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INTRAPLATE SEISMICITY AND SEISMIC RISK IN THE ATLANTIC OCEAN BASED ON TELESEISMICALLY OBSERVED EARTHQUAKES

by

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Intraplate seismicity and seismic risk in the Atlantic Ocean based on teleseismically observed earthquakes

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The work described in this report has been carried out for the Department of the Environment as part of its radioactive waste management research programme. The results will be used in the formulation of Government policy but at this stage do not necessarily represent that policy

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PREFACE

This report forms part of a programme to assess the suitability of the deep ocean floor for the disposal of high-level radioactive waste. In particular, it addresses the problem of earthquakes and their effects in the deep sea environment.

Much work on the feasibility of radioactive waste disposal in the seabed has been concentrated on the effectiveness of sediments as a barrier to the migration of radionuclides. Since the ground motions associated with earthquakes have the potential to disrupt sediments and even to initiate mass movement, it is clearly important to quantify the frequency and magnitude of such events. Most of the earth's seismicity is confined to relatively narrow zones which are well known and disposal sites can be located away from such areas to minimise the risk from earthquakes. Infrequent, but sometimes large, earthquakes do occur away from these zones, however, and because of the long duration over which radioactive waste will need to be contained it is necessary to establish whether such events could represent a significant problem on such a time scale.

Detailed estimation of seismicity in the vicinity of potential disposal sites will ultimately require recordings from nearby ocean-bottom seismographs. Records of large earthquakes at land stations for the past 70 years already exist, however, and represent a database from which overall levels of activity can be estimated, even for areas of low activity. In this report such data is used to assess the level of seismicity in the regions of the Atlantic Ocean situated away from the recognised active zones. The results presented indicate only the average level of activity but enable the significance of earthquakes to the problem of nuclear waste disposal to be put into the correct perspective.

CONTENTS

SUMMARY

This report is concerned with the seismicity and seismic risk within the intraplate regions of the Atlantic Ocean and forms part of a programme to assess the suitability of the ocean floor for the disposal of high-level radioactive waste. The results presented here are based on existing files of earthquake data for the period 1913-1979 inclusive.

During the above period earthquakes with magnitudes up to (Ms) 7.2 have been observed with epicentres within the intraplate region. Observations of oceanic intraplate earthquakes worldwide suggest an upper limit of (Ms) 7.3 on the magnitude of these events.

Apart from an active zone to the E and NE of the Caribbean, seismicity appears uniformly distributed but with the observed level of activity in the North Atlantic twice that in the south. In the North Atlantic the earthquakes have the cumulative magnitude frequency distribution:

$$\mathrm{Log}_{10}N = -5.63 - 0.44\ \mathrm{Ms}$$

where N is the number 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 2000-10,000 years. The large range is the result of several factors, the most important being the detailed distribution of activity near a given site and the ground motion attenuation function, both of which are poorly known.

1. INTRODUCTION

Most of the earth's seismicity can be accounted for within the framework of plate tectonics. In this theory the earth's outermost shell or "lithosphere" is divided into a relatively small number of regions or "plates" which behave as rigid units. These plates are known to move relative to each other, propelled by forces which are not, at present, well understood. At the plate margins this relative movement results in the majority of the earth's earthquakes. Earthquakes are much less frequent, although not absent, away from the plate margins and the existence of such "intraplate" earthquakes indicates that some movement within the plates does take place. This report is concerned with the seismicity and potential seismic hazard within the intraplate regions of the Atlantic ocean.

Quantitative estimation of intraplate seismicity is frequently difficult because the number of earthquakes recorded is small during the time period for which we have data. This is particularly serious for oceanic areas because of the inevitable absence of historical records of felt earthquakes predating instrumental recordings. In addition there are at present no long term recordings from instruments deployed on the sea bed. The only source of information comes from "teleseismic" earthquakes, that is, those large enough to be identified and located using records from distant seismological stations on land. For these reasons it is not possible at present to be "site specific" in our assessment of seismic hazard. Instead, seismicity data from large regions has been used and assumptions made about its detailed distribution.

Although instrumental recordings of earthquakes date from the turn of the century, routine data collection and earthquake location did not start until 1913 with the International Seismological Summary (ISS). Between 1960 and 1964 our ability to detect and locate earthquakes was considerably improved by the introduction of the World Wide Standardised Seismological 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. For this reason the results presented here are primarily based on data for the period 1964-1979 inclusive. Data from before 1964 have been used, however, in the discussion of the upper limit on magnitude.

2. ATLANTIC INTRAPLATE EARTHQUAKES 1964-1979

2.1 Definition of the intraplate Region

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 was defined as the bottom of the continental slope. Between latitudes 12°N and 22°N, however, the Atlantic is bounded in the west by an active plate margin, the Caribbean arc. The search region was, therefore, terminated at approximately 150 km east of this margin as defined by islands forming the arc. 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 150 km from all these seismically active regions. It is not desirable to include regions nearer than 150 km to active plate margins for two reasons: firstly, the plate boundaries are not always well defined and the possibility of accidentally including plate boundary regions must be avoided; secondly, the results of the search will tend to become contaminated with small plate margin events which can have mislocations in excess of 100 km. 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 search 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 extended the time coverage to the end of 1979.

2.2 Removal of Spurious Events

The file search yielded 182 events which are listed in Appendix 1. As already mentioned, there is a problem that the results of any search for a relatively inactive intraplate region can be contaminated by small earthquakes mislocated from nearby plate margins. Although the search region was designed to keep this to a minimum, as a precaution the original epicentre determinations in the bulletins were carefully examined to check their authenticity as intraplate events. If there is any doubt they have been marked "deleted" in Appendix 1 (followed by a code giving the reason), and excluded from subsequent analyses. Most of the events were so marked because the standard confidence limits on their epicentres overlap the edge of the search region where it lies next to an active plate margin. Man-made explosions and events which may have arisen from a chance association of arrival time data were also noted. Suspected foreshocks and aftershocks were separated and, since at the low overall seismic activity observed such sequences represent isolated clusters spatially and temporally, they were each 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 are shown in Figure 1.

2.3 Spatial Distribution of the Earthquakes

The most obvious feature seen in Figure 1 is a WNW-ESE 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 (see Minster et al., 1974). As the level of seismicity may be more characteristic of an active plate margin, these earthquakes have been 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 epicentres of the larger events worldwide for correlations with bathymetric and geological features has been made by Bergman and Solomon (1980). Their conclusion is that oceanic intraplate events are commonly found in association with suspected zones of crustal weakness (such as fracture zones) but not necessarily with large bathymetric features.

Focal depths listed in Appendix 1 are all less than 100 km with many assigned a nominal value of 33 km. It should be emphasised 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 below the sea bed.

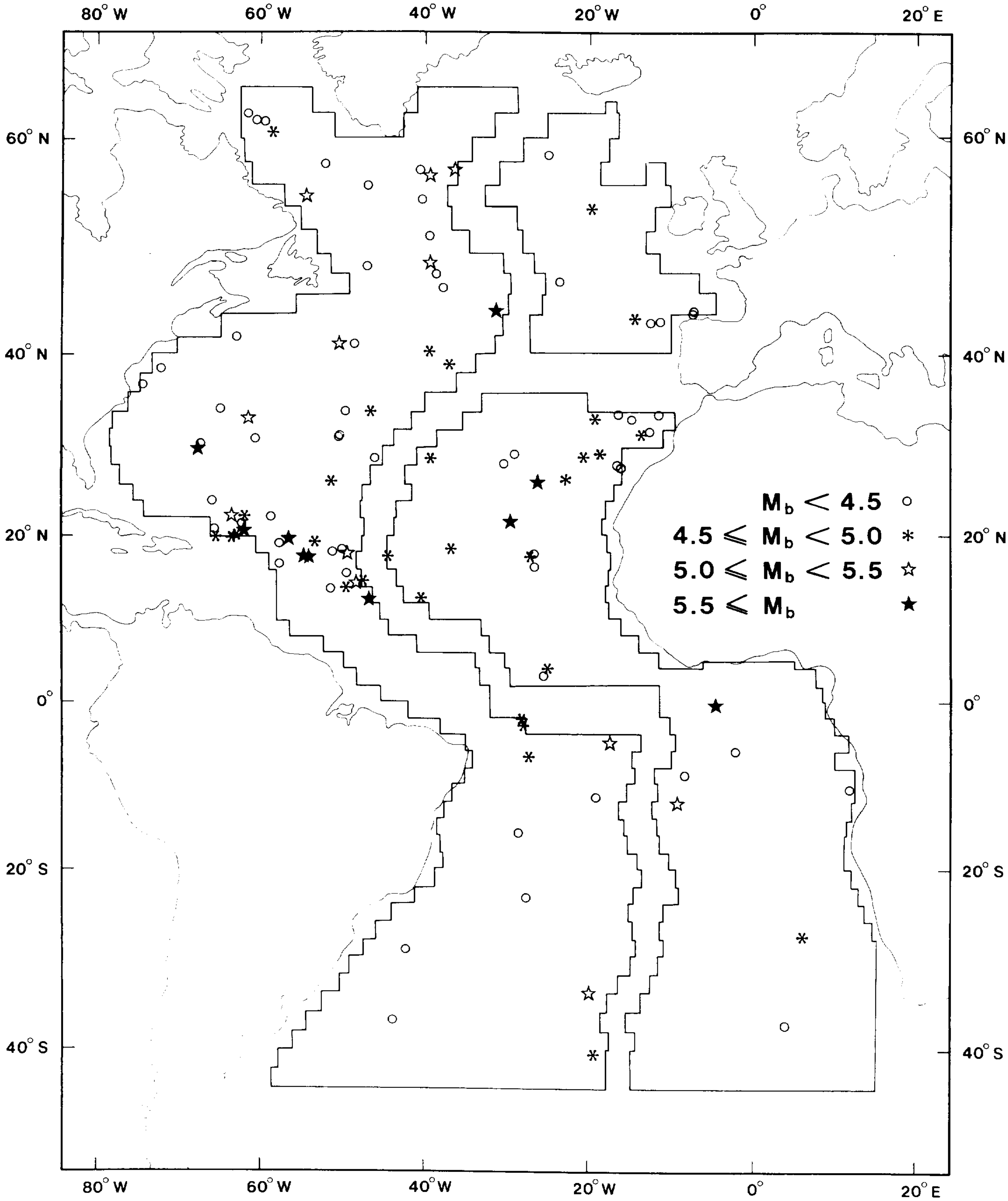

Figure 1. Teleseismically observed intra plate earthquakes in the Atlantic Ocean during the period 1964-1969 inclusive. The region assumed to be intra-plate is also indicated.

