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seismological detection and identification of underground nuclear explosions

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Contents

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An assessment of world-wide seismological capabilities in detecting and identifying underground nuclear explosions based on information submitted by co-operating countries in accordance with the United Nations General Assembly Resolution 2604A (XXIV).

Évaluation à l'échelle mondiale des possibilités de détection et d'identification des explosions nucléaires souterraines fondée sur les renseignements fournis par les pays participants conformément à la résolution 2604A (XXIV) de l'Assemblée générale des Nations Unies.

Preface

As a first step in clarifying what seismological resources would be available for world-wide exchange purposes to facilitate a comprehensive test ban prohibiting underground nuclear explosions, Canada proposed a resolution asking the Secretary-General of the United Nations to circulate to governments a request that they supply information concerning seismograph stations from which they would be prepared to supply records on the basis of guaranteed availability. This resolution (2604A) was adopted at the 1836th plenary meeting of the Twenty-Fourth United Nations General Assembly on December 16, 1969.

Following receipt by the Secretary-General of the solicited seismograph station summary information, the next logical step in clarification was an assessment of the significance of the guaranteed station data for purposes of detecting and identifying underground nuclear explosions. The Arms Control and Disarmament Division of the Department of External Affairs requested the Earth Physics Branch of the Department of Energy, Mines and Resources to prepare such a technical assessment. A preliminary assessment was completed and distributed at the Conference of the Committee on Disarmament (CCD) in early August 1970, prior to an informal meeting on August 12, 1970, of the CCD on a Comprehensive Test Ban. At the time of preparation of the preliminary assessment, the returns to the Secretary-General's questionnaire were incomplete, the assessment being made on the basis of returns from 54 countries, only 33 of which reported information concerning seismograph stations on their territory. The report for which this preface is being written is the final version of the assessment and is based on returns from 75 countries received by the Secretary-General to August 15, 1970, 45 of the countries reporting information on seismograph stations.

These assessments, both the preliminary and final versions, present conceptual seismological schemes whereby existing seismological facilities throughout the world are applied to a test ban situation. It is necessary in such a hypothetical study to neglect all feasibility problems and financial consequences, and to examine the theoretical capability without prejudice to the necessity or otherwise of implementing such a scheme in any test ban situation. In reality, however, the analysis attempts to answer the following question: for country A, an event is either known or reported or thought to have occurred at approximately a certain time in country B; using world-wide data guaranteed by governments, what is the possibility that country A can form an opinion as to whether the event took place, and whether it was an earthquake or an underground nuclear explosion, and how does this capability for country A deteriorate as the size of an underground explosion is reduced? To answer this question, there is a requirement only for availability on demand of a limited amount of seismological data for this ad hoc purpose. However, the analysis does attempt to answer the further question: if some agency, international or national, had access to the daily abstracted seismological data that is guaranteed, to what levels of earthquake magnitude or explosion yield could an event be determined to occur, to what levels could the event be identified as either an earthquake or an explosion, and to what accuracy could it be located?

In our assessment, country A and country B described above are entirely general. This approach could, of course, be extended in a variety of ways working from the world-wide ensemble of stations. If country A is concerned about the possibility of clandestine testing in countries B, C and D only, for example, the problem of the minimum additional information required to meet certain levels of guarantee is, in our opinion, solvable by similar analyses. The general problem we have studied is, in many ways, the most difficult. Another example of the application of such a dialectic approach would arise in considering the application of this analysis to "verification by challenge": the approach used allows calculation of the limits of the effectiveness of a refutation of a challenge by the provision of seismological information. Extension to stations not reported in the UN returns is, in principle, straightforward for country A with a country B, C, D problem, or for the general case.

It may be of value to explain here briefly how this final assessment differs in content and format from the preliminary analysis distributed and discussed in the CCD in August, 1970. The principal reason for preparing a second edition is to include in the analysis all seismograph station data received by the Secretary-General after completion of the earlier preliminary analysis. We have, in addition, made other changes, the most important of which are as follows.

(1) On the basis of new information received the effective sensitivities of two long period arrays have been increased.

(2) A more elegant method of defining detection probabilities of events on the basis of station sensitivities is employed.

(3) All global detection and identification capabilities are defined at the 90 per cent probability level.

(4) All formal calculations are made using conceptual global networks of fixed numbers of stations.

(5) Explosion thresholds are stated in both equivalent earthquake magnitudes and explosive yields.

(6) Additional published and unpublished research results are discussed.

This paper is long because we felt it important to describe unequivocally at each state in the developing theme exactly what assumptions are made, giving our rationale for them. We have, perforce, needed to make a number of scientific judgments at different points in the development, and these we have attempted to explain fully so that any of our colleagues who read this paper can more easily form their own professional judgment about them. In addition, in a serious attempt to make the scientific significance of this document understandable to readers outside the seismological community, we have judged it useful to labour some points that would be simply appreciated by seismologists. However, of necessity, the entire document is couched in seismological terminology. So that the results of the analysis may be more comprehensible to a wider audience of readers, we present here a brief, non-technical summary of the basic procedures and conclusions. To do so we must retain three basic seismological terms; these are: "magnitude" (m), the logarithmic scale that is employed to define the size of both earthquakes and underground explosions (the reader is referred to Table VIII in the text for an easily understood equivalence between m and explosion yield), "P wave", the first arriving seismic wave which propagates through the body of the earth, and "Rayleigh wave", the most important (in this study) seismic wave that propagates around the surface of the earth. The summary follows.

Using data quoted in the UN returns and published in the open literature, the capability of each conventional and array station is described in terms of its ability to detect P waves and Rayleigh waves as a function of distance from the event. All such stations are reduced to two conceptual global networks, one that is used for global P wave detection calculations and the other for global Rayleigh wave detection calculations. The basic formally calculated results are global contours of m values for which there will be a 90 per cent probability of detection, by a certain number of stations, of P waves and Rayleigh waves from earthquakes and explosions. These are defined as the *thresholds of detection.*

The detection thresholds are m4.2 for explosion and earthquake P waves in Europe and North America, deteriorating to m4.5 for Asian coverage and further to m5.0 in parts of the southern hemisphere (all capabilities are much poorer in the southern hemisphere and any further discussion of this half of the earth is omitted here). The thresholds are m4.8 for Rayleigh waves from earthquakes in North America and northern Europe, deteriorating to m5.1 for generally complete Asian coverage. The thresholds are one magnitude unit larger for Rayleigh waves from correspondingly located explosions. A number of important empirical results from the seismological literature are cited to illustrate that these formally calculated detection thresholds can be considered conservative.

The most generally applicable identification criterion, the relative excitation of P and Rayleigh waves, has a threshold of application equal to the threshold of detection of explosion Rayleigh waves, i.e., m5.8 – m6.0 in much of the northern hemisphere. This rather high explosion identification threshold can be reduced in a number of ways. (a) By employing special processing of Rayleigh wave data from one or two of the highest sensitivity stations, the average northern hemisphere threshold can be reduced to m5.6 – m5.8. (b) By taking advantage of highly efficient Rayleigh wave propagation over purely continental paths, the threshold has been reduced to m5.0 in North America, but an equal reduction remains unproven for other continental areas. (c) By employing identification criteria that rely only on P wave data, the criteria can, in theory, be applied near the lower P wave detection threshold. One such criterion is proven successful for one station-region combination at an identification threshold of m4.9; all other documented attempts have resulted in overlapping populations of earthquakes and explosions at all magnitudes. (d) By employing the absence of recorded waves, for example, long period Rayleigh waves, to identify explosions, on the basis that had the event concerned been an earthquake the waves in question would have been observed, the threshold of identification can be reduced. Illustrations are presented to show that existing thresholds can be reduced by m0.5 by accepting these criteria. (e) By employing more than one imperfect criterion, analyses can result in statistical probabilities (rather than certainty) that an event in question falls into an earthquake or explosion category.

A very brief and oversimplified summary of the results and conclusions of this assessment is that the global system of stations produces proven detection, location and identification of underground nuclear explosions down to yields of about 60 kilotons in hardrock in most of the northern hemisphere: the threshold is 10-20 kilotons for certain test sites only, and this lower threshold cannot be reached on a global basis with this ensemble of stations. We complete the study by making a number of recommendations, which, with very little financial commitment, will provide some basic data required to define existing capabilities better and that may significantly improve them.

The problems of evasion are not treated in great depth in this analysis. In principle, a potential violator of a Comprehensive Test Ban could attempt either to reduce the size of the seismic signals from a clandestine explosion of a given yield by suitable choice and artificial modification, if necessary, of the variables of the emplacement medium, or attempt to simulate an earthquake-like seismic signal by multiple firing techniques, or depend on major simultaneous natural earthquake signals to obscure the artificial event, or events, of interest. The advantages and disadvantages, limits of feasibility, etc., in these different techniques are not analyzed in this document, which treats all explosion yields in terms of their hardrock equivalents.

We are indebted to many colleagues, both in Canada and abroad, who, after a careful study of our preliminary assessment, have made valuable suggestions for improvements for incorporation in this final edition.

However, we accept sole responsibility for the interpretations we have placed on the data in the UN returns, and for the scientific contents and judgments contained in the paper.

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1. Introduction

1.1 The General Assembly resolution

At the Twenty-Fourth United Nations General Assembly, Canada proposed a resolution, 2604A, which was adopted at the 1836th plenary meeting on December 16, 1969, by a vote of 99 to 7, with 13 abstentions. In summary form, the resolution requested the United Nations Secretary-General tó circulate to governments a request that they supply information concerning seismological stations from which they would be prepared to supply records on the basis of guaranteed availability and to provide certain information about each of such stations. This resolution, which had been proposed and discussed in the Conference of the Committee on Disarmament (CCD) in Geneva in 1969, was designed to assist in clarifying what resources would be available for the eventual establishment of an effective world-wide exchange of seismological information which would facilitate the achievement of a comprehensive test ban.

Very simply, therefore, the aim of the resolution was to achieve a limited first step of clarification. This modest proposal is a first step in any process whereby seismology could assist in clarifying for national states the implications of the essentially political decision involved in any form of test ban treaty.

Pursuant to Resolution 2604A, the Secretary-General circulated on January 30, 1970, a note soliciting responses to the questionnaire appended to the resolution, which specified the details concerning conventional seismograph stations and array stations that governments were invited to submit to the Secretary-General.

At the time of preparation of this analysis of the returns, 75 countries had replied to the Secretary-General's note*: 45 countries reporting information for seismograph stations on their territory, 22 countries reporting no operational seismograph stations on their territory, and eight countries indicating that in their view the purposes of the resolution were unnecessary or preferring to maintain a voluntary form of seismological data exchange and including no data on seismograph stations in their returns. The national states in each of these categories are listed in Table I.

1.2 Usable data in the UN returns

For purposes of compiling this assessment, the authors examined all data in all returns submitted by countries listed in Table I(a). These included the summary documents, A/7967 to A/7967/Add.5, circulated by the Secretary-General, together with all additional diagrammatic and tabular data deposited in the archives of the United Nations.

The returns containing seismograph station data varied considerably in general format and in the form and contents of tabular and diagrammatic material. The data required for this study were for each seismograph station, the geographic co-ordinates, the magnification of any operational short-period vertical (SPZ) seismograph at a period of 1 second, and the magnification of any operational long-period vertical (LPZ) seismograph at a period of 15 or 20 seconds. Thus, we required, in addition to data on array stations (see section 2.2), the fundamental operating gain of all available vertical component seismographs which we have defined as "conventional".

A great variety of types of seismographs are in operation throughout the world and have been listed by the

Table I. Countries submitting returns in response to UN Secretary-General's questionnaire

(a) Countries reporting information for seismograph stations on their territory:

Australia, Austria, Belgium, Brazil, Canada, Ceylon, China, Colombia, Denmark, Ethiopia, Finland, Germany (Fed. Rep.), Greece, India, Indonesia, Iran, Ireland, Israel, Italy, Jamaica, Japan, Korea (Rep. of), Luxembourg, Madagascar, Malawi, Mexico, Monaco, Morocco, Netherlands, New Zealand, Norway, Pakistan, Philippines, Portugal, Spain, Sweden, Switzerland, Thailand, Turkey, United Arab Republic, United Kingdom, United States of America, Venezuela, Vietnam (Rep. of), Yugoslavia

(b) Countries reporting no operational seismograph stations on their territory:

Burundi, Cambodia, Cameroon, Costa Rica, Cyprus, Dahomey, Ghana, Guyana, Kuwait, Laos, Malaysia, Mali, Malta, Nauru, Niger, Nigeria, San Marino, Singapore, Sudan, Tanzania, Uganda, Zambia

(c) Countries replying to the circular of the Secretary-General preferring to retain a bilateral and voluntary form of seismological data exchange, and which so indicated in their UN return, including no data on seismograph stations:

Bulgaria, Byelorussian Soviet Socialist Republic, Czechoslovakia, Hungary, Mongolia, Romania, Ukrainian Soviet Socialist Republic, Union of Soviet Socialist Republics

host countries in their returns. The primary decision for inclusion of a particular seismograph station in this analysis rested in all cases on our ability to define from the information available the operational magnification at the required period. In numerous cases a secondary decision was made to exclude a particular station (which we choose to call a "special station"), if it was judged that the overall response characteristics were not suitable to general teleseismic recording of the short- and long-period seismic waves to be considered, or if, even though defined, the magnification at the required period was so low as to make a negligible contribution in the world-wide context. For example, in the former category high frequency microearthquake seismographs were excluded, and in the latter, low magnification "strong-motion" seismographs.

The selection of the stations to be included required considerable judgment. We are aware that either our ignorance concerning particular seismograph types or our misinterpretation of the available data may have contributed errors and omissions; we apologize at the outset to any country whose data may have been so treated.

1.3 Scope and purposes of present study

This study is made with the basic assumption that the identification of underground nuclear explosions as such is possible in principle for any event, provided that the seismic signals generated by it can be detected with a suitable signal-to-noise ratio at an appropriate number of stations at suitable distances. We largely neglect the possibility of seismic signals from an event of potential interest being obscured by a very large natural earthquake, although we dwell briefly on this subject in Chapter 6.

In Chapter 2, the information provided on the conventional and array seismograph stations is summarized. Chapter 3 outlines one method of reducing this heterogeneous information on station capabilities to obtain a single sensitivity parameter which can be applied in Chapters 4 and 5 to P wave and Rayleigh wave detection calculations. The total of 300 available independent seismograph stations is reduced for purposes of detection calculations to two conceptual world-wide networks, one for P wave detection calculations and the other for Rayleigh wave detection calculations. In choosing to define the world-wide capabilities of conceptual networks of stations rather than of isolated individual stations, or station sub-sets, we are assuming that, in an effective world-wide exchange of seismological information (of either an ad hoc or continuous nature), the combined seismological resources of all participating nations can, in theory, be applied to the problem at hand.

In Chapters 4 and 5, using an explicitly defined detection probability calculation, we present in terms of the P wave magnitude the capabilities of the

* This includes all returns available up to and including Document A/7967/Add.5. Numerous UN member countries remain which have submitted no return of any type (positive or negative) to the Secretary-General. Although it will be important to assess the significance of any late returns which may yet be received, based on other sources of information concerning world seismograph stations, we believe no late returns will contain station data which will significantly alter the conclusions of this assessment.

networks in detecting earthquake P and Rayleigh waves originating at any point on the earth. In Chapter 6 we present some illustrations of situations on the real earth which can alter the capabilities derived in the formal calculations; these include advantages gained from lateral inhomogeneities in the earth, special propagation paths, and special instrumental and signal processing capabilities, as well as disadvantages resulting from global seismicity patterns and interference effects. The general conclusion of Chapter 6 is that the formal calculations can be considered conservative.

Chapter 7 relates the results of Chapters 4 and 5 directly to the problem of the detection of underground explosions. To do so we characterize underground explosions as a fixed source of P wave energy, i.e., as equivalent P wave magnitude earthquakes. However, we do present all formal and empirical detection and identification thresholds for explosions in terms of both P wave magnitude and equivalent hardrock explosion yield.

Chapter 8 is a generalized discussion of the suite of possible identification criteria with particular reference to both published and unpublished results obtained from the data recorded at conventional and array stations included in the returns. The purposes are to define identification thresholds on the basis of the formal detection calculations and to clarify some of the interacting possibilities of improving the identification thresholds. These include the use of short-period discriminants which are intrinsically of great appeal, if they will work adequately, certain highly efficient Rayleigh wave propagation paths, where proven to occur, and the use of combinations of many imperfect discrimination criteria.

In the final chapter we give the specific and general conclusions that can be drawn from this study, and make some recommendations which, with a modest investment of effort and finances, can both better define and significantly improve earthquake-explosion discrimination capabilities.

2. Seismograph stations

2.1 Conventional stations

All seismograph stations for which the host country will guarantee access to seismological data, a total of 300 stations, are listed in Table II. The stations, each designated by its three-letter international code (ESSA, 1970a), are listed alphabetically by country, and within each country alphabetically by station code.

A conventional station is defined as one which, at a minimum, has either an SPZ seismograph with a known magnification at 1 second, or an LPZ seismograph with a known magnification near 20 seconds. An LPZ magnification quoted within the range 15-30 seconds is accepted. The remaining stations in Table II are either array stations (see section 2.2) or special stations (see section 1.2) which have a "YES" entered in the last column. Some of the conventional stations in Table II are listed as containing additional special seismographs. The magnifications in Table II are quoted in K (thousands).

2.2 Array stations

Seven SPZ arrays and five LPZ arrays considered in this study are listed in Tables III and IV, respectively. For an array station to be considered for our purposes as such, it must have three or more SPZ or LPZ sensors with an aperture adequate to produce a signal-to-noise improvement ideally equal to the square root of the number of sensors following delayed-sum signal processing, and have the sensors connected to a central location with either on-line or off-line (preferably digital) elementary delay-and-sum (phasing) facilities. Alternatively, the signal-to-noise gains from processing modes must have been published. Some of the array stations contain, or have associated with them, horizontal SP and LP seismographs; these are noted in the last column of Table III.

Four countries indicated possession of SPZ arrays which are not included as such in this study; these are listed in the lower part of Table III with the reason for omission stated in the "Comments" column.

3. Sensitivities of stations assumed in this study

3.1 SPZ conventional stations

Each country was asked to specify in its UN return the operational magnification of any reported short-period seismograph at a period of 1 second. These values, where available, are listed in Table II and are the only data, except for some special cases for which additional data has appeared in the literature, from which a judgment can be made of the operational sensitivities of the SPZ stations.

The standard short-period or hot-pen (helicorder) record or seismogram is normally of one-day duration with a speed of 60 mm per minute, 15 minutes of data per line, and thus 2.5 mm between adjacent lines. It is the usual practice to have the operational seismograph magnification set to yield a certain background noise amplitude appropriate to this trace spacing. In order to define the detection capabilities of the Stations, the basic assumption we have made is that the noise levels, and thus the operational magnifications, are such that a P wave signal will be identified on the records 50 per cent of the time if it reaches a trace amplitude of 1 mm. There are a number of known cases for which this assumption will yield conservative estimates of station sensitivities; Canadian stations, particularly, with which we are most familiar, will be discussed in section 6.2.

A further complication is that in the UN returns, there are also cases of stations where the quoted magnification is believed by us to be a maximum rather than the normal operational value; in these cases resulting sensitivities will be too large.

However, in order to proceed further, the 1 mm, 50 per cent signal detection assumption is applied to all stations without consideration of possible exceptions, and is believed to be realistic, if slightly conservative.

