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Intraplate Seismic Risk in the Atlantic Ocean based on teleseismically observed earthquakes, 1964-79

R.C. Lilwall

January, 1981

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NATURAL ENVIRONMENT RESEARCH COUNCIL
INSTITUTE OF OCEANOGRAPHIC SCIENCES

INSTITUTE OF OCEANOGRAPHIC SCIENCES

Wormley, Godalming,
Surrey GU8 5UB
(042-879-4141)

(Director: Dr. A. S. Laughton)

Bidston Observatory,
Birkenhead,
Merseyside L43 7RA
(051-653-8633)
(Assistant Director: Dr. D. E. Cartwright)

Crossway,
Taunton,
Somerset TA1 2DW
(0823-86211)
(Assistant Director: M. J. Tucker)

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Work carried out under contract to the Department of the Environment

Institute of Oceanographic Sciences,
Brook Road,
Wormley,
Godalming,
Surrey, GU8 5UB

SUMMARY

As part of a program to assess the suitability of the ocean floor for the disposal of high level radioactive waste, the seismicity of the Atlantic Ocean floor is being studied. In this report, a preliminary assessment of seismic risk in the intraplate areas of the Atlantic ocean is presented, based on existing files of earthquake data for the period 1964-1979 inclusive. Earthquakes with magnitudes (m_b) in excess of 6.0 occur within this region. The upper limit possible on magnitude may be well above the observed maximum value but it is difficult to estimate because of the limited time interval considered. Apart from an active zone to the NE and E of the Caribbean, seismicity appears uniformly distributed but with the overall level of activity in the North Atlantic twice that in the south. In the North Atlantic the earthquakes have the cumulative magnitude frequency distribution:

$$\text{Log}_{10}N = -5.63-0.44M$$

given in terms of events per square km per annum. For this level of activity a given site would experience peak ground accelerations in excess of 0.1g at intervals of between 2500 and 10,000 years. This large range is the result of several factors such as the choice of an upper magnitude limit, the detailed distribution of activity near the site, and the ground motion attenuation function, all of which are poorly known.

INTRODUCTION

The distribution of the earth's seismicity can be explained within the framework of plate tectonics. The earth's uppermost zone or "lithosphere", can be divided into a relatively small number of regions or "plates" which are assumed to behave as rigid units. These plates are known to move relative to each other, propelled by forces which are not at present well understood. Relative movement along adjacent plate margins results in the majority of the earth's earthquakes which can be described as "interplate". Although earthquakes are less frequent away from plate margins, the existence of such "intraplate" earthquakes indicates that some movement does take place within the plates themselves. This report is concerned with the seismicity and potential seismic hazard within the intraplate regions of the Atlantic ocean.

Estimation of intraplate seismicity is made difficult because the number of earthquakes recorded is small during the time period for which we have data. This is even more serious for oceanic areas because of the near absence of historical records of felt earthquakes. The only source of information comes from "teleseismically observed" earthquakes, that is, those large enough to be recorded instrumentally by distant seismic stations. For this reason it is not possible at present to be "site specific" in our assessment of seismic hazard but instead use seismicity data from large regions and make assumptions about its detailed distribution.

Between 1960 and 1964 the ability of the world's seismological observations to detect and locate earthquakes was considerably improved by the addition of the World Wide Standardised Seismograph Network (WWSSN). At about the same time computers enabled more accurate estimates of earthquake locations and in particular, from 1964 the International Seismological Centre (ISC) started publishing its Bulletin containing the results of such computations. It was decided therefore to use data for the period 1964-1979 inclusive in this preliminary study.

FILE SEARCH FOR ATLANTIC INTRA-PLATE EARTHQUAKES

Before a search of the available files of past earthquakes could be made it was necessary to define the exact region of interest. We wish to include only the deep ocean intraplate regions so both continental-shelf and plate boundaries must be excluded. The edge of the deep ocean region along most of the Atlantic's margins is easily defined as the bottom of the continental slope. Between latitudes 12° and 22° however, the Atlantic is bounded in the west by an active plate margin, the Caribbean loop. The search region was therefore terminated at approximately 150km short of this margin. Another active plate boundary, the Mid-Atlantic Ridge divides the whole region in two along a roughly north-south line, and in addition the region to the east of the Mid-Atlantic Ridge, is further divided by an active plate boundary approximately along a line from the Azores to Gibraltar. The search region was terminated at about 150km from all these seismically active regions. It is not desirable to include regions nearer than 150km to active plate margins for two reasons; firstly the plate boundaries are not always well defined and the possibility of accidentally including interplate activity must be avoided, secondly the results of the search will tend to become contaminated with small interplate events which can have mislocations in excess of 100km. The north and south limits of the search region were set at 65°N and 44°S respectively because outside these latitudes both plate boundaries and continental margins are more difficult to define. The data file searched includes all earthquakes with epicentres computed by the ISC for the period 1964 to 1975 inclusive, and also the preliminary determinations of epicentres (denoted PDE) published by the National Earthquake Information Service in the United States of America. The latter extends the time coverage to within about 6 months of the present.

The results of the file search are listed in the Appendix (182 earthquakes). As already mentioned there is the possibility of contamination of any search for a relatively inactive intraplate region by interplate earthquakes mislocated from adjacent plate boundaries. To eliminate such events, the original epicentre determinations in the bulletins for all the 182 events were carefully examined and if there is any doubt about their authenticity as intraplate events they have been marked "deleted" (followed by a code giving the reason), and not included in further analysis. Most of these events were so marked because the standard confidence limits on their epicentres overlap the edge of the search region, usually where it lies next to an active plate boundary. Suspected foreshocks and aftershocks were also separated and eliminated from subsequent analyses. This means that a mainshock, together with its associated foreshocks and aftershocks, is treated as one event for the purpose of estimating seismic hazard. Over a third of the events listed were removed for the reasons given above. The search region and the final set of epicentres accepted are shown in figure (1).

DISTRIBUTION OF THE EARTHQUAKES

The most obvious feature seen in figure (1) is a NW-SE trending zone from the eastern Caribbean to the Mid-Atlantic Ridge. This zone contains approximately 25% of the observed earthquakes and probably results from deformation caused by a slight relative motion of the North and South American plates. As the level of seismicity may be more characteristic of an interplate region, these earthquakes were treated separately. Elsewhere seismic activity appears to be distributed fairly uniformly but with fewer events in the southern Atlantic. This latter observation may indicate a genuine difference but allowance must be made for spatial variation in the event detection ability of the seismological observatory network. A few of the smaller events may be associated with centres of volcanic activity such as the Canary Islands. A more detailed examination of the earthquake epicentres for correlations with bathymetric and geological features is beyond the scope of this initial report.

Focal depths listed in the Appendix are all less than 100km with many assigned a value of 33km. It should be emphasized that depth of focus determinations, especially for very shallow events situated away from observing stations, are unreliable. A safe and conservative assumption for all these earthquakes is that they occurred within the oceanic crust, that is within 10 kms of the sea bed.

MAXIMUM MAGNITUDES

The largest events found in the search had magnitudes in excess of 6.0 on the short period body wave scale (denoted m_b). Earthquakes of this size would be potentially destructive to nearby man-made structures. Since the time period considered (16 years) is relatively short it seems likely that even larger earthquakes may occur. It is important to the assessment of seismic risk to know the upper limit on the possible magnitudes of earthquakes for a region. Analysis of extremes can be used to ascertain whether the upper magnitude limit has been approached within the time period considered, and in addition will give useful estimates on the frequency of recurrence of lesser events.

To make such an analysis of the earthquakes listed in the Appendix, the time period is first divided into equal intervals and a list of the largest event in each interval compiled. For many natural phenomena the frequency and size of these maximum events (called extremes) follow relatively simple rules (Gumbel, 1958). If there is no upper bound, then the probability P that an extreme will take a value M or less is given by a double exponential distribution:

$$P = \exp(-\alpha e^{-\beta M}) \qquad \text{——— (1)}$$

where α and β are constants. From the above definition of P, the probability that an extreme will exceed M is given by 1.0-P and the return period for this to happen can be defined as 1.0/(1.0-P). If equation (1) holds then a plot of M against the double logarithm of P should be linear. If the extremes M do show some physical upper limit then the plot will not be linear but tends to become assymptotic to this limit as P approaches unity. For the Atlantic ocean intraplate events, but excluding those from the zone east of the Caribbean, the annual extremes were listed (Table 1). These annual extremes were ranked in ascending order of size and for the j^{th} largest (Mj) of N extremes, j/(N+1) is an estimate of the probability P_j corresponding to the value M_j. Table 1 shows these estimates of P_j and M_j and figure (2) shows a plot of the double logarithm of P_j against values of M_j.

Although a straight line could be fitted through all the points, the one shown in figure (2) is only through those in excess of body wave magnitude 5.0 because, as is demonstrated in the next section, many events below this size may pass undetected. The fitted line is given by:

$$\text{Log}_e\ (-\text{Log}_e\ P) = 11.2-2.27\ m_b \qquad \text{——— (2)}$$

or

$$P = \exp(-73130\, e^{-2.27 m_b}) \qquad (3)$$

There appears to be no evidence in the 16 year period considered here that any of the events have approached an upper limiting magnitude.

Bergman and Solomon (1980) have compiled a catalogue of the larger oceanic intraplate earthquakes for the whole world. The largest in their list was magnitude (m_b) 6.5 and using equation (3) above, the return period in the Atlantic to exceed this size is 35 years. This suggests that further work on data prior to 1964 may be useful but we may need to double the sampling period at least to obtain a reliable assessment of the largest magnitude.

The intraplate region of the Atlantic is the site of large earthquakes. For events with magnitudes (m_b) in excess of 6.0 the return period is only 12 years and there is no evidence to suggest that larger events cannot occur. The observed activity is spread thinly over a large region however and to assess the risk of strong ground motion at any one point it is necessary to quantify the seismicity in terms of the frequency of different magnitudes per unit area.