3. MAGNITUDE FREQUENCY DISTRIBUTION

3.1 Definitions

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

$$\mathrm{Log}_{10}N = a - b\,M \qquad (1)$$

where N is the cumulative number of earthquakes with magnitude M or greater, a and b are constants. These constants depend on the seismicity and on the magnitude scale used for M. The majority of magnitudes in Appendix 1 are measured in terms of the short period body wave scale (denoted m_b). They are based on the measured amplitudes of the initial P-wave arrival seen on instruments with peak sensitivity centred at 1-second period. Unfortunately, for larger earthquakes with source durations greater than 1 sec, the m_b scale progressively becomes a less reliable measure of earthquake "size" and the surface wave scale (denoted M_s here) based on the amplitude of 20 sec period surface waves is more appropriate. The onset of this effect occurs between m_b values of 6.0 to 6.5 above which the scale saturates. During the period 1964-1979 the maximum observed m_b value for the Atlantic intraplate events was 6.1 and, therefore, the measured m_b values were used unmodified for the magnitude frequency plots. Where however, data with larger m_b values than these are used or we wish to extrapolate to larger values as in sections 4 and 5, the surface wave scale is used and appropriate conversions from m_b to M_s made where necessary.

3.2 Detection Thresholds

In general, plots of $\mathrm{Log}_{10}N$ against M follow the above linear relationship but flatten off at small magnitudes because the ability of the observing seismological network to detect such events declines. This is illustrated in Figure 2 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 at 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 2 illustrates a simple graphical method of estimating the corresponding magnitude thresholds.

The Atlantic intraplate events come from a wide area over which the detection

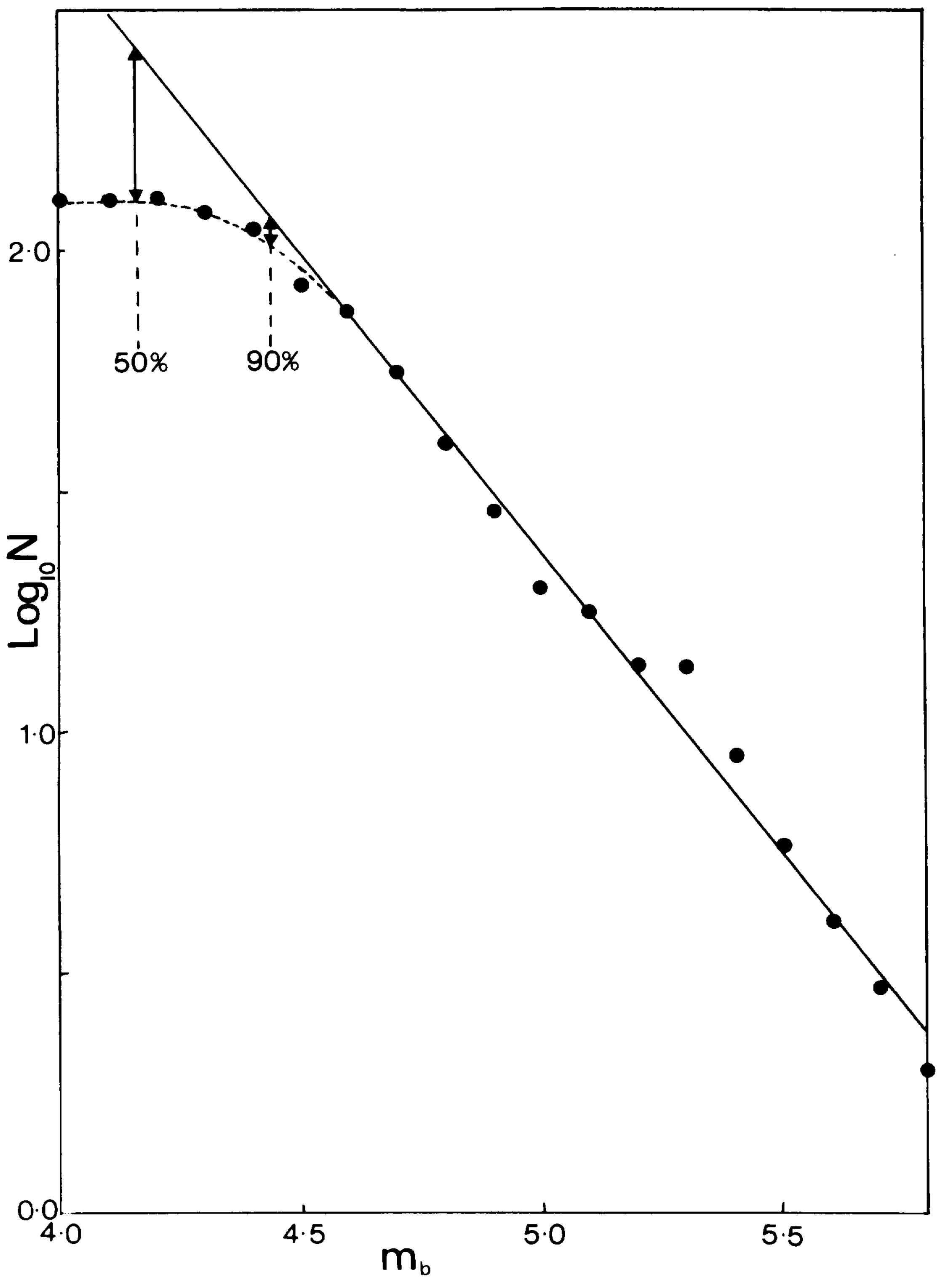

Figure 2. Magnitude frequency plot of Mid-Atlantic ridge earthquakes between 15°N and 25°N illustrating method of estimating 50% and 90% detection thresholds which in this example are circa m_b = 4.2 and 4.4 respectively. The detection level for events with m_b greater than 4.5 is near 100%.

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 2. Figures 3 and 4 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 collects more data. The 50% levels in Figure 3 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 northern 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.

3.3 Average Magnitude Frequency Relation

Figure 5 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:

$$\text{Log}_{10}N = 6.15 - 1.0\ m_b \qquad (2)$$

and was fitted only to points with m_b greater than 5.0. A value for 1.0 for the constant "b" in equation 1 is considered low. By comparison, typical values found in this study for the Mid-Atlantic Ridge events range between 1.3 and 1.8 and are 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, high stress drops and homogeneous structure. Equation 2 can be normalised to give the count N in terms of events per year per km².

$$\text{Log}_{10}N = -2.74 - 1.0\ m_b \qquad (3)$$

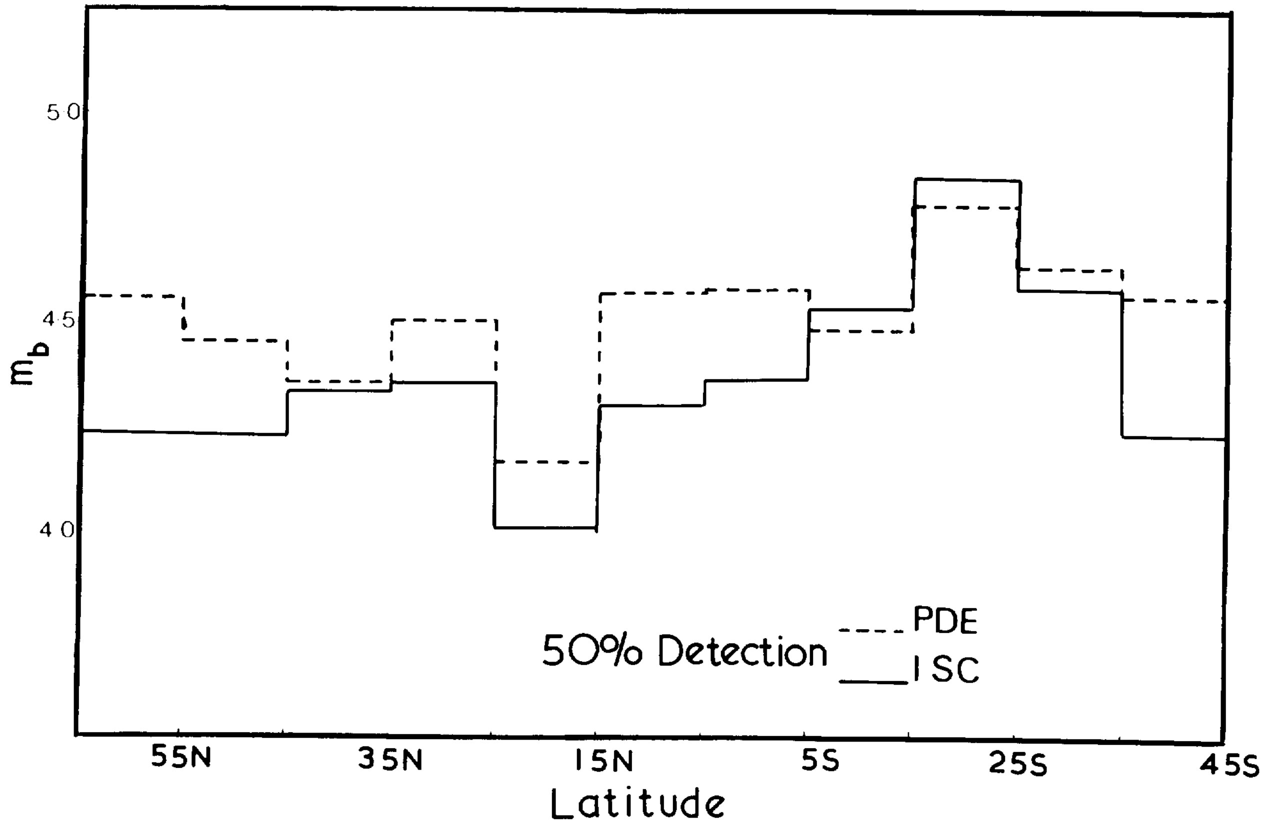

Figure 3. I.S.C. and PDE 50% detection thresholds for Mid-Atlantic Ridge events as a function of latitude.