The formula relating P wave signal displacement with P wave magnitude is

$$m = \log(A/T) + Q(\Delta,h) \qquad \ldots . 1$$

where A is the vertical ground displacement in microns, T is the

Table II. World seismograph stations

	Latitude ° '	Longitude ° '	Country	SPZ Mag. (K)	LPZ Mag. (K)	Horizontal SP	Horizontal LP	Special
ADE	34 58 S	138 43 E	AUSTRALIA	25.	.8	N,E	N,E	
AGE	8 49 S	148 05 E	AUSTRALIA	3.				
AVO	22 35 S	150 37 E	AUSTRALIA	33.				
BOV	36 48 S	147 14 E	AUSTRALIA	17.8				
BRS	27 24 S	152 47 E	AUSTRALIA	70.		N,E	N,E	
CAB	35 56 S	146 26 E	AUSTRALIA					YES
CAN	35 19 S	149 00 E	AUSTRALIA	54.5	9.	N,E	N,E	YES
CLV	33 41 S	136 30 E	AUSTRALIA					YES
CTA	30 05 S	146 15 E	AUSTRALIA	100.	3.	N,E	N,E	
DAR	12 25 S	130 49 E	AUSTRALIA	13.				
DLN	34 43 S	149 11 E	AUSTRALIA	17.				
ESA	09 44 S	150 49 E	AUSTRALIA	38.		N,E		YES
GRK	6 04 S	145 24 E	AUSTRALIA	5.				
HLA	33 32 S	150 55 E	AUSTRALIA	32.				
HTT	33 26 S	138 56 E	AUSTRALIA			N		YES
INV	34 58 S	149 40 E	AUSTRALIA	10.				
JIN	36 26 S	148 36 E	AUSTRALIA					YES
JNL	33 50 S	150 01 E	AUSTRALIA	58.				
KDB	9 28 S	147 10 E	AUSTRALIA	10.				
KET	4 20 S	152 02 E	AUSTRALIA	*N/A		N,E		
KHA	36 13 S	148 08 E	AUSTRALIA					YES
KLG	30 47 S	121 27 E	AUSTRALIA	50.		N,E		
KOA	6 13 S	155 37 E	AUSTRALIA	39.8				
LAE	6 43 S	146 59 E	AUSTRALIA	10.		N,E		
LMT	41 37 S	146 09 E	AUSTRALIA	50.				
MAW	67 36 S	62 53 E	AUSTRALIA	35.				YES
MCQ	54 30 S	158 57 E	AUSTRALIA	N/A				
MEA	34 13 S	148 24 E	AUSTRALIA	N/A				
MEK	26 37 S	118 33 E	AUSTRALIA					YES
MOM	2 04 S	127 25 E	AUSTRALIA	N/A				
MOO	42 27 S	147 11 E	AUSTRALIA	50.				
MTV	38 24 S	146 34 E	AUSTRALIA	N/A				
MUN	31 59 S	116 12 E	AUSTRALIA	25.	.4	N,E	N,E	YES
NIA	29 03 S	167 58 E	AUSTRALIA	10.				
PNA**	32 00 S	138 10 E	AUSTRALIA					YES
PMG	9 25 S	147 09 E	AUSTRALIA	50.	3.	N,E	N,E	YES
RAB	4 12 S	152 10 E	AUSTRALIA	12.5	.8	N,E	N,E	YES
RAL	4 13 S	152 12 E	AUSTRALIA					YES
RIV	33 50 S	151 10 E	AUSTRALIA	12.5	.8	N,E	N,E	
SAV	41 43 S	147 11 E	AUSTRALIA	50.				
SFF	42 20 S	146 18 E	AUSTRALIA	50.				
SUL	4 13 S	152 12 E	AUSTRALIA					YES
SNL**	33 53 S	138 38 E	AUSTRALIA	N/A				
TAO**	35 37 S	148 17 E	AUSTRALIA	N/A				
TAU	42 55 S	147 19 E	AUSTRALIA	25.	.8	N,E	N,E	
TAV	4 14 S	152 13 E	AUSTRALIA					YES
TBL	4 06 S	145 01 E	AUSTRALIA	1.7				
TOO	37 34 S	145 29 E	AUSTRALIA	25.	N/A	N,E	N,E	
TRR	42 18 S	146 27 E	AUSTRALIA	50.				
UMB**	30 14 S	139 08 E	AUSTRALIA	N/A				

Table II (Cont'd)

Code	Latitude ° ′	Longitude ° ′	Country	SPZ Mag. (K)	LPZ Mag. (K)	Horizontal SP	Horizontal LP	Special
VUL	4 17 S	152 09 E	AUSTRALIA					YES
WAB	5 30 S	143 44 E	AUSTRALIA	25.		N,E		
WAM	36 12 S	148 53 E	AUSTRALIA					YES
WAN	4 12 S	152 11 E	AUSTRALIA					YES
WER	33 57 S	150 35 E	AUSTRALIA	35.		N,E		
WRA	19 57 S	134 20 E	AUSTRALIA	(ARRAY,SEE TABLE 3)				
VIE	48 15 N	16 22 E	AUSTRIA					YES
VKA	48 16 N	16 19 E	AUSTRIA	5.		N,E		
DOU	50 06 N	4 36 E	BELGIUM	300.	3.	N,E	N,E	
GIP	50 36 N	5 58 E	BELGIUM					YES
UCC	50 48 N	4 22 E	BELGIUM					YES
WRM	49 50 N	5 23 E	BELGIUM	4.				YES
RDJ	22 54 S	43 13 W	BRAZIL		N/A		N,E	
ALE	82 29 N	62 24 W	CANADA	60.	3.7	N,E	N,E	
BLC	64 19 N	96 01 W	CANADA	26.	3.8	N,E	N,E	
FBC	63 44 N	68 28 W	CANADA	32.	2.6	N,E	N,E	
FCC	58 46 N	94 05 W	CANADA	36.	4.1	N,E	N,E	
FFC	54 43 N	101 59 W	CANADA	39.	4.2	N,E	N,E	
FSJ	54 26 N	124 15 W	CANADA	29.	2.0	N,E	N,E	
GWC	55 17 N	77 45 W	CANADA	28.	4.0	N,E	N,E	
INK	68 17 N	133 30 W	CANADA	68.	3.1	N,E	N,E	
LHC	48 25 N	89 16 W	CANADA	23.	2.8	N,E	N,E	
MBC	76 14 N	119 22 W	CANADA	72.	3.6	N,E	N,E	
OTT	45 24 N	75 43 W	CANADA	24.	3.2	N,E	N,E	
PHC	50 42 N	127 26 W	CANADA	14.	1.9	N,E	N,E	
PNT	49 19 N	119 37 W	CANADA	50.***	2.6	N,E	N,E	
RES	74 41 N	95 54 W	CANADA	60.	3.2	N,E	N,E	
SCH	54 49 N	66 47 W	CANADA	29.	3.0	N,E	N,E	
SES	50 24 N	111 02 W	CANADA	42.	3.5	N,E	N,E	
SFA	47 07 N	70 50 W	CANADA	21.	1.8	N,E	N,E	
STJ	47 34 N	52 44 W	CANADA	8.4	.9	N,E	N,E	
VIC	48 31 N	123 25 W	CANADA	22.	1.9	N,E	N,E	
YKA	62 30 N	114 36 W	CANADA	(ARRAY,SEE TABLE 3 AND 4)				
YKC	62 29 N	114 29 W	CANADA	44.	2.2	N,E	N,E	
COC	6 54 N	79 52 E	CEYLON					YES
ALS	23 31 N	120 48 E	CHINA					YES
ANP	25 11 N	121 31 E	CHINA	6.3	.8	N,E	N,E	
CHY	23 30 N	120 25 E	CHINA					YES
HEN	22 00 N	120 45 E	CHINA					YES
HSI	23 06 N	121 22 E	CHINA					YES
HSN	24 48 N	120 58 E	CHINA					YES
HWA	23 58 N	121 37 E	CHINA					YES
ILA	24 46 N	121 45 E	CHINA					YES
KAU	22 37 N	120 16 E	CHINA					YES
LAY	22 02 N	121 33 E	CHINA					YES
PNG	23 32 N	119 33 E	CHINA					YES
TAI	23 00 N	120 13 E	CHINA					YES
TAP	25 02 N	121 31 E	CHINA					YES
TAW	22 21 N	120 54 E	CHINA					YES
TCU	24 09 N	120 41 E	CHINA					YES

Table II (Cont'd)

Code	Latitude ° '	Longitude ° '	Country	SPZ Mag. (K)	LPZ Mag. (K)	Horizontal SP	Horizontal LP	Special
TTN	22 45 N	121 09 E	CHINA					YES
YUS	23 29 N	120 57 E	CHINA					YES
BOG	4 37 N	74 04 W	COLOMBIA	12.5	3.0	N,E	H	
CHN	4 58 N	75 37 W	COLOMBIA	N/A			N,E	
FUQ	5 28 N	73 44 W	COLOMBIA					YES
GAL	10 47 N	75 16 W	COLOMBIA	N/A			N,E	
COP	55 41 N	12 26 E	DENMARK	12.5	.8	N,E	N,E	YES
GDH	69 15 N	53 32 W	DENMARK	25.	1.5	N,E	N,E	
KTG	70 25 N	21 59 W	DENMARK	12.5	.8	N,E	N,E	
NOR	81 36 N	16 41 W	DENMARK	5.	.8	N,E	N,E	
AAE	9 02 N	38 46 E	ETHIOPIA	50.	1.5	N,E	N,E	
HEL	59 14 N	24 55 E	FINLAND	18.				
JOE	62 39 N	29 42 E	FINLAND	33.				
KEV	69 45 N	27 01 E	FINLAND	25.	1.5	N,E	N,E	
KJN	64 06 N	27 42 E	FINLAND	46.		N,E		
NUR	60 31 N	24 39 E	FINLAND	25.	1.5	N,E	N,E	YES
OUL	65 05 N	25 54 E	FINLAND	200.	1.5			
SOD	67 22 N	26 38 E	FINLAND	47.				YES
GRF	49 42 N	11 13 E	GERMANY(FD.REP)	50.	15.	N,E	N,E	
ARG	36 13 N	28 8 E	GREECE					YES
ATH	37 58 N	23 43 E	GREECE	12.5	1.5	N,E	N,E	
JAN	29 39 N	20 51 E	GREECE					YES
PLG	40 22 N	23 27 E	GREECE					YES
PRK	39 15 N	26 16 E	GREECE					YES
VAM	35 24 N	24 12 E	GREECE					YES
VLS	38 11 N	20 35 E	GREECE					YES
GBA	13 36 N	77 26 E	INDIA		1.2	(SEE TABLE 3)		
DJA	6 11 S	106 50 E	INDONESIA					YES
DNP	8 39 S	115 12 E	INDONESIA					YES
LEM	6 50 S	107 37 E	INDONESIA	25.	.8	N,E	N,E	
MED	3 33 N	98 41 E	INDONESIA					YES
MKA**	5 04 S	119 38 E	INDONESIA					YES
TNG	6 11 S	106 30 E	INDONESIA					YES
KER	34 21 N	47 06 E	IRAN	6.		N,E		
MJL**	36 46 N	49 23 E	IRAN	80.		N,E		
MSH	36 19 N	59 35 E	IRAN	12.5	1.5	N,E	N,E	
SHI	29 31 N	52 32 E	IRAN	100.	1.5	N,E	N,E	
SRI	36 46 N	49 23 E	IRAN					YES
TAB	38 04 N	46 20 E	IRAN	12.5	1.5	N,E	N,E	
TEH	35 44 N	51 23 E	IRAN	10.	.3	N,E	N,E	
VAL	51 56 N	10 15 W	IRELAND	12.5	.8	N,E	N,E	
EIL	29 5 N	35 0 E	ISRAEL	N/A	N/A	N,E	N,E	
HAF	32 48 N	35 1 E	ISRAEL	N/A				
JER	31 46 N	35 11 E	ISRAEL	N/A	N/A	N,E	N,E	
AQU	41 21 N	13 24 E	ITALY	N/A	N/A	N,E	N,E	
FIR	43 47 N	11 15 E	ITALY					YES
MES	38 12 N	15 33 E	ITALY	4.8		N,E		YES
RMP	41 49 N	12 42 E	ITALY	N/A	N/A	N,E	N,E	YES
TRI	45 43 N	13 46 E	ITALY	50.	3.	N,E	N,E	YES
HOJ	18 00 N	76 45 W	JAMAICA	10.				

Table II (Cont'd)

Code	Latitude ° ′	Longitude ° ′	Country	SPZ Mag. (K)	LPZ Mag. (K)	Horizontal SP	Horizontal LP	Special
PRJ	17 56 N	76 51 W	JAMAICA	N/A				
STH	18 05 N	76 49 W	JAMAICA	3.4				
DDR	36 00 N	139 12 E	JAPAN	36.	.8	N,E	N,E	YES
IHR	33 41 N	133 28 E	JAPAN					YES
KYS	35 12 N	140 09 E	JAPAN	11.		N,E		
MAT	36 33 N	138 13 E	JAPAN	100.	3.	N,E	N,E	
MTJ	36 13 N	140 07 E	JAPAN	42.	.7	N,E	N,E	YES
OIS	34 06 N	135 19 E	JAPAN					YES
SHK	34 32 N	132 41 E	JAPAN	10.2	1.4	N,E	N,E	YES
SRY	35 37 N	139 16 E	JAPAN	45.		N,E		
TSK	36 12 N	140 07 E	JAPAN	14.				YES
URS	33 32 N	133 29 E	JAPAN					YES
WKU	34 11 N	135 10 E	JAPAN					YES
WMY	33 39 N	133 41 E	JAPAN					YES
SEO	37 34 N	126 58 E	KOREA (REP)	50.	1.5	N,E	N,E	
LUX	49 36 N	6 08 E	LUXEMBOURG					YES
TAN	18 55 S	47 33 E	MADAGASCAR	75.9				YES
CLK	15 41 S	34 59 E	MALAWI	20.		N,E		
CHH	28 38 N	106 05 W	MEXICO					YES
COM	16 15 N	92 08 W	MEXICO	20.				YES
GUM	20 41 N	103 19 W	MEXICO					YES
LCG	21 09 N	101 42 W	MEXICO	17.5		N,E		
LNM	21 07 N	101 40 W	MEXICO					YES
MAZ	23 11 N	106 24 W	MEXICO					YES
MER	20 57 N	89 37 W	MEXICO					YES
MNZ	19 03 N	104 20 W	MEXICO					YES
OAX	17 01 N	96 46 W	MEXICO					YES
OXM	19 18 N	99 43 W	MEXICO	120.				
PBJ	16 29 N	95 25 W	MEXICO	48.				YES
PIM	18 16 N	101 53 W	MEXICO	170.				YES
PMM	17 14 N	93 33 W	MEXICO	82.				YES
PPM	19 04 N	98 38 W	MEXICO	120.				
TAC	19 24 N	99 12 W	MEXICO					YES
TMM	25 45 N	100 12 W	MEXICO	50.		N,E		
TPM	18 59 N	99 04 W	MEXICO	120.				
UNM	19 20 N	99 11 W	MEXICO	6.3	1.5	N,E	N,E	
VCM	19 12 N	96 08 W	MEXICO					YES
VHM	17 09 N	96 47 W	MEXICO	67.				
MON	43 44 N	7 26 E	MONACO	N/A	N/A			
AVE	33 18 N	7 25 W	MOROCCO	30.		N,E		
IFR	33 31 N	5 08 W	MOROCCO	80.		N,E		
RBA	34 01 N	6 50 W	MOROCCO		1.0			
RBZ	33 56 N	6 50 W	MOROCCO	30.				
TIO	30 57 N	7 16 W	MOROCCO	50.				
DBN	52 06 N	5 11 E	NETHERLANDS		.5		N,E	YES
HEE	50 53 N	5 59 E	NETHERLANDS					YES
RSB	50 53 N	5 50 E	NETHERLANDS					YES
WIT	52 49 N	6 40 E	NETHERLANDS	6.5				YES
AFI	13 55 S	171 47 W	NEW ZEALAND	12.5	.8	N,E	N,E	
KRP	37 56 S	175 32 E	NEW ZEALAND	35.		N,E		

Table II (Cont'd)

Code	Latitude ° '	Longitude ° '	Country	SPZ Mag. (K)	LPZ Mag. (K)	Horizontal SP	Horizontal LP	Special
MJZ	43 59 S	170 28 E	NEW ZEALAND	30.		N,E		
MNG	40 37 S	175 29 E	NEW ZEALAND	49.				
MSZ	44 40 S	167 55 E	NEW ZEALAND	53.				
RAR	21 13 S	159 46 W	NEW ZEALAND	6.3	.4	N,E	N,E	
SBA	77 51 S	166 45 E	NEW ZEALAND	6.3	.8	N,E	N,E	
WEL	41 17 S	174 46 E	NEW ZEALAND	6.3	.8	N,E	N,E	
BER	60 23 N	5 20 E	NORWAY		6.		N,E	
KBS	78 55 N	11 55 E	NORWAY	25.	1.5	N,E	N,E	
KON	59 39 N	9 38 E	NORWAY	50.	1.5	N,E	N,E	
NOS**	60 49 N	10 50 E	NORWAY	(ARRAY,SEE TABLE 3 AND 4)				
TRO	69 38 N	18 56 E	NORWAY	50.		N,E		
NIL	33 39 N	73 15 E	PAKISTAN	100.	3.0	N,E	N,E	
QUE	30 11 N	66 57 E	PAKISTAN	200.	6.0	N,E	N,E	
BAG	16 25 N	120 35 E	PHILIPPINES	25.	3.0	N,E	N,E	
DAV	7 08 N	125 37 E	PHILIPPINES	6.3	3.0	N,E	N,E	
MAN	16 40 N	121 05 E	PHILIPPINES	12.5	1.5	N,E	N,E	
COI	40 12 N	8 26 W	PORTUGAL	8.				
CNG	26 18 S	32 11 E	PORTUGAL	N/A	N/A			YES
LIS	38 43 N	9 09 W	PORTUGAL	3.5				
PDA	37 45 N	25 40 W	PORTUGAL					YES
PTO	41 08 N	8 37 W	PORTUGAL	50.	3.	N,E	N,E	
SDB	14 56 S	13 34 E	PORTUGAL	N/A	N/A			
ALI	38 21 N	0 29 W	SPAIN	8.5		N,E		
ALM	36 51 N	2 28 W	SPAIN	8.5		N,E		
FBR	41 25 N	0 09 E	SPAIN	6.3		N,E		YES
LGR	42 27 N	2 30 W	SPAIN	6.8		N,E		
MAL	36 44 N	4 25 W	SPAIN	50.	1.5	N,E	N,E	
SFS	36 28 N	6 12 W	SPAIN	2.5				YES
TEN	28 27 N	16 14 W	SPAIN	8.5		N,E		
TOL	39 53 N	4 03 W	SPAIN	25.	1.5	N,E	N,E	YES
DEL	56 28 N	13 52 E	SWEDEN	13.5				
HFS	60 08 N	13 42 E	SWEDEN	(ARRAY,SEE TABLE 3 AND 4)				
KIR	67 50 N	20 25 E	SWEDEN	13.8	1.2			YES
SKA	63 35 N	12 17 E	SWEDEN	14.5				
UDD	60 05 N	13 36 E	SWEDEN	13.0				
UME	63 49 N	20 14 E	SWEDEN	75.	5.5	N,E	N,E	
UPP	59 52 N	17 38 E	SWEDEN	40.		N,E		YES
BAS	47 32 N	7 35 E	SWITZERLAND					YES
CHU	46 51 N	9 32 E	SWITZERLAND					YES
COS**	46 12 N	8 51 E	SWITZERLAND					YES
NEU	47 00 N	6 57 E	SWITZERLAND					YES
ZUR	47 22 N	8 35 E	SWITZERLAND					YES
ANK	39 55 N	32 49 E	TURKEY	15.				
CIN	37 36 N	28 05 E	TURKEY	15.				
DMK	41 49 N	27 45 E	TURKEY	N/A				
DRB	39 35 N	28 38 E	TURKEY	N/A				
ERD	40 24 N	27 48 E	TURKEY	N/A				
ERZ	39 55 N	41 16 E	TURKEY	15.				
EZN	39 46 N	26 20 E	TURKEY	N/A				
GPA	40 17 N	30 19 E	TURKEY	N/A				

Table II (Cont'd)

Code	Latitude ° '	Longitude ° '	Country	SPZ Mag. (K)	LPZ Mag. (K)	Horizontal SP	Horizontal LP	Special
ISK	41 04 N	29 04 E	TURKEY	150.	1.5	N,E	N,E	YES
IST	41 03 N	28 59 E	TURKEY	25.	1.5	N,E	N,E	
KAS	41 22 N	33 46 E	TURKEY	18.				
RAM	37 46 N	41 18 E	TURKEY	50.	.6	N,E	N,E	
CHG	18 47 N	98 59 E	THAILAND	400.	3.0	N,E	N,E	
SNG	7 10 N	100 37 E	THAILAND	25.	3.0	N,E	N,E	
HLW	29 51 N	31 20 E	UNITED ARAB REP	50.	3.	N,E	N,E	
EKA	55 20 N	3 10 W	UNITED KINGDOM	(ARRAY,SEE TABLE 3)				
ESK	55 20 N	3 11 E	UNITED KINGDOM		5.			
WOL	51 19 N	1 13 W	UNITED KINGDOM		15.			
AAM	42 18 N	83 39 W	UNITED STATES	25.	1.5	N,E	N,E	
ALP**	65 13 N	146 00 W	UNITED STATES	(ARRAY,SEE TABLE 4)				
ALQ	34 57 N	106 28 W	UNITED STATES	200.	3.0	N,E	N,E	
ATL	33 26 N	84 20 W	UNITED STATES	50.	1.5	N,E	N,E	
BHP	8 58 N	79 33 W	UNITED STATES	12.5	.8	N,E	N,E	
BKS	37 53 N	122 14 W	UNITED STATES	25.	3.0	N,E	N,E	
BLA	37 13 N	80 25 W	UNITED STATES	50.	3.0	N,E	N,E	
BOZ	45 36 N	111 38 W	UNITED STATES	200.	3.0	N,E	N,E	
COL	64 54 N	147 48 W	UNITED STATES	100.	1.5	N,E	N,E	
COR	44 35 N	123 18 W	UNITED STATES	12.5	.8	N,E	N,E	
DAL	32 51 N	96 47 W	UNITED STATES	25.	1.5	N,E	N,E	
DUG	40 12 N	112 49 W	UNITED STATES	400.	3.0	N,E	N,E	
FLO	38 48 N	90 22 W	UNITED STATES	50.	3.0	N,E	N,E	
GEO	38 54 N	77 04 W	UNITED STATES	25.	1.5	N,E	N,E	
GOL	39 42 N	105 22 W	UNITED STATES	400.	1.5	N,E	N,E	
GSC	35 18 N	116 48 W	UNITED STATES	100.	1.5	N,E	N,E	
GUA	13 32 N	144 55 E	UNITED STATES	6.3	.8	N,E	N,E	
JCT	30 29 N	99 48 W	UNITED STATES	200.	1.5	N,E	N,E	
KIP	21 25 N	158 54 W	UNITED STATES	12.5	.8	N,E	N,E	
LAO	46 41 N	106 13 W	UNITED STATES	(ARRAY,SEE TABLE 3 AND 4)				
LON	46 45 N	121 49 W	UNITED STATES	100.	1.5	N,E	N,E	
LUB	33 35 N	101 52 W	UNITED STATES	25.	1.5	N,E	N,E	
OGD	41 04 N	74 37 W	UNITED STATES	50.	.8	N,E	N,E	
OXF	34 31 N	89 25 W	UNITED STATES	50.	3.0	N,E	N,E	
RCD	44 05 N	103 13 W	UNITED STATES	25.	1.5	N,E	N,E	
SCP	40 49 N	77 52 W	UNITED STATES	50.	3.0	N,E	N,E	
SHA	30 42 N	88 08 W	UNITED STATES	6.3	1.5	N,E	N,E	
SJG	18 07 N	66 09 W	UNITED STATES	50.	.8	N,E	N,E	
SPA	90 00 S	0 00	UNITED STATES	100.	.4	N,E	N,E	
TUC	32 19 N	110 47 W	UNITED STATES	200.	3.	N,E	N,E	
WES	42 23 N	71 19 W	UNITED STATES	50.	3.	N,E	N,E	
CAR	10 26 N	66 55 W	VENEZUELA	25.	3.	N,E	N,E	YES
CUM	10 41 N	66 22 W	VENEZUELA	4.5		N,E		
LGN	10 05 N	71 16 W	VENEZUELA	3.6				
MEV**	8 32 N	71 09 W	VENEZUELA	3.2				
NHA	12 13 N	109 13 E	VIET-NAM (REP)	75.	1.5	N,E	N,E	
LJU	46 03 N	14 32 E	YUGOSLAVIA	20.	2.5	N,E	N,E	
OHR**	41 07 N	20 48 E	YUGOSLAVIA	28.		N,E		
SKO	41 58 N	21 26 E	YUGOSLAVIA	35.	1.0	N,E	N,E	
VAY**	41 19 N	22 34 E	YUGOSLAVIA	25.		E		

Table II (Cont'd)

Footnotes:

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* N/A (NOT AVAILABLE) INDICATES A SEISMOGRAPH IN OPERATION AT STATION BUT MAGNIFICATION COULD NOT BE DEFINED FROM INFORMATION AVAILABLE.

