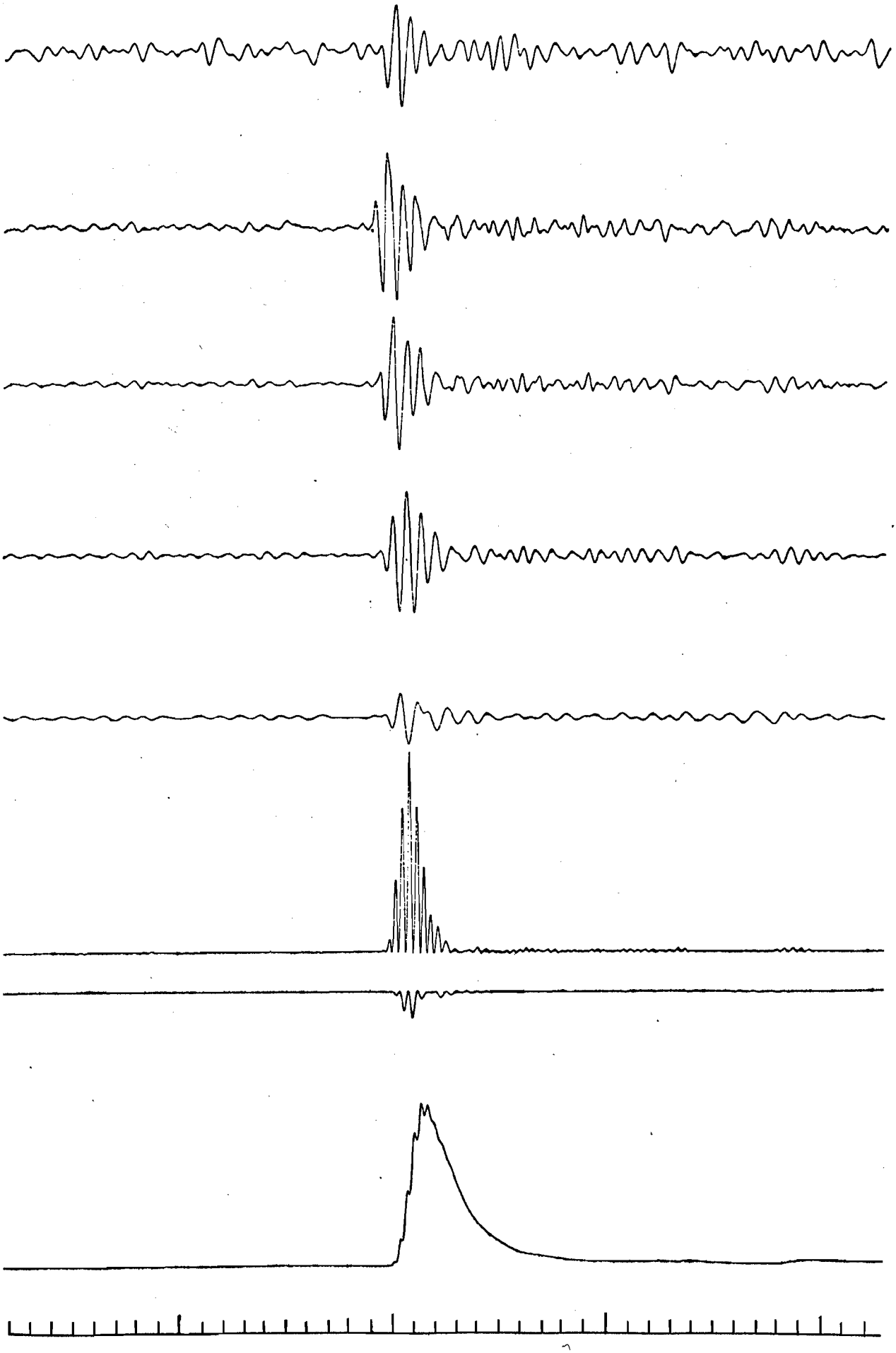

FIGURE 3. TYPICAL PROCESSED P WAVE RECORD

APPENDIX C

SURFACE WAVE ATTENUATION

During this study it was noticed that there was a general tendency for the surface wave magnitude of an event in the Sino-Soviet region to increase with distance. The distance normalising term used in the magnitude formula obviously does not strictly apply for events travelling across the USSR. To remove this problem and make M_s constant over a large distance range it is suggested that the distance terms given in table 2 will give more consistent answers than Gutenberg's $B(\Delta)$ term.

TABLE 2

Preferred Distance Normalising Term for M_s Determination for Trans-Eurasian Transmission Paths

$\Delta°$	$B(\Delta)$	$\Delta°$	$B(\Delta)$
10	1.02	55	1.66
15	1.15	60	1.71
20	1.25	65	1.76
25	1.34	70	1.79
30	1.41	75	1.83
35	1.46	80	1.86
40	1.51	85	1.89
45	1.57	90	1.92
50	1.62		

APPENDIX D

SEISMIC STATIONS USED IN THE ANALYSIS

D1. SHORT PERIOD STATIONS

Four UKAEA type arrays [8] situated at:-

EKA Eskdalemuir, Scotland.

YKA Yellowknife, Canada.

GBA Gauribidanur, India.

WRA Warramunga, Australia.

D2. LONG PERIOD STATIONS

CHG Chiengmai, Thailand.

COL College, Alaska.

MAT Matsushiro, Japan.

MSH Meshed, Iran.

NDI New Delhi, India.

NHA Nhatrang, South Vietnam.

QUE Quetta, Pakistan.

SEO Seoul, Korea.

SHI Shiraz, Iran.

SHL Shillong, India.

TAB Tabiz, Iran.

APPENDIX E

SIGNAL TO NOISE RATIO

The signal to noise ratio for each P wave detected is estimated by dividing the amplitude of the signal by the amplitude of the noise with the same apparent frequency in the preceding 30 seconds. This measurement is made on the summed array output trace filtered in the band $\frac{1}{2}$ - 4 Hz.

The signal to noise ratio for each event at each array is shown as a function of magnitude in figures 4 to 7. It can be seen that at each array the signal to noise ratio increases as a function of magnitude but the scatter is large. No attempt has been made to predict the probability of an event having a particular signal to noise ratio. Signals of equal amplitude to the background noise can be detected by means of their frequency content.