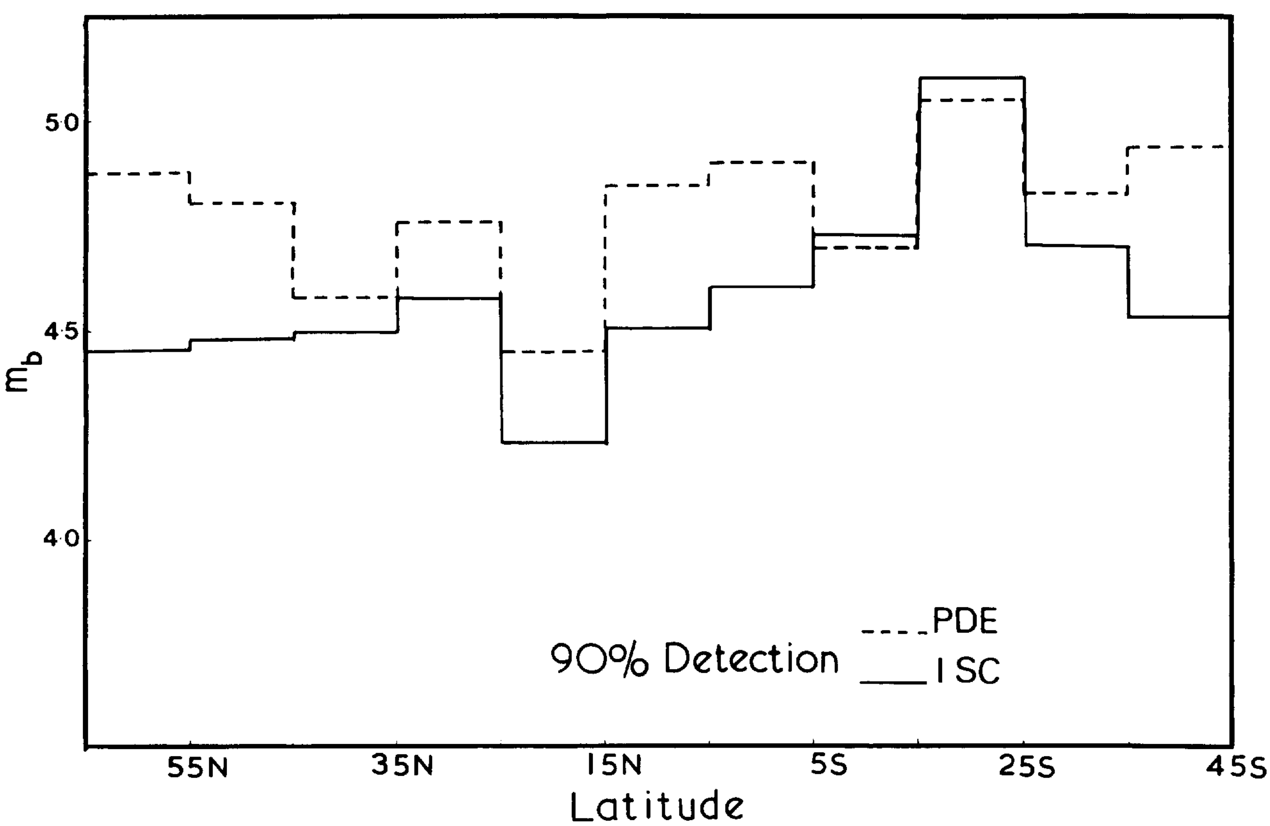

Figure 4. I.S.C. and PDE 90% detection thresholds for Mid-Atlantic Ridge events as a function of latitude.

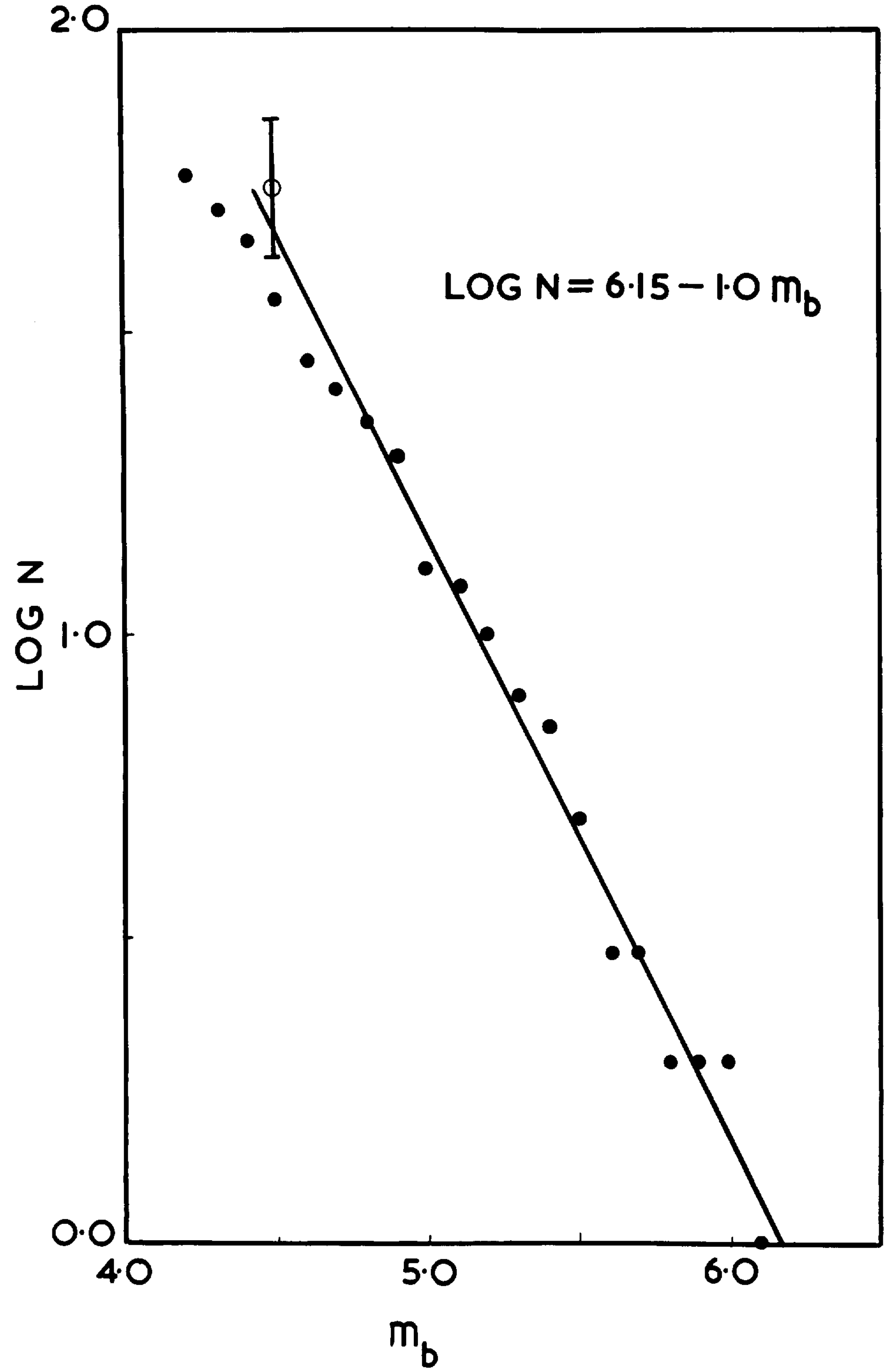

Figure 5. Cumulative magnitude frequency plot for Atlantic Ocean intraplate earthquakes but excluding those East and North East of the Caribbean (region D in Figure 7). Straight line obtained by least squares fit to points with m_b greater than 5.0. Open circle with 90% confidence limits shows count for $m_b \geqq 4.5$ after correction for detection levels (sum of regions A + B + C + E in Table 1 = 55.3 events).

3.4 Regional Variation in Activity

Equation 3 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 1, 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 to correct these counts for the percentage detection expected. Figure 6 shows the percentage detection levels as a function of latitude for the Mid-Atlantic Ridge events of magnitude 4.5 or greater, obtained by the converse of the process shown in Figure 2. The counts for intraplate events with magnitude m_b greater than 4.5 were corrected assuming the detection levels at the bottom of Figure 6 which are a weighted mean for 12 years ISC and 4 years PDE detection capability.

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 (1.0 - 17)*
B	13	16.41	10.03	10.2 (6.0 - 16)*
C	12	15.36	7.11	13.5 (7.8 - 22)*
D	15	15.30	2.36	40.5 (27 - 59)*
E	10	21.16	28.88	4.6 (2.5 - 7.8)*
A + B + C	27	34.14	19.9	10.7 (7.5 - 15)*
A + B + C + E	37	55.30	48.78	7.1 (5.4 - 9.1)*

Table 1 - Estimates of the rate of occurrence of events with body wave magnitude m_b greater than or equal to 4.5 based on the observed numbers and corrected for the observed detection levels. *Confidence limits are at 90% level and assume that raw counts are from earthquakes occurring as Poisson events.

Figure 7 shows a simple regionalisation used to test for variations in seismicity. The seismicity levels in terms of numbers of events with magnitude equal to or greater than 4.5 for each region is given in Table 1. When the counts