** CODES SO DESIGNATED ARE ADOPTED HERE AND DO NOT APPEAR IN U.S. DEPT. OF COMMERCE, ESSA PUBLICATION - SEISMOGRAPH STATION ABBREVIATIONS -, APRIL, 1970.

*** PNT SPZ MAGNIFICATION OF 25K IN THE CANADIAN SUBMISSION TO THE UNITED NATIONS WAS IN ERROR.

/ THE PHILIPPINES SPZ AND LPZ MAGNIFICATIONS FOR BAG AND DAV ARE BELIEVED BY THE AUTHORS TO HAVE BEEN INADVERTENTLY REVERSED IN THE PHILIPPINES RETURN.

Table III. SPZ array stations

Code	Latitude	Longitude	Country	Number of Elements	Effective Magnification	Other Components
GBA	13 36 N	77 26 E	India	20	210 K	See GBA in Table II
EKA	55 20 N	3 10 W	United Kingdom	22	135 K	See ESK in Table II
HFS	60 08 N	13 42 E	Sweden	3	140 K	See HFS in Table IV, LPN and LPE at one element
LAO*	46 41 N	106 13 W	United States of America	345	1250 K	All LP elements (Table IV) contain LPN and LPE
NOS*	60 49 N	10 50 E	Norway	147	1250 K	All LP elements (Table IV) contain LPN and LPE
WRA	19 57 S	134 20 E	Australia	20	300 K	None
YKA	62 30 N	114 36 W	Canada	19	400 K	See YKC in Table II and YKA in Table IV
SPZ Arrays Not Included:						Comments
GRF	49 42 N	11 13 E	Germany (Fed. Rep. of)	7		Incomplete; included as a single station (Table II)
SAA	15 38 S	47 59 W	Brazil	19		Incomplete; no magnification or noise figures given
HEL	59 14 N	24 55 E	Finland	3		No phasing facility; also conventional station (Table II)
DDR	36 00 N	139 12 E	Japan	Irregular		Microearthquake array; also conventional station (Table II)

* LAO and NOS are commonly referred to in the literature as LASA and NORSAR, respectively.

Table IV. LPZ array stations

Code	Latitude	Longitude	Country	Number of Elements	Effective Magnification
ALP	65 13 N	146 00 W	United States of America	19	120 K
HFS	60 08 N	13 42 E	Sweden	3	28 K
LAO	46 41 N	106 13 W	United States of America	17	120 K
NOS	60 49 N	10 50 E	Norway	19	120 K
YKA	62 30 N	114 36 W	Canada	3	28 K

corresponding period in seconds, and Q is the distance (Δ) and focal depth (h) calibrating function. Considering only a fixed focal depth of h = 25 km, using a fixed signal period of T = 1 sec, and making the appropriate conversion of units, the 50 per cent 1 mm seismogram signal can be converted to a 50 per cent interval probability (I.P.) magnitude detection value as follows:

$$m_{50}(\Delta) = Q(\Delta) - \log V, \quad \ldots . 2$$

where V is the magnification in K at a period of 1 second. Thus each SPZ station with a known (and fixed) magnification has a 50 per cent I.P. magnitude detection capability as a function of distance only, defined by Equation 2.

3.2 SPZ array stations

It is essential when considering world-wide detection capabilities involving mixed array and conventional stations to devise a technique whereby array stations can be considered as extra-sensitive single stations with assumed *effective* magnifications which depend on the character and geometry of the array and the signal processing technique adopted. Each of the SPZ arrays must, therefore, be considered separately using all available information to decide on this effective magnification.

The U.K.-type arrays. The data available for the four U.K.-type short-period arrays (YKA, WRA, GBA and EKA; see Table III) are an approximate 50 per cent annual noise level for each of the arrays (Burch, 1969), and a well-defined detection capability for the YKA array (Anglin, 1970). The noise levels, converted to equivalent m at a distance of Δ = 60°, are m4.0, m4.1, m4.3, and m4.5 for YKA, WRA, GBA and EKA, respectively. In this calculation, Burch has assumed a unity signal-to-noise ratio for a single sensor, which is equivalent to a signal-to-noise ratio of approximately four for the phased sum. Anglin's results for YKA based on automatic array detection with digital delayed-sum and correlogram processing indicate an average 50 per cent I.P. detection capability of $m_{50}4.3$ at epicentral distances about 60°. The YKA capability using an automatic detection algorithm is $\delta m_{50}0.3$ poorer than the equivalent noise calculation because the algorithm assumes no prior knowledge of where to focus the beams and must limit the occurrence of false event (noise) triggers to a reasonable number. With no equivalent detection figures available for the other arrays, it is assumed that using an equivalent processing technique the δm0.3 difference would apply, and the 60° m_{50} values are converted to an effective magnification V using Equation 2. This results in the effective magnification for these arrays shown in Table III.

HFS (SPZ). No detection figures are available for HFS, but the 1-second noise is quoted as 12.5 mμ* (Swedish UN return). Assuming $\sqrt{3}$ signal-to-noise improvement using a phased sum, the signal will be detectable 50 per cent of the time with a displacement of about 7 mμ. This converts to the effective magnification of 140 K given in Table III.

LAO (SPZ). The quoted 50 per cent I.P. detection capability for LAO (SPZ) is given (SIPRI, 1968) as m3.8, using beam-forming techniques. Assuming a mid-third zone distance of 60°, this converts using Equation 2 to the effective magnification of 1250 K given in Table III.

NOS (SPZ). No noise levels, operating magnification or detection capabilities are available for NOS; this is due principally to the short period of time it has been in operation.** However, because of the importance of NOS to world-wide detection, an effective magnification has been assigned to it for purposes of this study. Although it has fewer elements than LAO (see Table III), it does have a more suitable geometry, and on this basis is assigned an effective magnification equal to that of LAO, 1250 K.***

3.3 LPZ conventional stations

Each country was asked to specify the magnification of its long-period stations at 15 or 20 seconds; the returns included values in the range from 15 to 30 seconds. Since conventional long-period seismographs usually have generally flat magnification within the range from 10 to 30 seconds, the quoted value is assumed to apply at 20 seconds; the values for LPZ are listed in Table II.

* This single sensor noise level appears unusually high in comparison to noise data available for similar environments elsewhere in the world, and is believed to include noise at periods slightly above 1 second. If this is true, a narrow band filtering of the HFS data (this is applied to the YKA data prior to automatic processing) would increase the effective magnification determined for HFS by a factor of 2 or more.

** At the time of preparation of this report, the authors understand that full array operation at NOS can be expected in the autumn of 1970. Parts of the array have been operational for some time.

*** If these assumptions concerning NOS are in error, the assumed effective magnification for this array may, in fact, be different by up to about a factor of 2; this, however, would have no important effect on P wave detection described in later chapters.

The dominant noise on conventional LPZ seismograms is commonly near 6-second periods and due to oceanic microseisms. A conventional LPZ seismograph writes one line per hour with 10 mm between adjacent lines. It is assumed for purposes of discussing the detection of 20-second Rayleigh waves that the shorter period noise level and thus the operational magnification are such that a 20-second signal will be identifiable 50 per cent of the time if it reaches a trace amplitude of 2 mm. From our experience this seems a reasonable practical criterion to adopt in order to proceed further.

There are two single LPZ stations (GRF in Germany and WOL in the U.K.) in the returns which possess magnetic tape recording facilities. This tape facility, with extra electronic filtering during recording or on playback from the magnetic tape to reject the shorter period noise, allows quotation of a magnification at least three times higher than the conventional photographic stations.

The formula adopted for relating Rayleigh wave signal to a surface wave magnitude is

$$M = \log(A/T) + 1.66 \log \Delta + 3.3 \quad \ldots\ 3$$

where A is the maximum vertical Rayleigh wave trace amplitude converted to ground displacement in microns, and T is the corresponding period in seconds. Considering a Rayleigh wave period of 20 seconds and making the appropriate units conversion, the 50 per cent detection signal level of 2 mm is related to the 50 per cent I. P. Rayleigh wave magnitude by the formula

$$M_{50}(\Delta) = 1.66 \log \Delta - \log V + 2.3 \quad \ldots\ 4$$

where V is the LPZ 20-second magnification in K. Thus each LPZ station has, for a fixed magnification, a 50 per cent I.P. Rayleigh wave detection capability as a function of distance only, given by Equation 4.

3.4 LPZ array stations

As for the SPZ array stations, the LPZ arrays can be assigned an effective magnification on the basis of available noise data and detection capabilities. The basic assumptions concerning LPZ arrays are that they include sufficient filtering capability that the 6-second noise can be ignored, and that they have a data processing facility for forming phased sums.

YKA (LPZ). An unpublished study by the authors has shown that the 50 per cent noise at YKA is about 60 $m\mu$ near 20 seconds. Assuming a $\sqrt{3}$ signal-to-noise improvement due to a phased sum and a 2.0 signal-to-noise ratio for signal detection, the 50 per cent I.P. signal will be 70 $m\mu$ which can be converted to the effective magnification of 28 K given in Table IV.

HFS (LPZ). The quoted 20-second noise for HFS (Swedish UN return) is identical to that for YKA and the effective magnification will also be 28 K.

LAO (LPZ). The quoted Rayleigh wave detection capability for LAO (Capon *et al.*, 1967b) is m4.5 at the 60 per cent I.P. level, which can be converted to m4.4 at the 50 per cent I.P. level or M3.0 (see section 3.5) at the 50 per cent I.P. level. This is for $\Delta = 85°$, but includes matched filtering. The matched filtering which yields a detection improvement of 8 db (δMO.4) will be removed here, but discussed in a later section. Following this correction, the 50 per cent I.P. for Rayleigh detection is M3.4, which converts (using $\Delta = 85°$) from Equation 4 to the effective magnification of 120 K given in Table IV.

NOS (LPZ) and ALP. No noise or detection figures are available for NOS and ALP. Although there may be a slightly higher noise level at these sites (comparable to northern Canada and Sweden) than at LAO, NOS and ALP were designed for optimum LPZ detection and on this basis are assigned effective LPZ magnifications equal to the empirically defined value for LAO, 120 K.

3.5 Rayleigh wave detection in terms of m_{50}

In order to refer to both P wave and Rayleigh wave detection in terms of a single magnitude scale, the M_{50} Rayleigh wave magnitudes determined from Equation 4 are converted to equivalent m_{50} using the equation

$$M_{50} = 1.59\, m_{50} - 3.97 \quad \ldots\ 5$$

This is the original (Gutenberg and Richter, 1956) relationship relating M and m and applies reasonably well to any world distribution of earthquakes.

The only specific study of Rayleigh wave detection which directly supports this adopted formulation is by Simons and Goforth (1967). They present Rayleigh wave detection probabilities as a function of P wave magnitude, epicentral distance and LPZ magnification using a large suite of widely distributed earthquakes recorded at five sensitive LPZ stations in the United States. Their data for equivalent m_{50} interval probability of Rayleigh wave detection versus epicentral distance for fixed magnifications agree with the formulation of Equations 4 and 5 within δm_{50}0.2 over the distance range from 35° to 90°. At nearer distances they illustrate an improvement in Rayleigh wave detection roughly equivalent to the improvements gained from continental path propagation discussed in section 6.3. Capon *et al.* (1967b) present M versus m data which, when combined as a world-wide average, support the adoption of Equation 5, but when considered on a regional basis show that variations in the M versus m relationship occur.

Thus, with the adoption of Equation 5, the P wave magnitude, m_{50}, for which there is a 50 per cent interval probability of Rayleigh wave detection, can be determined as a function of distance for any station with an available LPZ magnification.

4. Global P wave detection

4.1 Individual station detection probability functions

The basic input data for the P wave detection calculations are the individual station $m_{50}(\Delta)$ values defined in section 3.1 and 3.2. To determine the probability of detecting a given magnitude event at a given site by a group of stations with various capabilities (various m_{50}), we require a detection probability function for each station which varies with the event magnitude. Ideally, we need either the noise amplitude probability distribution or an empirically defined detection probability distribution versus m for each station. Since this type of station information is available for only a very small percentage of the stations being considered, a general approximation must be used.

The only empirically defined individual station P wave detection probabilities of which we are aware are from an unpublished study by the authors of the capabilities of the Canadian SPZ stations SES, OTT and ALE. For these stations, the magnitude range between the 10 and 90 per cent interval probabilities of detection is δm0.8 to 1.0, with the 50 per cent I.P. magnitude near the centre of the range.

Assuming that the probability of locating an event by a given network of stations is directly related to individual station probabilities of detection events, some location statistics can contribute to this problem. Some tests made by the authors on the detection capability in a number of European and Asian regions using data for 1965, published by the International Seismological Centre, give a magnitude difference δm0.4 to 0.5 between the 50 and 90 per cent capability. Evernden (1970b) has published some diagrams indicating the world-wide capability of the United States Coast and Geodetic Survey system. Our interpretation of the occurrence slopes again leads to a correction of δm0.4 to change from 50 to 90 per cent interval probability magnitudes.

Noise probabilities indicate a smaller range of equivalent magnitudes than do the actual detection probabilities given above. A study by the authors (Basham and Whitham, 1966) of short period microseismic noise on Canadian seismograms shows that the 90 per cent cumulative noise is on the average a factor of about three greater than the 10 per cent cumulative noise: a difference in equivalent magnitudes of δm0.5. We believe that the actual detection probability range is greater than this because of the requirement of a larger signal-to-noise ratio for detection in the presence of high noise than in low noise.

Statistically, the most likely shape expected for an individual station detection probability function versus magnitude would be an integrated normal curve, with each station expected to have a somewhat different effective normal variance. Since these individual station probability curves are not available, and there are other uncertainties in these calculations of equal or greater magnitude, a linear probability function, suitable to the above illustrated empirical data, of the form

$$P(m) = m - m_{50} + 0.5 \quad (0 \leq P(m) \leq 1) \qquad \ldots 6$$

will be employed; P(m) is the probability that a station with capability m_{50} (defined in section 3.1) will detect the P wave of an earthquake of magnitude m. This is simply an increase of 0.1 in detection probability for each δm0.1 increase, with the P = 0.5 centred on the adopted m_{50}.

4.2 90 per cent detection probabilities for an event

In order to find, for a specific point on the earth, the earthquake magnitude that will have P waves detected with a required probability by a given number of stations, we require some knowledge of the probability distribution of numbers of detections, as a function of the magnitude of the event, that can be expected from a large suite of available stations having a wide range of P wave detection capabilities. If the average number of detections is small relative to the total number of stations, the probability distribution of the number of detections can be closely approximated by the Poisson distribution for each magnitude under consideration. If one then considers at the specific point in question a range of event magnitudes, one has a family of Poisson curves. For each of these curves the procedure in section 4.1 describes how the number of detections can be calculated. How one employs this family of curves for purposes of detection probability calculations depends on the requirements of the exercise. We have chosen to define the P wave detection capability of the group of stations under consideration as the earthquake magnitude at a given site for which there will be a 90 per cent probability of detection by a minimum given number of stations (N). To do this we employ the cumulative form of the above family of Poisson distributions and calculate that earthquake magnitude for which the cumulative Poisson distribution indicates a 90 per cent probability of detection by ≥N stations. This computational procedure was used for all detection calculations presented in the remainder of this report.

4.3 The 46-station SPZ network

There are 199 stations in Table II (including the seven SPZ arrays) which have some degree of SPZ detection capability, i.e., a known SPZ magnification at 1 second. It will be seen in the following sections that most of the lower magnification SPZ stations will not contribute in any highly significant way to discussions of global P wave detection capabilities. The first requirement, therefore, is to reduce the total of 199 SPZ stations to a conceptual world-wide network of a manageable number of SPZ stations which can be used to discuss global P wave detection.

In sections 4.5 and 4.6, the principal P wave detection results of this study will be presented as global contour maps, the calculations for the contours being made at 146 grid points on the earth separated by 20° in both latitude and longitude. The procedure adopted to define an SPZ network was to choose for each grid point the four stations with the best P wave detection capability, i.e., with the lowest m_{50} values (see Equation 2). If, at the fourth lowest m_{50} value, there was more than one station with the same capability, the additional stations were also included. The total number of individual stations chosen by such a process was 46 (the seven SPZ array stations and 39 SPZ conventional stations). This 46-station SPZ network is shown in Figure 1 and will be used exclusively for all P wave detection calculations which follow. In addition, however, we have illustrated in Figure 1 the locations of the 30 additional stations which have SPZ magnifications ≥50 K. Many of these stations, although not employed in detection calculations made here, are of importance in considering regional studies and, in fact, have been used in particular research studies which will be cited in later sections. It can be noted that most of these additional stations are located in

North America and Europe. It should also be noted that a number of southern hemisphere stations selected for inclusion in the 46-station network by the procedure defined above have SPZ magnifications less than 50 K; this is due to the paucity of high SPZ magnification stations in the southern hemisphere.

Although it may appear that the 46-station SPZ network as defined will have a poorer P wave detection capability than a larger network consisting of all 199 SPZ stations, in fact, the N-station detection limit as we have defined it (see section 4.2) will not, for small values of N and for a general point on the earth's surface, be significantly different whether using the 46-station or a 199-station network.

4.4 P wave detection at specific sites

Although the principal result of this chapter will be global P wave detection contour maps, it is of value to begin with a discussion of P wave detection capabilities for events at seven specific sites: (a) as an illustration of the procedures which will be generalized to the global coverage, and (b) to define for these sites the formal detection capabilities of the 46-station SPZ network which will, in later sections, be compared with empirical detection capabilities published in the literature.

The sites chosen for examination in the light of available seismograph station data are seven of the active nuclear explosion test sites; these seven sites, each assigned a 3-letter site code, are listed in Table V, and plotted in Figure 2. It must be emphasized that the discussion at this point applies only to earthquakes, that is, to hypothetical or real (if they happen to occur) earthquakes at a depth of 25 km, at or near (say, with epicentres within about 10° of) the seven sites chosen for study. The conclusions drawn for conceivable earthquakes at these sites will, of course, be expanded in later chapters to a discussion of both the detection and identification of underground nuclear explosions at these same sites.

All presumed underground nuclear explosions have been detonated in the northern hemisphere. It is for purposes of comparing and contrasting detection capabilities at a southern hemisphere site that MUR (an atmospheric explosion test site) has been included with the six northern hemisphere sites in this study.

Table V. Nuclear explosion test sites given special consideration in this report

Site Code	Location	Latitude	Longitude
NTS	Nevada, U.S.A.	37.2 N	116.5 W
KAZ	E. Kazakh, U.S.S.R.	49.7 N	78.1 E
SAH	Southern Algeria	24.2 N	5.1 E
CHI	Northwest China	41.4 N	88.3 E
ALU	Aleutian Islands	51.4 N	179.2 E
NVZ	Novaya Zemlya	73.4 N	54.8 E
MUR	Mururoa Island	22.0 S	139.0 W

The epicentral distance range considered for P wave detection calculations is $0 \leq \Delta \leq 90°$. Although the magnitude computational formula, and therefore the P wave detection capability, is poorly defined at distances less than 20°, any reasonably sensitive seismograph station will detect P waves from quite small earthquakes at the near distances. Thus it is necessary to devise an approximation to include in the detection calculations all stations nearer than 20° to a particular site. The approximation used here is an extrapolation of the Q distance calibration function (see Equation 1) to zero distance; the empirical Q* function from Basham (1969a) is employed in the range from 12° to 20°, and a somewhat arbitrary value of Q=6.4 is employed between 0° and 12°. There are more accurate procedures for calculating P wave magnitudes at the near distances (see, for example, Evernden, 1967), but they require a regionally-dependent calibration of the appropriate P phase arrivals and amplitudes. Without such phase calibration available for a general point on the earth's surface, some approximation must be employed; the one chosen will not significantly distort the resulting P wave detection results. The 90° outer limit of epicentral distance for detection calculations is the limit of the so-called "third zone", a distance slightly less than the one at which P waves begin to be diffracted by the earth's core.