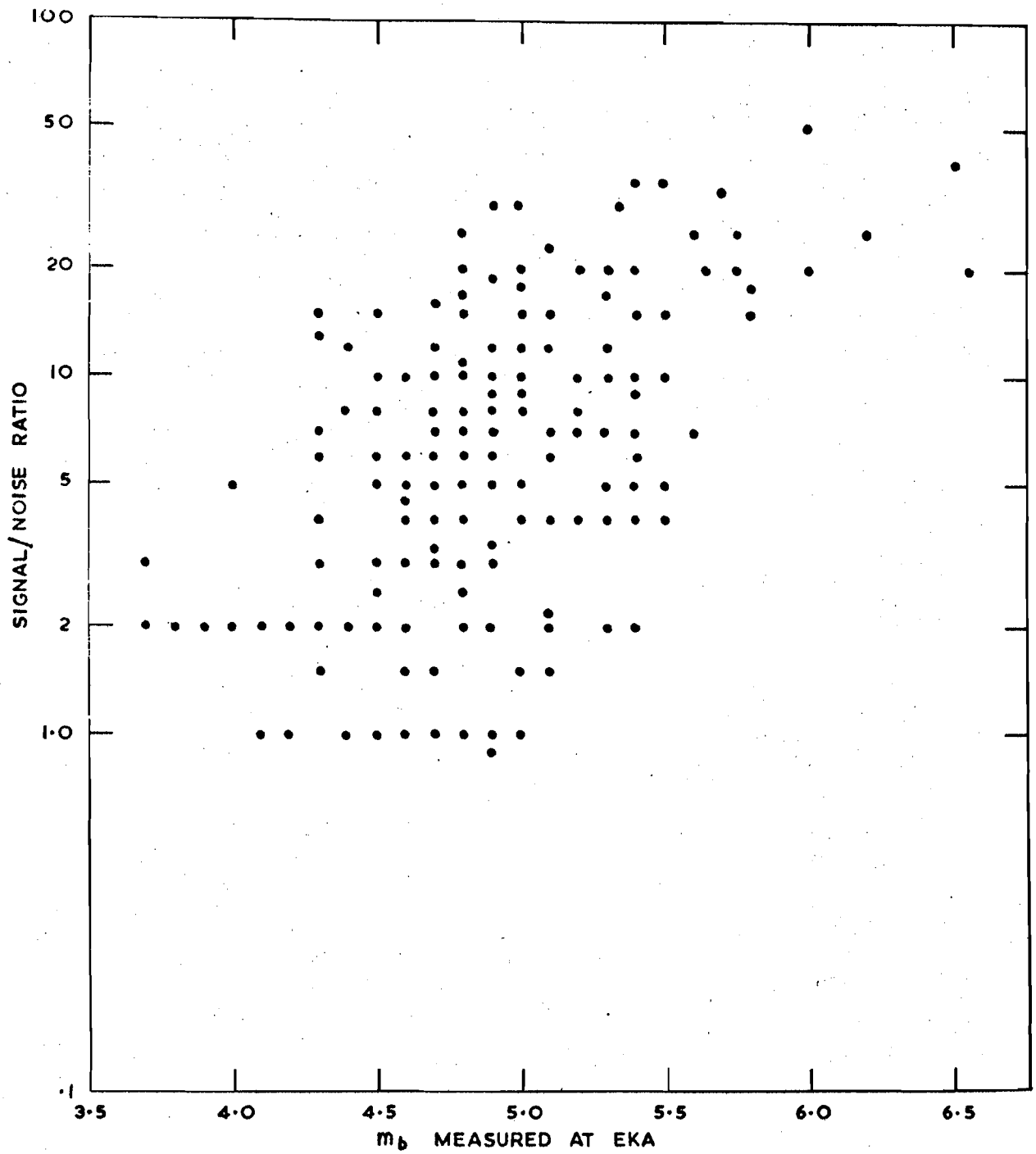

FIGURE 4. SIGNAL TO NOISE RATIO AS A FUNCTION OF MAGNITUDE AT EKA

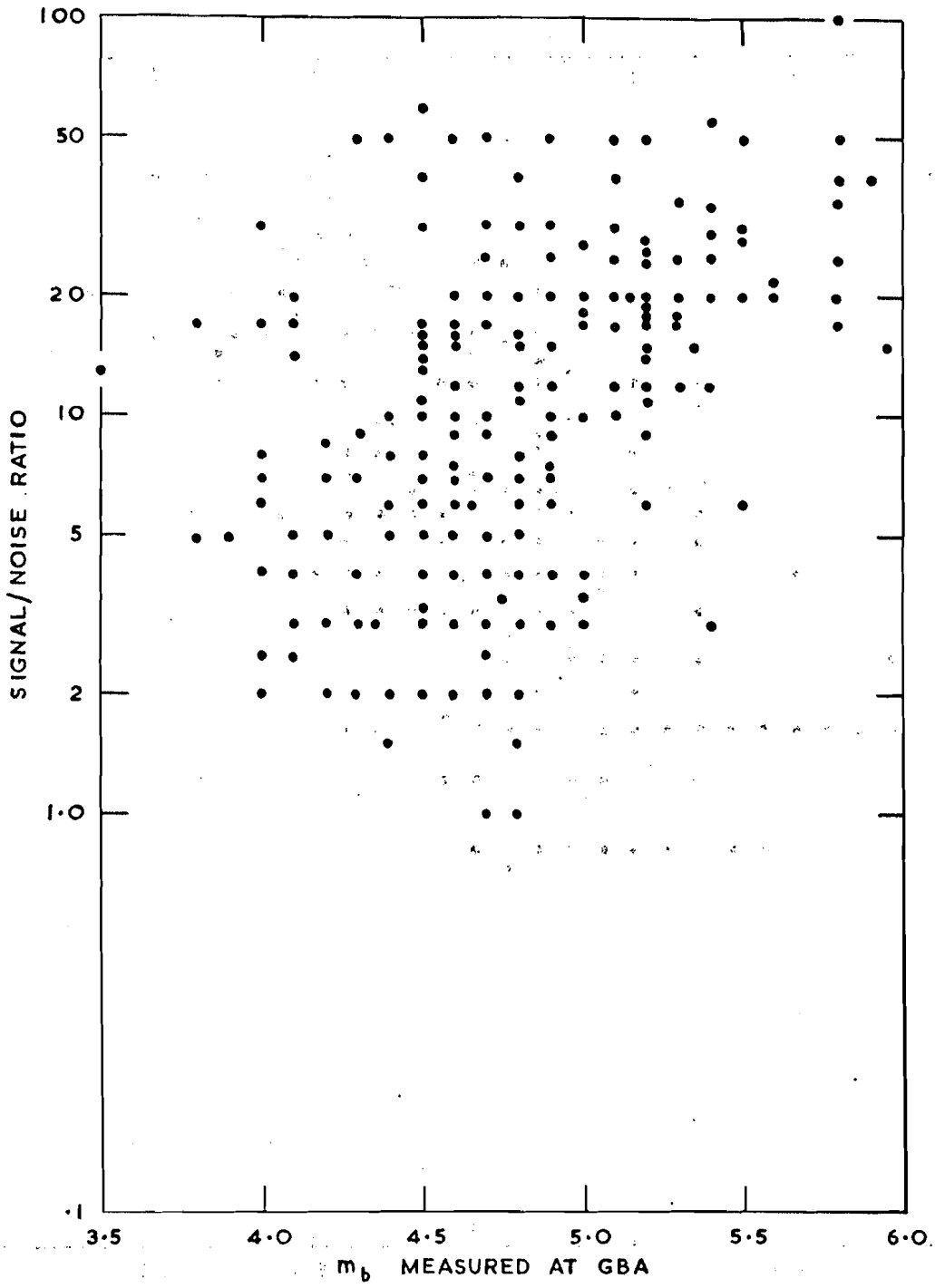

FIGURE 5. SIGNAL TO NOISE RATIO AS A FUNCTION OF MAGNITUDE AT GBA

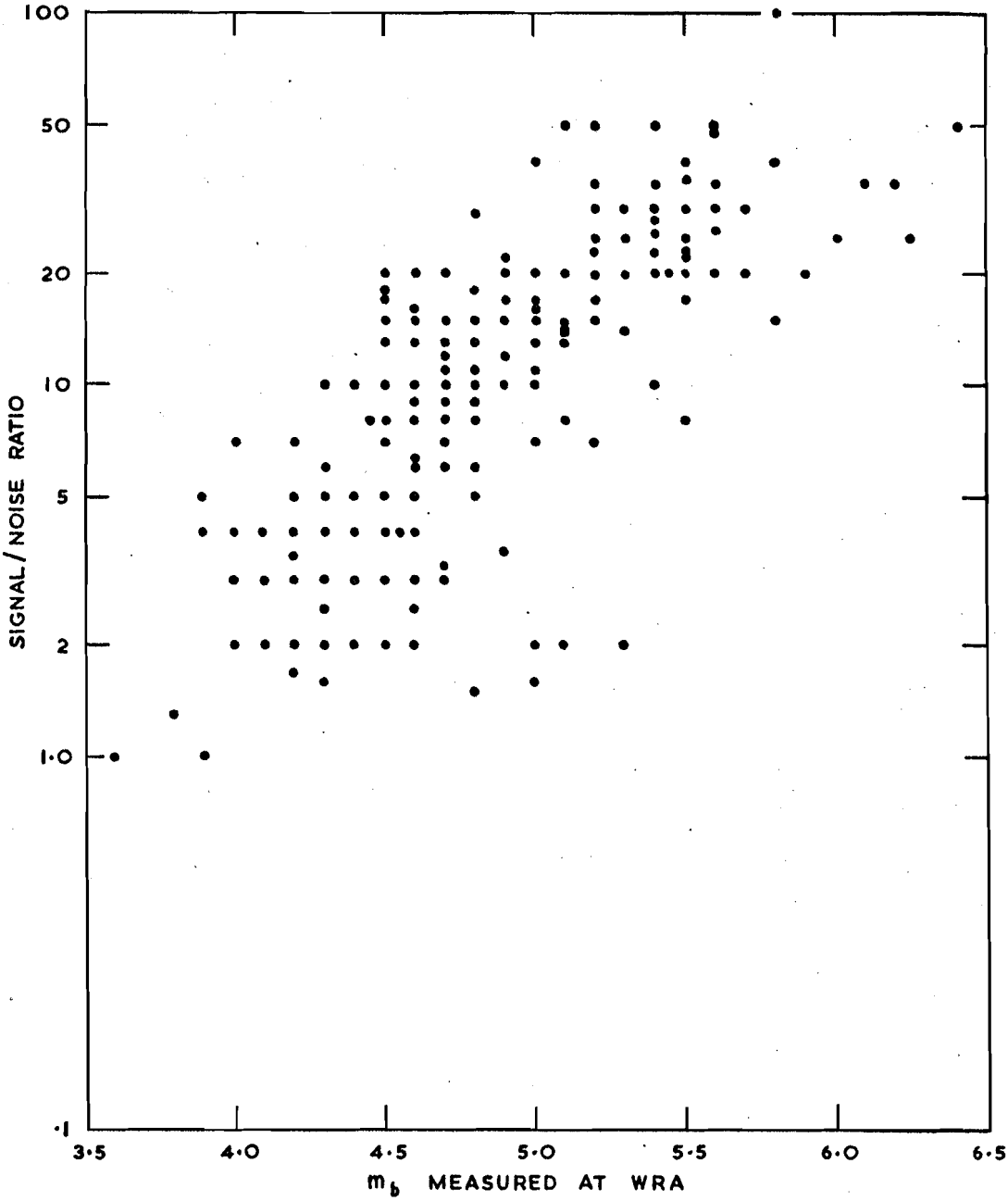

FIGURE 6. SIGNAL TO NOISE RATIO AS A FUNCTION OF MAGNITUDE OBSERVED AT WRA

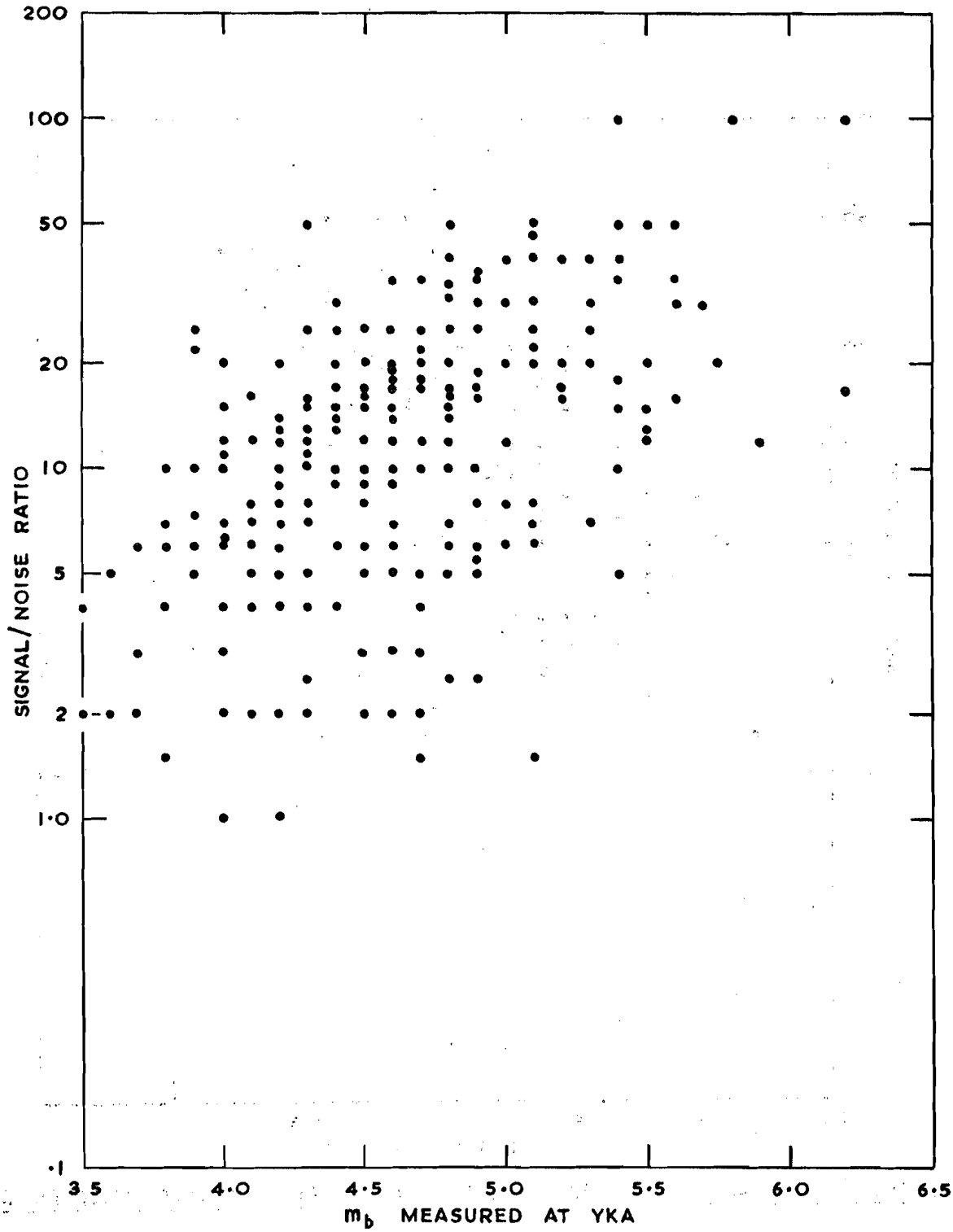

FIGURE 7. SIGNAL TO NOISE RATIO AS A FUNCTION OF MAGNITUDE AT YKA

APPENDIX F

ENERGY RATIOS AND MAGNITUDE

The energy ratio measured for each event recorded at a station is plotted against the station magnitude for each array in figures 8 - 11. The explosions, identified on m_b:M_s criterion, are indicated by the open circles. These plots demonstrate the limited value of complexity in discrimination studies. To test the effectiveness of combining the output of the four arrays, the complexity at each station for a particular event has been averaged and plotted against average array magnitude. This is illustrated in figure 12. The separation between the earthquake and explosion populations is enhanced but is still not very effective. Thus, complexity is used as a diagnostic aid rather than a discriminant.