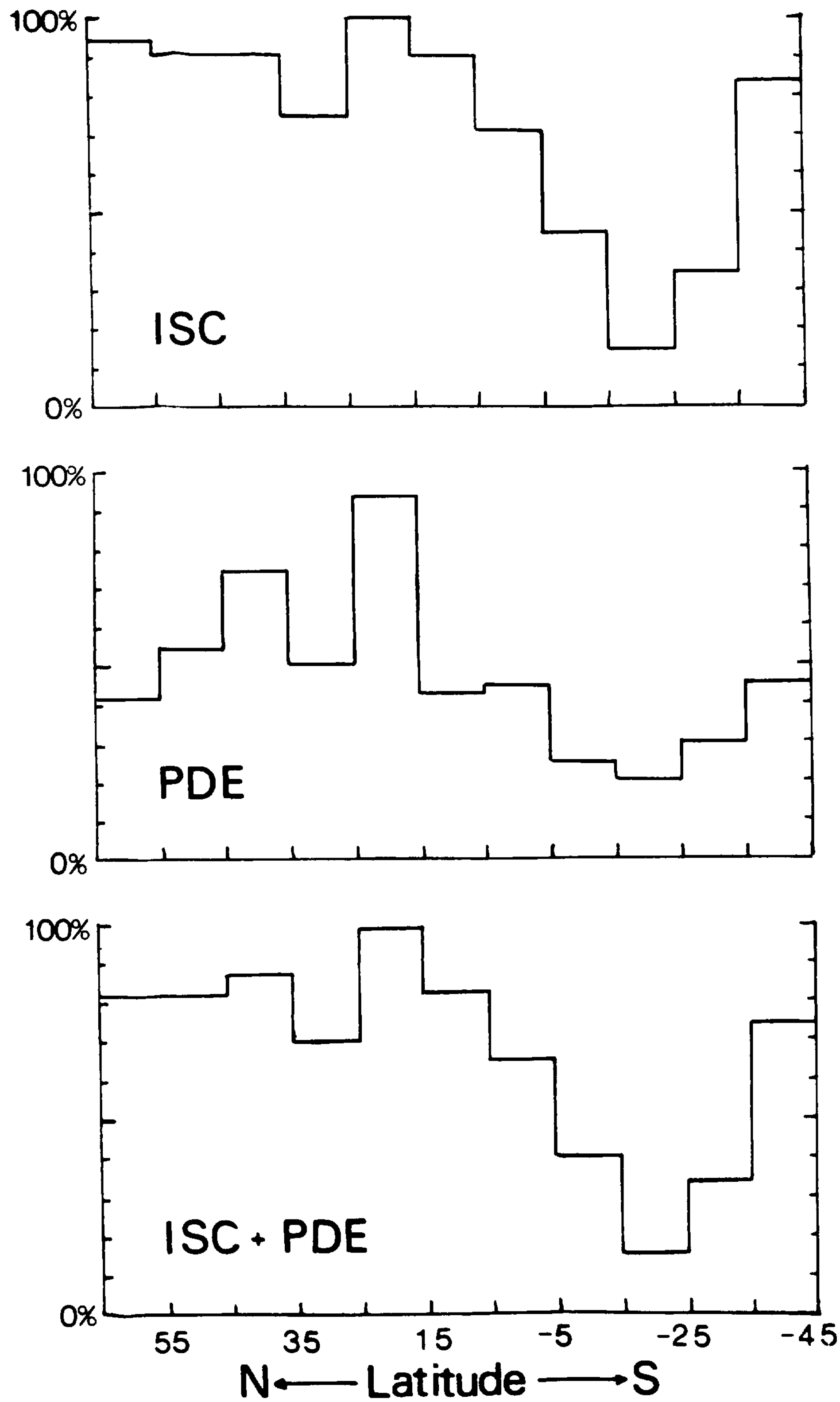

Figure 6. Percentage detection levels for events with magnitude $m_b \geq 4.5$ showing latitude variation for both ISC and PDE determinations. Bottom histogram shows a weighted mean of 12 years ISC and 4 years PDE detection.

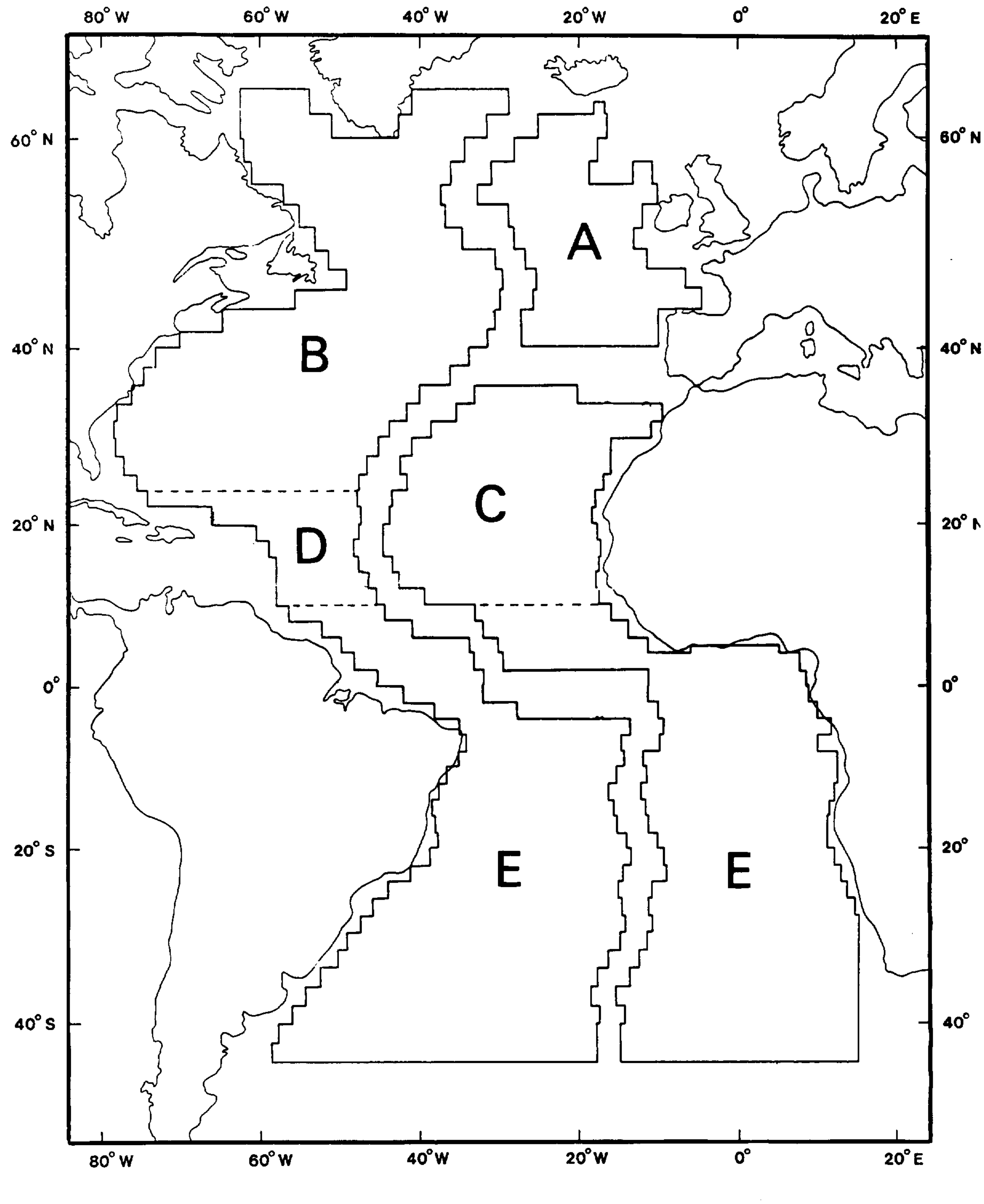

Figure 7. A simple regionalisation used in study of seismicity rates (Table 1).

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 yr per km^2, however, region E is still less active than any of the other regions except A. Activity in region D is by far the highest and justifies its exclusion from the general 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 twice that found for the south; however, this difference is only significant at the 90% level.

Assuming a "b" value of 1.0 and a count of 10.7×10^{-8} per year per km^2 (see Table 1) for events with magnitude 4.5 or greater, the magnitude frequency relation for the Northern Atlantic (regions A, B and C) then becomes:

$$\text{Log}_{10}N = -2.47 - 1.0\ m_b \qquad (4)$$

where N is in terms of events per year per km^2.

3.5 Conversion to Surface Wave Magnitude M_s

It is desirable to express the relationship (4) in terms of the surface wave scale M_s. As mentioned previously, the m_b scale does not accurately reflect true increases in earthquake size above m_b values of about 6.0-6.5. In addition, very few results have been published which relate ground motions, such as peak acceleration, to magnitudes on the m_b scale.

Figure 8 shows a plot of m_b against M_s values for oceanic intraplate events worldwide listed by Bergman and Solomon (1980). The straight line fitted through the points gives:

$$m_b = 0.44\ M_s + 3.16 \qquad (5)$$

conversely

$$M_s = 2.27\ m_b - 7.18 \qquad (6)$$

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° dip slip focal mechanisms in intraplate

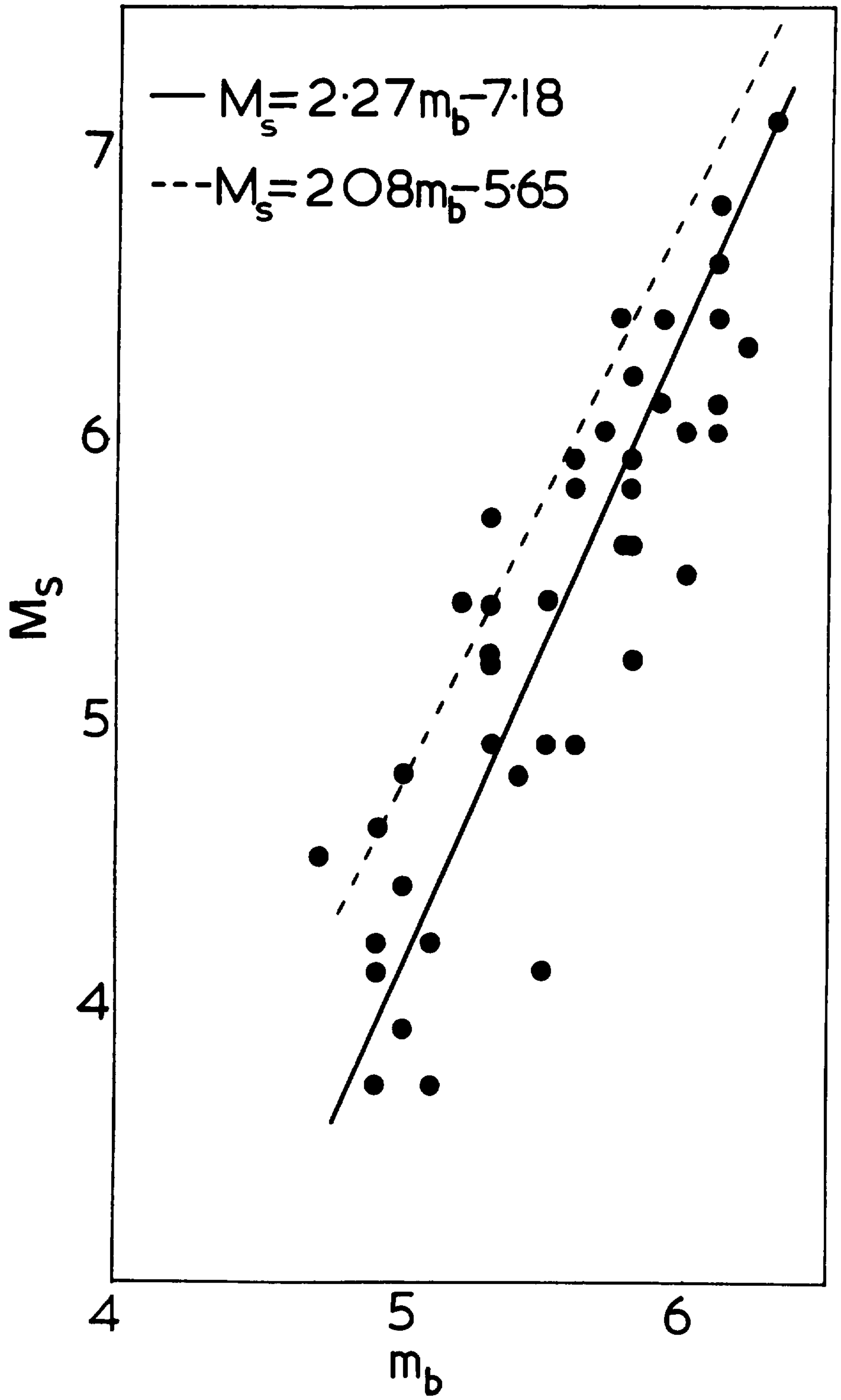

Figure 8. Plot of surface wave magnitude M_s against body wave magnitude m_b for oceanic intraplate earthquakes listed in Bergman and Solomon (1980). Solid line fitted to data shown. Dashed line fitted to an unselected world sample of events by Marshall (1970) shows that intraplate events have m_b values enhanced by 0.2-0.3 units.

events would also favour higher m_b values; 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 4 and 5 can be combined to give the magnitude frequency distribution in terms of M_s for the North Atlantic:

$$\mathrm{Log}_{10}N = -5.63 - 0.44\ M_s \tag{7}$$

As before, N is in terms of events per year per km². In the following sections our discussions on magnitude are in terms of this (M_s) scale.