Using the detection computational procedure described in section 4.2, the P wave detection capability of the 46-station SPZ network for earthquakes at the seven specific sites are given in Table VI. The m values listed are those earthquake magnitudes for which there will be a 90 per cent probability of detection by $\geq$N stations; m values are listed for N= 4, 6, 8 and 10. The number of stations within the $0 \leq \Delta \leq 90°$ detection range for each site are also indicated.

To avoid the repeated use of a long phrase throughout this report, we will employ the wording "N-station threshold", and rely on the reader to recall the exact computational procedure as described in sections 4.1 and 4.2, and the more explicit meaning described by the table heading in Table VI. For example, from Table VI, the *4-station* P wave detection *threshold* of the 46-station network for earthquakes at the site NTS is m4.0.

Table VI. Earthquake m magnitudes at specific sites for which there is a 90 per cent probability of P wave detection by $\geq$N stations

N	NTS (22)*	KAZ (26)	SAH (22)	CHI (23)	ALU (33)	NVZ (31)	MUR (27)
4	4.0	4.2	4.3	4.3	4.2	4.1	4.5
6	4.2	4.4	4.4	4.4	4.4	4.3	4.6
8	4.3	4.5	4.6	4.6	4.5	4.4	4.7
10	4.5	4.6	4.7	4.8	4.6	4.5	4.9

* Number of stations from 46-station SPZ network within detection range ($\Delta \leq 90°$).

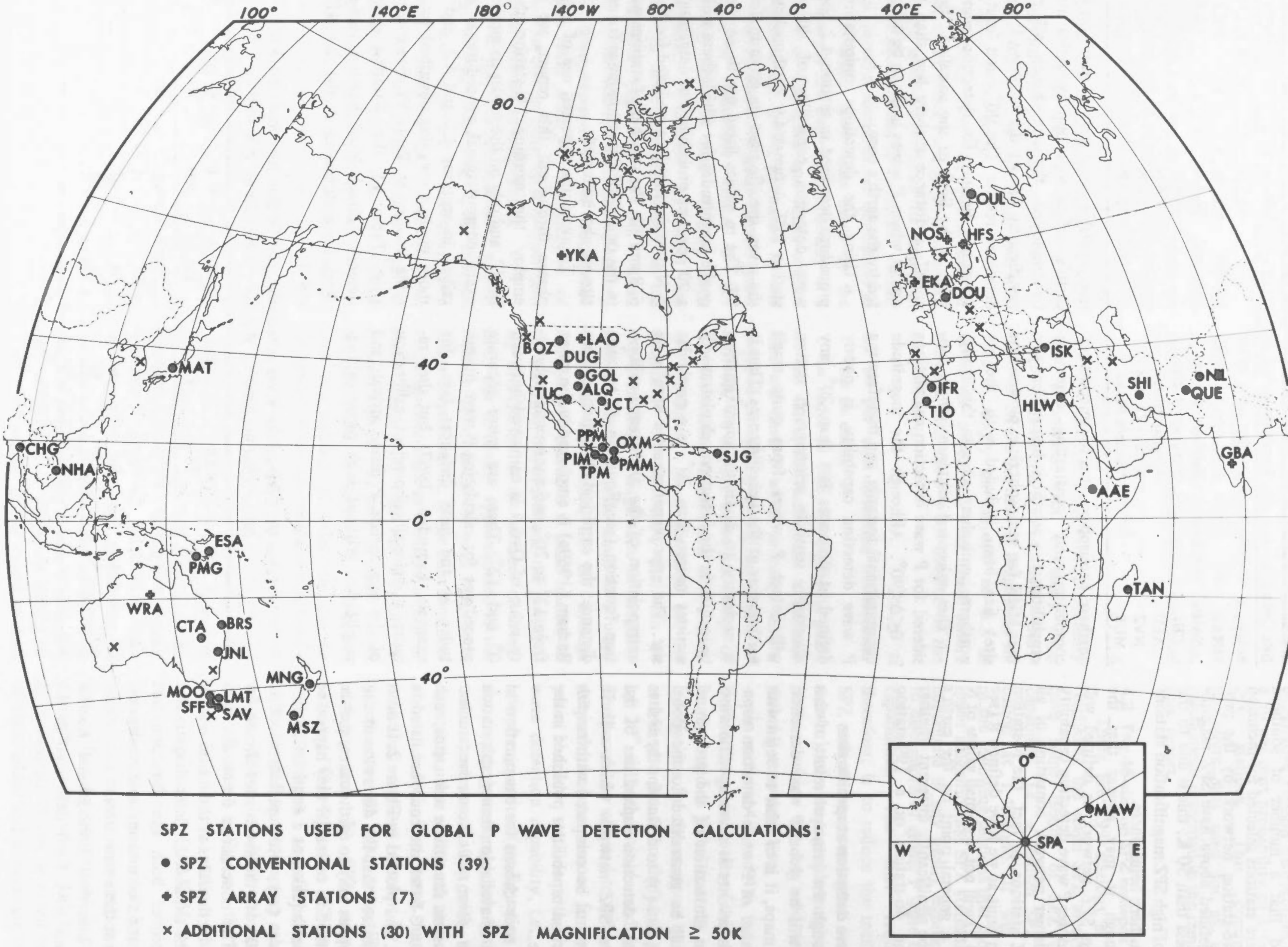

Figure 1. Conventional and array stations in the 46-station SPZ network used for global P wave detection calculations. The 30 station locations shown without station code names are all additional stations from Table II with SPZ magnification ≥ 50 K.

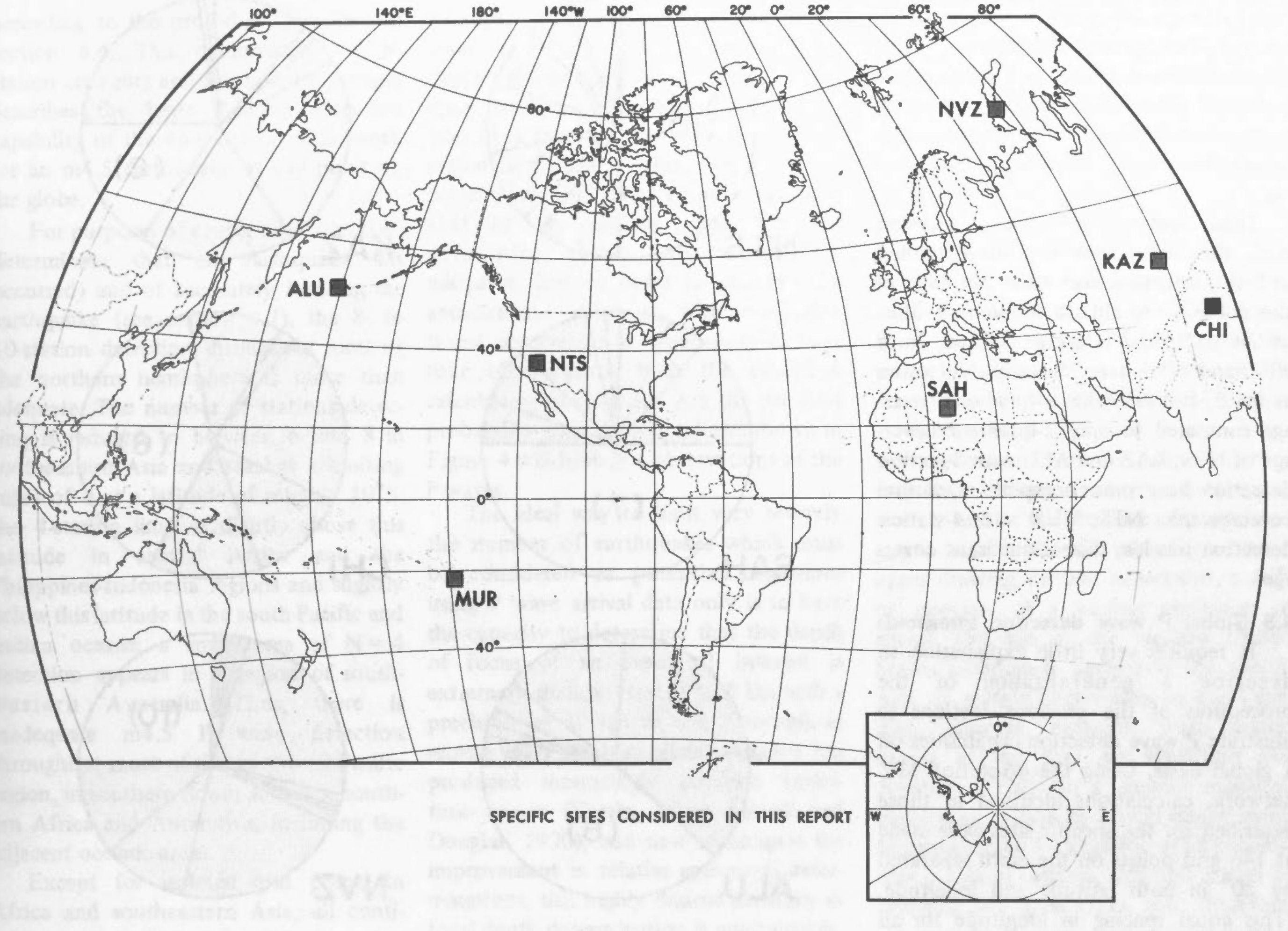

Figure 2. Nuclear explosion test sites given special consideration in this report.

A brief examination of the results of Table VI will illustrate some characteristics of P wave detection which will have general validity in the global context:
(a) The higher latitude sites (ALU and NVZ) have more stations within detection range than do mid-latitude sites in the northern hemisphere.
(b) The N-station detection thresholds are within δm0.3 of being equivalent at all northern hemisphere specific sites; the extremes within this range show NTS and NVZ thresholds to be roughly δm0.3 lower than the SAH and CHI thresholds.
(c) The N-station detection threshold for the southern hemisphere site, MUR, is approximately δm0.3 higher than the average for the northern hemisphere sites.
(d) The 10-station detection thresholds are about δm0.4 greater than the 4-station thresholds at all specific sites.

Because of asymmetries in P wave radiation patterns and for purposes of estimating epicentre location errors when using small numbers of stations (see section 4.7), it is important to define the source-to-station azimuthal coverage provided by the stations at the threshold being discussed. The threshold magnitudes derived for N stations are statistically determined on the basis of all stations of the network within detection range. However, for purposes of illustrating azimuthal coverage, it is adequate to examine the azimuthal coverage provided by the best N stations at the N-station threshold. The threshold magnitude to be examined here for P wave detection at the specific sites (and for global coverage; see section 4.6) is m4.5. Thus, we wish to examine the azimuthal coverage provided by the best N stations for which the N-station threshold is m4.5 at each site. The values of N for some sites are apparent in Table VI; for example, we will examine the azimuthal coverage provided by the best 10 stations for NTS, the best eight stations for KAZ, etc.

The P wave azimuthal coverage for m4.5 earthquakes is illustrated for the seven specific sites in Figure 3. The radial plots show both individual station azimuths from the source (solid radial lines) and a method of shading which illustrates azimuthal coverage in a more general way, the principal use of the shading to be an illustration of the global results in section 4.6. The rules adopted for the shading are as follows: (1) any quadrant (NW, SW, SE or NE) which contains more than one station is completely filled (e.g., NE and SE for NTS); (2) for a single station in a quadrant, the area between the station line and the nearest filled section is filled (e.g., part of SE for CHI); and (3) any single station separated by more than 90° in azimuth from the nearest filled section is represented by a 30° "pie-slice" (e.g., see MUR).

Thus, from Figure 3, one can examine both the number of stations detecting and the effective azimuthal coverage at the m4.5 threshold. A number of illustrative comparisons are as follows: both NVZ and NTS have 10-station detection at m4.5, but NVZ has 3-quadrant coverage compared to only 2-quadrant coverage of NTS; KAZ and ALU with 8-station detection have more complete azimuthal coverage than NTS; MUR with 4-station detection has less than 2-quadrant coverage.

4.5 Global P wave detection thresholds

It requires very little explanation to describe a generalization of the procedures of the previous sections to illustrate P wave detection capabilities on a global basis. Using the 46-station SPZ network, calculations identical to those described for the specific sites were made at 146 grid points on the earth separated by 20° in both latitude and longitude. (This equal spacing in longitude for all latitudes produces denser coverage at high latitudes, but is useful for contouring on Mercator-type map projections.)

A contour map of the 4-station P wave detection threshold is shown in Figure 4; the contour interval used is δm0.2. The broad feature of these contours is a general increase in the 4-station threshold from m4.2 in the north to m5.0 in the south. The distribution of high magnification stations produces one dominant "low" and one "high" on the map. The "low" of m4.0 in southern North America results from a concentration of sensitive stations (see Figure 1); the "high" of m5.0 in the south Atlantic Ocean results from a paucity of stations in South America and southern Africa. The station sensitivities and distribution in the northern hemisphere are sufficient to produce a broad, flat 4-station threshold at m4.2 over North America, Europe and northern Asia, deteriorating to m4.5 for virtually complete Asian and north African coverage.

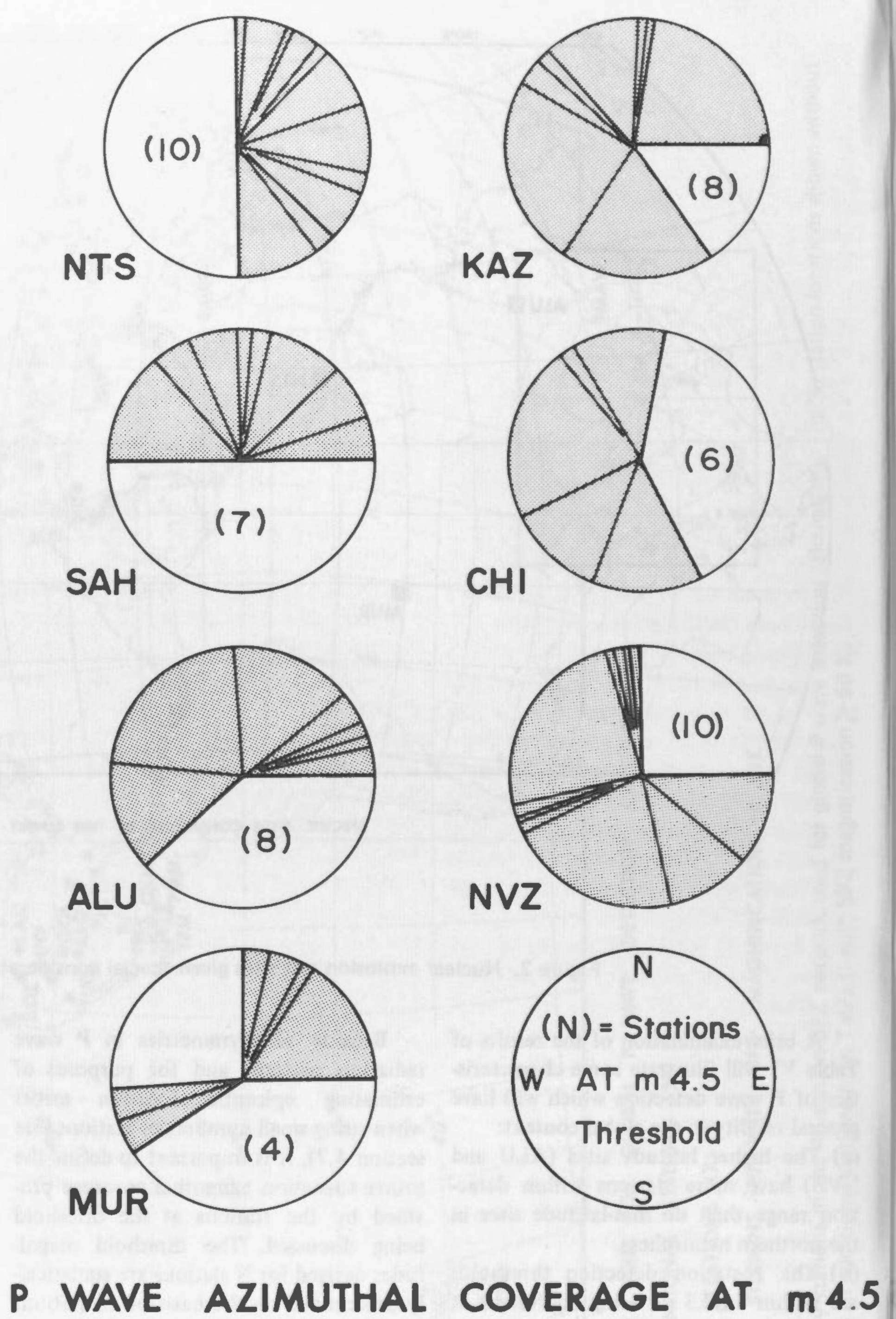

Figure 3. Number of stations detecting and azimuthal coverage provided by the 46-station SPZ network for earthquake P waves at a threshold m4.5 at the seven specific sites. See text for procedure for choosing N and representing azimuthal coverage by radial plot shading.

4.6 P wave detection and azimuthal coverage at m4.5

The number of stations detecting P waves at a threshold magnitude m4.5 is contoured in increments of 2 in Figure 5. The contour numbers are equivalent to the numbers in parentheses in each radial plot in Figure 3. Also shown in Figure 5 at each grid point for which $N \geq 4$, is an azimuthal coverage radial plot drawn according to the procedure described in section 4.4. This combination of N-station contours and azimuthal coverages describes the basic P wave detection capability of the 46-station SPZ network for an m4.5 earthquake at any point on the globe.

For purposes of simple detection (i.e., determining that an earthquake has occurred) and of accurately locating the earthquake (see section 4.7), the 8- to 10-station detection throughout most of the northern hemisphere is more than adequate. The number of stations detecting is reduced to between 6 and 8 in southeastern Asia and reaches a limiting value of 4 at a latitude of roughly 10°S; the 4-station limit is slightly above this latitude in central Africa and the Philippines-Indonesia regions and slightly below this latitude in the south Pacific and Indian oceans; a small area of $N = 4$ detection appears in a region of southwestern Australia. Thus, there is inadequate m4.5 P wave detection throughout most of the southwest Pacific region, in southern South America, southern Africa and Antarctica, including the adjacent oceanic areas.

Except for isolated grid points in Africa and southeastern Asia, all continental areas which have $N \geq 4$ station detection are represented in azimuth by at least 2-quadrant coverage. The most obvious inadequate azimuthal coverage occurs in the eastern Pacific Ocean for which all detecting stations are in North America, resulting in only 1-quadrant coverage.

4.7 P wave detection and epicentral determination

Whatever assumptions are made to define adequate P wave detection capabilities, the problem of using these detected P waves to compute the epicentre and the focal depth of the earthquake must be considered. We have defined as an adequate P wave detection capability the 4-station thresholds which are illustrated in Figure 4. Assuming a known travel-time curve for regional and teleseismic distance, for detection by only a small number of stations, the depth and origin time of an event can largely be traded against each other, and so there are only three significant unknowns, latitude, longitude and origin time. A zero depth, or some other fixed depth, restraint is usually made in the epicentral calculation with P wave detection by a small number of teleseismic or regional stations, when other phase information or data from very close stations are lacking. Therefore, in principle, three observations are adequate, but in order to confirm the approximate epicentre with one additional observation it is necessary to have four observations. With the detection calculation used, there is a 90 per cent probability that the magnitudes shown in Figure 4 will have ≥ 4 observations of the P waves.

The ideal way to limit very severely the number of earthquakes which must be considered as potential explosions using P wave arrival data only is to have the capacity to determine that the depth of focus of an event of interest is extremely shallow (say, 0 to 5 km with a precision of ±1 km or so). Although in recent years much excellent research has produced increasingly accurate travel-time curves (Herrin, 1968; Lilwall and Douglas, 1970), and new techniques for improvement in relative epicentral determinations, this highly desired accuracy in focal depth determination is unattainable, even with some tens or hundreds of observations. This is because there are lateral complexities in the earth. In practice, a small number of P wave observations (say, 10 or less) cannot determine a focal depth to better than ±10 km at best.

In principle, there are two possibilities of interest with a small number of detecting stations. The first involves co-operation by nuclear testing powers in releasing publicly the times and positions of a number of suitably large explosions for each test site in order to obtain accurate empirical travel-time corrections for each testing area for the network of observing stations. The only study known to us of the effect of these corrections for a small network at one test site is one by Weichert and Newton (1970) using some NTS explosions recorded on the Canadian network. When corrections were obtained for 13 Canadian stations from publicly released data, and calculations made using the network on other NTS explosions, the focal depth could not be estimated better than ± 5 km. If the calculations are repeated with no known corrections (i.e., no master events in the public domain), the situation is impossible and errors of many tens of km in the best computed depth of focus can occur. We estimate that with a small network, reasonably adequately distributed in azimuth, but with no master event control, all events with a nominal focal depth from zero to about 50 km could be potential surface focus events—or in this context, potential explosions. A further complication is that the master event technique may not give control over a very large distance from the master event site because of the presence of crustal and upper mantle lateral inhomogeneities—again drawing on our experience, a shift of position of a nuclear explosion of about 150 km in the western United States completely destroyed the usefulness of station corrections to the Canadian network obtained from master events at the first site (Weichert and Newton, 1970). In a control situation, there is no reason to expect master event information to be available at all conceivable points of interest, although it may be available for some areas, and, therefore, we can dismiss the matter from further practical consideration in this paper.