MAGNITUDE FREQUENCY DISTRIBUTION

Seismicity is conveniently expressed in terms of magnitude frequency relationships of the form:

$$\log_{10} N = a - bM \qquad (4)$$

where N is the cumulative number of earthquakes with magnitude M or greater, a and b are constants. In general plots of $\log_{10} N$ against M follow the above linear relationship but tail off at small magnitudes because the ability of the observing seismological network to detect such events declines. This is illustrated in figure (3) which shows a plot for events on a section of the Mid-Atlantic Ridge. It is possible to express the detection capability of the network of any point in terms of the magnitude at which a certain percentage of the total are seen. These percentages are usually chosen to be 50% and 90% and figure (3) illustrates a method of estimating the corresponding magnitude thresholds.

The Atlantic intraplate events come from a wide area over which the detection capability of the network varies considerably. Consequently the tail off in the observed magnitude frequency distribution is not sharp and it is not obvious which magnitude should be chosen, above which the linear form can be assumed. Fortunately it is possible to estimate the detection threshold as it varies with latitude in the Atlantic by drawing magnitude-frequency curves for sections of the seismically active Mid-Atlantic Ridge and finding the 50% and 90% levels as in figure (3). Figures (4) and (5) show the results of the ISC and PDE determinations for the 16 year period. Both figures show that in general the ISC has the lower thresholds, as expected, since this agency takes longer and collects more data. The 50% levels in figure (4) indicate that event counts for events less than magnitude (m_b) 4.5 will be greatly underestimated everywhere and even for magnitudes above 4.5 in the southern Atlantic. The 90% levels are typically 0.3 units above the 50% levels and indicate that although the ISC has nearly 100% detection for events above 4.5 in the southern Atlantic it is necessary to restrict event counts to magnitude 5.0 and above in the south to be free from the effects of detection threshold.

Figure (6) shows the magnitude frequency plot for the Atlantic intraplate events excluding those from the active zone east of the Caribbean. The straight line has the form:

$$\mathrm{Log}_{10} N = 6.15 - 1.0\ m_b \qquad \text{—— (5)}$$

and was fitted only to points with m_b greater than 5.0. A value for 1.0 for the constant "b" in equation (4) is low when based on the short period body wave scale (m_b). Typical values found in this study for the Mid-Atlantic Ridge events range between 1.3 and 1.8 similar to those found in a study on "b" values by Francis (1968). A detailed interpretation of "b" values is not appropriate in this report but it is worth mentioning that a low value for intraplate events is not unexpected, as in general low values are associated with regions having relatively uniform stresses and homogeneous structure. Equation (5) can be normalised to give counts per square km per annum.

$$\mathrm{Log}_{10} N = -2.74 - 1.0\ m_b \qquad \text{—— (6)}$$

This magnitude frequency relation is an average for the North and South Atlantic. We do not have sufficient information to check for regional variations in the "b" value but the apparent differences in numbers of events between the northern and southern oceans suggests that the overall level of activity, which is related to the constant "a" in equation (4), may vary. A way to investigate this and be relatively free from corrections caused by variation in detection thresholds is to count events with magnitudes greater than m_b = 5.0 for different regions but this yields counts too small to give significant results. The alternative adopted was to count events with magnitudes of 4.5 and greater and correct these counts for the percentage detection expected. Figure (7) shows the percentage detection levels as a function of latitude for the Mid-Atlantic Ridge events, obtained by the converse process of that shown in figure (3). The corrections actually used are means weighted for 12 years of ISC and 4 years of PDE detection capability as shown at the bottom of figure (7).

Figure (8) shows a simple regionalisation used to test for variations in seismicity. The seismicity levels in terms of numbers of events with magnitude equal or greater than 4.5 for each region is given in table 2. When the counts are corrected for detection thresholds, all regions show an increase, but for the southern region E, the count has to be doubled. When the counts are normalised to counts per square km however region E is still significantly less active than each of all the other regions except A. Activity in region D is by far the highest and justifies its exclusion from the seismic risk statistics. The NE Atlantic region A shows low counts but the area is also relatively small. An overall activity for the northern Atlantic was therefore obtained by summing regions A, B and C. The activity for the North Atlantic appears to be about double that for the South Atlantic.

Assuming a "b" value of 1.0 and a count of 10.7×10^{-8} per square km per annum (see Table 2) for events with magnitude 4.5 or greater, the magnitude frequency relation for the Northern Atlantic (regions A, B and C) then becomes:

$$\text{Log}_{10} N = -2.47 - 1.0\, m_b \qquad \text{——— (7)}$$

where N is in terms of events per square km per annum.

BODY WAVE (m_b) AND SURFACE WAVE (M) MAGNITUDES

All the statistics so far described have been in terms of magnitudes measured on the short period body wave scale m_b. This scale is the most frequently measured for events recorded by stations at teleseismic distances but has certain disadvantages; firstly the scale does not accurately reflect true increases in earthquake size (seismic movement) above m_b values of about 6.5, and secondly very few results have been published which relate ground motions such as peak acceleration to magnitudes on this scale. The long period surface wave magnitude scale (here denoted by capital M) overcomes these objections and it is desirable to relate m_b to M for the oceanic intraplate earthquakes.

Figure (9) shows a plot of m_b against M values for oceanic intraplate events listed in a paper by Bergman & Soloman (1980). A straight line has been fitted through the points which gives:

$$m_b = 0.44\,M + 3.16 \qquad \text{———} \quad (8)$$

This line is clearly displaced 0.2 to 0.3 m_b units with respect to that found by Marshall (1970) for an unselected sample of world events (dashed line). Several explanations for this are possible; there may be less absorption of the higher frequency seismic waves (which determine m_b) in the upper mantle beneath intraplate regions, a predominance of 45^o dip slip focal mechanisms in intraplate events would also favour higher m_b values and finally higher stress drops (as evidenced by the low "b" values) may enhance higher frequencies with some faulting processes, again giving relatively high m_b values.

Equations (7) and (8) can be combined to give the magnitude frequency distribution in terms of M for the North Atlantic.

$$\text{Log}_{10}N = -5.63 - 0.44M \qquad \text{———} \quad (9)$$

As before, N is in terms of events per square km per annum.

Although the future addition of further data may give minor changes to the estimates of seismicity incorporated in equations (7) and (9), unlike our knowledge concerning the upper limit on magnitude, these equations appear well constrained by the data over 16 years.

GROUND MOTIONS

The previous two sections have been concerned with the estimation of the average level of seismicity for the North Atlantic expressed in terms of the magnitude frequency relation (4). With some assumptions it is now possible to estimate the frequency of occurrence of ground motions at a given site. The technique used here is that of Cornell (1968) and subsequently extended by Cornell and Vanmarck (1969). The earthquakes are assumed to occur as Poisson events confined within source regions described by simple geometrical configurations. Seismicity is described by the linear magnitude frequency law with an optional upper magnitude limit. To relate the occurrence of events to resulting ground motions however, the method requires some relationship between ground motion, magnitude and distance of an event.

It is not proposed here to survey the large amount of literature concerning ground motions (such as intensity, peak acceleration, velocity etc.) and their relation to distance and magnitude. Relationships between these quantities vary regionally and a simple equation such as used below is certainly an oversimplification. An intraplate site situated on an unconsolidated sedimentary column beneath several kms of water is clearly atypical and it is doubtful if any of the published relations are applicable. It was decided therefore to use the attenuation formula suggested in the original study by Cornell (1968) for peak ground acceleration Ap.

$$Ap = 2000.0\ e^{0.8Ms}\ R^{-2} \qquad \text{———} \quad (10)$$

where R is the modified slant distance D of earthquake to site in kms.

$$R^2 = D^2 + 400 \qquad \text{———} \quad (11)$$

Equation (10) is for California and may underestimate ground motion for intraplate regions.

The simplest model for the spatial distribution of seismicity is to assume that events can occur equally everywhere. Seismicity is then described by an areal source stretching from directly beneath the site out to a distance at which the largest event has negligible effect.

Return periods are then independent of the exact site location. Table (3) shows some results obtained for an areal source 5km depth assuming a level of seismicity given by equation (9). A value of 0.1g was chosen for the minimum rock acceleration of interest as this value is at a level where liquefaction and slope stability may become a problem with ocean bottom sediments (see Ove Arup and Partners Report, 1980). Return periods are dependent on the maximum magnitude chosen (given in terms of surface wave magnitude M); at the 0.1g level return periods for the entire likely range (M = 7.0 to 9.0) vary by a factor of almost 2.0. Assuming an upper magnitude limit of M = 7.5 (equivalent to m_b = 6.5 and in excess of any value seen for an oceanic intraplate event since 1963) the return period for 0.1g peak acceleration is 9200 years corresponding to an annual probability of approximately 10^{-4}.

There is some evidence (Sykes, 1978; Bergman and Solomon, 1980) that intraplate earthquakes do not occur radomly in space but concentrate along old zones of weakness. Within oceanic areas these zones of weakness mostly correspond to fracture zones which result from offsets along constructive plate boundaries such as the Mid-Atlantic Ridge. Fracture zones may be frequent features in the Atlantic, possibly as little as 50km apart, and may have only minor bathymetric expression. If seismicity is restricted to such zones then the seismic risk will depend on their separation and whether the site in question is directly on a zone or in between. The zones can be modelled in terms of parallel faults with various separations. Table (3) gives results, assuming an overall areal rate of seismicity given by equation (9), for faults assumed to be 50, 100 and 200 km apart. Return periods are given for the position of maximum risk (site on a fault) and minimum risk (site half way between faults). For faults only 50km apart and at the 0.1g level, the maximum and minimum return periods differ only slightly and approximate that for an areal source (i.e. circa 10,000 years). If the fault zone separation is increased the return periods for sites on the faults decrease because higher activity is assigned to the fault. Conversely risk mid-way between is greatly reduced and becomes effectively zero if the maximum magnitude earthquake is unable to generate the ground motion of interest.

For all the examples considered, the highest risk (site on fault with faults 200km apart) corresponds to a return period of 2400 years, or an annual probability of 4×10^{-4}, for peak acceleration at the 0.1g level. This assumes an upper limiting magnitude of Ms = 7.5 It must be emphasised at this point that the results in Table 3 can only be regarded as preliminary and that they are only intended to give a broad indication of the level of risk likely to be encountered.