4. MAXIMUM MAGNITUDES

4.1 Introduction

For the period 1964-1979 the largest event found in the Intraplate Atlantic (excluding region D in Figure 7) had a magnitude $M_s = 6.4$ ($m_b = 6.0$). Earthquakes of this size are potentially destructive to nearby man-made structures. Since the time period considered (16 years) is relatively short it is likely that larger earthquakes can occur. It is important in the assessment of seismic risk to know the upper limit on the magnitudes possible for a region. Two approaches are described below to estimate this upper limit; the first involves looking at historical data prior to 1964, while the second is a more detailed statistical analysis on the more complete recent data.

4.2 Historical Data 1913-1963

Use of longer time intervals can give a more reliable estimate of maximum magnitude. The file of earthquake data maintained by the Institute of Geological Sciences (Burton, 1978) was, therefore, searched for the time period prior to 1964 for any earthquakes within the intraplate region. Nearly 100 events from 1913-1963 were found to be located by the International Seismological Summary (ISS, the predecessor of the ISC) within this region. For various reasons (see Appendix 3) the epicentres are suspect and so it was decided to relocate these events. A full description of the method and results is given in Appendix 3. The relocated events are listed in Appendix 2. After relocation only 38 of the

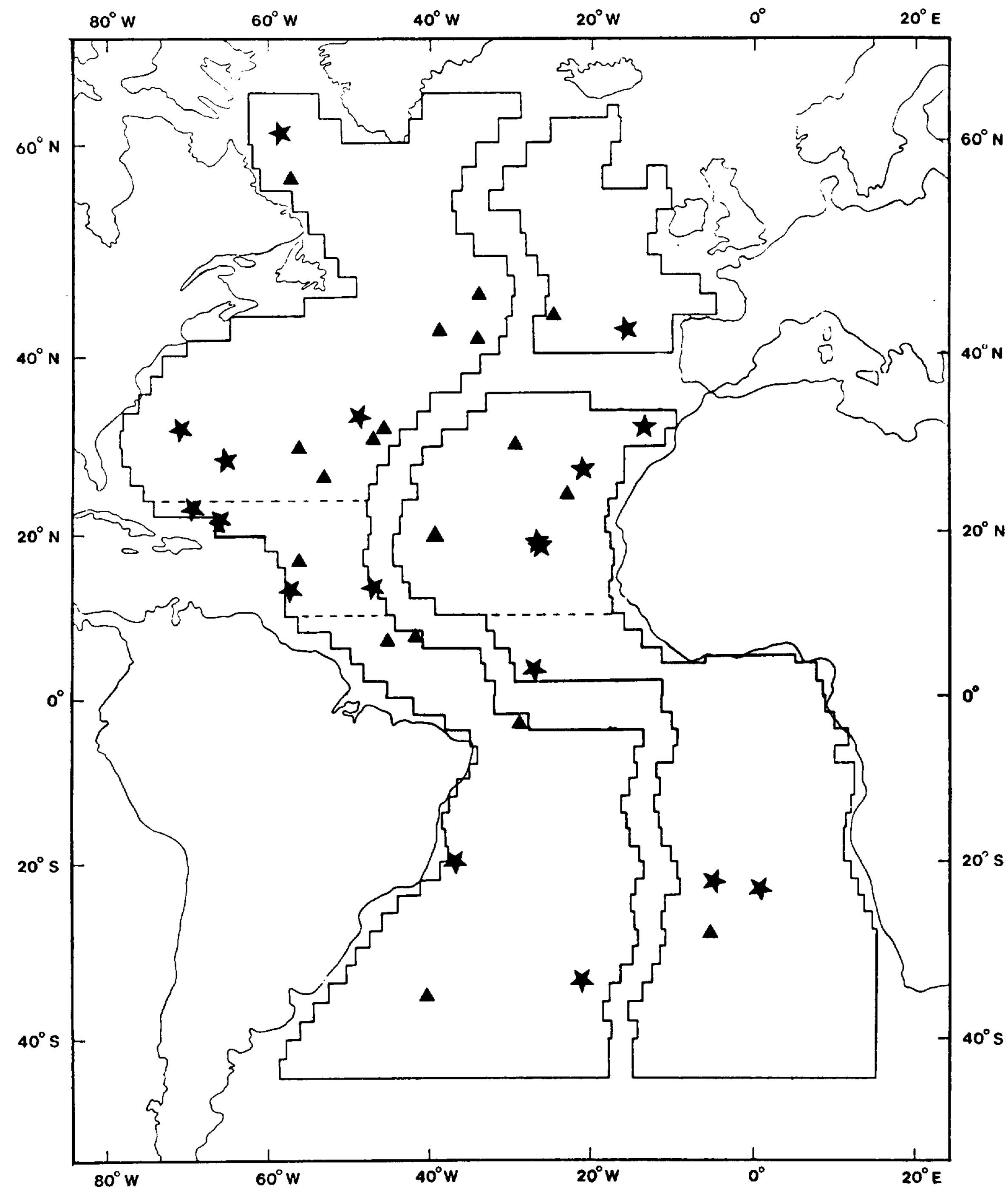

Figure 9. Relocated epicentres for the period 1913-1963. Triangles are events having no assigned magnitude; stars mark events with magnitude (M_s) ≧ 5.5.

events could be assumed with any confidence to be within the intraplate region; these events are shown in Figure 9. The North Atlantic appears more active than the south but, as before, much of this effect may be the result of variable detection. The active zone E and NE of the Caribbean (region D) is less evident, although the largest event occurred within this region at magnitude (M_s) 7.2. Excluding region D (Figure 7) the largest event for the whole period was on 15 August 1941 and occurred some 200 km NW of the Cape Verde Islands with magnitude (M_s) 6.7.

4.3 Use of Extreme Value Statistics

Analysis of extremes can be used to check whether there is any evidence in the data available for an upper limit on magnitude and, in addition, gives useful estimates on the frequency of occurrence of lesser events. To make such an analysis the data is first divided up into equal time intervals and the largest event or extreme for each time interval taken.

The theory of extremes (Gumbel, 1958; Fisher and Tippett, 1928) predicts that the frequency distribution of these largest values follows relatively simple rules. In particular, the probability $P(X < x)$ that any extreme X be less than x is given by:

$$P(X < x) = \exp(-[1 - k(x - u)/\alpha]^{\frac{1}{k}}) \quad (8)$$

where α, u and k are constants. If $k < o$ then the distribution of x is described as Fisher-Tippett FT2 and has a lower bound, if $k > o$ the distribution is Fisher-Tippett FT3 and has an upper bound. The bound in both cases is given by $u + \alpha/k$. If $k = o$ then equation 8 reduces to the double exponential form

$$P(X < x) = \exp(-\exp(-(x - u)/\alpha)) \quad (9)$$

in which case there are no upper or lower bounds and the distribution is Fisher-Tippett FT1.

Annual extremes in terms of M_s for the Atlantic intraplate data during the period 1964-1979 were taken from Appendix 1 excluding events from region D (Figure 7). From these data estimates of u, α and k assuming distribution 8 and u and α assuming distribution 9 were found (fuller details of the method of estimation, statistics and results are described in Appendix 4). The results are