The second possibility for improvement was well demonstrated by Evernden (1969a). A striking improvement in precision of depth of focus can be obtained when an independent estimate of the origin time can be made from time differences between certain seismic phases on the record at a small number of near stations. This, for the 46-station SPZ network under study, is impossible—insufficient stations are reported at distances of 150-1000 km from already known test sites. From conceivable test sites, the station distribution is worse, and once again we can, therefore, dismiss precision in focal depth determination as a feasible identification technique at the limits of detection by a small number of stations.

Reasoning along these lines is the summary basis for the generally accepted contention that with a finite number of sensitive stations all earthquakes with

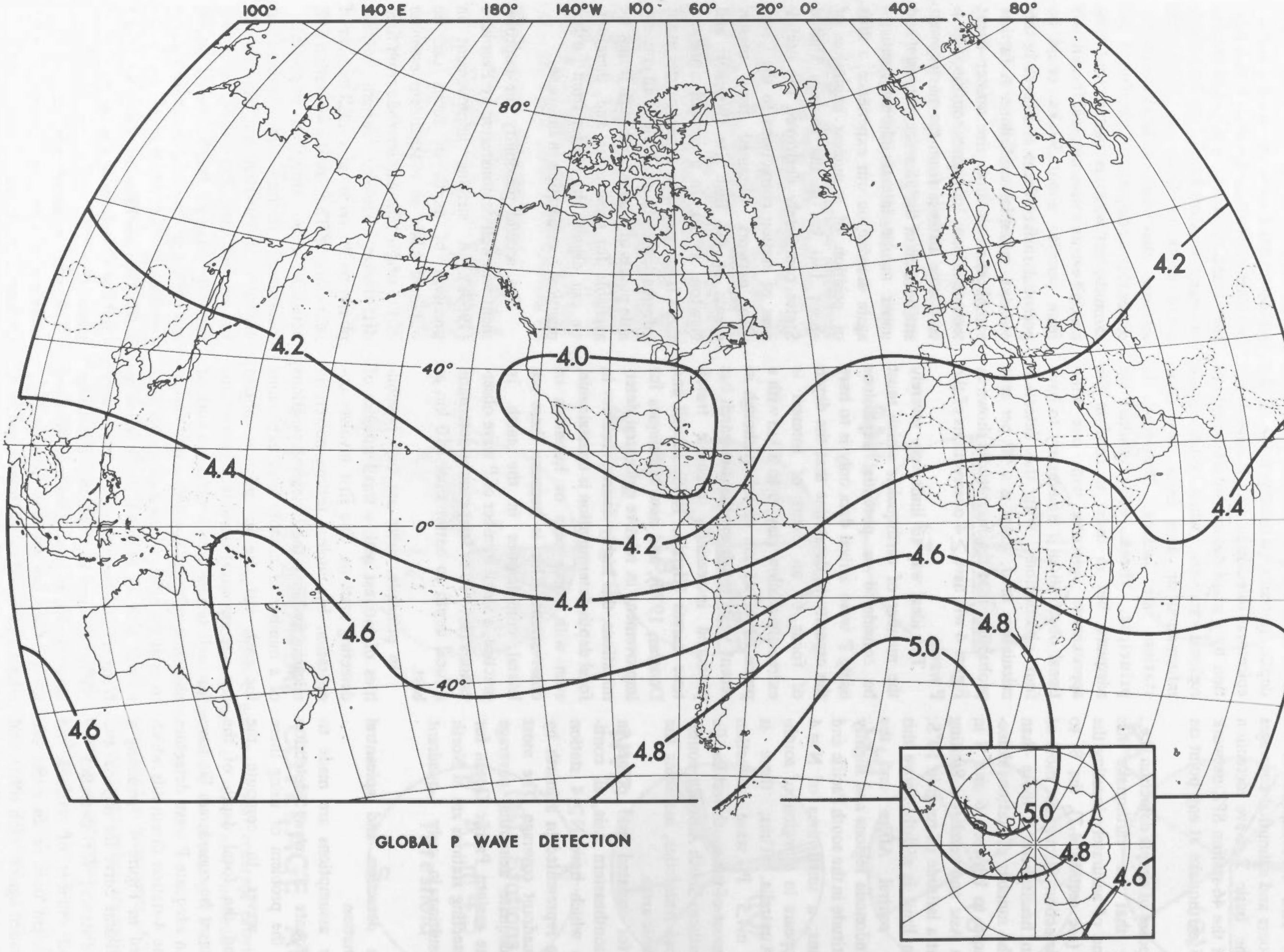

Figure 4. Global contours of the 4-station earthquake P wave detection threshold. A shallow earthquake with this P wave magnitude will have a 90 per cent probability of P wave detection by ≥ 4 stations of the 46-station SPZ network.

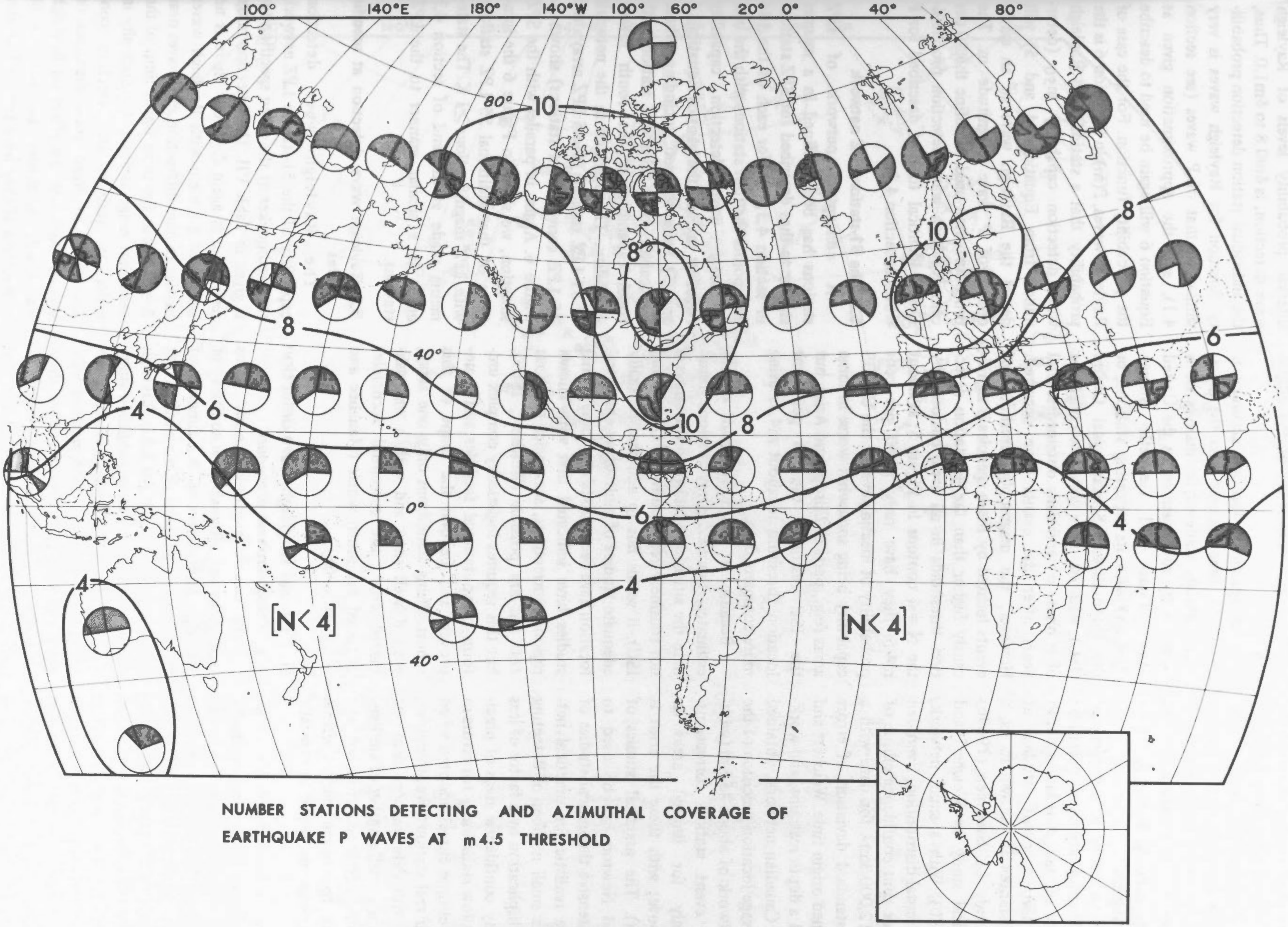

Figure 5. Number of stations detecting and azimuthal coverage provided by the 46-station SPZ network for earthquake P waves at a threshold m4.5. See text for procedure for representing azimuthal coverage by radial plot shading.

crustal depths need testing, in principle, as potential nuclear explosions against a number of identification criteria. The depth of focus derivable in the general case, in practice, with a small number of detecting stations, even if reasonably well distributed in azimuth, is too uncertain for use as a criterion.

It is now necessary to consider the question of location accuracy, accepting this ambiguity of, say, ±30 km in depth of focus. Two relevant studies at teleseismic distances are known to us, a theoretical study by Evernden (1969b) and a practical study by Weichert and Newton (1970). With a small network, and a 1-quadrantal distribution, Evernden gives a 95 per cent confidence ellipse of area about 12,000 km^2 for data with a 0.5 second standard deviation of errors and a restrained origin time. Weichert and Newton used a depth restraint, and working with the Canadian network, obtained a typical average location precision of the Canadian network of about 45 km (without master event station corrections, available only for limited areas as described above; with these the error is about 5 km). The practical studies of Weichert and Newton can be used to show the extensive theoretical studies of Evernden are realistic for practical networks with a small number of detecting stations: multiplication by a factor of less than 2 in any confidence areas of precision should allow statistically for errors in the best travel-time curves adopted when working with real stations. We, therefore, believe that with data in more than one quadrant from a small number of stations, and with no master control but the best possible travel-time curves, errors in epicentral positions should be typically 20-45 km.

Referring to the azimuthal coverage presented in Figure 5, it can be concluded that, using the 46-station network, errors in epicentral position for m4.5 events at all locations enclosed by the N = 4 contour should not exceed 20-45 km. There may be minor exceptions to this at the fringe of the N = 4 contour and at other isolated locations of poor azimuthal coverage, for which cases the 95 per cent confidence ellipses (see Evernden, 1969b) may be elongated and the exact precision would require knowledge of the ellipse shapes.

This epicentral location accuracy is about two times poorer than the precision routinely achieved for many station locations by such agencies as the United States Coast and Geodetic Survey (USCGS) with its reporting stations, or the International Seismological Centre (ISC), with its more complete collection of P phase observations obtained several years after the events have occurred. However, the magnitude thresholds of events located by these agencies is significantly higher than the 46-station detection thresholds in all areas enclosed by the N = 4 contour in Figure 5; at about m4.5 they have only a 50 per cent probability of locating events, the USCGS capability being somewhat worse in some areas (e.g., parts of Europe and Asia), but the ISC restoring the 50 per cent location threshold to about m4.5, using more complete data.

Because, at the lower limit of our estimates, the SPZ array stations dominate the situation (data from the arrays is not routinely reported to the USCGS and ISC), it seems fair to add that no really adequate studies of multi-array epicentral location have been published. Some partial studies have indicated that with known regional corrections, accuracies of about ±60 km are possible (Weichert, 1969), but this requires logistically complex uniform computational facilities and is unproven and beyond the scope of this report. Using data from only one array, even if well sited and with a well calibrated crust, the epicentral accuracies obtained are much worse (Manchee and Weichert, 1968).

5. Global Rayleigh wave detection

5.1 Computational procedure

The two data sources known to us that present interval probabilities of Rayleigh wave detection as a function of the P wave magnitudes of the earthquakes are by Lacoss (1969a) for LAO Rayleigh wave detection, and an unpublished study by the authors of Rayleigh wave detection at the Canadian LPZ stations SES, OTT and ALE. Both these studies show that the P wave magnitude range, between the 10 per cent and 90 per cent interval probability levels of Rayleigh wave detection, is δm0.8 to δm1.0. Thus, the individual station detection probability function for Rayleigh waves is very similar to that of P waves (see section 4.1), and the approximation given as Equation 6 will again be used to describe the probability function. For the case of Rayleigh waves, P(m) in Equation 6 is the probability that a station with Rayleigh wave detection capability m_{50} (determined from Equations 4 and 5) will detect the Rayleigh wave of an earthquake of P wave magnitude m. The procedure then used to define the 90 per cent Rayleigh wave detection probabilities is identical to that described for P waves in section 4.2.

5.2 The 51-station LPZ network

A conceptual network of LPZ stations has been defined in a manner similar to that described for SPZ stations in section 4.3; i.e., for each of the 146 grid points the four stations with the best Rayleigh wave detection capability (smallest m_{50} on the basis of Equations 4 and 5) were selected, including, where applicable, more than one station with equal capability at the fouth lowest capability. This resulted in the network of 51 LPZ stations (the 5 LPZ arrays and 46 LPZ conventional stations) shown in Figure 6. Again, in parallel with the SPZ situation, we show in Figure 6 the locations of the additional 55 LPZ stations with LPZ magnifications ≥1 K. The statements made at the end of section 4.3 apply in a similar manner to the LPZ stations.

5.3 Rayleigh wave detection at specific sites

The Rayleigh wave detection capability of the 51-station LPZ network for earthquakes at the seven specific sites is given in Table VII. The detection range restriction is again $\Delta \leq 90°$. There is no associated problem with Rayleigh waves similar to core diffraction of P waves near $\Delta = 90°$, but the same upper limit of the detection range is applied, principally in order to restrict all detection considerations to third zone distances or shorter. Although the effect on Rayleigh waves will, in theory, be only one of attenuation if they have travelled greater

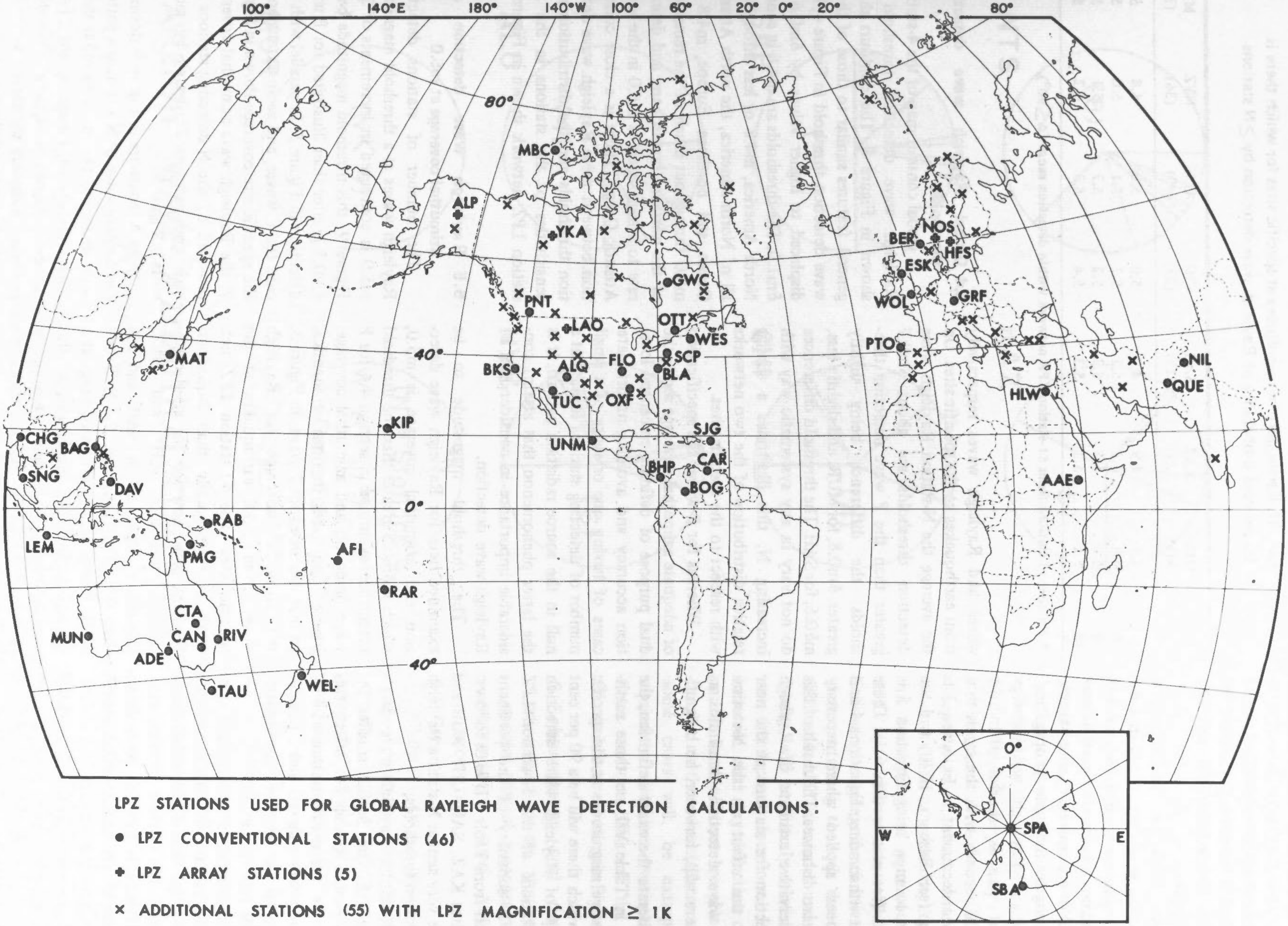

Figure 6. Conventional and array stations in the 51-station LPZ network used for global Rayleigh wave detection calculations. The 55 station locations shown without station code names are all additional stations from Table II with LPZ magnification ≥ 1 K.

distances, there would be problems at great distances of associating both the Rayleigh and P wave to a specific event for stations having both LPZ and SPZ instrumentation.

However, there is an associated problem at the near distances in that the detection equations applied, Equations 4 and 5, are known to be inaccurate at near distances. For near distances, and particularly for continental path propagation, the dominant Rayleigh wave energy appears at periods shorter than the assumed 20 seconds with the result that the distance decrement in Equation 3 is too strong (see Basham, 1970) and the conversion to m_{50} using Equation 5 is invalidated (see also section 6.3). These effects notwithstanding, Equations 4 and 5 have been applied where necessary down to zero distances. The result of this is a conservative estimate of Rayleigh wave detection for stations at the near distances; the effect on the N-station Rayleigh wave detection thresholds as defined here will, however, be insignificant.

To reiterate the exact definition, the m values in Table VII are those earthquake P wave magnitudes at the specific sites for which there will be a 90 per cent probability of Rayleigh wave detection by ≥N stations of the 51-station LPZ network. A summary of the pertinent conclusions from Table VII is as follows:
(a) the sites KAZ, SAH, CHI, ALU and NVZ have very similar N-station Rayleigh wave detection thresholds,
(b) the N-station Rayleigh wave detection thresholds are δm0.2 smaller for NTS and δm0.3 greater for MUR, this being due to the concentration of LPZ stations in North America and a paucity of stations in the southern hemisphere, respectively (see Figure 6),
(c) the high-latitude sites (ALU and NVZ) have more LPZ stations within detection range than do the mid-latitude sites,
(d) the 10-station Rayleigh wave detection thresholds are about δm0.4 greater than the 4-station thresholds.

A comparison of Tables VI and VII will illustrate the relative capabilities of the 46-station SPZ network and the 51-station LPZ network in detecting P waves and Rayleigh waves respectively from earthquakes at the specific sites. On the average the N-station Rayleigh wave detection thresholds are about δm0.7 greater than the P wave detection thresholds, the difference being slightly greater, δm0.8, for MUR, and slightly less, mδ0.6, for SAH. The threshold differences do not vary in any systematic way with increasing N; this illustrates a similar relative distribution of the two networks with respect to the specific sites.

Table VII. Earthquake m magnitudes at specific sites for which there is a 90 per cent probability of Rayleigh wave detection by ≥N stations

N	NTS (31)*	KAZ (29)	SAH (27)	CHI (27)	ALU (40)	NVZ (36)	MUR (31)
4	4.7	4.9	4.9	5.0	5.0	4.8	5.3
6	4.9	5.1	5.1	5.1	5.1	5.0	5.4
8	5.0	5.2	5.2	5.2	5.2	5.1	5.5
10	5.1	5.3	5.3	5.4	5.3	5.2	5.6

* Number of stations from 51-station LPZ network within detection range (Δ≤90°).

Whereas for P waves the specification of adequate azimuthal coverage serves the dual purpose of defining epicentral location accuracy and avoiding unfortunate cases of having one or more of a small number of detecting stations located at a null in the source radiation pattern, it is the latter phenomenon that attains considerable importance in consideration of Rayleigh wave detection.