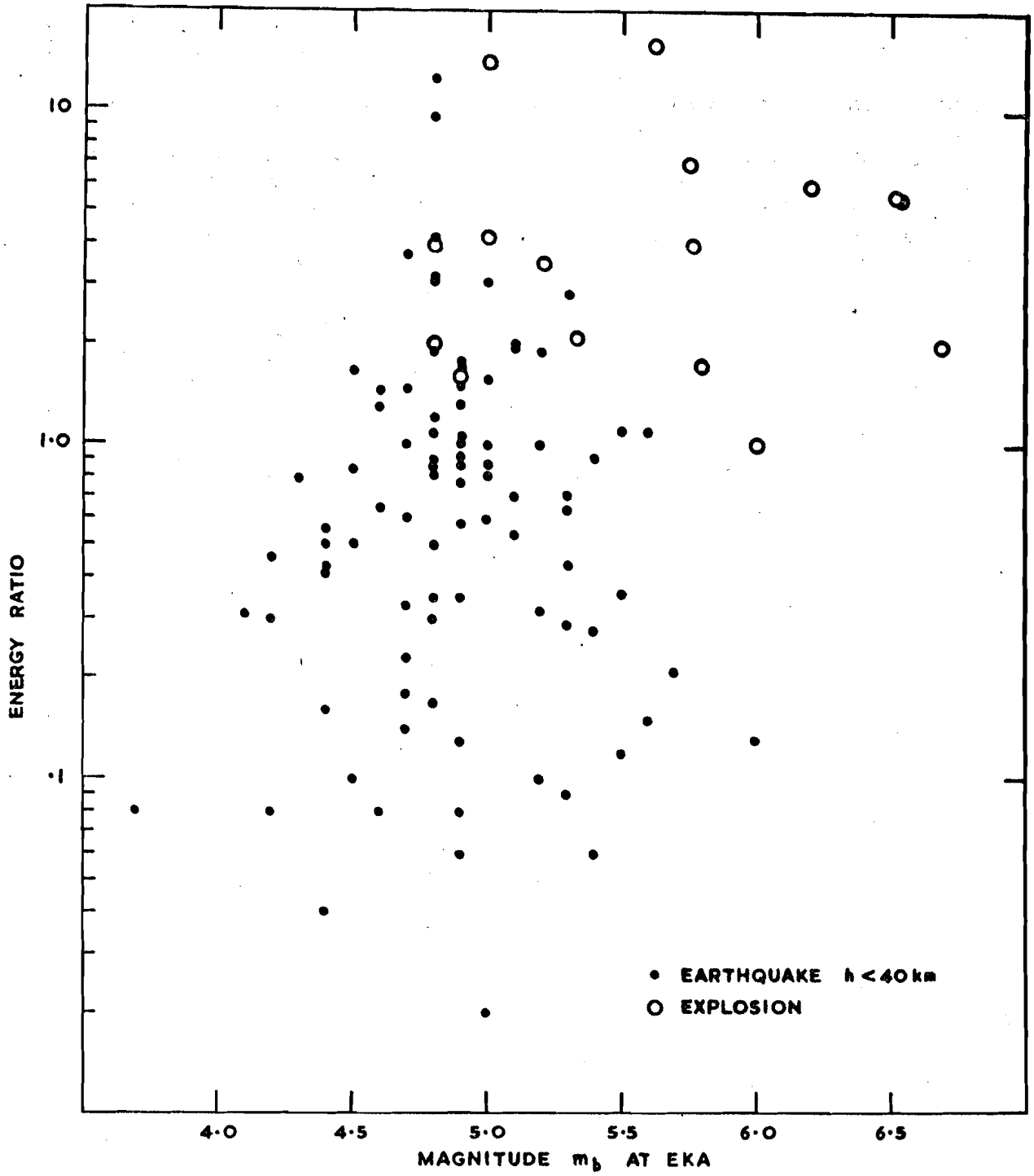

FIGURE 8. ENERGY RATIO AS A FUNCTION OF MAGNITUDE AT EKA

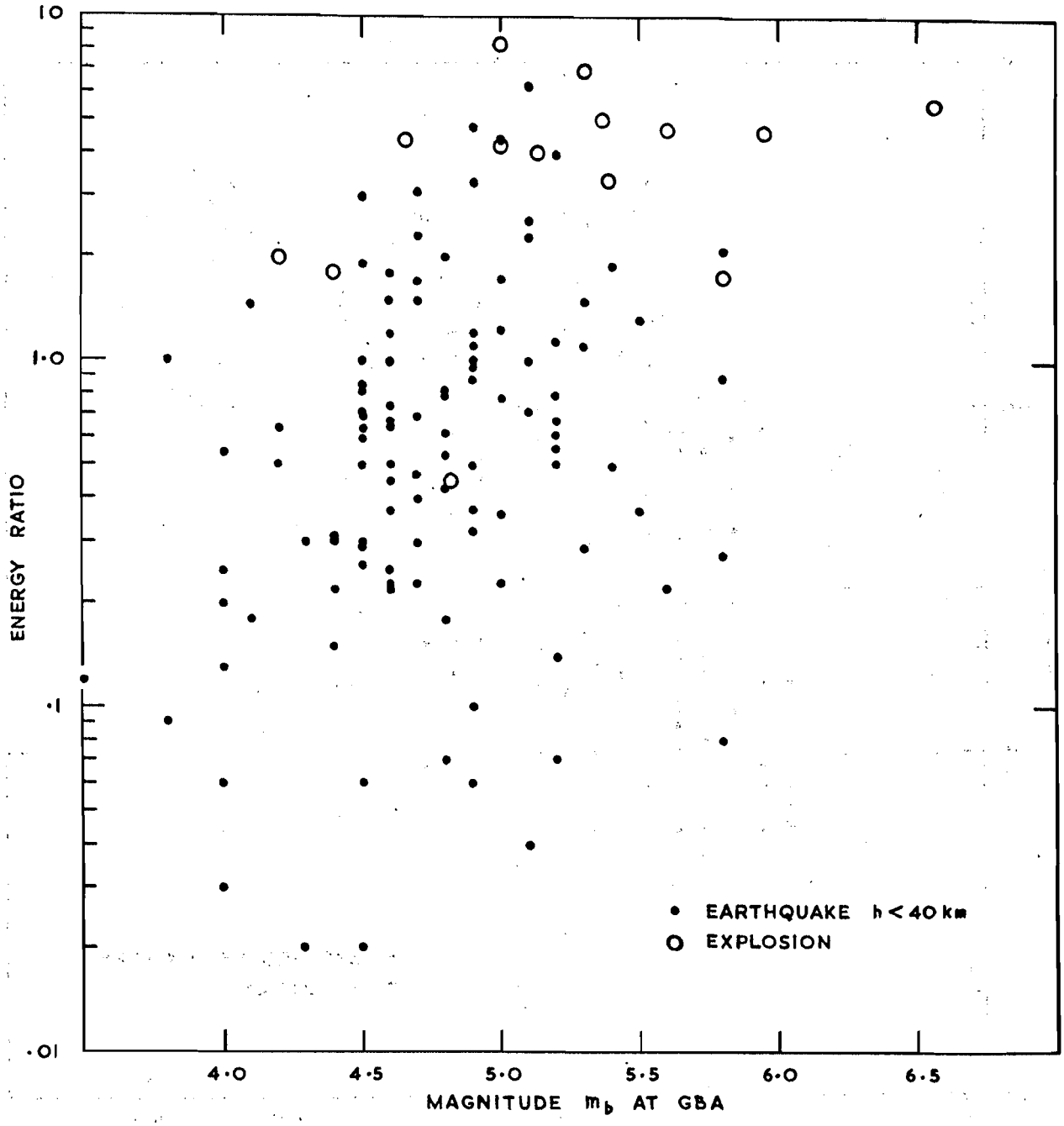

FIGURE 9. ENERGY RATIO AS A FUNCTION OF MAGNITUDE AT GBA

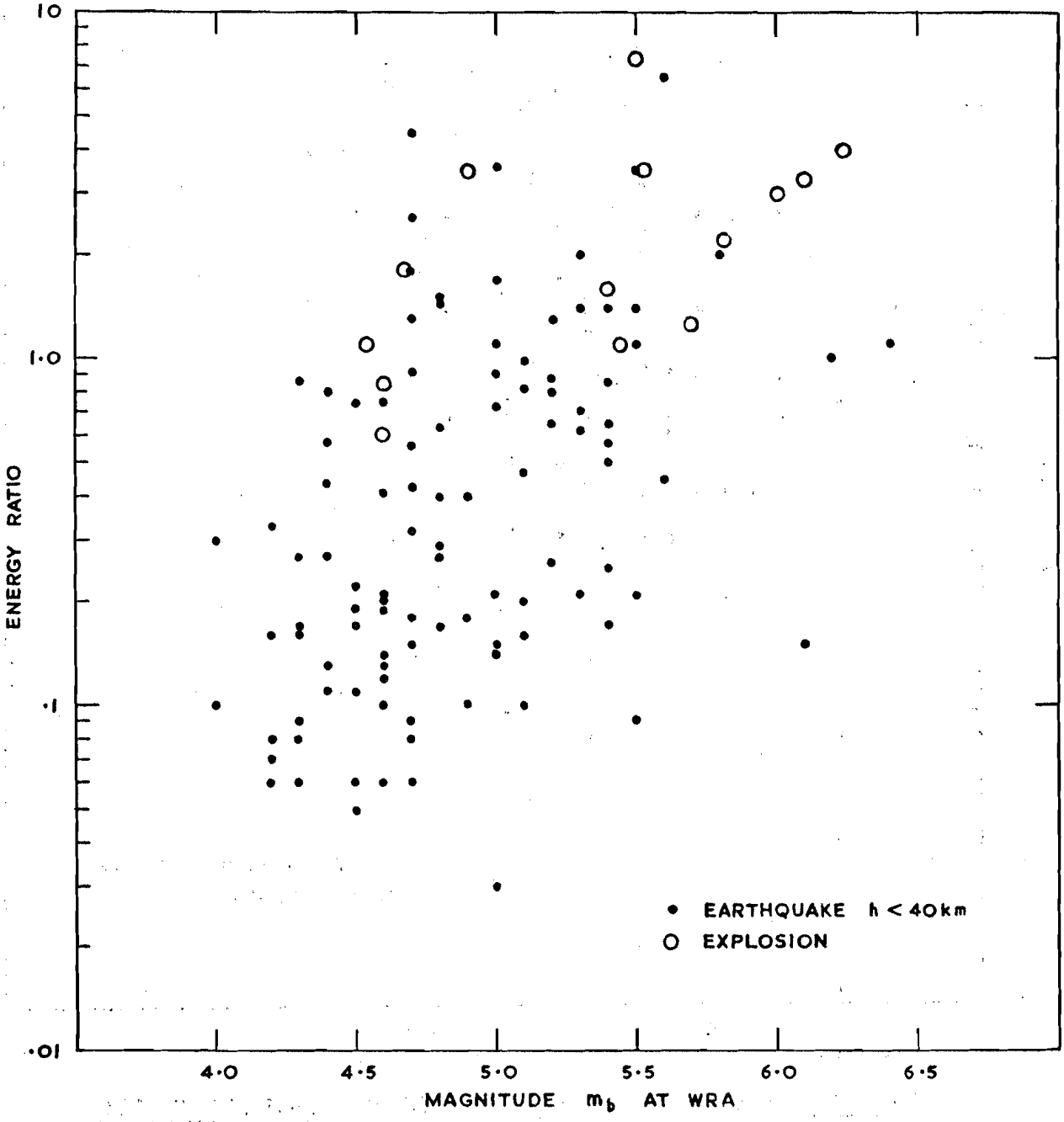

FIGURE 10. ENERGY RATIO AS A FUNCTION OF MAGNITUDE AT WRA

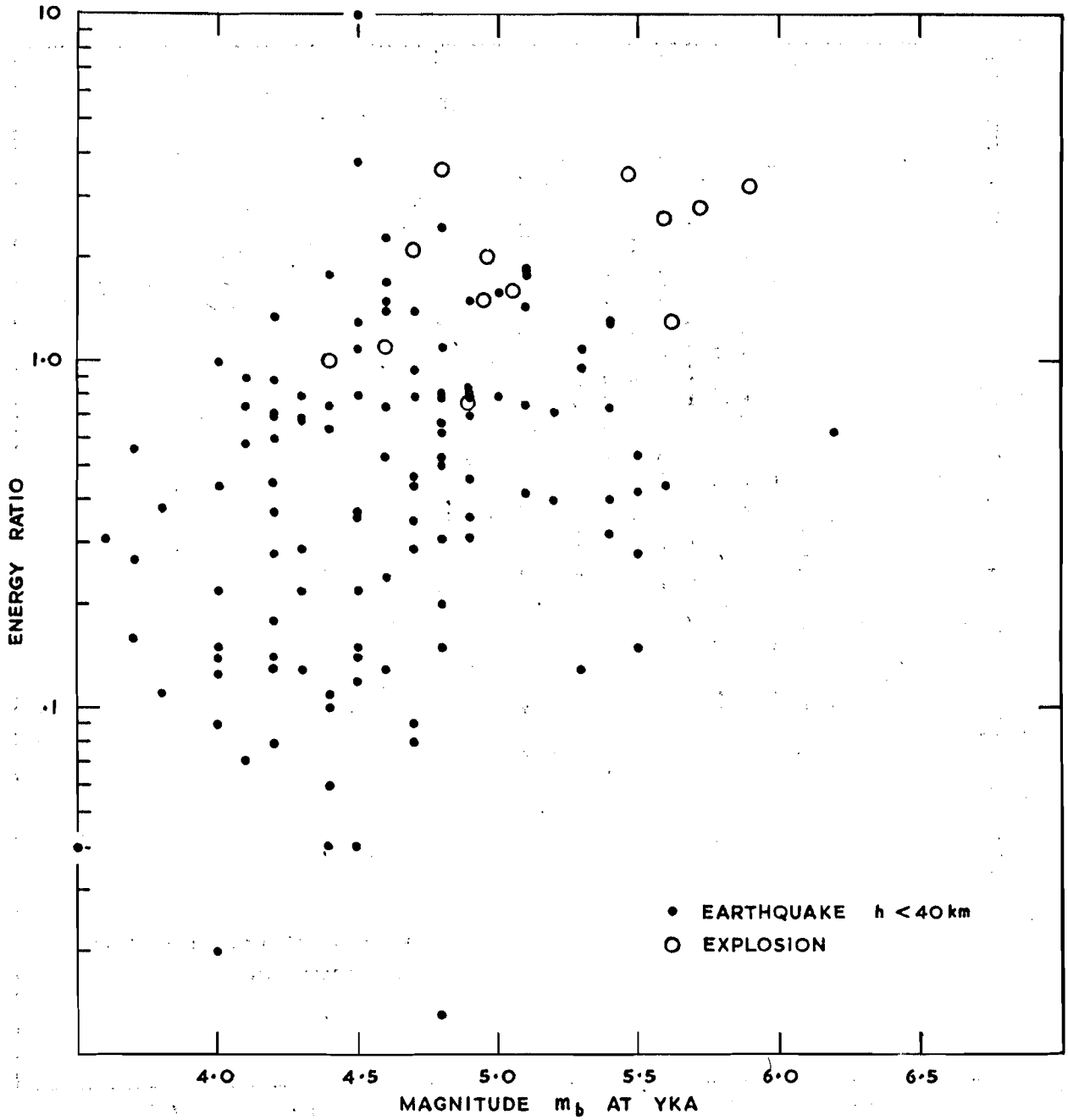

FIGURE 11. ENERGY RATIO AS A FUNCTION OF MAGNITUDE AT YKA

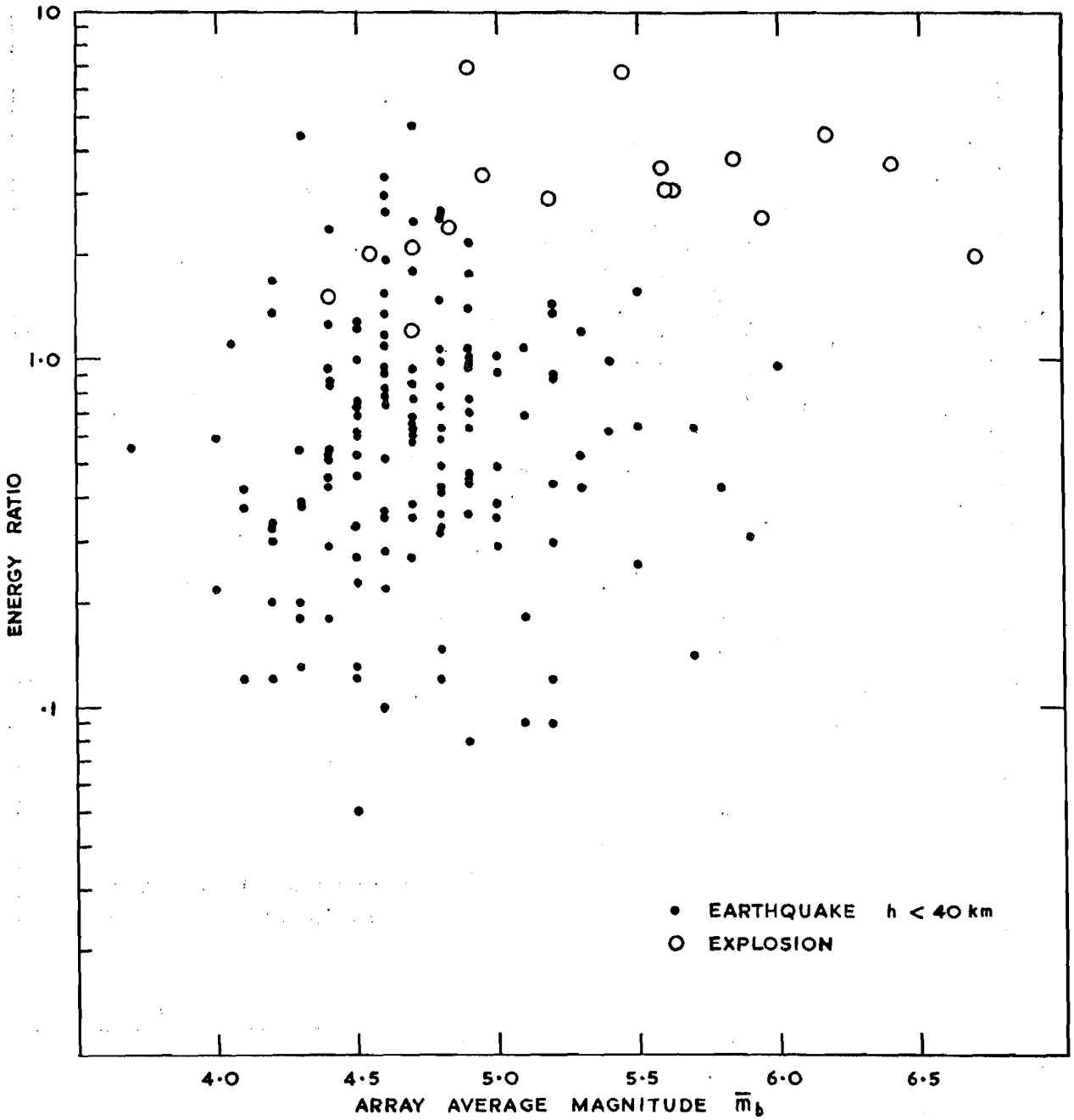

FIGURE 12. m_b AVERAGE FOR ALL ARRAYS v's E.R. AVERAGE FOR ALL ARRAYS

APPENDIX G

NATURAL FREQUENCY OF OCCURRENCE

The total number of events recorded by the USCGS as a function of magnitude has been plotted in the cumulative curve given in figure 13. This curve is for events at all depths and gives a 90% detection level of 4.9. Extrapolating to m_b 3.5 implies that there may be some 7000 events per annum in this area above magnitude 3.5. Thus, a well sited array station may expect to record about 20 events per day which would require processing.

This figure would diminish if a central data processing facility received accurate P wave arrival times from a network of stations and was able to estimate the depth with reasonable accuracy. If it were possible to remove some events quickly as being deep and not explosions this would cut down the amount of processing required for discrimination studies.

In the study reported here events with a depth greater than 40 km have been rejected and the cumulative plot for the residual events is given in figure 14. Note the slope is virtually the same but extrapolating back to m_b 3.5 we find only 2500 events per annum occurring above this magnitude and depth of 40 km. Thus, an average of 7 "shallow" events per day would be recorded.