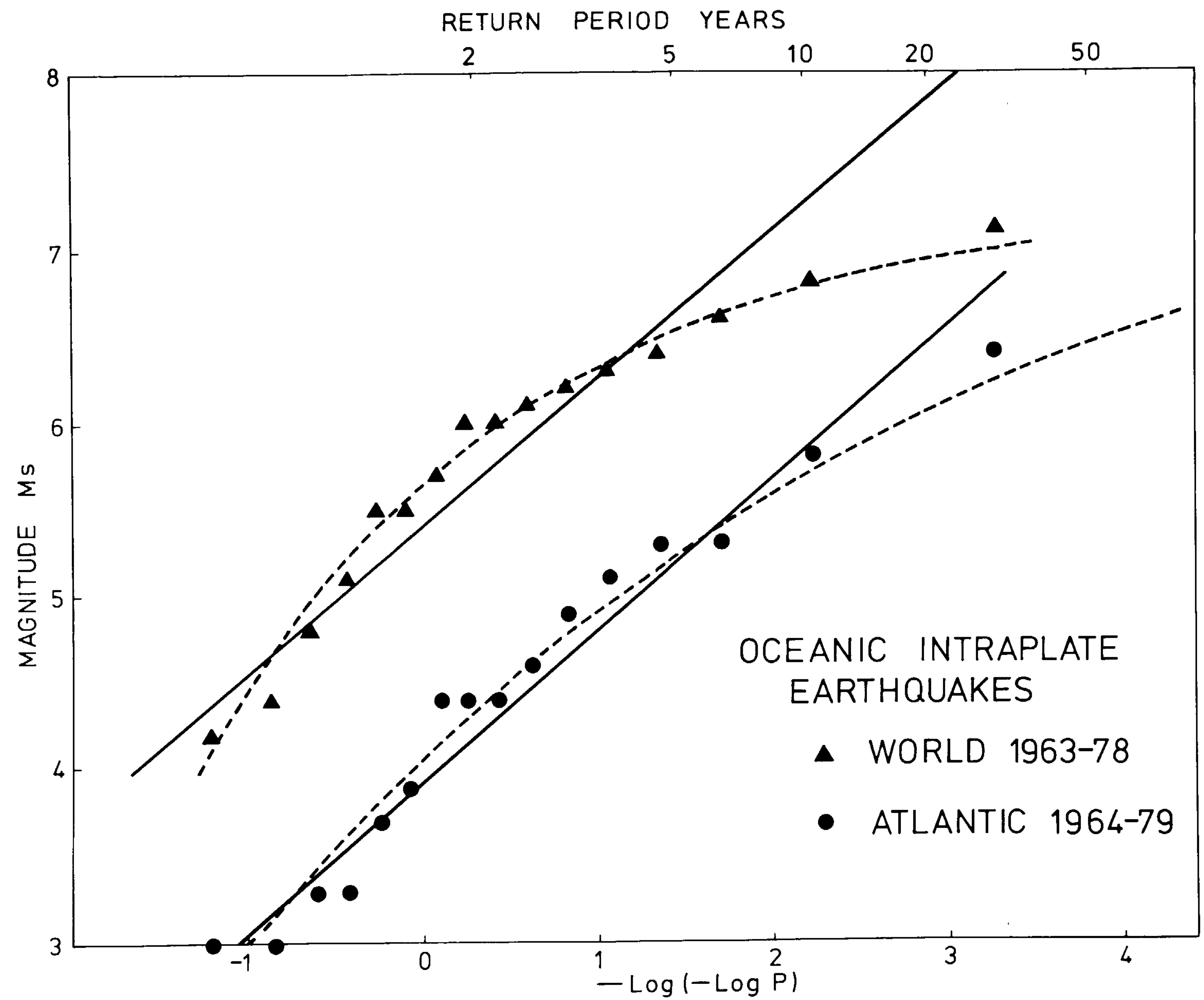

Figure 10. Annual extreme magnitudes (M_s) for Atlantic ocean intraplate earthquakes (circles) and world oceanic intraplate earthquakes (triangles) plotted against the negative double logarithm of P (see text). Dashed curves and solid lines are the maximum likelihood estimates for the extreme value FT3 and FT1 distributions respectively.

illustrated in Figure 10 where the double logarithm of P estimated from our data is plotted against the corresponding magnitude. Although, as expected, the convex upward FT3 distribution appears to be a better fit than the linear FT1 distribution it is shown in Appendix 4 that the difference in the fits to the observed data for the two distributions are not statistically significant. The Atlantic data alone are, therefore, insufficient to define whether an upper bound exists. Also shown in Figure 10 are the results of applying the same analysis to the list of all the earth's oceanic intraplate earthquakes as listed by Bergman and Solomon (1980). Here the FT3 distribution is clearly a better representation and the difference between this and the FT1 fit is significant at the 97.5% level. The upper magnitude limit indicated by this curve is (M_s) 7.3. From these results and the observations described in the previous section magnitude (M_s) 7.5 is suggested as a conservative upper magnitude to be used in seismic risk estimates.

The intraplate region of the Atlantic is clearly the site of large earthquakes. For events with magnitudes (M_s) in excess of 6.0 it can be seen from Figure 10 that the return period is in the region of only 12-18 years. The observed activity is spread thinly over a large region, however, and in the next section some values of the return period of strong ground motion at a given site are estimated.

5. RETURN PERIOD OF STRONG GROUND MOTION AT A SINGLE SITE

5.1 Introduction

A major contribution to seismic risk on structures on or in the seabed arises from the possible disruption of the sediments. Such disruption can result from slope instability and liquefaction during ground shaking. Assessment of whether such phenomena will occur is complicated and requires knowledge of the detailed variation of sediment properties with depth and the amplitude and duration of shaking (e.g. Seed, 1976). This is beyond both the scope of this report and our present knowledge of the nature of the sediments. The analysis given here is limited to a simple assessment of the frequency of ground motions having the potential of causing these effects.

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 (1) and an upper limit on magnitude. 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 an attenuation relationship between ground motion, magnitude and distance of an event from the site.

5.2 Ground Motion Attenuation Equations

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 kilometres of water is clearly atypical and it is doubtful if any of the published relations are applicable. It was, therefore, decided to use the attenuation formula due to Esteva and Rosenblueth (1964) and used in the original study by Cornell (1968). The peak acceleration Ap in cm sec^{-2} is

$$Ap = 2000\ R^{-2}\ e^{0.8\ Ms} \qquad (10)$$

where R is the modified slant distance D of earthquake to site in km given by:

$$R^2 = D^2 + 400 \qquad (11)$$

Equation 10 is for "firm" ground in California (Cornell, 1968) and may underestimate ground motions for the same magnitude earthquakes in intraplate regions (e.g. Milne and Davenport, 1969). In addition, peak accelerations for small events at short range may be underestimated (Hanks and Johnson, 1976). Nevertheless, equation 10 has not been modified here since this would give undue weight to the ground motions resulting from small frequent earthquakes which may not have the duration to initiate liquefaction. It should be noted, however, that resulting risk estimates in terms of peak acceleration of short duration may not be conservative.

5.3 Peak Acceleration Return Periods

To compute return periods for peak acceleration we need to model the seismicity (described by the magnitude frequency relation 7) in terms of its distribution around the site. The simplest model for the spatial distribution of seismicity is to assume that events can occur with equal probability everywhere.

SOURCE TYPE	M_s max	Acceleration RETURN PERIODS in years x 10^3		
		0.1g	0.25g	0.5g
Areal, i.e. seismicity uniformly distributed everywhere	7.0	11	58	312
	7.5	9	44	184
	8.0	8	36	130
	8.5	7	31	100
	9.0	7	27	82
Faults 50 km Apart – Site on Fault	7.5	8	36	117
Faults 50 km Apart – Site between Faults	7.5	11	57	380
Faults 100 km Apart – Site on Fault	7.5	5	18	59
Faults 100 km Apart – Site between Faults	7.5	21	1000	∞
Faults 200 km Apart – Site on Fault	7.5	2	9	29
Faults 200 km Apart – Site between Faults	7.5	∞	∞	∞

Table 2 - Return periods for 0.1g, 0.25g and 0.5g maximum ground accelerations for a range of source geometries and maximum magnitudes. Results of return period computations are here rounded to nearest 1000 years.

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 2 shows some results obtained for an areal source of 5 km depth assuming the level of seismicity given by equation 7. A value of 0.1g was chosen for the minimum 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. At the 0.1g level return periods for the entire range (M_s = 7.0 to 9.0) vary by a factor of less than 2.0. At the 0.5g level the variation is greater but still less than 2.0 over the likely range (M_s = 7.5 to 8.5). From Table 2 it can be seen that the annual probability of exceedance at the 0.1g level is of the order 10^{-4} falling to the order 10^{-5} at 0.5g.

There is some evidence (Sykes, 1978; Bergman and Solomon, 1980) that intraplate earthquakes do not occur randomly 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 50 km 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 2 gives results, assuming an overall areal rate of seismicity given by equation 7, 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 50 km apart and at the 0.1g level, the maximum and minimum return periods differ only slightly and approximate those 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 midway 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 200 km apart) corresponds to a return period of 2000 years, or an annual probability of 5×10^{-4}, for peak acceleration at the 0.1g level. This assumes an upper limiting magnitude of M_s = 7.5. These results indicate that it is important to establish the degree to which the observed seismicity is concentrated along suspected zones of weakness.

The ground motion equation 10 may not be appropriate to a seabed or intraplate environment. Its use here is probably not conservative in seismic risk estimation because the fall off of observed Intensity (and hence acceleration) with epicentral distance is slower in intraplate regions than in seismically more active zones (e.g. Milne and Davenport, 1969). To illustrate the effect of this on return periods, use of Esteva and Rosenblueth's (1964) Modified Mercalli Intensity (I) attenuation relation for California.

$$I = 6.0 + 1.5\ M_s - 2.5\ \mathrm{Log}\ R \tag{12}$$

gives a return period of circa 9000 years for Modified Mercalli Intensity 7 (roughly 0.1g) for an areal source with maximum magnitude 7.5. Use of the relation:

$$I = 6.0 + 1.5\ M_s - 1.9\ \mathrm{Log}\ R \tag{13}$$

found by Lilwall (1976) for Great Britain reduces the return period to circa 4000 years. The difference is, however, smaller for the other source geometries considered.

Clearly, although the seismicity, as described by the magnitude frequency relation 7, appears well constrained by the data, uncertainties in source distribution and ground motion attenuation result in a wide variation in risk estimates. Taking 0.1g peak acceleration as a conservative value at which liquefaction and slope instability become possible then these uncertainties result in the range 2000-10,000 years for the return period.

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APPENDIX 1

Atlantic Ocean Intraplate Earthquakes 1964-1979

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) U.S. Department 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, minutes, seconds, GMT.

LATITUDE and LONGITUDE of epicentres are in degrees and decimals with S and W negative.

Focal depth Z is in km.

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. A + after an MS value indicates that it has been computed from the MB value using the equation

$$MS = 2.27*MB - 7.13$$

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 explosions.