The study points to several areas at which future work should be directed. We have little idea of the upper magnitude limit. Further work to include the available historical record prior to 1964 may improve this, in spite of the relatively poor seismological network then in operation. Whether the spatial distribution of seismicity is restricted to zones of weakness or not also effects our risk estimates. Detailed study of the epicentre locations of the events, possibly including relocations, should enable their correlation with suspected weak zones to be assessed. Finally the ground motion equation (10) is not appropriate for a sea bed or intraplate environment and its use here is probably not conservative in the estimation of risk. Until direct information for ocean bottom environments becomes available, it will be necessary to test the sensitivity of our estimates in table (3) to likely variations in this function.

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YEAR	Extreme m_b	RANK j	P_j $=j/17$
1964	5.5	13	0.765
1965	5.3	11	0.647
1966	4.8	5	0.294
1967	5.1	9	0.529
1968	5.2	10	0.588
1969	4.9	6	0.352
1970	4.6	4	0.235
1971	6.0	15	0.882
1972	5.1	8	0.470
1973	4.6	3	0.176
1974	5.4	12	0.706
1975	4.5	2	0.118
1976	5.1	7	0.411
1977	5.5	14	0.823
1978	6.1	16	0.941
1979	4.4	1	0.059

<u>TABLE 1</u> - Annual extreme magnitudes for the Atlantic Intraplate Region 1964-1979. Events in the zone E and NE of the Caribbean are excluded. Values of P_j are estimates that a given extreme will be less than or equal to that observed.

REGION	Observed Number events $m_b \geq 4.5$	Corrected Number events $m_b \geq 4.5$	Area $Km^2 \times 10^6$	Events $m_b \geq 4.5$ per yr per km^2 $\times 10^{-8}$
A	2	2.37	2.76	5.4 ± 3.8
B	13	16.41	10.03	10.2 ± 2.8
C	12	15.36	7.11	13.5 ± 3.9
D	16	16.30	2.36	43.2 ± 10.8
E	10	21.16	28.88	4.6 ± 1.5
A+B+C	27	34.14	19.9	10.7 ± 2.1

TABLE 2. Estimates of the rate of occurrence of events with body wave magnitude m_b greater than 4.5 based on the observed numbers and corrected for the observed detection levels.

SOURCE TYPE		M max	Acceleration RETURN PERIODS in years x 10^3		
			0.1g	0.25g	0.5g
Areal		7.0	11	58	312
		7.5	9.2	44	184
		8.0	8.2	36	130
		8.5	7.4	31	100
		9.0	6.8	27	82
Faults 50 km Apart	Site on Fault	7.5	7.8	36	117
	Site between Faults		11	57	380
Faults 100 km Apart	Site on Fault	7.5	4.8	18	59
	Site between Faults		21	1000	∞
Faults 200 km Apart	Site on Fault	7.5	2.4	9.1	29
	Site between Faults		∞	∞	∞

TABLE 3 Return periods for 0.1g, 0.25g and 0.5g maximum ground accelerations for a range of source geometries and maximum magnitudes.

APPENDIX

ATLANTIC OCEAN INTRA-PLATE EARTHQUAKES 1964-1979
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THIS LISTING CONTAINS EARTHQUAKES LOCATED BY THE INTERNATIONAL SEISMOLOGICAL CENTRE(ISC) FOR THE PERIOD 1964-1975, AND THE PRELIMINARY DETERMINATIONS OF THE NATIONAL EARTHQUAKE INFORMATION SERVICE(NEIS) US DEPT OF THE INTERIOR FOR THE PERIOD 1976-1979. ALL EVENTS FOUND WITHIN THE SEARCH REGION ARE LISTED

DATE IS IN THE FORM DAY-MONTH-YEAR
TIME IS IN FORM HOURS MINS SECONDS GMT
LAT AND LONG OF EPICENTRES ARE IN DEGREES AND DECIMALS WITH S AND W NEGATIVE
FOCAL DEPTH Z IS IN KMS
MS AND MB ARE THE SURFACE AND BODY WAVE MAGNITUDES. A * AFTER MB VALUES INDICATES THAT IT HAS BEEN RECOMPUTED OMITTING STATIONS AT DISTANCES LESS THAN 20 DEGREES. A VALUE OF 0.0 HAS BEEN ASSIGNED TO THOSE EVENTS FOR WHICH NO MAGNITUDE VALUE HAS BEEN ESTIMATED
NSTN EQUALS THE NUMBER OF STATIONS USED TO LOCATE THE EVENT
NCAT IS NUMBER OF EVENT IN CATALOGUE OF BERGMAN AND SOLOMON (1980)

EVENTS MARKED 'DELETED' FOLLOWED BY A,B,C OR D HAVE NOT BEEN INCLUDED IN THE STATISTICAL STUDY FOR THE FOLLOWING REASONS

A THESE EVENTS HAVE POORLY CONSTRAINED EPICENTRES OR HAVE POTENTIAL EPICENTRAL ERRORS WHICH INDICATE THAT THE EVENT MAY HAVE OCCURRED OUTSIDE THE SEARCH AREA

B EXAMINATION OF THE DATA USED TO LOCATE THESE EVENTS SUGGESTS THAT THE EVENT MAY BE THE RESULT OF A SPURIOUS ASSOCIATION OF ARRIVAL TIME DATA

C THESE EVENTS IDENTIFIED AS MAN MADE EXLOSIONS

D THESE EVENTS APPEAR TO BE AFTERSHOCKS OF A MAIN EVENTS OUTSIDE THE SEARCH AREA

OTHER EVENTS ARE MARKED DELETED AS THEY ARE IDENTIFIED AS FORESHOCKS (DENOTED 'FSHOCK') OR AFTERSHOCKS(DENOTED 'ASHOCK') OF EVENTS WITHIN THE SEARCH AREA

DATE	TIME	LAT	LONG	Z	MS	MB	NSTN	NCAT			
9- 1-64	9 57 56.9	-43.19	-14.67	0	0.0	0.0	7			DELETED	A
12- 2-64	11 24 6.3	46.80	-37.70	33	0.0	4.3	6				
21- 2-64	4 56 16.0	13.59	-51.34	0	0.0	4.2	5				
4- 3-64	0 48 9.2	44.10	-30.40	33	0.0	4.2	7			DELETED	A
22- 5-64	5 38 40.9	27.90	-16.04	34	0.0	4.3	21				
22- 6-64	17 50 43.6	54.90	-40.20	33	0.0	4.2	6				
21- 8-64	23 26 16.0	29.00	-29.10	33	0.0	4.0	7				
4- 9-64	16 53 57.0	20.00	-64.40	33	0.0	3.9*	6			DELETED	A
6- 9-64	10 51 40.0	22.50	-67.00	0	0.0	0.0	4			DELETED	A
17- 9-64	15 2 1.5	44.58	-31.34	24	0.0	5.5	173	7			
17- 9-64	22 7 40.2	38.70	-71.90	0	0.0	0.0	15				
7-10-64	22 53 18.9	20.27	-60.40	25	0.0	0.0	7			DELETED	A
11-10-64	0 43 15.0	-5.00	-17.60	33	0.0	5.0	10				
23-10-64	1 56 5.1	19.30	-56.11	43	0.0	6.1*	236	10			
23-10-64	16 46 19.5	19.07	-57.50	25	0.0	3.7*	8	11			
10-11-64	19 26 41.2	47.40	-23.60	31	0.0	4.3	26				
24-12-64	4 3 2.0	18.00	-60.00	0	0.0	0.0	4			DELETED	A
20- 2-65	16 29 30.0	26.10	-51.20	33	0.0	4.5	17				
29- 3-65	13 10 18.2	34.20	-64.30	10	0.0	4.1	18				
10- 8-65	8 21 6.2	61.24	-60.10	33	0.0	4.0	25				
12- 8-65	6 27 18.5	13.10	-42.60	33	0.0	4.4	10			DELETED	A
21- 9-65	3 26 37.1	40.77	-50.13	21	0.0	5.3	170	19			
20-11-65	7 28 29.5	58.30	-34.10	33	0.0	4.3	5			DELETED	A
30-11-65	11 50 3.0	-28.00	5.50	33	0.0	4.5	10				
20- 3-66	18 28 35.8	21.96	-58.90	10	0.0	4.4*	16	25			
19- 5-66	0 12 26.0	20.00	-61.20	10	0.0	0.0	5			DELETED	A
28- 5-66	11 28 59.8	27.90	-16.60	0	0.0	4.4	8				
12- 6-66	20 20 59.0	-2.93	-28.29	20	0.0	4.8	41				
29- 7-66	4 36 25.1	36.70	-74.13	1	0.0	4.4*	68				
5-12-66	1 59 5.0	16.60	-57.40	0	0.0	4.4*	7			DELETED	A
3- 1-67	5 12 55.0	51.60	-38.90	33	0.0	4.3	6			DELETED	A
2- 2-67	18 34 19.6	-12.80	-9.40	33	0.0	5.1	8				
4- 2-67	14 8 50.0	24.00	-65.70	1	0.0	0.0*	7				
19- 4-67	21 44 15.0	20.20	-63.10	41	0.0	0.0	5		FSHOCK	DELETED	A
20- 4-67	4 17 42.1	-41.14	-19.33	33	0.0	4.9	25				
22- 5-67	6 23 29.0	20.43	-65.76	26	0.0	4.3*	43				
12- 6-67	0 8 11.0	11.80	-47.20	33	0.0	0.0	5			DELETED	A
30- 6-67	3 4 41.5	38.90	-36.70	33	0.0	4.5	23				
10- 7-67	19 43 58.6	19.30	-53.10	56	0.0	4.8	20	34			
26- 9-67	11 0 56.0	19.50	-60.00	0	0.0	0.0*	6			DELETED	A
3-12-67	0 0 35.5	58.40	-24.90	33	0.0	4.4	6				
28-12-67	12 47 17.0	48.00	-38.60	33	0.0	4.2	7				
20- 1-68	10 54 50.0	40.00	-23.00	33	0.0	4.1	6			DELETED	A
20- 2-68	2 19 49.5	12.40	-46.94	12	0.0	5.5	172				
20- 2-68	8 8 31.2	16.72	-57.76	26	0.0	4.3	17				
5- 3-68	18 58 39.0	15.60	-57.90	18	0.0	0.0	10			DELETED	A
13- 5-68	8 49 50.0	43.70	-25.50	33	0.0	4.2	7			DELETED	A
9- 7-68	6 13 31.9	-10.66	12.09	0	0.0	4.2	20				
11- 7-68	21 39 14.2	33.90	-15.59	38	0.0	4.4	27				
3- 9-68	15 37 0.3	20.58	-62.30	34	0.0	5.6	191	50			
14- 9-68	1 37 6.0	56.80	-39.80	33	0.0	5.2	37				
9- 1-69	4 22 48.0	41.00	-34.30	33	0.0	4.2	5			DELETED	A
21- 1-69	8 4 45.0	27.70	-48.80	33	0.0	4.0	12			DELETED	A
20- 3-69	7 41 29.0	18.60	-49.60	33	0.0	4.4	9				
8- 5-69	20 47 8.6	33.30	-11.80	33	0.0	0.0	12				
14- 6-69	1 8 32.0	20.06	-64.19	14	0.0	3.6	13		FSHOCK	DELETED	
14- 6-69	1 11 31.0	20.05	-64.20	5	0.0	4.1	23		FSHOCK	DELETED	
30- 6-69	18 36 25.3	20.03	-64.14	25	0.0	5.1	97				
30- 6-69	20 27 33.7	20.23	-64.10	36	0.0	0.0	6		ASHOCK	DELETED	
23- 7-69	8 34 37.7	56.00	-47.00	33	0.0	4.1	12				
25- 7-69	21 30 33.3	12.44	-40.75	9	0.0	4.8	60	60			