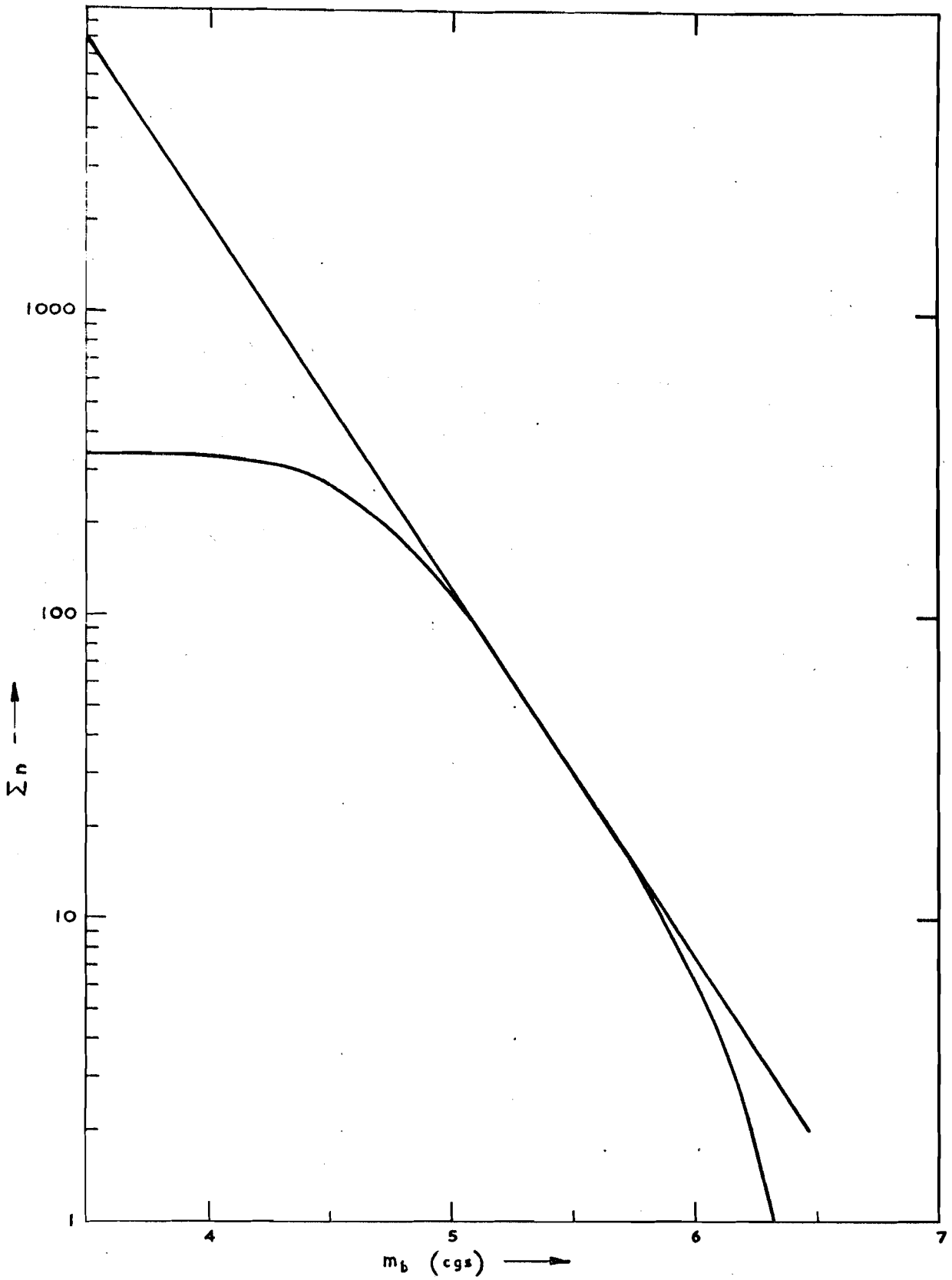

FIGURE 13. CUMULATIVE PLOT OF EARTHQUAKES AT ALL DEPTHS versus MAGNITUDE

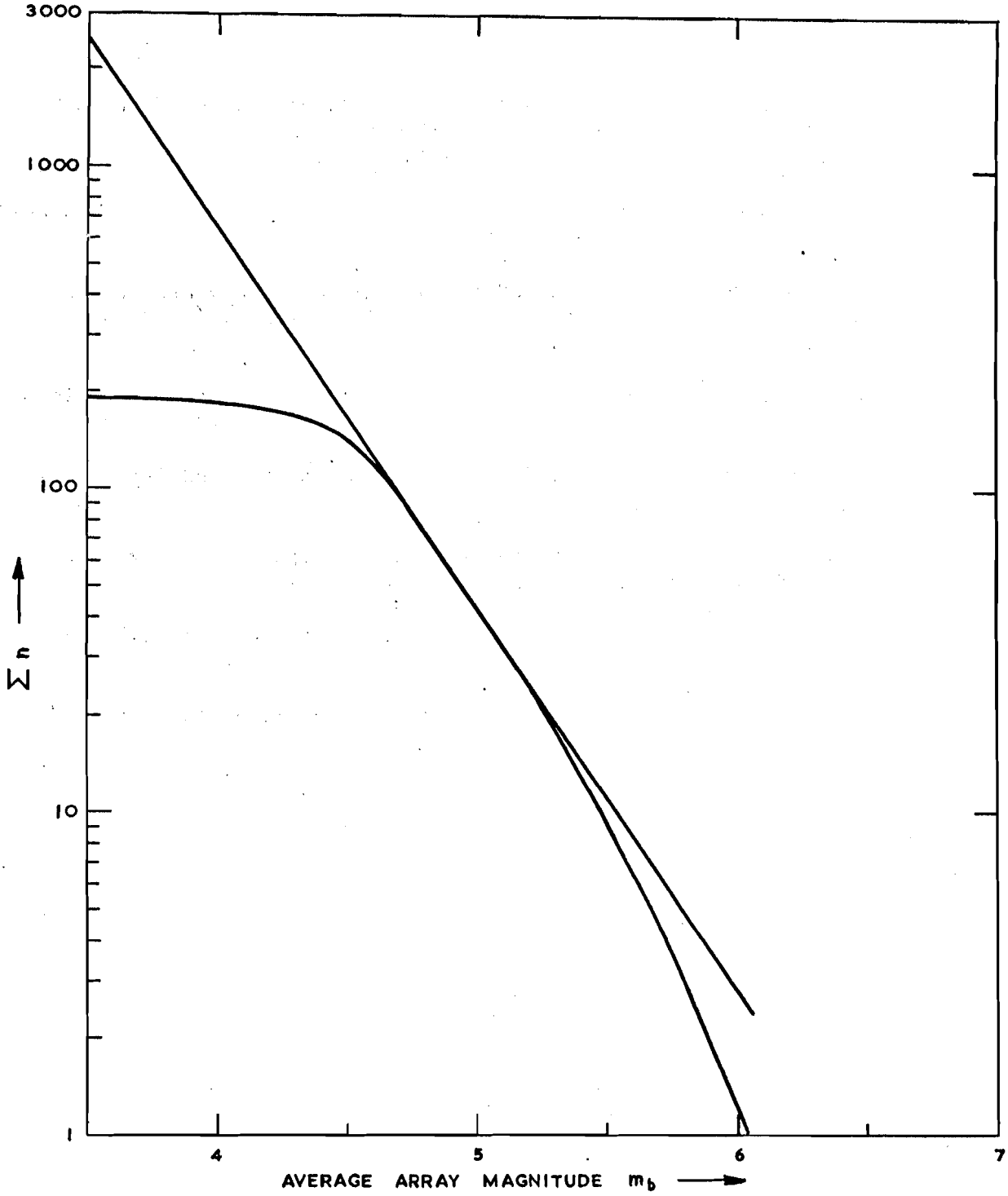

FIGURE 14. CUMULATIVE PLOT OF EARTHQUAKES versus MAGNITUDE
EARTHQUAKES < 40 kms

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