D. These events appear to be aftershocks of a main event 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	LCNG	Z	MS	MB	NSTN	NCAT			
9- 1-64	9 57 56.9	-43.19	-14.67	0			7			DELETED	A
12- 2-64	11 24 6.3	46.80	-37.70	33		4.3	6				
21- 2-64	4 56 16.0	13.59	-51.34	0		4.2	5				
4- 3-64	0 48 9.2	44.10	-30.40	33		4.2	7			DELETED	A
22- 5-64	5 38 40.9	27.90	-16.04	34		4.3	21				
22- 6-64	17 50 43.6	54.90	-40.20	33		4.2	6				
21- 8-64	23 26 16.0	29.00	-29.10	33		4.0	7				
4- 9-64	16 53 57.0	20.00	-64.40	33		3.9*	6			DELETED	A
6- 9-64	10 51 40.0	22.50	-67.00	0			4			DELETED	A
17- 9-64	15 2 1.5	44.58	-31.34	24	5.3+	5.5	173	7			
17- 9-64	22 7 40.2	38.70	-71.90	0			15				
7-10-64	22 53 18.9	20.27	-60.40	25			7			DELETED	A
11-10-64	0 43 15.0	-5.00	-17.60	33	4.2+	5.0	10				
23-10-64	1 56 5.1	19.80	-56.11	43	6.3	6.1*	236	10			
23-10-64	16 46 19.5	19.07	-57.50	25		3.7*	8	11			
10-11-64	19 26 41.2	47.40	-23.60	31		4.3	26				
24-12-64	4 3 2.0	18.00	-60.00	0			4			DELETED	A
20- 2-65	16 29 30.0	26.10	-51.20	33	3.0+	4.5	17				
29- 3-65	13 10 18.2	34.20	-64.30	10		4.1	18				
10- 8-65	8 21 6.2	61.24	-60.10	33		4.0	25				
12- 8-65	6 27 18.5	13.10	-42.60	33		4.4	10			DELETED	A
21- 9-65	3 26 37.1	40.77	-50.13	21	4.9+	5.3	170	19			
20-11-65	7 28 29.5	58.30	-34.10	33		4.3	5			DELETED	A
30-11-65	11 50 3.0	-28.00	5.50	33	3.0+	4.5	10				
20- 3-66	18 28 35.8	21.96	-58.90	10		4.4*	16	25			
19- 5-66	0 12 26.0	20.00	-61.20	10			5			DELETED	A
28- 5-66	11 28 59.8	27.90	-16.60	0		4.4	8				
12- 6-66	20 20 59.0	-2.93	-28.29	20	3.7+	4.8	41				
29- 7-66	4 36 25.1	36.70	-74.13	1		4.4*	68				
5-12-66	1 59 5.0	16.60	-57.40	0		4.4*	7			DELETED	A
3- 1-67	5 12 55.0	51.60	-38.90	33		4.3	6			DELETED	A
2- 2-67	18 34 19.6	-12.80	-9.40	33	4.4+	5.1	8				
4- 2-67	14 8 50.0	24.00	-65.70	1		0.0*	7				
19- 4-67	21 44 15.0	20.20	-63.10	41			5			DELETED	A
20- 4-67	4 17 42.1	-41.14	-19.33	33	3.9+	4.9	25				
22- 5-67	6 23 29.0	20.43	-65.76	26		4.3*	43				
12- 6-67	0 8 11.0	11.80	-47.20	33			5			DELETED	A
30- 6-67	3 4 41.5	38.90	-36.70	33	3.0+	4.5	23				
10- 7-67	19 43 58.6	19.30	-53.10	56	3.7+	4.8	20	34			
26- 9-67	11 0 56.0	19.50	-60.00	0		0.0*	6			DELETED	A
3-12-67	0 0 35.5	58.40	-24.90	33		4.4	6				
28-12-67	12 47 17.0	48.00	-38.60	33		4.2	7				
20- 1-68	10 54 50.0	40.00	-23.00	33		4.1	6			DELETED	A
20- 2-68	2 19 49.5	12.40	-46.94	12	5.3+	5.5	172				
20- 2-68	8 8 31.2	16.72	-57.76	26		4.3	17				
5- 3-68	18 58 39.0	15.60	-57.90	18			10			DELETED	A
13- 5-68	8 49 50.0	43.70	-25.50	33		4.2	7			DELETED	A
9- 7-68	6 13 31.9	-10.66	12.09	0		4.2	20				
11- 7-68	21 39 14.2	33.90	-15.59	38		4.4	27				
3- 9-68	15 37 0.3	20.58	-62.30	34	5.5+	5.6	191	50			
14- 9-68	1 37 6.0	56.80	-39.80	33	4.6+	5.2	37				
9- 1-69	4 22 48.0	41.00	-34.30	33		4.2	5			DELETED	A
21- 1-69	8 4 45.0	27.70	-48.80	33		4.0	12			DELETED	A
20- 3-69	7 41 29.0	18.60	-49.60	33		4.4	9				
8- 5-69	20 47 8.6	33.30	-11.80	33			12				
14- 6-69	1 8 32.0	20.06	-64.19	14		3.6	13		FSHOCK	DELETED	
14- 6-69	1 11 31.0	20.05	-64.20	5		4.1	23		FSHOCK	DELETED	
30- 6-69	18 36 25.3	20.03	-64.14	25	4.4+	5.1	97				
30- 6-69	20 27 33.7	20.23	-64.10	36			6		ASHOCK	DELETED	
23- 7-69	8 34 37.7	56.00	-47.00	33		4.1	12				
25- 7-69	21 30 33.3	12.44	-40.75	9	3.7+	4.8	60	60			

DATE	TIME	LAT	LONG	Z	MS	MB	NSTN	NCAT			
26- 7-69	12 24 30.4	43.70	-14.56	33	3.3+	4.6	75				
11- 8-69	18 48 35.0	20.02	-64.29	26		4.4	17		ASHOCK	DELETED	
11- 8-69	20 16 35.1	20.06	-64.29	31	3.9+	4.9	65		ASHOCK	DELETED	
29- 9-69	4 35 51.0	12.90	-46.20	33	3.3+	4.6	9			DELETED	A
13-10-69	7 7 49.0	22.70	-40.50	33			8			DELETED	B
7-11-69	9 28 54.0	-37.00	-43.80	33			6				
14-11-69	8 31 30.0	20.02	-64.43	4			5		ASHOCK	DELETED	
15-11-69	22 24 8.4	20.01	-64.13	10			12		ASHOCK	DELETED	
24-11-69	6 52 20.9	17.44	-26.54	30		4.2	5				
24-11-69	9 12 52.0	28.00	-30.70	33		4.4	5				
24-11-69	21 14 13.2	60.49	-58.88	33	3.9+	4.9	103				
2- 1-70	11 53 35.0	15.00	-57.50	33			5			DELETED	A
3- 1-70	14 15 0.0	15.40	-58.00	33			6		ASHOCK	DELETED	A
4- 1-70	0 15 47.0	16.01	-58.70	67			5			DELETED	A
18- 1-70	1 23 59.0	40.00	-39.90	33	3.0+	4.5	5				
19- 1-70	1 19 12.7	15.00	-53.65	92			5			DELETED	A
22- 2-70	7 42 49.0	16.40	-58.70	35			7		ASHOCK	DELETED	
22- 2-70	12 35 5.0	13.40	-46.50	33			9		ASHOCK	DELETED	A
5- 3-70	4 56 24.9	53.89	-19.70	25	3.3+	4.6	78				
1- 4-70	9 18 20.0	20.00	-43.50	33		4.2	8			DELETED	A
19- 5-70	19 17 40.0	18.00	-60.00	23			5			DELETED	A
25- 6-70	16 8 54.8	39.62	-71.07	0	4.2+	5.0	98			DELETED	C
20- 8-70	16 34 15.3	38.96	-72.36	0		4.0	30			DELETED	C
17- 9-70	11 29 24.8	26.65	-22.86	33	3.0+	4.5	49				
4-10-70	2 4 34.0	10.16	-38.59	15		4.3	5			DELETED	A
22-10-70	2 36 24.0	13.81	-49.73	25	3.7+	4.8	58				
2-11-70	9 40 5.0	0.0	-32.70	33		4.0	6			DELETED	A
22-12-70	5 48 58.0	17.60	-36.40	33			10		FSHOCK	DELETED	
12- 1-71	17 35 57.1	62.08	-61.89	0			10				
1- 5-71	4 6 37.6	18.30	-36.92	33	3.7+	4.8	38				
4- 6-71	20 47 32.8	33.86	-46.69	33	3.5+	4.7	14				
26- 7-71	2 18 10.3	58.38	-24.35	0			10			DELETED	A
3- 8-71	5 34 27.1	28.43	-39.20	33	3.9+	4.9	87				
3- 8-71	20 59 30.3	28.38	-39.40	33	3.5+	4.7	36		ASHOCK	DELETED	
30- 9-71	21 24 10.8	-0.44	-4.89	0	6.4+	6.0	261	76			
18-11-71	8 25 53.7	32.96	-19.45	33	3.0+	4.5	9				
7-12-71	12 4 18.7	55.04	-54.45	0	5.1+	5.4	208				
19- 1-72	0 37 7.5	31.36	-13.81	33	3.9+	4.9	107				
8- 4-72	0 54 57.3	18.03	-59.58	0			7			DELETED	A
4- 6-72	16 48 15.1	20.20	-65.71	19	3.3+	4.6	90				
14- 7-72	7 30 11.2	20.77	-63.28	0			7				
5- 9-72	23 8 25.4	20.33	-64.80	0			8		ASHOCK	DELETED	
20-10-72	4 33 49.9	20.60	-29.68	0	5.8+	5.7	312	83			
30-10-72	1 50 35.7	22.34	-61.96	0	3.9+	4.9	72	84			
7-11-72	12 5 14.3	49.05	-39.42	0	4.4+	5.1	142	85			
4- 3-73	14 15 20.5	3.78	-25.29	0		4.4	7				
7- 4-73	12 8 8.4	31.58	-12.92	33			5				
24- 5-73	0 52 16.1	57.55	-29.39	0		3.8	4			DELETED	A
5- 6-73	0 22 10.3	34.16	-49.42	0		4.4	5				
29- 6-73	23 44 17.6	51.84	-39.73	33			21				
3- 7-73	8 32 4.7	18.67	-51.32	0			5				
8- 7-73	6 53 43.9	-16.03	-28.41	0			4				
24- 7-73	20 3 19.3	-11.56	-19.65	33			24				
26- 9-73	22 53 15.3	3.40	-25.62	0	3.3+	4.6	8				
12-10-73	3 54 28.1	61.32	-59.50	33		4.2	31				
18-10-73	13 48 38.5	20.04	-62.85	33	3.7+	4.8	59				
29-10-73	12 21 1.8	17.28	-26.60	33	3.0+	4.5	18		FSHOCK	DELETED	
14-11-73	7 23 11.1	28.39	-46.04	0		4.1	7				
18- 1-74	21 14 51.2	-34.08	-20.15	33	5.1+	5.4	63				
3- 2-74	20 20 22.7	-29.50	-42.54	33		4.4	5				
31- 3-74	21 12 59.9	17.04	-26.42	51	3.9+	4.9	86				