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26- 7-69	12 24 30.4	43.70	-14.56	33	0.0	4.6	75				
11- 8-69	18 48 35.0	20.02	-64.29	26	0.0	4.4	17		ASHOCK	DELETED	
11- 8-69	20 16 35.1	20.06	-64.29	31	0.0	4.9	65		ASHOCK	DELETED	
29- 9-69	4 35 51.0	12.90	-46.20	33	0.0	4.6	9			DELETED	A
13-10-69	7 7 49.0	22.70	-40.50	33	0.0	0.0	8			DELETED	B
7-11-69	9 28 54.0	-37.00	-43.80	33	0.0	0.0	6				
14-11-69	8 31 30.0	20.02	-64.43	4	0.0	0.0	5		ASHOCK	DELETED	
15-11-69	22 24 8.4	20.01	-64.13	10	0.0	0.0	12		ASHOCK	DELETED	
24-11-69	6 52 20.9	17.44	-26.54	30	0.0	4.2	5				
24-11-69	9 12 52.0	28.00	-30.70	33	0.0	4.4	5				
24-11-69	21 14 13.2	60.49	-58.88	33	0.0	4.9	103				
2- 1-70	11 53 35.0	15.00	-57.50	33	0.0	0.0	5			DELETED	A
3- 1-70	14 15 0.0	15.40	-58.00	33	0.0	0.0	6		ASHOCK	DELETED	A
4- 1-70	0 15 47.0	16.01	-58.70	67	0.0	0.0	5			DELETED	A
18- 1-70	1 23 59.0	40.00	-39.90	33	0.0	4.5	5				
19- 1-70	1 19 12.7	15.00	-53.65	92	0.0	0.0	5		ASHOCK	DELETED	A
22- 2-70	7 42 49.0	16.40	-58.70	35	0.0	0.0	7		ASHOCK	DELETED	
22- 2-70	12 35 5.0	13.40	-46.50	33	0.0	0.0	9		ASHOCK	DELETED	A
5- 3-70	4 56 24.9	53.89	-19.70	25	0.0	4.6	78				
1- 4-70	9 18 20.0	20.00	-43.50	33	0.0	4.2	8			DELETED	A
19- 5-70	19 17 40.0	18.00	-60.00	23	0.0	0.0	5			DELETED	A
25- 6-70	16 8 54.8	39.62	-71.07	0	0.0	5.0	98			DELETED	C
20- 8-70	16 34 15.3	38.96	-72.36	0	0.0	4.0	30			DELETED	C
17- 9-70	11 29 24.8	26.65	-22.86	33	0.0	4.5	49				
4-10-70	2 4 34.0	10.16	-38.59	15	0.0	4.3	5			DELETED	A
22-10-70	2 36 24.0	13.81	-49.73	25	0.0	4.8	58				
2-11-70	9 40 5.0	0.0	-32.70	33	0.0	4.0	6			DELETED	A
22-12-70	5 48 58.0	17.60	-36.40	33	0.0	0.0	10		FSHOCK	DELETED	
12- 1-71	17 35 57.1	62.08	-61.89	0	0.0	0.0	10				
1- 5-71	4 6 37.6	18.30	-36.92	33	0.0	4.8	38				
4- 6-71	20 47 32.8	33.86	-46.69	33	0.0	4.7	14				
26- 7-71	2 18 10.3	58.38	-24.35	0	0.0	0.0	10			DELETED	A
3- 8-71	5 34 27.1	28.43	-39.20	33	0.0	4.9	87				
3- 8-71	20 59 30.3	28.38	-39.40	33	0.0	4.7	36		ASHOCK	DELETED	
30- 9-71	21 24 10.8	-0.44	-4.89	0	0.0	6.0	261	76			
18-11-71	8 25 53.7	32.96	-19.45	33	0.0	4.5	9				
7-12-71	12 4 18.7	55.04	-54.45	0	0.0	5.4	208				
19- 1-72	0 37 7.5	31.36	-13.81	33	0.0	4.9	107				
8- 4-72	0 54 57.3	18.03	-59.58	0	0.0	0.0	7			DELETED	A
4- 6-72	16 48 15.1	20.20	-65.71	19	0.0	4.6	90				
14- 7-72	7 30 11.2	20.77	-63.28	0	0.0	0.0	7				
5- 9-72	23 8 25.4	20.33	-64.80	0	0.0	0.0	8		ASHOCK	DELETED	
20-10-72	4 33 49.9	20.60	-29.68	0	0.0	5.7	312	83			
30-10-72	1 50 35.7	22.34	-61.96	0	0.0	4.9	72	84			
7-11-72	12 5 14.3	49.05	-39.42	0	0.0	5.1	142	85			
4- 3-73	14 15 20.5	3.78	-25.29	0	0.0	4.4	7				
7- 4-73	12 8 8.4	31.58	-12.92	33	0.0	0.0	5				
24- 5-73	0 52 16.1	57.55	-29.39	0	0.0	3.8	4			DELETED	A
5- 6-73	0 22 10.3	34.16	-49.42	0	0.0	4.4	5				
29- 6-73	23 44 17.6	51.84	-39.73	33	0.0	0.0	21				
3- 7-73	8 32 4.7	18.67	-51.32	0	0.0	0.0	5				
8- 7-73	6 53 43.9	-16.03	-28.41	0	0.0	0.0	4				
24- 7-73	20 3 19.3	-11.55	-19.65	33	0.0	0.0	24				
26- 9-73	22 53 15.3	3.40	-25.62	0	0.0	4.6	8				
12-10-73	3 54 28.1	61.32	-59.50	33	0.0	4.2	31				
18-10-73	13 48 38.5	20.04	-62.85	33	0.0	4.8	59				
29-10-73	12 21 1.8	17.28	-26.60	33	0.0	4.5	18		FSHOCK	DELETED	
14-11-73	7 23 11.1	28.39	-46.04	0	0.0	4.1	7				
18- 1-74	21 14 51.2	-34.08	-20.15	33	0.0	5.4	63				
3- 2-74	20 20 22.7	-29.50	-42.54	33	0.0	4.4	5				
31- 3-74	21 12 59.9	17.04	-26.42	51	0.0	4.9	86				