The threshold magnitude to be examined here for Rayleigh wave detection and azimuthal coverage is m5.0, which is δm0.5 greater than the threshold magnitude examined in section 4.4 for P wave detection and azimuthal coverage. Figure 7 illustrates, in a manner identical to that described for P waves in Figure 3, the azimuthal coverage for Rayleigh waves from m5.0 earthquakes at the specific sites. The 51-station LPZ network provides greater than 2-quadrant Rayleigh wave coverage for m5.0 earthquakes at KAZ, CHI and NVZ, 2-quadrant coverage for SAH, and less than 2-quadrant coverage for NTS and ALU. Fewer than 4-station coverage at a particular threshold magnitude, in this case m5.0, is considered inadequate detection; this is the case illustrated for MUR in Figure 7.

5.4 Global Rayleigh wave detection thresholds

A global contour map of the 4-station Rayleigh wave detection threshold is shown in Figure 8. The contours show general features similar to those of the P wave detection threshold in Figure 4, but displaced to higher values by δm0.6 to δm1.0. The thresholds are m4.6 in central North America, m4.8 or less throughout all of North America, the north Atlantic Ocean and northern Europe, m4.8 to m5.0 throughout much of the remainder of the northern hemisphere, and deteriorate to a high value of m6.0 in the south Atlantic Ocean. There is a close correlation between these Rayleigh wave detection thresholds and the distribution and sensitivities of the stations in the 51-station LPZ network shown in Figure 6.

5.5 Rayleigh wave detection and azimuthal coverage at m5.0

The number of stations detecting Rayleigh waves at a threshold magnitude m5.0 is contoured in increments of 2 in Figure 9, this threshold magnitude being δm0.5 greater than illustrated for P wave detection in Figure 5. In parallel with the case for P waves, and as an extension of the specific site coverage shown in Figure 7, the Rayleigh wave azimuthal coverage provided by the N detecting stations for each grid point is illustrated by radial plots in Figure 9.

The N contours in Figure 9 down to the limiting value of N = 4 have a pattern very similar to the m4.6 to m5.0 threshold contours of Figure 8; the N = 4 contour in Figure 9 and the m5.0 contour in Figure 8 display the same basic information. The azimuthal coverage for Ray-

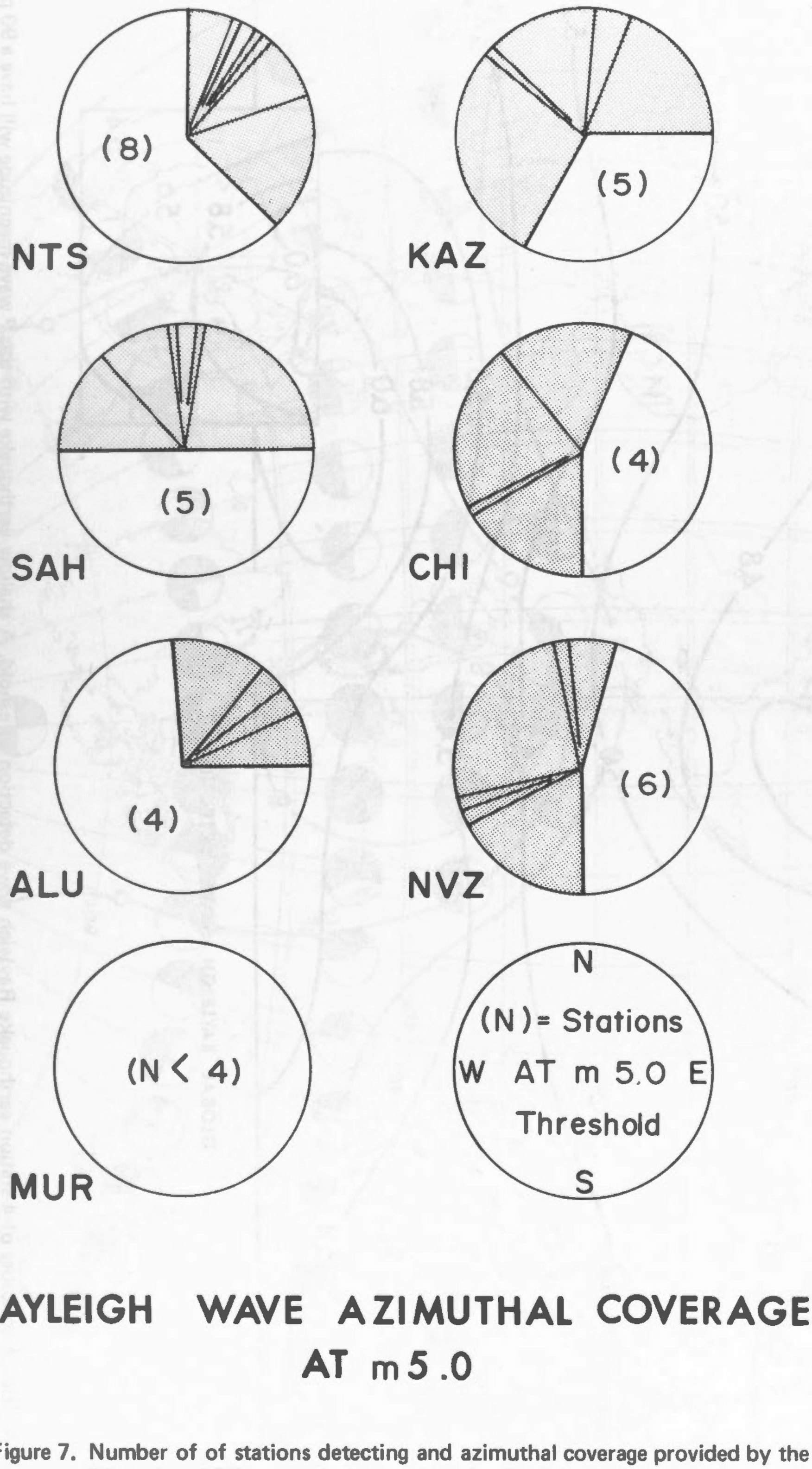

Figure 7. Number of of stations detecting and azimuthal coverage provided by the 51-station LPZ network for earthquake Rayleigh waves at a threshold m5.0 at the seven specific sites. See text for procedure for choosing N and representing azimuthal coverage by radial plot shading.

leigh waves is generally adequate, 2 or more quadrants, at all locations enclosed by the N = 6 contour, and, except for parts of northeastern and southwestern Asia, there is 2-quadrant coverage between the N = 4 and N = 6 contours.

In choosing to illustrate in Figure 9 the Rayleigh wave coverage at a threshold of m5.0, we have in effect limited consideration of Rayleigh wave detection to northern hemisphere locations. This is justified by the limited capabilities of both P and Rayleigh wave detection in the southern hemisphere illustrated on foregoing maps, which results directly from the lack of availability in the southern hemisphere of numerous sensitive SPZ and LPZ stations. Thus, in the following chapters much of the discussion, pertaining to both the conceptual SPZ and LPZ networks and published results, will be directly related to northern hemisphere locations. It follows, however, that any detection or identification thresholds we are able to define for the northern hemisphere can, and in some cases will, be extrapolated to equivalent southern hemisphere thresholds on the basis of the detection threshold contour maps in Figures 4 and 8.

6. Enhancement and degradation of detection on the real earth; special signal processing, global seismicity and interference phenomena

6.1 General

All the P and Rayleigh wave detection results presented to this point have assumed that the earth is a spherically symmetrical body for which the earth-wide radial average of its properties apply at any point. In particular, the P waves were assumed to obey everywhere the $Q(\Delta,h)$ distance-depth attenuation function and the Rayleigh waves the 1.66 log Δ distance attenuation function. The real earth is known to be quite different from this assumed average and, indeed, it has been the discovery of the numerous anomalies or vagaries in the earth that has led to understanding of important earth processes in recent years.

Many of the earth's vagaries, when sufficiently documented, can make important differences to the narrow field of

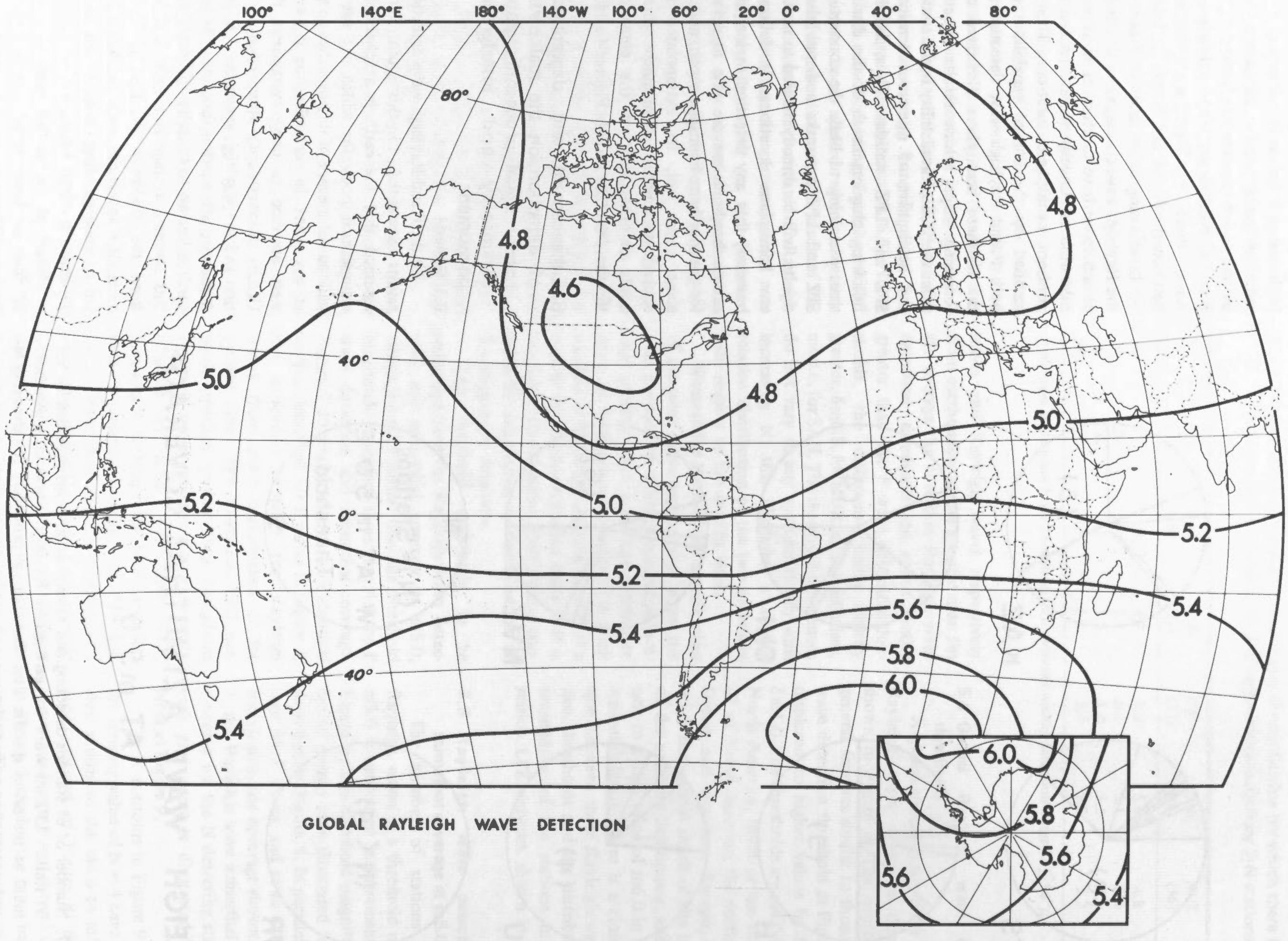

Figure 8. Global contours of 4-station earthquake Rayleigh wave detection threshold. A shallow earthquake with this P wave magnitude will have a 90 per cent probability of Rayleigh wave detection by ≥ 4 stations of the 51-station LPZ network.

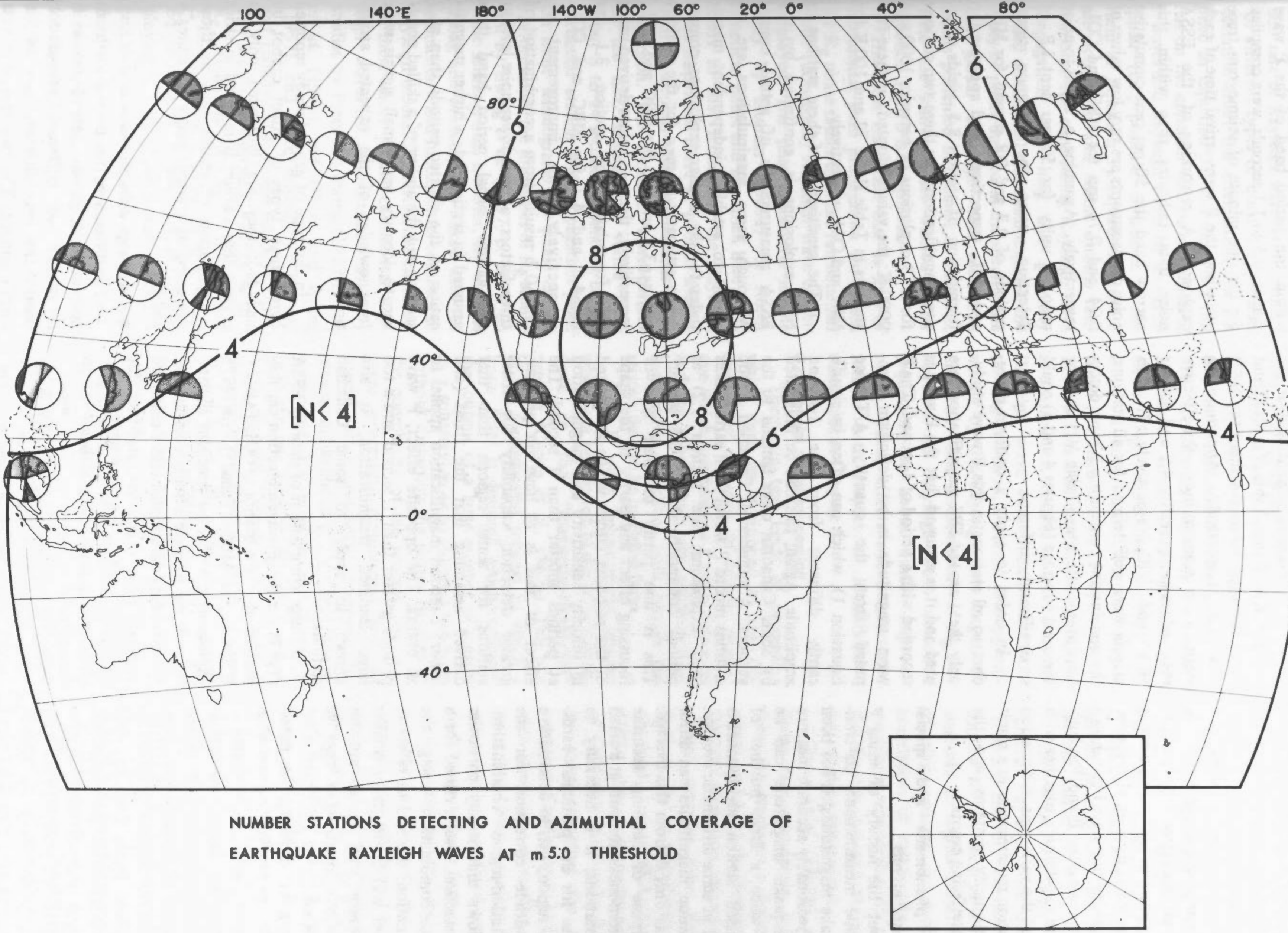

Figure 9. Number of stations detecting and azimuthal coverage provided by the 51-station LPZ network for earthquake Rayleigh waves at a threshold m5.0. See text for procedure for representing azimuthal coverage by radial plot shading.

investigation being considered here: the simple detection of P and Rayleigh waves at given stations for certain magnitude earthquakes. This chapter will deal with some of these phenomena to show how they might change the broad picture of detection so far presented. In addition, this is a useful point in the text to present any specialties of instrumental response and data processing that have been shown capable of improving the P and Rayleigh wave detection capabilities, together with a discussion of the variations in detection and identification requirements as a result of global seismicity patterns and the presence of interfering events.

6.2 P wave phenomena and special instrumental effects

Throughout the history of using P wave amplitude measurements to compute earthquake magnitudes, it has been found that a reasonably accurate measure of the earthquake magnitude can be found only when a large number of widely dispersed station measurements are combined in some arithmetic average. Individual station magnitudes can differ by as much as $\delta m 1.0$ from this average. For the purpose of defining accurate magnitudes from measurements at a small number of stations, it is necessary to calibrate these for the particular earthquake source region, i.e., to determine a station magnitude correction for the particular station-region combination. Thus, it follows that at any particular magnitude detection level defined for a station-region combination using the average Q function, the real or effective detection level will be larger or smaller than the average level by an amount equivalent to the positive or negative station correction.

There is great difficulty in determining the effect of such phenomena on the world-wide P wave detection discussed here because for only a few station-region combinations have such effects been well defined, a problem to be given some emphasis in a later chapter on recommendations. Some Canadian data can be used to illustrate the importance of station-region phenomena to P wave detection. Using two stations with large corrections from the study by Basham (1969a), it can be seen that MBC has a correction of −0.7 and VIC a correction of +0.9 for P waves originating near the test site KAZ* (see Table V). MBC and VIC have m_{50} values for this site of 4.9 and 5.5, respectively. Applying the station corrections to m_{50}, the effective m_{50} values are in reality 4.2 and 6.4 for MBC and VIC, respectively. If such effects were well defined for all stations, the conclusions concerning P wave detection at specific sites (Table VI) and for the areal coverage (Figures 4 and 5) could be significantly different.

In order to apply a uniform procedure to all stations in this P wave study, only the 1-second SPZ magnifications are used and it is assumed that the P wave is recorded with a period of 1 second. The P wave magnitude is by definition computed from the quantity A/T (see Equation 1), which can often be significantly different from the 1-second amplitude. Again, this can be illustrated by some Canadian cases familiar to the authors. A number of Canadian Arctic stations record P waves from earthquakes (and explosions; see section 7.2) at periods commonly 0.6 to 0.8 second. This is due partly to some type of focussing effect and partly to the shape of the response curves which are peaked in velocity sensitivity and magnification at periods shorter than 1 second. The effect of this is to have, in practice, greater detection capability for these stations for some regions than that derived assuming that the fixed (and lower) 1-second magnification applies to all events. The opposite effect, P wave periods greater than 1 second and a too large assumed magnification, is also known to apply to some Canadian stations.

A large compilation of data by ESSA (1967) on the P wave detection capabilities of the two stations, COL (Alaska, U.S.A.) and MBC (Canada), for NTS explosions provides an excellent illustration of the positive effects described in the preceding paragraphs. ESSA compiled detection and magnitude statistics for these two stations for 194 NTS explosions in the period, September 1961 to March 1967; in addition, noise statistics within the period band of the P wave signals, 0.5 to 1.1 seconds, were compiled for the one minute of seismogram trace preceding the P wave arrival time of each explosion. A reworking of the ESSA noise data indicates that within this narrow band the 50 per cent cumulative noise displacements are very low values of 0.34 and 0.74 mμ for MBC and COL, respectively. Assuming a signal-to-noise ratio of unity for 50 per cent I.P. of detection, using the common signal periods of 0.7 and 0.8 second for MBC and COL, respectively, and applying the formulation of section 3.1, yields effective magnifications for these two stations for NTS explosions of between 1000 and 2000 K; the values adopted for these two stations in Table II are 72 and 100 K for MBC and COL, respectively.

The sensitivities of these stations to NTS explosions is confirmed by the ESSA measurements of actual events. Although some manipulations are required to establish independent magnitudes for the smaller explosions, conservative estimates of m_{50} for the stations are $m_{50}3.9$ and 4.0 for MBC and COL, respectively; the m_{50} values derived using the formulation of section 3.1 are $m_{50}4.6$ and 4.7 for MBC and COL, respectively. This improvement of $\delta m_{50}0.7$ results from a combination of three factors: a much lower noise level in the narrow signal period band than assumed in section 3.1, a higher magnification at the shorter periods than at 1 second, and the ability of a skilled observer to identify very small signals with foreknowledge of the expected arrival times.

In the type of general study reported here, these types of effect cannot be included; they are illustrated only to suggest that caution is required in strict interpretation of results such as those presented as contour maps in Figures 4 and 5.

6.3 Rayleigh wave phenomena

The differences that the real earth can make to Rayleigh wave detection occur as a result of different propagation phenomena over different parts of the earth's surface. The two related effects

* These station corrections were determined from explosions, but are known to apply equally well to earthquakes near that region.

requiring attention are the real attenuation rate of Rayleigh waves with distance for different types of crust (i.e., possible deviation from the attenuation rate implied in Equation 3), and the effect this has on the *apparent* relative excitation of P waves and Rayleigh waves by an earthquake (i.e., possible deviations in the form of Equation 5). Equations 3 and 5 are acceptable and usable average relationships for considering Rayleigh wave propagation over long and generally mixed continental and oceanic paths, the types of paths implied in the specific site and global Rayleigh wave detection results presented in Chapter 5. However, there are known cases where neither equation 3 nor 5 is acceptable.