DATE	TIME	LAT	LONG	Z	MS	MB	NSTN	NCAT			
8- 4-74	9 1 37.3	19.42	-42.93	0	0.0	4.3	6			DELETED	A
17- 4-74	23 8 59.5	21.98	-43.24	0	0.0	4.4	6			DELETED	A
11- 5-74	6 32 3.3	-23.87	-27.95	33	0.0	0.0	7				
15- 5-74	16 50 35.2	24.01	-43.15	0	0.0	4.3	11			DELETED	D
16- 5-74	0 44 23.4	30.71	-44.72	0	0.0	4.1	7			DELETED	D
19- 6-74	20 6 28.6	41.17	-48.42	33	0.0	3.8	5				
25- 7-74	17 38 26.0	33.34	-29.62	33	0.0	0.0	5			DELETED	B
16- 8-74	7 16 45.7	57.25	-40.62	33	0.0	4.0	5				
19- 9-74	19 59 30.4	-12.19	-12.00	33	0.0	4.3	6			DELETED	A
22-10-74	12 41 16.5	60.71	-24.45	0	0.0	0.0	4			DELETED	D
2-11-74	2 18 58.0	18.11	-60.17	0	0.0	0.0	7			DELETED	A
20-11-74	16 27 41.9	-2.46	-28.01	33	0.0	4.9	24				
24-11-74	6 19 32.9	44.29	-7.11	0	0.0	0.0	11				
7-12-74	10 10 46.6	-7.23	-27.91	33	0.0	4.7	9				
20-12-74	17 1 0.5	33.81	-16.35	0	0.0	0.0	6				
22- 1-75	0 26 36.1	29.16	-18.70	0	0.0	4.5	33				
17- 2-75	17 3 59.6	31.34	-50.78	33	0.0	4.2	8				
22- 4-75	14 37 8.9	58.28	-40.40	0	0.0	0.0	4			DELETED	A
17- 5-75	22 0 30.4	17.58	-44.51	0	0.0	4.6	14				
18- 5-75	20 43 45.9	21.32	-59.00	33	0.0	0.0	5			DELETED	A
20- 7-75	20 8 34.9	26.24	-53.59	33	0.0	0.0	6			DELETED	B
28-10-75	14 34 24.8	-37.82	3.76	33	0.0	0.0	8				
19-11-75	23 27 23.1	48.79	-47.05	33	0.0	4.3	5				
3-12-75	21 8 0.0	-7.06	-2.50	33	0.0	0.0	4				
13-12-75	9 24 22.7	57.95	-52.06	0	0.0	4.4	22				
15-12-75	13 35 8.1	16.17	-26.68	33	0.0	0.0	6				
17-12-75	8 5 19.6	41.81	-62.94	33	0.0	0.0	10				
19-12-75	15 24 40.4	31.04	-60.67	33	0.0	0.0	7				
29-12-75	5 40 31.2	15.80	-49.59	16	0.0	0.0	12				
30-12-75	9 31 50.0	-8.86	-8.88	33	0.0	0.0	5				
14- 3-76	23 12 24.6	41.66	-69.97	0	0.0	0.0	11		ASHOCK	DELETED	A
31- 7-76	1 7 53.7	31.19	-51.33	33	0.0	4.2	6				
24-11-76	21 50 54.6	32.97	-61.50	33	0.0	5.1	102	126			
28-12-76	2 57 38.2	22.13	-63.48	33	4.4	5.2	65	128			
6- 2-77	0 30 49.9	17.87	-49.51	33	0.0	5.2	106				
16- 2-77	0 49 31.2	25.97	-26.25	33	0.0	5.5	148	131			
26- 2-77	22 43 48.9	28.52	-20.83	10	0.0	4.7	68				
3-10-77	4 38 33.7	14.14	-48.18	33	4.7	5.1	89				
12-10-77	0 53 29.0	14.10	-48.23	33	4.6	5.1	47		ASHOCK	DELETED	
17-11-77	15 2 41.8	43.01	-12.52	33	0.0	0.0	14				
13-12-77	1 14 18.6	17.35	-54.84	33	6.4	5.7	201				
24- 3-78	0 42 36.3	29.80	-67.40	20	5.8	6.1	272	145			
24- 3-78	5 32 31.5	29.64	-67.38	33	0.0	0.0	15		ASHOCK	DELETED	
24- 3-78	13 38 5.1	29.55	-67.71	33	0.0	0.0	12		ASHOCK	DELETED	
12- 4-78	0 29 52.3	29.92	-67.29	33	0.0	0.0	11		ASHOCK	DELETED	
13- 4-78	6 0 38.3	57.12	-36.62	32	4.8	5.2	192				
13- 4-78	21 15 18.1	29.70	-67.19	33	0.0	0.0	23		ASHOCK	DELETED	
15- 4-78	16 26 9.9	29.69	-67.39	33	0.0	4.6	15		ASHOCK	DELETED	
19- 4-78	11 32 16.7	29.83	-67.36	20	0.0	4.3	41		ASHOCK	DELETED	
24- 4-78	5 44 56.0	30.04	-67.78	33	0.0	4.5	19		ASHOCK	DELETED	
4- 5-78	5 44 47.2	29.93	-67.51	33	0.0	4.7	39	147	ASHOCK	DELETED	
30- 7-78	10 17 41.3	44.14	-7.28	10	0.0	0.0	22				
11- 8-78	8 6 25.8	29.83	-68.01	33	0.0	0.0	27		ASHOCK	DELETED	
26- 9-78	6 51 9.7	30.02	-67.54	33	0.0	4.3	20				
17-10-78	8 14 2.1	14.61	-48.00	33	3.9	4.8	18				
23-11-78	21 31 58.2	29.69	-67.64	33	0.0	0.0	16		ASHOCK	DELETED	
6-12-78	13 28 35.5	17.44	-54.78	10	5.8	5.5	160	155			
28- 4-79	20 27 13.2	43.17	-11.44	10	0.0	0.0	39				
9- 5-79	18 35 36.4	21.29	-62.12	33	0.0	4.9	19				
30-12-79	17 38 17.6	-36.27	-15.31	10	0.0	0.0	6			DELETED	A

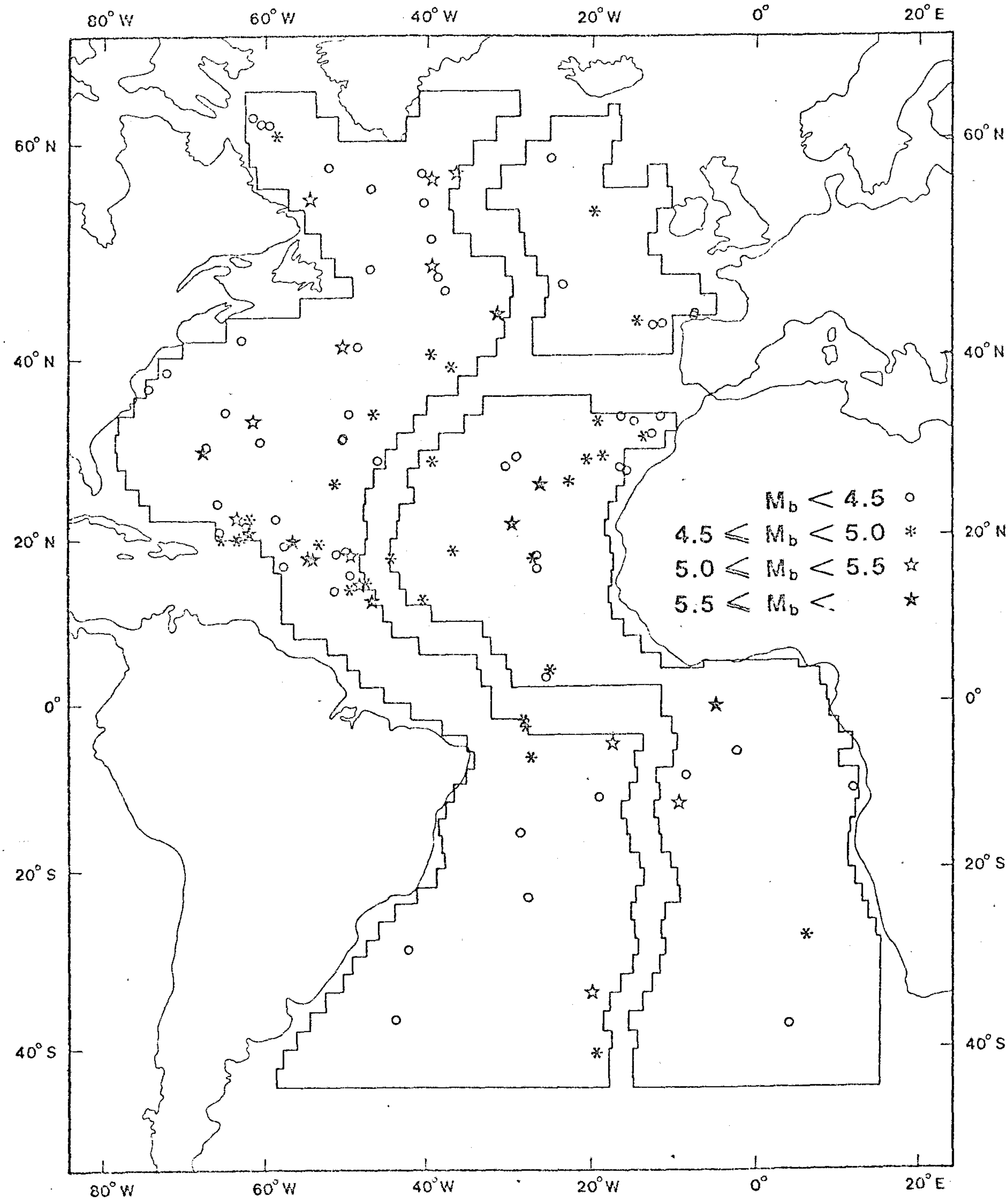

Figure (1). Teleseismically observed intraplate earthquakes in the Atlantic Ocean during the period 1964-1979 inclusive.