The most important case is that of continental path propagation for which the R_g phase rather than the fundamental mode (20-second) Rayleigh wave can be employed. The phase measured in the study by Basham (1969a) for North American paths and identified here as R_g refers to that section of the Rayleigh wave dispersion curve at periods shorter than 20 seconds which shows little or no dispersion. The dominant wave periods on the LPZ seismograms varied from about 8 to 14 seconds depending on the particular station and propagation path. On most seismograms the phase clearly conformed to the properties of R_g identified by Ewing *et al.* (1957, p. 219); on some seismograms, however, R_g was less strong and probably was mixed with the sedimentary and fundamental continental Rayleigh modes. The distinctive character of these short period continental Rayleigh waves is demonstrated in early studies by Press and Ewing (1952), Press *et al.* (1956) and Oliver and Ewing (1957), and more recently by Basham and Halliday (1969) and ESSA (1970b). The results of Basham (1970) show that R_g attenuates as $\Delta^{-0.8}$ rather than $\Delta^{-1.66}$, appropriate to 20-second waves in Equation 3. The disadvantage of employing the R_g phase is that its shorter period is much nearer the periods of the dominant oceanic microseismic band. However, Rayleigh wave detection using the R_g phase has improved on 20-second detection in both North America (Basham, 1969a; Evernden, 1970c) and Asia* (Thirlaway, see SIPRI (1968)).

Rayleigh wave magnitudes calculated from R_g are, because of larger inherent amplitudes and smaller rates of attenuation, significantly different from those calculated from 20-second Rayleigh waves; R_g magnitudes are typically 0.6 – 1.1 larger than 20-second magnitudes (Basham, 1969b, 1970; Evernden, 1970c). This difference can be considered as a correction relating R_g and 20-second Rayleigh wave magnitudes; when considering detection, however, it is approximately by this Rayleigh wave magnitude difference that measurement of R_g can improve on Rayleigh wave detection (equivalent to about $\delta m0.4$ improvement). These effects will be discussed further with respect to identification thresholds in Chapter 8.

6.4 Special signal processing

There are two kinds of processing which must be mentioned in any discussion of detection of seismic phases: one which can enhance P wave detection and the other which can enhance Rayleigh wave detection; both require the seismic data to be in digital form.

The P wave enhancement process which can be applied to digital SPZ array data is the "maximum-likelihood" process (Capon *et al.*, 1967a). This is a highly sophisticated process in which a linear filter is designed which combines the output of a large number of sensors in a subarray so as to suppress the noise without distorting the signal. Because of the complexity of the process, the computer processing requirement and the special array geometry required for maximum-likelihood processing, it can be considered for possible application at only the two large aperture SPZ arrays, LAO and NOS. However, it can make an important improvement in the P wave detection capability: the LAO improvement quoted in SIPRI (1968) is $m_{90}3.9$ for maximum-likelihood processing compared with $m_{50}3.8$ for standard beam forming. This is an m_{50} improvement of about $\delta m0.3$ (see section 4.1). However, since we consider here N-station P wave detection thresholds with $N \geq 4$, the possible application of maximum-likelihood processing at the two arrays that already have the best detection capability without the application of this special process will have little effect on our conclusions.

* The improvement for Asia is our interpretation of the SIPRI statement which reads in part: "When magnitude determination at 20 seconds proves impossible at near distances, Thirlaway considers 12-second period waves and applies an appropriate correction."

The process which has been used to enhance Rayleigh wave detection is the "matched filtering" process which can be applied to any long period seismic data available in digital form. The matched filtering process is simply a cross-correlation of signal plus noise with a waveform representing the pure signal. If the signal is present in the noise, it will be enhanced by this process.

Capon *et al.* (1967b), using a simple linear frequency-sweep reference waveform (to represent a dispersed Rayleigh wave) on LAO data, demonstrate an 8 db ($\delta M0.4$) detection improvement over a phased sum for Asian Rayleigh waves. Basham, in an unpublished study, has obtained, using YKA data, a similar $\delta M0.4$ detection improvement for Gulf of California earthquake Rayleigh waves by cross-correlating the full Rayleigh wavetrain (including R_g) of a large event with wavetrains of smaller events hidden by noise. Using Equation 5, the $\delta M0.4$ values can be considered equivalent to 0.2 to 0.3 improvement in m_{50}.

It is only the LPZ array facilities and possibly a few of the conventional stations that will have LPZ data readily available in digital form, and thus have the potential (it will require additional off-line digital processing) capability to apply matched filters. However, since the world-wide Rayleigh detection is strongly dominated by the LPZ arrays, the N-station Rayleigh wave detection thresholds for small values of N (say, N = 4) have the potential of being reduced by about $\delta m0.2$ using this process.

6.5 Global seismicity and interference phenomena

To this point, we have considered the thresholds of detection of P waves and

Rayleigh waves for the conceptual networks; for both waves we have considered azimuthal coverage provided by the detecting stations. Before proceeding further, it is important to make a number of distinctions as follows for a general approach to the identification problem. All points on the earth's surface are not conceivable locations for underground nuclear explosions for a variety of obvious reasons. However, conceivable locations (this includes test sites in present use) can be in either seismic areas, or areas with minor and often ill-defined seismic activity, or virtually aseismic areas. For each of these three situations, the problem of explosion identification is, in practice, different. The highly seismic and the virtually aseismic areas of the earth are geophysically and geographically well defined; see, for example, Barazangi and Dorman (1969). Areas of low seismicity are, however, present which have an earthquake occurrence rate and areal extent which are less well defined, and these complicate the problem.

The philosophy of identification adopted in Chapter 8 is that, given an event which requires identification, the location of that event is both a conceivable location for an underground explosion and a probable location for a natural earthquake. This is the most conservative approach, since in an aseismic region the threshold for identification is the threshold for detection with adequate location accuracy: in a region of major or minor seismicity the threshold for identification is appreciably higher as will be demonstrated later. A potential violator, in a test ban context, is assumed in this approach to have access to a seismic region in which clandestine testing may theoretically be attempted.

Some specific examples may clarify the distinction we are seeking to make. A shallow seismic event in the earth's crust beneath a highly populated area is extremely unlikely to be a clandestine underground explosion, whereas a shallow seismic event in an historically aseismic Precambrian shield area is unlikely to be a natural earthquake, and would at least be a suspicious event in a test ban context. In the former example, the requirement for identification is obviated; in the latter example there could be immediate suspicion of clandestine testing for any event above the detection threshold, even though formal identification by techniques to be described later would only be possible if the event were above the higher identification threshold.

A further assumption in our treatment of detection and identification is that events being considered are recorded in the presence of continuous natural background noise, but in the absence of other unrelated but simultaneously occurring events. Over a long time period, say, one year, some approximate assumptions concerning the number of P waves visible at a relatively sensitive station per day and the duration of the P wave signal can be used to estimate that the probability of having an interfering P wave disrupt or mask the P wave of the event under consideration will be about 1 per cent, and will, therefore, not seriously alter calculations of P wave detection probabilities. The case of interfering Rayleigh waves is somewhat more important. Some unpublished studies by the authors have shown that the probability of encountering an interfering Rayleigh wave at any point in time on an LPZ record is about 15 per cent. If it is assumed that no useful measurement can be made in the presence of an interfering event, regardless of the magnitude of the event of interest, then the interval probability of Rayleigh wave detection from an event of interest will be zero 15 per cent of the time, i.e., limited to a maximum of 85 per cent. If this were combined in a statistical approximation with the Equation 6 detection probability function, the Rayleigh wave detection probability of an individual station would be reduced by about 0.1 over the m-range covered by Equation 6. The consequent effect on the N-station Rayleigh wave detection thresholds would be an increase in the threshold of about $\delta m 0.1$. This correction will not be made, so it must be remembered that the results presented apply only in the absence of interfering Rayleigh waves.

A further complication, by a potential violator design, can arise if one anticipates the worst possible combination of the global seismicity and interference phenomena mentioned above, the phenomena of earthquake swarms and aftershock sequences. There are numerous occurrences annually of swarms of earthquakes (many earthquakes of varying magnitude occurring within a relatively small area) and sequences of earthquakes of generally diminishing number and magnitude following a large earthquake. The problems of discriminating a possible explosion from within one of these sequences would be much more severe: (a) if it were suspected at a location near the earthquake sequence, because of the great number of natural events with which it must be compared and by which it might be masked, and (b) if it were suspected at a location anywhere else on earth, because of the presence on all world seismograms of interfering P and Rayleigh waves resulting from the natural event sequence.

7. Detection of underground explosions

7.1 Assumed characteristics of the explosions

All discussions of detection to this point have assumed the P and Rayleigh waves originated from an earthquake with a focal depth of about 25 km. Here, all available information will be applied to interpret the same network detection capabilities assuming the source of the waves is an underground nuclear explosion of shallow depth.

Numerous references have appeared in the literature relating the size of the explosion (the explosive yield), the medium in which the explosion is detonated and the effects of cavity decoupling (where feasible) to the seismic magnitude; see, for example, SIPRI (1968) and Evernden (1970a). For purposes of relating the yield of an explosion to an equivalent earthquake, Table VIII presents for hardrock media the range of explosion yields in kilotons that are associated in various literature sources with specific P wave magnitudes. The formally calculated and empirically determined P wave magnitude thresholds to be discussed will, where appropriate, be equated using the data of Table VIII to equivalent hardrock yields. We note that these yield figures for any magnitude would need multiplication by a factor up to 10 for low yield explosions in, for example, dry alluvium. Decoupling factors of more than 100 have been obtained by detonating low yield explosions in suitable cavities. Since we can add nothing new in a discussion of the effects of the variables of explosion emplacement, we note the vital relevance of these problems to test ban considerations, and proceed.

Table VIII. Range of hardrock nuclear explosion yields associated with specific P wave magnitudes

P Wave Magnitude (m)	Yield Range (Kilotons)
4.0	1 – 3
4.5	3 – 10
5.0	10 – 20
6.0	100 – 200

7.2 Explosion P waves

It is the P waves which, by definition, are used to equate underground explosions to equivalent earthquakes, and any discussion of P wave detection can, in theory, apply to both explosion and earthquake sources. However, there are two effects that can make minor differences to explosion P wave detection.

The first is the Q(Δ,h) distance calibrating function used to compute P wave magnitudes. For the earthquakes, a Q for a fixed depth of 25 km was applied to computations of P wave detection. Underground explosions are confined, by engineering considerations, to a maximum depth of about 3 km, and thus the appropriate Q would be the one for this depth, or, say, for surface focus events (h = 0). The Q function being used has Q(Δ,0) equal to Q(Δ,25 km) over 50 per cent of the 20° to 90° range, 0.1 larger than Q(Δ,25 km) over 36 per cent of the range, and 0.1 smaller than Q(Δ, 25 km) over the remaining 14 per cent of the range. Thus, the maximum difference for explosions at a single station can be $\delta m_{50}0.1$, but is more likely to be negligible when considering N-station thresholds.

The second factor is a characteristic of recorded explosion P waves which contributes to their identification using short period discrimination criteria, but which can also alter the ability to detect them. This is the generally impulsive character and shorter dominant periods of explosion P waves. The effects of this have been described in section 6.2 in relation to more favourable short period instrumental effects and, although the effect is important to detection at certain stations, it is difficult to include in a consideration of global coverage.

Therefore, bearing in mind the two factors discussed above, together with the other phenomena described in section 6.2, all the P wave detection results so far presented can be assumed to apply equally to earthquakes and underground explosions. The positive effects described in section 6.2 suggest that the calculations presented earlier in Table VI, for example, err on the side of being slightly conservative – in any case we believe them to be realistic and the best ones that can currently be made. Figure 5, for example, can be interpreted as showing conservatively the number of network stations detecting P waves, and the azimuthal coverage, for underground nuclear explosions of 3-10 kilotons yield, detonated in hardrock.

7.3 Explosion Rayleigh waves

The fundamental difference between an earthquake and an underground explosion is in the nature of the source and, in particular, in the geometry and size of the source. The major influence this has on the resulting seismic waves is a marked reduction in the excitation of explosion surface waves compared to a similar P wave magnitude earthquake. A review of theoretical consideration of this phenomenon has been given by Liebermann and Pomeroy (1969). This effect provides one of the most useful criteria for distinguishing between an earthquake and an underground explosion, a matter given full consideration in section 8.3. Here we shall be concerned with the effect this phenomenon has on changing the detection capabilities for explosion Rayleigh waves compared with the case for earthquakes. The problem will be attacked by determining the average amount by which explosion Rayleigh waves are reduced, and applying this to the detection results already presented for earthquakes.

The reduction in explosion Rayleigh waves will appear in a new form of Equation 5 which can be applied to explosions. It is apparent that each study of M versus m for explosion, reported in the literature, results in a different form of Equation 5; see, for example, SIPRI (1968), Liebermann and Pomeroy (1969), Capon *et al.* (1967b), Basham (1969a, 1969b) and Liebermann and Basham (1970). However, earthquake Rayleigh wave detection was computed using an earth-wide average value of M versus m given as Equation 5; it is convenient, therefore, to adopt an earth-wide average form of Equation 5 for explosions. Studies which have been based on earthquakes and explosions in the same geographic region and restricted to or adjusted to only 20-second waves (Capon *et al.*, 1967b; Basham, 1969b) show earthquake and explosion M versus m relationships nearly parallel and separated by 1.5 to 2.0 in M. Magnitudes based on R_g (Basham, 1969a; Evernden, 1970c) also show parallel relationships, but they tend to be nearer, separated by about 1.4 in M. For purposes of discussion of global explosion Rayleigh wave detection, a parallel relationship separated by 1.5 in M will be applied. Thus, Equation 5 for explosions takes the form

$$M_{50} = 1.59\ m_{50} - 5.47 \quad \ldots.\ 7$$

Rather than present new tables and figures for explosion Rayleigh wave detection, the difference this makes can be stated quite simply. The application of Equations 4 and 7 to explosions increases all Rayleigh wave m_{50} station capabilities presented for earthquakes by about 1.0. The R_g relationships have slopes near 1.4 rather than 1.59 as in Equation 7; because they are separated by $\delta M1.4$ rather than $\delta M1.5$ to 2.0, the $m_{50}1.0$, the N-station threshold magnitudes will shift upward an equal amount. That is, Table VII and Figure 8 apply to explosion Rayleigh wave detection with the threshold magnitudes increased by 1.0, and Figure 9 applies to explosions at a threshold m6.0, or 100-200 kilotons in hardrock. It should be recalled that Figure 9 presents the situation without the gains from matched filtering, obtainable at particular stations, or from the continental path propagation, obtainable for particular station-site combinations.

At a later stage, explosion yield equivalents will be reintroduced briefly in a discussion of important new relationships between explosion yield and surface wave magnitudes (R_g and 20-second) which have recently been defined.

8. Identification of earthquakes and explosions

8.1 Identification criteria

The state-of-the-art in seismological discrimination between natural earthquakes and underground explosions to the year 1968 is presented in excellent summary form in the SIPRI (1968) document. A table in that document (p. 62) lists 10 discrimination criteria, three of which are described as "positive identifiers" above a certain threshold magnitude, and seven of which (including the positive identifiers) are described as "diagnostic aids" to identification.

A great deal of research has been published on these 10 and other discrimination criteria since 1968. The basic conclusions concerning discrimination, however, have not changed significantly from those presented in the SIPRI document: the same three "positive identifier" criteria are considered of most value in identifying underground explosions. The three criteria are listed by SIPRI as surface wave: body wave magnitude, Rayleigh wave spectra, and P wave spectra. The concept of these three criteria in total or in combination can be considered as discriminating between earthquakes and explosions on the basis of the total spectrum of seismic energy released by the two types of sources. Although some of the less useful criteria will be considered in various ways in this chapter, the majority of the discussion will be confined to these three criteria and this concept of differences in the total seismic wave spectrum between earthquakes and explosions.

The entire discussion can be confined to consideration of only shallow focus (say $h < 50$ km) earthquakes by assuming the capability exists, either by least-square hypocentral determination or by observation of pP phases, of accurately defining focal depths greater than 50 km and thereby positively identifying such deep events as earthquakes. Section 4.7 explains why, in the low magnitude range, all shallow focus earthquakes are potential explosions in terms of the accuracy achievable in depth of focus.

Differences in the total seismic spectra of earthquakes and explosions appear over a wide range of frequencies, and are apparent in a wide variety of both body wave and surface wave phases. They are most distinct, or most easily measured, within the short period P waves, in the relative excitation of Rayleigh and P waves and within the Rayleigh waves. These three criteria are the major topics for discussion in the next three sections.

8.2 P wave spectral ratio

The P wave spectral ratio criterion often uses a measure of the ratio of energy in two frequency bands in the P wave. The results have shown that shallow earthquakes tend to have relatively more low frequency energy in the P wave than do explosions. Results using this type of method are available from studies in the U.S.S.R. (see SIPRI, 1968), Japan (see SIPRI, 1968), United States (see Lacoss, 1969b) and Canada (see Basham *et al.*, 1970, and Weichert, 1970). Both the methods and the conclusions differ among these studies. The Japanese and U.S.S.R. methods use measurements from visual seismograms; the United States and Canadian methods use Fourier analysis of digital array data.

The conclusions of the U.S.S.R. and Japanese studies, that the frequency content of P waves of earthquakes and explosions are sufficiently different so as often to be apparent on visual seismograms, are quite valid, but the method is not sufficiently rigorous and their statistics too poorly defined to be of value to a discussion of world-wide identification. Most seismologists have observed this characteristic of earthquake and explosion P waves: we require here a rigorously defined quantitative measure of this difference in frequency content and, therefore, will confine discussion to the United States and Canadian results.

The spectral ratio used for the LAO phased beam (Lacoss, 1969b) is the ratio of energy in a high frequency band (1.45 – 1.95 Hz) to the energy in a low frequency band (0.35 – 0.85 Hz), applied to P waves of both 10 and 20 seconds duration. The process applies a strict signal-to-noise ratio criterion in each frequency band. When plotted as spectral ratio versus LAO P wave magnitude, a suite of 82 earthquakes (with $h < 100$ km) and 33 explosions in Asia has the two populations separated nearly completely by a decision line which is a smooth function of magnitude; the exceptions are five earthquakes which appear on the explosion side of the decision line. Four of these earthquakes can be identified as such by the application of other discrimination criteria, an important point in itself which demonstrates the multivariate nature of the discrimination problem. Thus, for the process as defined, the spectral ratio at LAO has a high (but undefined) probability of correctly identifying both earthquakes and explosions in Asia.

Lacoss (1969a) presents some data on interval probabilities that the spectral ratio can be applied to a P wave. There is a 50 per cent I.P. of applying the spectral ratio at about m4.5, which is about δm0.6 greater than the magnitude of m3.9 at which there is a 50 per cent I.P. of LAO detecting the P wave.* Here, we cannot extrapolate this LAO success to other regions or to other short period arrays and can state only that LAO has a 50 per cent I.P. of identifying Asian events at the m4.5 level. Using either the I.P. distribution of Lacoss or adapting Equation 6 for this purpose, LAO spectral ratios will have a 90 per cent I.P. of identifying Asian events at about the m4.9 level.

* Note that in section 3.2 we assumed that the 50 per cent I.P. of LAO of a P wave was m3.8, using the SIPRI reference. The difference δm0.1 is due to a greater distance to KAZ than assumed to apply at mid-third zone distances in section 3.2.

The reason that these results cannot be extrapolated to other SPZ arrays or to a general world-wide coverage is that no other P wave spectral ratio study has yet shown equal success in identification. Basham *et al.* (1970) using YKA data show complete separation between small NTS explosions and aftershock earthquakes of large NTS explosions, but the data base was very restricted (three events of each type). However, the events ranged in magnitude from m4.2 to m4.6 with the smallest of the events having a sufficiently high signal-to-noise ratio to make the spectral ratio application meaningful. It appears, therefore, that the 90 per cent I.P. threshold of application (which will not necessarily be the threshold at which the criterion is a successful discriminant) may be significantly below m4.9; this process is being tested with a large suite of NTS explosions and United States earthquakes at the time of writing.

Weichert (1970) in a comprehensive examination of the spectral ratio method applied to Asian events cannot completely separate earthquakes and explosions using YKA data. His data sample goes down to magnitude m4.5 for earthquakes and m4.8 for explosions. The best process Weichert has found, average third moments of the P wave spectra, results in about 80 per cent of the shallow earthquakes overlapping 20 per cent of the explosions, with the data regionalized. Thus, as neither the Asian P wave spectral ratio data of Weichert nor the preliminary NTS spectral ratio data (E.B. Manchee, personal communication) using YKA records result in a threshold magnitude above which the criterion can be described as a "positive identifier", the Canadian P wave spectral ratio method is simply a "diagnostic aid" with overlapping population at all magnitudes.

The threshold of application of the P wave spectral ratio method (whether at that threshold it is a positive identifier or a diagnostic aid) is much lower than the threshold of application, particularly for explosions, of the two criteria requiring measurement of Rayleigh waves (see sections 8.3 and 8.4). The method, therefore, retains considerable value for the application, in the absence of positive identification, of a multivariate analysis (the combined application of all available imperfect criteria to the problem of discrimination). This multivariate analysis can include, in addition to spectral ratio data, correlogram complexity data such as that described by Whitham *et al.* (1968), any depth of focus information, "negative" Rayleigh wave criteria (see section 8.5), etc.