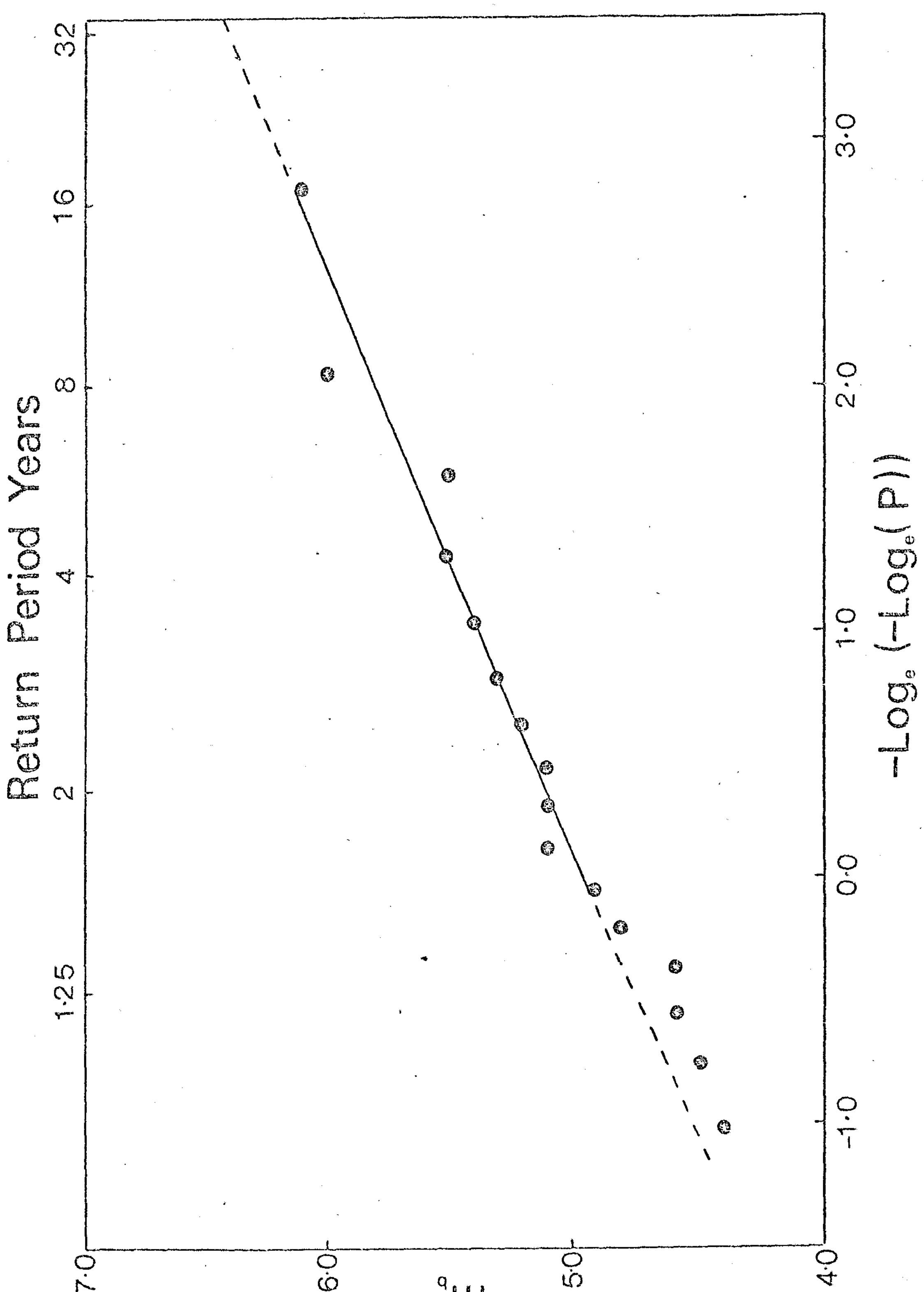

Figure (2). Observed annual maximum m_b magnitudes for period 1964-1969 plotted against $-\text{Log}_e\,(-\text{Log}_e\,P)$ where P is the estimated probability that in any year this maximum will not be exceeded. Straight line gives $\text{Log}_e\,(-\text{Log}_e\,P) = 11.2-2.27m_b$ which corresponds to a b value in the magnitude frequency distribution of 0.99.

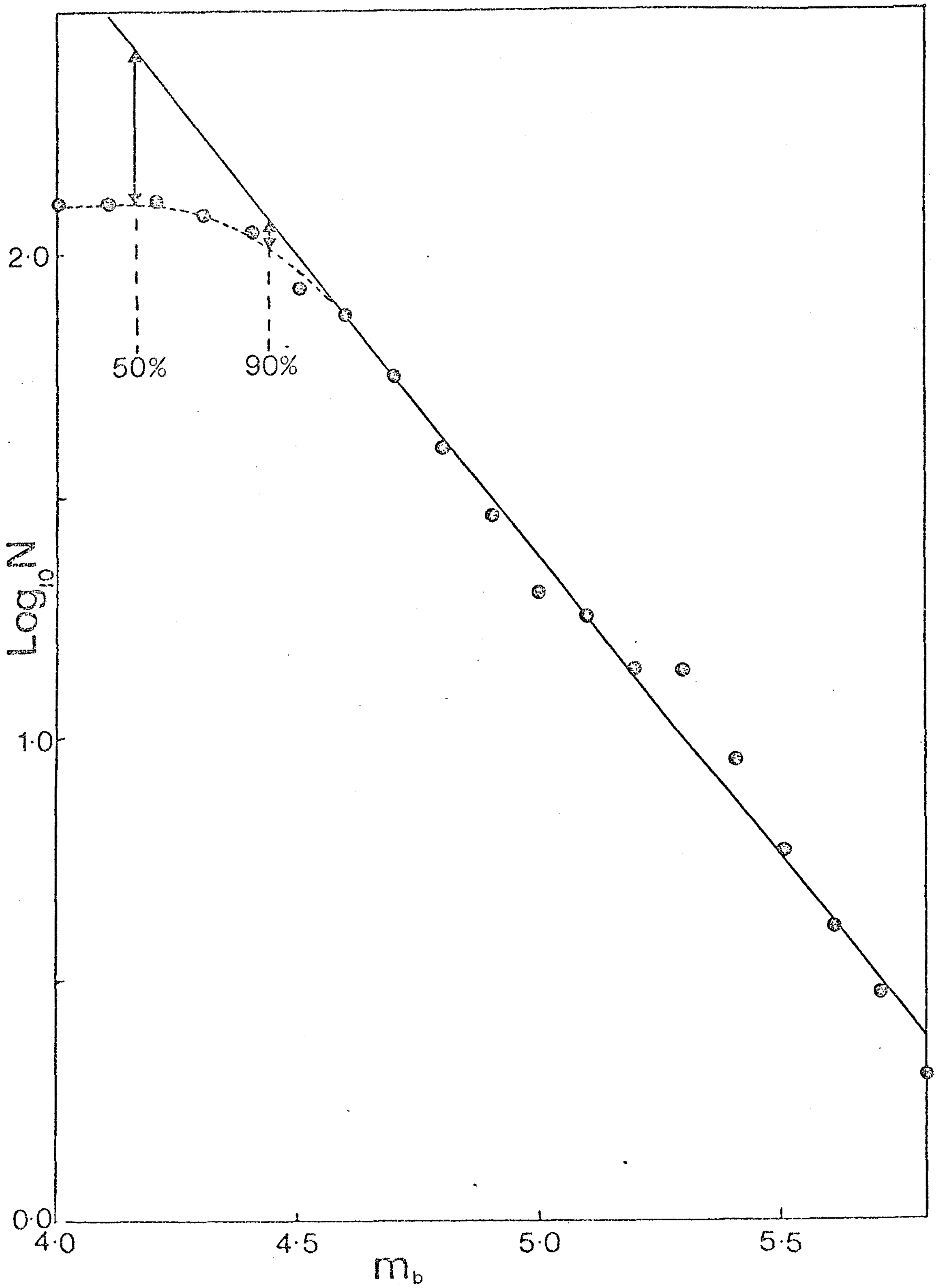

Figure (3). Magnitude frequency plot of Mid-Atlantic ridge earthquakes between 15°and 25°N illustrating method of estimating 50% and 90% detection thresholds which in this example are circa m_b = 4.2 and 4.4 respectively. The detection level for events with m_b of 4.5 and greater is near 100%.

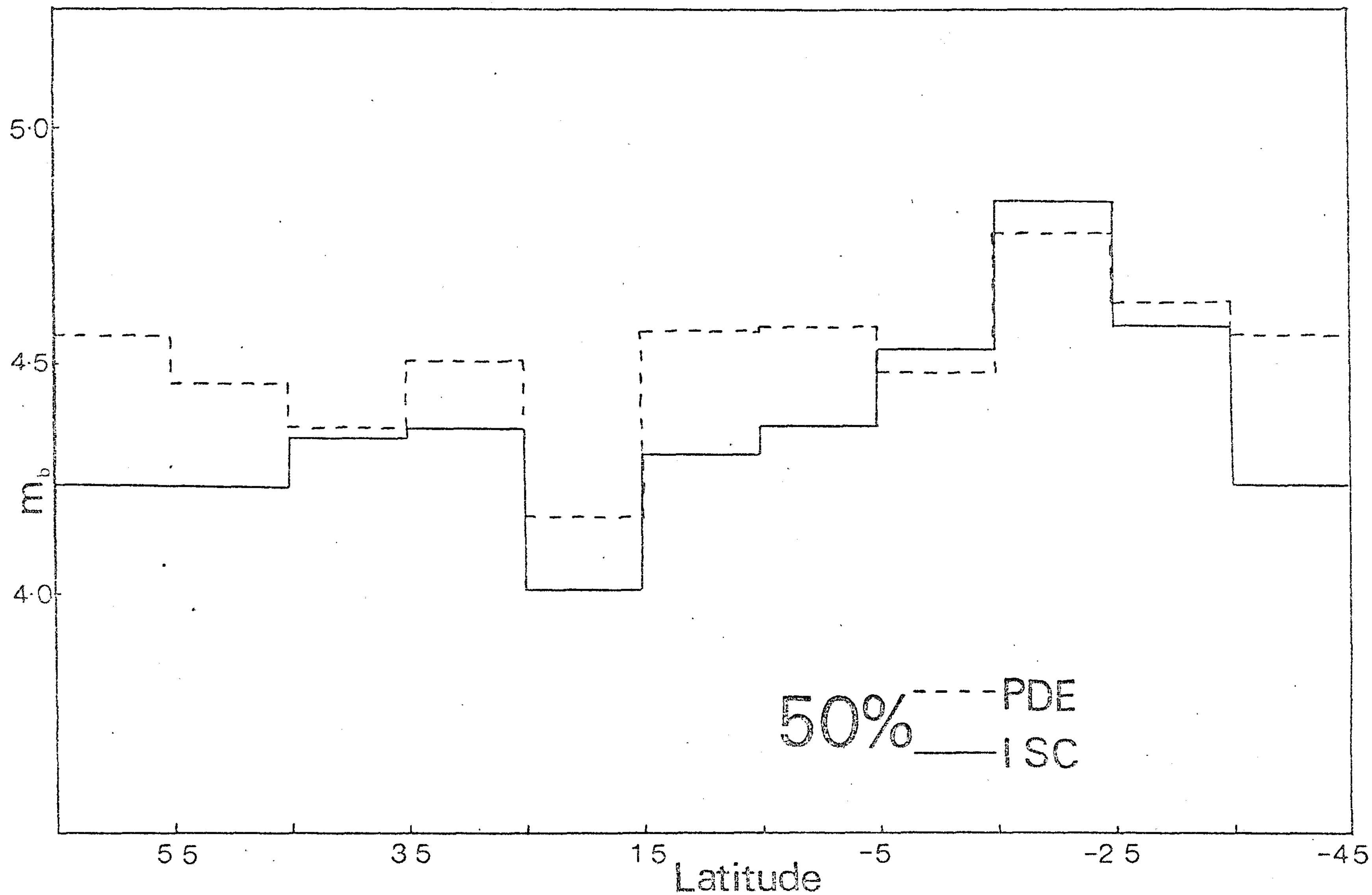

Figure (4). ISC and PDE 50% detection thresholds of Mid-Atlantic Ridge events as a function of latitude.

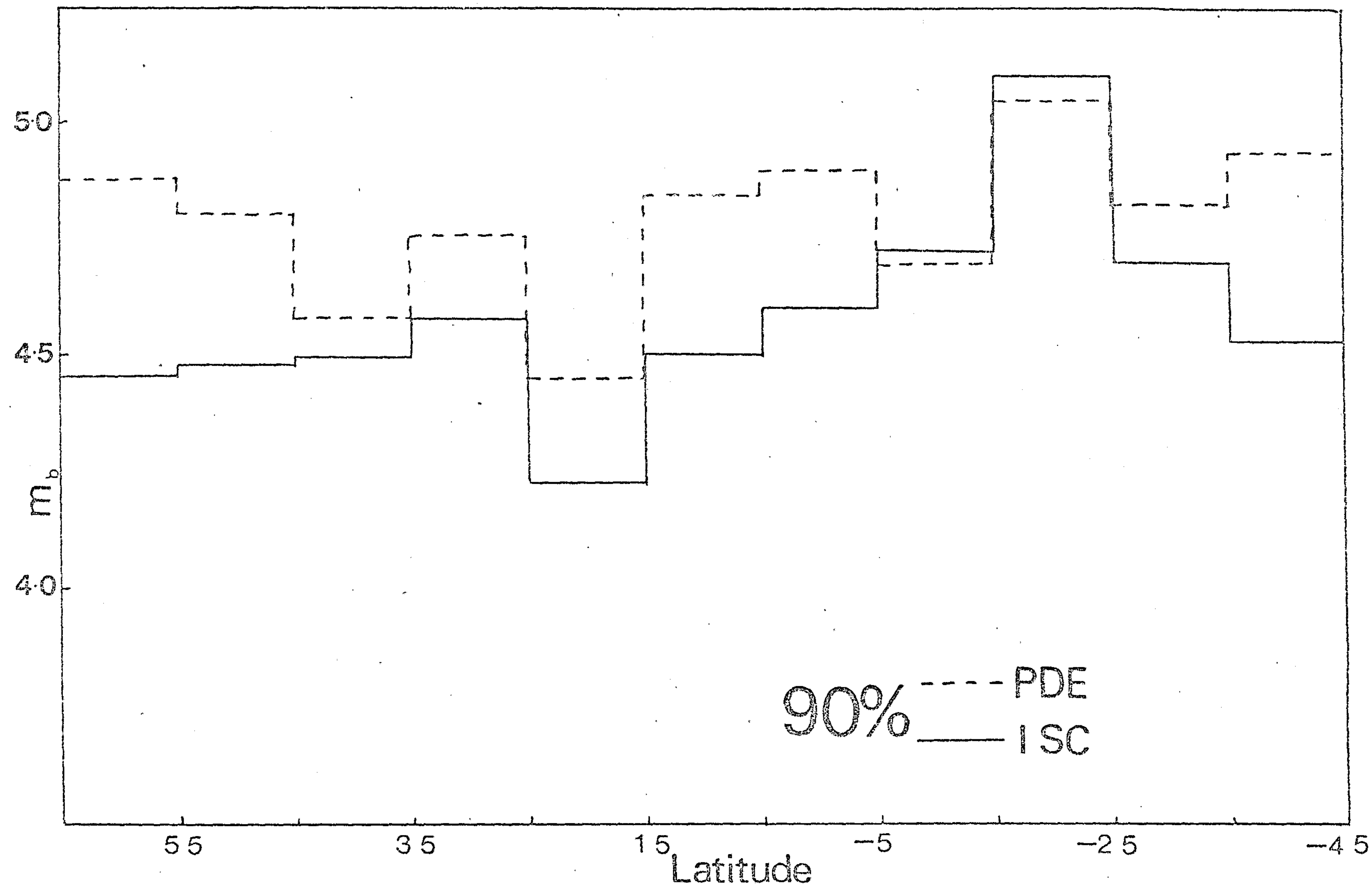

Figure (5). ISC and PDE 90% detection thresholds of Mid-Atlantic Ridge events as a function of latitude.

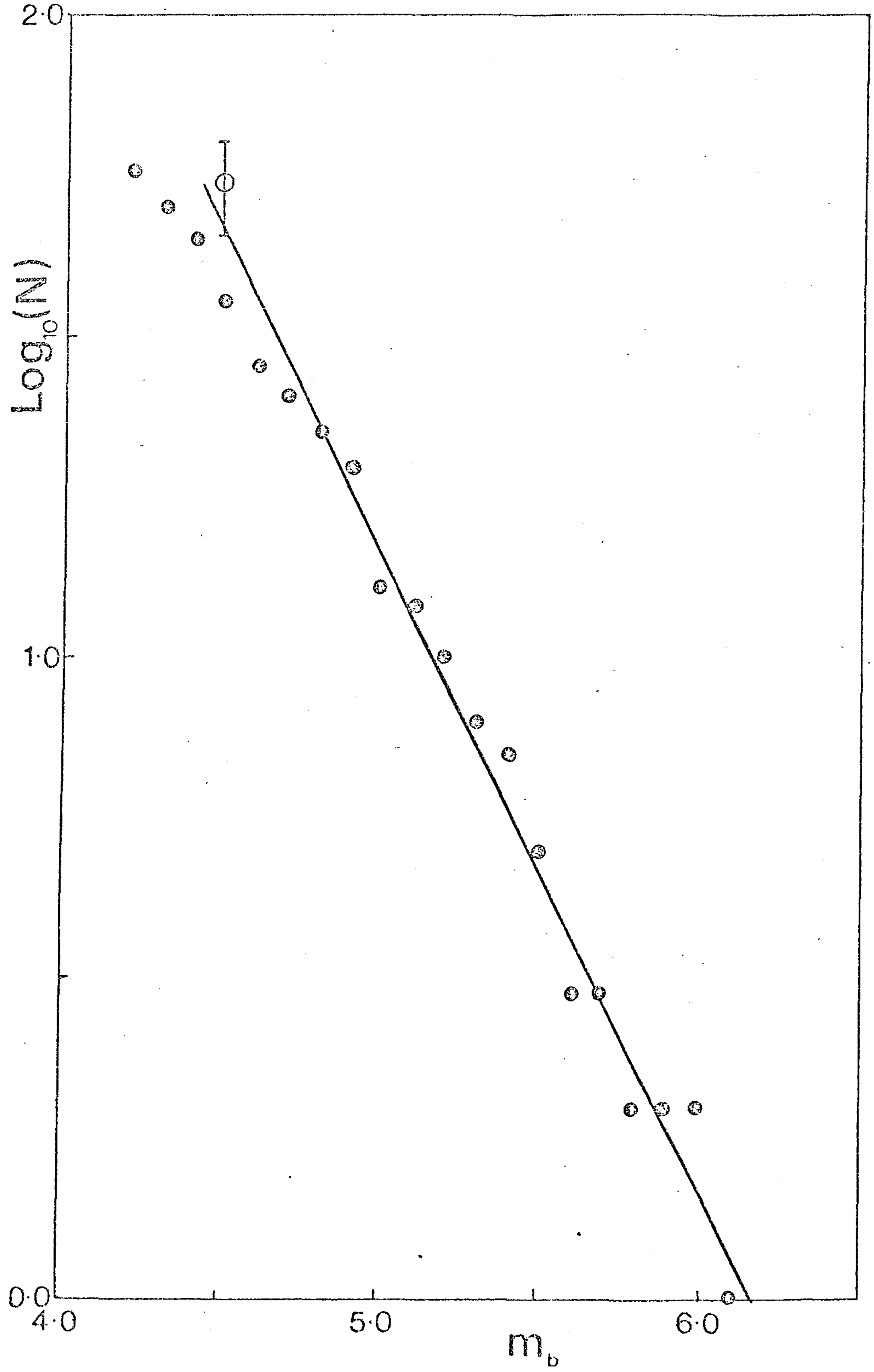

Figure (6). Cumulative magnitude frequency plot for Atlantic Ocean intraplate earthquakes but excluding those east and northeast of the Caribbean (region D in figure 8). Straight line fitted to points with m_b greater than 5.0, has form $\log N = 6.15 - 1.0 m_b$. Open circle with standard error limits shows value for $m_b = 4.5$ after correction for detection levels (Table 2).