8.3 Relative excitation of P and Rayleigh waves

The spectral ratio described in the previous section is confined to a narrow frequency band within the P wave signal. Similar differences between earthquakes and explosions at longer periods of the total spectrum are usually described by a measure of the relative excitation of the long period surface waves (Rayleigh) and the short period body waves (P), or as a ratio of two bands of energy within the long period waves (see section 8.4)

The simplest method of defining the relative excitation of P and Rayleigh waves is to use the straightforward phase amplitude measurements required for calculation of magnitudes from the two types of waves, i.e., by comparing earthquakes and explosions by their M versus m relationships. It is for this discrimination criterion that the greatest body of results are available; SIPRI (1968) contains all significant results achieved prior to that date; see also Capon et al. (1969), Lacoss (1969b), Liebermann and Pomeroy (1969), Basham (1969a, 1969b), Molnar *et al.* (1969), Lambert *et al.* (1969), Liebermann and Basham (1970) and Evernden (1970c) for more recent results. In 1968, arguments were still raised about the validity of this criterion at low magnitudes: we now believe that there is clear proof (see, for example, Evernden, 1970c) that, provided the appropriate waves can be detected, the method works at least down to magnitudes below those considered in this report.

The form of M versus m for earthquakes and explosions and the separation between populations when plotted in this manner have been discussed briefly in section 7.3. Although the scatter of individual events with respect to average relationships of the forms of Equations 5 and 7 is very large, and the regional variations in Rayleigh wave propagation phenomena produced large variations in the forms of Equations 5 and 7, in all studies the populations of earthquakes and explosions are sufficiently separated to allow consideration of this criteria as the most successful positive identifier of shallow earthquakes and underground explosions. It is apparent from each set of research results that the magnitude threshold above which the criterion can be applied is (in the absence of interfering Rayleigh waves) equal to the magnitude threshold at which the explosion Rayleigh wave can be detected. This occurs because, as explained in sections 5.3 and 5.4, the earthquake Rayleigh wave detection threshold is about δm0.7 higher than the P wave detection threshold and because, as explained in section 7.3, the explosion Rayleigh wave detection threshold is about δm1.0 higher than the earthquake Rayleigh wave threshold. Thus, the problem of discrimination using this technique reduces to one of detecting explosion Rayleigh waves and can be considered in the separate ways that Rayleigh wave detection has been considered in previous sections.

Consider first the six northern hemisphere specific sites in Table V, and adopt 4-station thresholds with some azimuthal variation as adequate for identification purposes. The earthquake Rayleigh wave detection thresholds of m4.7 – m5.0 (see Table VII) increase to explosion detection and identification thresholds of m5.7 to m6.0, using the gross average properties of the earth and ignoring for the moment the advantages gained by Rg continental propagation and matched filter processing. The equivalent available empirical study supports this formal calculation: Basham (1969b) demonstrates positive identification of KAZ and NVZ explosions at a threshold of about m6.0 using relatively insensitive conventional Canadian stations; this threshold can, therefore, be expected to reduce to about m5.7 using more sensitive conventional and array stations from the 51-station LPZ network.

Applying matched filters to specific site explosions, the possible threshold reduction is δ0.2 to δm0.3, assuming each of the stations involved has the capability of applying the matched filtering process (see section 6.4). The only published result is, in effect, one-station coverage for which the threshold has naturally been reduced below the 4-station requirement we have adopted. Lacoss (1969a) demonstrates that applying matched filters to LAO data for KAZ explosion Rayleigh waves yields a 90 per cent probability of detection (and, therefore, of identification) at about m5.4. This, of course, is using one of the most sensitive LPZ systems being considered in this study. It can be estimated from the above data that the 4-station matched filtering threshold, restricted to stations capable of matched filtering, is about m5.6 at the northern hemisphere specific sites.

The possible improvement using R_g and purely continental paths has been demonstrated only for NTS explosions using Canadian and United States stations* (Basham, 1969a; Evernden, 1970c). In this case the available stations are those confined to the same continental mass as the events of interest and thus there is the benefit of shorter propagation paths (maximum Δ about 40°) as well as the smaller R_g wave attenuation with distance (see Basham, 1970). An estimate of the empirical 4-station threshold of explosion R_g detection, and therefore of explosion identification, is about m5.0 using Canadian stations in the distance range 13° to 40°, and about m4.7 using United States stations as near as about 3°. Thus, the use of lower sensitivity conventional stations and taking advantage of shorter paths with purely continental propagation yields an explosion identification threshold lower than that of the most sensitive LPZ systems applying matched filtering to more distant events.

A short diversion to a discussion of some recently determined explosion yield versus Rayleigh wave magnitude relationships will clearly illustrate the proven and potential advantages of using the shorter period continental Rayleigh waves. Until recently the equivalent hardrock yield of an underground explosion has been defined only on the basis of empirically determined, but theoretically supported, relationships between yield and P wave magnitude (the relationships we are applying are shown in Table VIII). Evernden and Filson (1970), observing a similar non-linearity in m versus log-yield and M versus m, derived a new relationship between M and log-yield which has the form

$$M = 1.4 + 1.3 \log Y \qquad \ldots 8$$

where M is determined from 20-second Rayleigh waves and Y is the yield in kilotons. This linear relationship accurately represents the available yield data between yields of about 6 and 1000 kilotons, M2.5 to M5.5. Evernden and Filson also show for explosions that M_{Rg} determined from the 8 to 14 second (R_g) Rayleigh waves is equivalent to M + 1.1; this is in close agreement with the difference derived by Basham (1969b). Thus, we have

$$M_{Rg} = 2.5 + 1.3 \log Y \qquad \ldots 9$$

In an independent study using Canadian magnitude data, Ericsson* derived the relationship

$$M_{Rg} = 2.7 + 1.2 \log Y \qquad \ldots 10$$

Equations 9 and 10 can be considered equivalent; they produce the same M_{Rg} value, within 0.1, over the yield range of interest.

Consider for purposes of illustration an explosion 10-second R_g wave and an explosion 20-second Rayleigh wave recorded on a 4 K magnification LPZ seismogram with a trace amplitude of 5 mm at an epicentral distance of 20°. Using Equation 3, the M value of the explosion is 4.3. Using either Equation 3, or the more appropriate formula of Basham (1970) which is equivalent in this distance range, the M_{Rg} value is 4.6. From Equation 8 the M4.3 equivalent explosion yield is about 170 kilotons and from Equation 9 or 10 the M_{Rg} 4.6 equivalent explosion yield is about 40 kilotons. With the trace amplitude used above recorded on about 4 stations in the distance range near 20°, and using the fact that one or more of the stations (say, LPZ arrays) can have a larger effective magnification, the situation described is roughly equivalent to the (90 per cent) Rayleigh wave detection thresholds described in Chapter 5. Thus the explosion identification threshold using the R_g wave is about 40 kilotons, or a factor of about 4 in yield better than the threshold using 20-second Rayleigh waves.

Consider now the extrapolation of northern hemisphere earthquake Rayleigh wave detection thresholds (section 5.4) to explosion identification thresholds. Using the formal calculations for 20-second earthquake Rayleigh waves incremented δm1.0 to convert to explosions, the explosion identification thresholds using M versus m will be about m5.6 in central North America, m5.6 to m5.8 for the remainder of North America, the north Atlantic Ocean and northern Europe, and m5.8 to m6.0 throughout the remainder of the hemisphere; a realistic average for the northern hemisphere is about m5.8, or about 60 to 100 kilotons equivalent yield.

The Rayleigh wave detection threshold at any location in the northern hemisphere is highly influenced by the number of, and distance to, LPZ arrays within the 90° detection range. Since each of the LPZ arrays has data in a form suitable to matched filtering, the explosion identification thresholds can be reduced by about δm0.2 using this process, i.e., to about m5.4 in central North America and m5.8 in the poorest areas of the hemisphere, with a realistic average of m5.6, or about 40-60 kilotons yield in hardrock.

It is unreasonable, because of the distribution of available stations, to extrapolate to other northern hemisphere continental locations the R_g detection thresholds for NTS explosions achievable at nearby United States stations. However, the Canadian R_g results, an explosion identification threshold of about m5.0 (10-20 kilotons) for NTS at a mean distance of about 25°, may be

* All Canadian stations used by Basham (1969a) are shown in Figure 6, but only four are included in the 51-station LPZ network; Evernden (1970c) used moderate magnification Long Range Seismic Measurement stations, none of which are included in the United States UN return; however, the abundance of United States conventional stations shown in Figure 6 would have an equivalent capability.

* CCD/306, Swedish technical working paper for the Conference of the Committee on Disarmament, August 1969.

possible on any northern hemisphere continental mass, although this result remains unproven as yet outside of North America.

This 10 to 20 kiloton hardrock explosion identification threshold for NTS using Canadian stations is some three times lower than the threshold obtained above in the illustrative example used to compare R_g and 20-second wave detection. This difference between one empirical result and a theoretical study demonstrates the conservative nature of the assumptions made in defining the 50 per cent interval probability of Rayleigh wave detection at a station in section 3.3.

8.4 Rayleigh wave spectral ratio

The relative excitation of Rayleigh waves by earthquakes and explosions has been described in the previous section in relation to the P wave energy (or magnitude) of the events. Important differences between earthquakes and explosions have been shown to exist within the Rayleigh wave spectrum itself. This phenomenon was given brief coverage in the SIPRI document in diagrams illustrating the larger amount of longer period (30 seconds) Rayleigh wave energy in earthquakes compared to that in explosions. The discriminant has been quantified by Molnar *et al.* (1969) using new high-gain, long-period seismographs as a ratio of the energy in Rayleigh waves at periods of 19 to 22 seconds to the energy at periods of 40 to 60 seconds. Using special long-period seismographs installed in the eastern United States, this Rayleigh wave spectral ratio achieves complete separation of earthquakes and explosions in the western United States.

The special seismograph used by Molnar *et al.* is the first of a number of such systems planned by the United States for world-wide deployment. However, these systems have not been included in the United States UN return listing stations with guaranteed accessibility to data, and, therefore, cannot be considered as available to this study.

With further testing, the Rayleigh wave spectral ratio may prove to be an important discrimination criterion; the major difficulty apparent from the study by Molnar *et al.* is the rather high threshold of detection of the longer period Rayleigh waves, particularly for explosions. Using only the positive measurements presented by Molnar *et al.* (i.e., ignoring the noise-limited information on their figures), we estimate that using equipment of this type the thresholds of detection of Rayleigh waves are m3.6 and m4.9 for 20-second waves for earthquakes and explosions, respectively, and m3.8 and m5.3 for 40- to 60-second waves for earthquakes and explosions, respectively; this is for an epicentral distance of about 30°. The threshold of application of the Rayleigh wave spectral ratio will be at the larger set of magnitudes. Thus, the threshold of application of the positive ratio criterion is at a high magnitude, near m5.3, for explosions. However, the separation between populations in terms of the ratio or of the amplitude of the longer period waves is sufficiently great that absence of the longer period waves for explosions is a useful negative criterion (see following section) with possible application down to about m4.5. The procedure is feasible using any LPZ data capable of being bandpass filtered, and can be considered a possible discriminant using station data available to this study.

8.5 Identification by negative criteria

The explosion identification thresholds described in the previous sections are defined as being equal to the threshold of detection of explosion Rayleigh waves. The procedure to be discussed in this section is identification of explosions by the *absence* of a recorded wave on the basis that had the event been an earthquake of the same P wave magnitude, the wave in question would have been observable on the record. An associated concept is the identification of earthquakes as such by measurement of a factor which shows the event to conform to prior knowledge of earthquakes with respect to this factor.

Consider as an illustrative example the results presented by Basham (1969b) for identification of Asian events using M versus. m observations on Canadian stations. Detection of earthquakes using observed Rayleigh waves has a threshold of about m5.0; identification of explosions using observed Rayleigh waves has a threshold at about m6.0; because of the wide separation between populations, both can be considered positive identification. Because of the variation in detection thresholds due to variations in the noise levels, the largest earthquake whose Rayleigh wave can be obscured by noise is about m5.4. Thus, any event larger than m5.4 which does not have an observable surface wave (and which is known from other information to be shallow) can be identified as a probable explosion. As the magnitudes approach m6.0, the Rayleigh wave will again be observable for all events and M versus m will plot in either the explosion or earthquake population and yield positive identification. In this case, the threshold of probable identification is reduced by about δm0.6 from the threshold of positive identification by the application of a negative criterion.

The M versus m relationships of the earthquakes and explosions discussed in this example are near to the assumed world-wide averages given by Equations 5 and 7, i.e., for which earthquakes and explosions are separated by about δM1.5. Therefore, we estimate that extensive studies should demonstrate a usable negative criterion with an improvement of about δm0.5 on a world-wide basis. The general validity of this assumption, however, depends on the general scatter of populations with respect to the average trends and, for any regional application, to the closeness of the earthquake and explosion average M versus m trends. For example, the regional data for R_g for North American paths presented by Basham (1969a) shows M versus m trends separated by about δM1.4 and with data point scatter that nearly overlaps. In fact, the two sets of data in the study by Basham show a theoretical (formal) overlap at about the 2 per cent level; hence great care must be exercised in the development and application of negative criteria. However, provided precautions are taken to have information in several azimuths, and the appropriate studies are made of the probability distributions of scatter about trend lines, we can see no scientific objection to taking adavantage of this possibility in this context.

Negative criteria have been shown useful when applied to other seismic phases. Evernden (1969a) illustrates the possibilities of identification using long period S waves. He finds that earthquakes down to about m5.0 have observable long period S waves; whereas no explosions smaller than about m5.7 have observable long period S and, where explosion S waves are observed, they are about a factor of 10 smaller than those observed for similar magnitude earthquakes. Thus, the possibility of identification of explosions by absence or presence of long period S waves exists for any events greater than about m5.0. A similar criteria has been discussed by Evernden using Love and long period P waves. For the long period body phases particularly, the greatest problem is the nearness of the dominant periods of the phases to the peak in the microseismic noise spectrum and the probability of applying the discriminant (i.e., of detecting the signals in highly variable noise fields) may be small.

Although negative criteria cannot, by definition, provide positive identification of an underground explosion, the argument is substantially a tautological one. There are no sources of seismic energy of the sizes under discussion other than natural earthquakes or underground or underwater explosions; hence the certain elimination of the possibility of an earthquake origin provides a positive identification of an explosive source. Multivariate combinations of such negative criteria as the absence of the expected level of R_g, 20-second, or longer, period Rayleigh waves, long period S waves, long period P waves, and Love waves requires regionalized control data for its optimum application. Much work remains to be done with these techniques, but it seems very clear that the minimum improvements possible should be δm0.5 on existing generally applicable positive criteria such as 20-second M versus m and Rayleigh wave spectral ratios, and probably somewhat less on more restricted but more successful positive criteria such as M_{R_g} versus m.

9. Conclusions and recommendations

9.1 Summary and conclusions concerning existing capabilities

It will be apparent to the reader that the authors have relied on personal experience and on published and unpublished research results to make scientific judgments and extrapolations at many points in this assessment of global seismological detection and identification capabilities. In particular, we have in some instances extrapolated results available for North America to other parts of the world; this was necessary because for many parts of the world the required research has not been undertaken, or at any rate published. We will, therefore, present this chapter in two parts: this section will present the conclusions which can be drawn concerning the existing capabilities of the ensemble of conventional and array stations described in Chapter 2; the following section will contain some recommendations, which, for a modest investment of research effort and finances using existing facilities, may significantly improve on the currently defined capability.

The conclusions of this assessment can take the form of the P wave magnitude threshold at which existing seismological facilities have a certain capability of (a) detecting, (b) locating and (c) identifying a seismic event, and of how these capabilities can vary over the surface of the earth. For each of these functions we have defined as being adequate that threshold at which there is a 90 per cent probability of ≥4-station coverage, with adequate (2 or more quadrant) azimuthal coverage.

The lowest threshold derived is that for P wave *detection;* it is m4.5 (equivalent to 3 to 10 kiloton yield in hardrock) or lower for earthquakes or explosions occurring anywhere in the northern hemisphere, and deteriorates to a high value of m5.0 (equivalent to 10 to 20 kilotons) in part of the southern hemisphere. A fundamental conclusion of this assessment is that all extant capabilities are much poorer in the major portion of the southern hemisphere; this fact will not be emphasized further. In terms of locating the epicentres of events using detected P waves, the location accuracy will be typically better than 20-45 km for any seismic event larger than the P wave detection threshold magnitude for any region (see Figure 4) plus 0.2.

The 20-second earthquake Rayleigh wave detection threshold is about δm0.6 higher than the P wave threshold, leading to the conclusion that existing LPZ facilities are relatively less sensitive than existing SPZ facilities. The explosion Rayleigh wave detection threshold is about δm1.0 higher than the equivalent threshold for earthquakes. Thus, because of the difficulty of detecting explosion 20-second Rayleigh waves, the formally calculated threshold of explosion identification using the M versus m criterion remains at a rather high level, about m5.6 to m6.0 for the northern hemisphere. Matched filtering can reduce these values by about δm0.2. It seems reasonable, therefore, to define the network system we have investigated as having a threshold capability of identifying 60 kiloton underground explosions in hardrock in the northern hemisphere.

Using stations available in the UN returns, this threshold is reduced to m5.0 in North America by taking advantage of the efficient continental propagation of the shorter period R_g Rayleigh waves. We are hesitant to extrapolate the North American R_g results to other continental masses because equivalent success remains unproven (see section 9.2). The m5.0 threshold can be reached using 20-second Rayleigh waves only by degrading the number of observations (and hence the probability of application) and relying on the matched filtered data from one or two very high-gain long period facilities. This more restricted m5.0 capability, which is not yet proven to be generally applicable, can be regarded as explosion identification in the 10 to 20 kiloton hardrock range.

The identification threshold can be reduced below m5.0 only by employing criteria whose thresholds of application are below the explosion Rayleigh wave detection thresholds with equipment currently deployed. The criterion with greatest appeal is the P wave spectral ratio, which can in theory be applied close to the P wave detection threshold. The spectral ratio method for one station-region combination is a positive identifier at the m4.9 level; others show potential application at lower levels but result in overlapping populations.

Thus, we conclude that to consistently achieve an identification threshold below m5.0 all available identification criteria must be brought to bear as a multivariate analysis. The problem of assembling the necessary regionalized data to achieve identification below m5.0 for any conceivable test site in the northern hemisphere is a formidable one. This results, in our opinion, in a tendency to neglect the intrinsic power of the different methods, and leads naturally to the alternative concept of increasing the detection capability for explosion Rayleigh waves by a major investment in widely distributed arrays designed to achieve, for example, the capability of detecting Rayleigh waves for any m4.5 explosion.

We believe that an appropriate intermediate step, between acceptance of the existing rather limited capability as defined earlier in this chapter and commitment of extensive international resources to a widely deployed, highly sophisticated, integrated system of modern array stations, would be further definitive national assessments of existing capabilities and, where necessary, minor adjustments in facilities and techniques designed to improve modestly these capabilities. Some recommendations and suggestions for implementation of this intermediate step are given in the following section.

9.2 Recommendations for improving capabilities using existing facilities

The conclusions of this assessment that result from the formal detection calculations are closely tied to the initial assumptions required to define individual station capabilities in terms of quoted operating magnifications. The assumptions we have made, in the absence of supporting definitive empirical data, are of necessity conservative: witness the conservative assumed general P wave detection capabilities of stations MBC and COL compared with their empirically defined capability for a particular site, described in section 6.2. If, on the average, our assumptions for both SPZ and LPZ station capabilities are conservative, then additional empirical data of individual station P and Rayleigh wave detection capabilities will, when inserted into the formal calculations, improve on our assessment of existing global detection. This, among all suggestions for studies given here, is the study most easily undertaken by national agencies; it simply requires documentation of probabilities of detection of P and Rayleigh waves as a function of event magnitude for the more important stations in each country.

In addition, it is important to obtain as soon as possible empirical capabilities for the two new large aperture arrays, the Norwegian SPZ/LPZ array NOS and the Unites States LPZ array ALP.

We have illustrated a number of cases in which geophysical peculiarities of the earth are assisting the discrimination process, and a few cases in which they may hinder the process. However, we are able to employ only those peculiarities with which we are familiar, from published and unpublished research and personal experience, and which pertain particularly to the North American situation. These phenomena are very important to global discrimination and urgently require documentation for other areas. Knowledge of P wave phenomena will be a by-product of any P wave detection studies that are undertaken; the Rayleigh wave phenomenon that needs extensive study in other regions is the significant reduction in detection and identification thresholds achieved in North America using the short period R_g waves. It is recommended that other countries with conventional stations on the same continental mass with earthquake and explosion sources further test the R_g applications.

The most widely applicable discrimination criterion, the M versus m discriminant, has a threshold of application that is controlled by the threshold of detection of explosion Rayleigh waves. The LPZ arrays are able to dominate the Rayleigh detection calculations principally because the recording and/or analysis procedures can reject the dominant long period noise band. But, because there are too few LPZ arrays to provide adequate Rayleigh wave detection, some conventional stations must be employed. The total number of LPZ stations required need not exceed 20 (i.e., significantly fewer than the 51 LPZ stations we have employed in Rayleigh wave detection calculations) if the included conventional stations had an improved capability; and a significant improvement of a conventional LPZ station can be achieved with modest investment. For example, WOL and GRF (see section 3.3) are considered to have magnifications about a factor of 3 greater than standard photographic recording stations because they record on magnetic tape and have the facility to filter and reject the dominant microseismic noise band. An alternative method that can be used on photographic recording seismographs is the addition of an electronic or electro-mechanical component designed to reject periods below, say, 10 seconds.

An improvement of this type on one LPZ seismograph in each of a number of countries could significantly improve Rayleigh wave detection, considering those countries in the UN returns that possess LPZ stations in reasonably quiet locations, and also considering the locations of existing LPZ arrays. Any additional new or improved stations (LPZ or SPZ) in the southern hemisphere would, of course, be of great value.

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