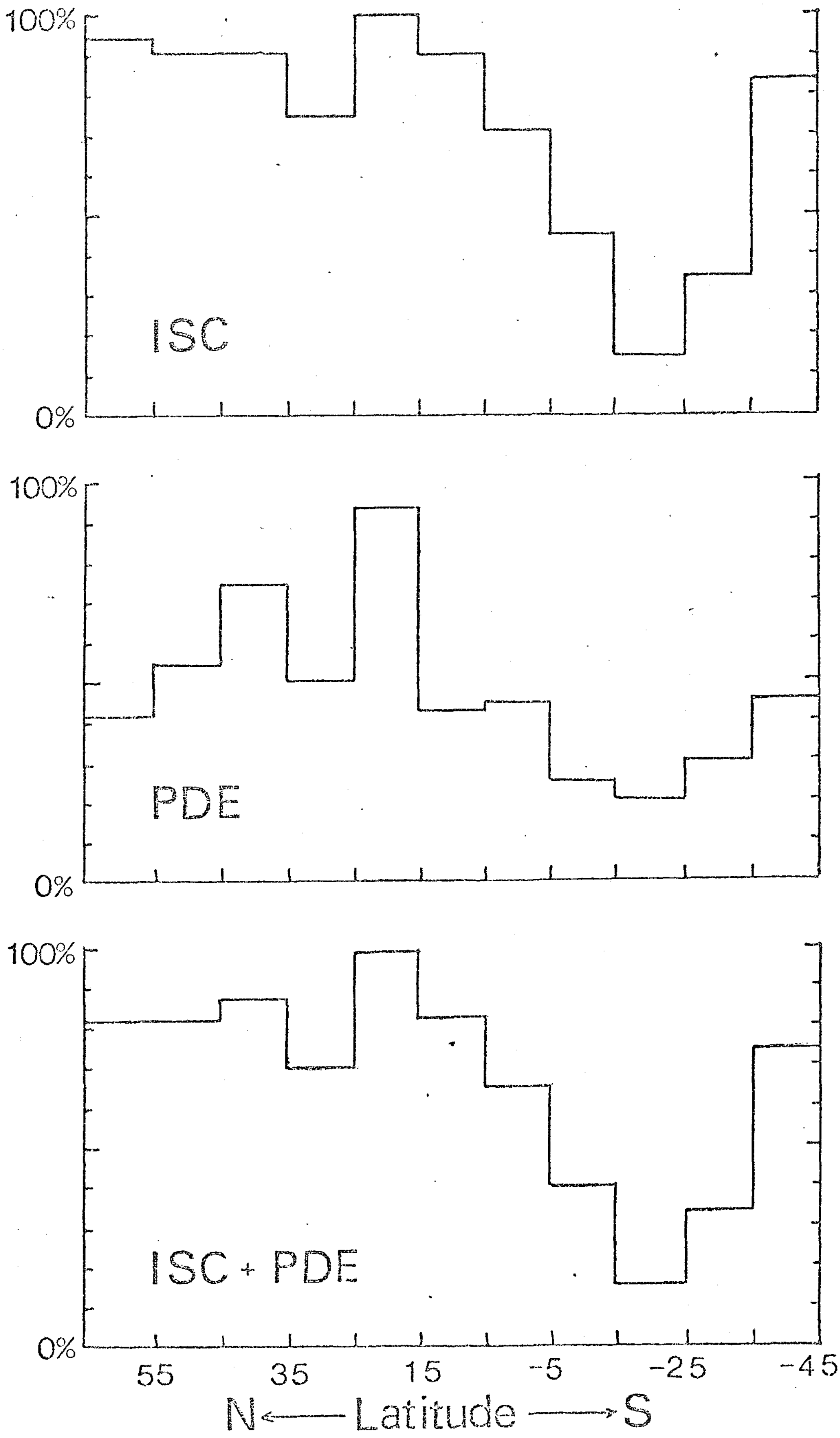

Figure (7). Detection levels for events with magnitude m_b of 4.5 and greater showing latitude variation for both ISC and PDE determinations. The bottom histogram shows weighted mean for 12 years of ISC and 4 years of PDE detections.

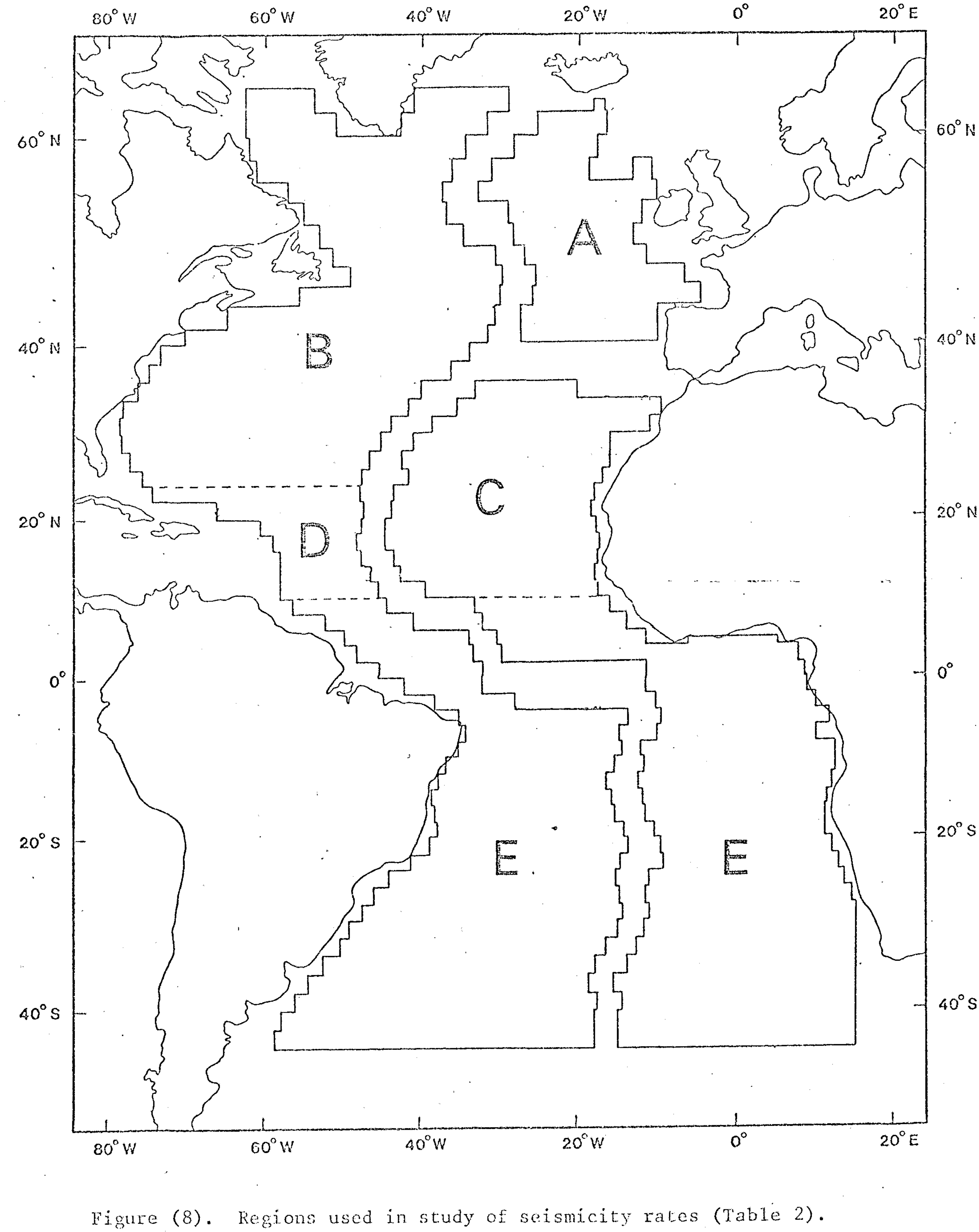

Figure (8). Regions used in study of seismicity rates (Table 2).

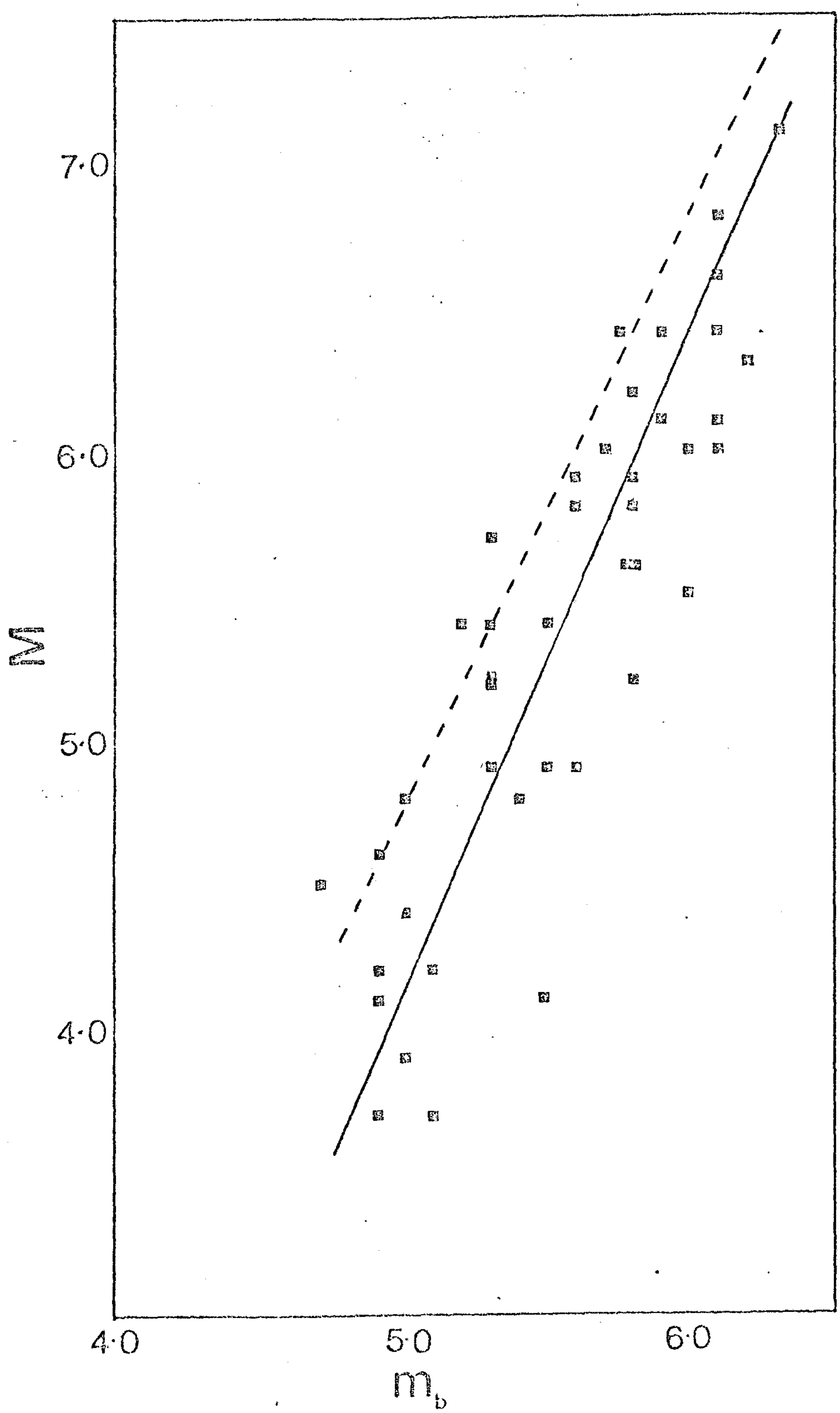

Figure (9). Plot of surface wave magnitude M against body wave magnitude m_b for oceanic intraplate earthquakes in Bergman and Solomon (1980). Solid line fitted to data has form $M = 2.26m_b - 7.15$. Dashed line fitted to an unselected world sample of events by Marshall (1970) shows that the intraplate events have m_b values enhanced by 0.2-0.3 units.