DATE	TIME	LAT	LONG	Z	MS	MB	NSTN	NCAT			
8- 4-74	9 1 37.3	19.42	-42.93	0		4.3	6			DELETED	A
17- 4-74	23 8 59.5	21.98	-43.24	0		4.4	6			DELETED	A
11- 5-74	6 32 3.3	-23.87	-27.95	33			7				
15- 5-74	16 50 35.2	24.01	-43.15	0		4.3	11			DELETED	D
16- 5-74	0 44 23.4	30.71	-44.72	0		4.1	7			DELETED	D
19- 6-74	20 6 28.6	41.17	-48.42	33		3.8	5				
25- 7-74	17 38 26.0	33.34	-29.62	33			5			DELETED	B
16- 8-74	7 16 45.7	57.25	-40.62	33		4.0	5				
19- 9-74	19 59 30.4	-12.19	-12.00	33		4.3	6			DELETED	A
22-10-74	12 41 16.5	60.71	-24.45	0			4			DELETED	D
2-11-74	2 18 58.0	18.11	-60.17	0			7			DELETED	A
20-11-74	16 27 41.9	-2.46	-28.01	33	3.9+	4.9	24				
24-11-74	6 19 32.9	44.29	-7.11	0			11				
7-12-74	10 10 46.6	-7.23	-27.91	33	3.5+	4.7	9				
20-12-74	17 1 0.5	33.81	-16.35	0			6				
22- 1-75	0 26 36.1	29.16	-18.70	0	3.0+	4.5	33				
17- 2-75	17 3 59.6	31.34	-50.78	33		4.2	8				
22- 4-75	14 37 8.9	58.28	-40.40	0			4			DELETED	A
17- 5-75	22 0 30.4	17.58	-44.51	0	3.3+	4.6	14				
18- 5-75	20 43 45.9	21.32	-59.00	33			5			DELETED	A
20- 7-75	20 8 34.9	26.24	-53.59	33			6			DELETED	B
28-10-75	14 34 24.8	-37.82	3.76	33			8				
19-11-75	23 27 23.1	48.79	-47.05	33		4.3	5				
3-12-75	21 8 0.0	-7.06	-2.50	33			4				
13-12-75	9 24 22.7	57.95	-52.06	0		4.4	22				
15-12-75	13 35 8.1	16.17	-26.68	33			6				
17-12-75	8 5 19.6	41.81	-62.94	33			10				
19-12-75	15 24 40.4	31.04	-60.67	33			7				
29-12-75	5 40 31.2	15.80	-49.59	16			12				
30-12-75	9 31 50.0	-8.86	-8.88	33			5				
14- 3-76	23 12 24.6	41.66	-69.97	0			11			DELETED	A
31- 7-76	1 7 53.7	31.19	-51.33	33		4.2	6				
24-11-76	21 50 54.6	32.97	-61.50	33	4.4+	5.1	102	126			
28-12-76	2 57 38.2	22.13	-63.48	33	4.6+	5.2	65	128			
6- 2-77	0 30 49.9	17.87	-49.51	33	4.6+	5.2	106				
16- 2-77	0 49 31.2	25.97	-26.25	33	5.3+	5.5	148	131			
26- 2-77	22 43 48.9	28.52	-20.83	10	3.5+	4.7	68				
3-10-77	4 38 33.7	14.14	-48.18	33	4.4+	5.1	89				
12-10-77	0 53 29.0	14.10	-48.23	33	4.4+	5.1	47		ASHOCK	DELETED	
17-11-77	15 2 41.8	43.01	-12.52	33			14				
13-12-77	1 14 18.6	17.35	-54.84	33	5.8+	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			15		ASHOCK	DELETED	
24- 3-78	13 38 5.1	29.55	-67.71	33			12		ASHOCK	DELETED	
12- 4-78	0 29 52.3	29.92	-67.29	33			11		ASHOCK	DELETED	
13- 4-78	6 0 38.3	57.12	-36.62	32	4.6+	5.2	192				
13- 4-78	21 15 18.1	29.70	-67.19	33			23		ASHOCK	DELETED	
15- 4-78	16 26 9.9	29.69	-67.39	33	3.3+	4.6	15		ASHOCK	DELETED	
19- 4-78	11 32 16.7	29.83	-67.36	20		4.3	41		ASHOCK	DELETED	
24- 4-78	5 44 56.0	30.04	-67.78	33	3.0+	4.5	19		ASHOCK	DELETED	
4- 5-78	5 44 47.2	29.93	-67.51	33	3.5+	4.7	39	147	ASHOCK	DELETED	
30- 7-78	10 17 41.3	44.14	-7.28	10			22				
11- 8-78	8 6 25.8	29.83	-68.01	33			27		ASHOCK	DELETED	
26- 9-78	6 51 9.7	30.02	-67.54	33		4.3	20				
17-10-78	8 14 2.1	14.61	-48.00	33	3.7+	4.8	18				
23-11-78	21 31 58.2	29.69	-67.64	33			16		ASHOCK	DELETED	
6-12-78	13 28 35.5	17.44	-54.78	10	5.3+	5.5	160	155			
28- 4-79	20 27 18.2	43.17	-11.44	10			39				
9- 5-79	18 35 36.4	21.29	-62.12	33	3.9+	4.9	19				
30-12-79	17 38 17.6	-36.27	-15.31	10			6			DELETED	A

APPENDIX 2

Atlantic Ocean Intraplate Earthquakes 1913-1963

This listing contains earthquakes located by the International Seismological Summary (ISS) within the intraplate region and relocated as described in Appendix 3. One event (25 August 1925) did not give a stable relocation and so the epicentre given is that of the ISS.

DATE is in the form day-month-year.

TIME is in form hours, minutes, seconds, GMT.

LATITUDE and LONGITUDE of epicentres are in degrees and decimals with S and W negative.

Focal depth Z is in kms.

MS is the surface wave magnitude as given by Gutenburg and Richter (1954) and Rothe (1969).

NSTN equals the number of stations used to locate the event.

NCAT is number of event in catalogue of Bergman and Solomon (1980).

Events are marked 'DELETED' for two reasons: they were relocated to a point outside the intraplate region or, on relocation, they remained in the intraplate region but have potential errors in epicentre which indicate that the event could have originated outside the region.

DATE	TIME	LAT	LONG	Z	MS	MB	NSTN	NCAT	
25-12-13	6 48 42.8	33.36	-33.38	0			30		DELETED
20- 4-17	9 56 44.8	48.94	-35.77	0			14		DELETED
16- 6-17	12 22 58.1	48.97	-24.09	0			11		DELETED
21- 8-17	21 38 47.4	-12.10	-13.27	0			27		DELETED
26-12-17	9 22 30.5	49.10	-26.32	0			6		DELETED
14- 1-18	20 3 41.5	49.75	-12.40	0			10		DELETED
15- 8-19	4 17 3.1	-34.90	-40.12	0			13		
18- 8-19	11 18 8.7	52.50	-35.09	0			7		DELETED
24- 6-20	5 49 16.6	62.61	-23.03	0			13		DELETED
26- 6-20	7 31 20.6	-9.41	-17.76	0			10		DELETED
21- 8-20	21 18 43.7	55.99	-11.78	0			13		DELETED
17- 9-20	23 50 46.7	31.17	-41.32	0			20		DELETED
23- 1-21	16 18 43.8	-0.91	-16.51	0			4		DELETED
20- 4-21	18 46 16.1	31.37	-47.36	0			17		
22- 4-21	16 4 1.7	43.33	-15.69	0	5.5		30		
30- 6-21	2 10 20.3	58.46	-32.87	0	5.5		37		DELETED
13- 7-21	10 16 30.4	-34.54	-9.05	0			20		DELETED
21- 8-21	1 9 15.6	30.23	-56.15	0			9		
19- 2-22	21 52 37.7	30.74	-29.76	0			20		
28- 7-22	23 42 41.7	28.75	-42.53	0			7		DELETED
22- 9-22	21 25 45.5	27.17	-42.54	0			15		DELETED
28- 2-23	22 18 24.9	43.79	-27.96	0			18		DELETED
4- 3-23	0 7 4.4	-14.33	0.46	0			23		DELETED
21- 7-23	14 1 43.5	38.66	-38.32	0			9		DELETED
30- 9-23	1 20 50.7	52.84	-32.28	0			125		DELETED
11-10-23	12 28 58.9	42.71	-39.15	0			14		
28-11-23	0 34 20.5	54.33	-36.76	0	5.5		15		DELETED
12-12-23	16 27 25.9	-7.62	-6.79	0			18		DELETED
5- 8-24	1 26 22.8	26.39	-37.96	0			12		DELETED
13-10-24	12 24 33.8	-34.95	-15.76	0			12		DELETED
19-10-24	23 52 16.0	28.43	-43.66	0			37		DELETED
25-10-24	19 9 37.7	25.02	-23.37	0			15		
26-11-24	6 50 34.7	1.37	-19.37	0			5		DELETED
14- 4-25	15 16 36.9	42.32	-22.83	0			5		DELETED
13- 6-25	20 22 55.7	-33.41	-20.71	0	6.0		23		
19- 6-25	16 33 24.7	41.70	-38.76	0			10		DELETED
5- 7-25	7 2 5.8	14.02	-45.93	0	6.0		37		DELETED
7- 8-25	17 23 46.1	51.81	-36.89	0			17		DELETED
11- 8-25	17 12 2.2	17.20	-41.84	0			8		DELETED
25- 8-25	12 56 36.0	-13.00	-10.00	0			14		DELETED
15-12-25	10 31 41.3	-22.35	-5.29	0	5.5		13		
27- 7-26	4 53 32.2	52.93	-34.77	0			15		DELETED
30- 9-26	4 16 50.2	19.84	-39.26	0			14		
7- 1-27	18 58 13.5	-20.22	-37.32	0			5		DELETED
30- 3-27	7 17 13.4	-42.28	0.96	0			4		DELETED
7- 8-27	21 39 44.6	-0.33	-15.91	0			12		DELETED
30-12-27	12 31 13.2	17.11	-56.62	0			17		
28-11-28	7 36 47.1	27.03	-53.20	0			20		
15- 3-29	17 57 23.7	32.08	-46.06	0			17		
4- 8-29	15 12 52.7	35.17	-34.86	0			10		DELETED
18-11-29	20 31 56.8	44.43	-56.00	0	7.2		208		DELETED
19-11-29	2 1 44.5	50.03	-55.84	0			8		DELETED
15-12-29	1 33 37.4	56.59	-33.78	0	5.5		33		DELETED
7- 3-30	6 41 3.5	32.85	-11.73	0	5.5		43		
25-12-30	13 7 29.9	-30.49	-12.57	0	6.2		34		DELETED
3- 4-31	21 31 59.0	-35.50	-17.91	0			15		DELETED
16- 8-31	8 6 23.7	28.70	-64.86	0	5.5		22		
18- 1-32	13 12 28.0	44.66	-31.99	0			18		DELETED
15- 7-32	21 1 9.8	15.10	-30.93	0			22		DELETED
26-11-32	17 16 55.6	-26.53	-11.99	0			9		DELETED
6- 1-33	19 10 17.1	-23.11	0.09	0	6.0		8		

CATE	TIME	LAT	LCNG	Z	MS	MB	NSTN	NCAT	
18- 1-33	8 37 27.9	-32.81	-19.11	0			23		DELETED
29- 6-33	18 29 33.1	59.76	-30.13	0			21		DELETED
12- 9-33	12 53 14.7	7.15	-44.92	0			11		
15- 6-34	6 34 26.3	61.13	-58.66	0	5.5		21		
1- 7-37	9 55 10.5	46.52	-28.13	0			30		DELETED
25- 9-37	4 29 45.0	44.29	-24.86	0			108		
21-11-37	20 29 28.0	36.07	-24.81	0			46		DELETED
15- 2-38	3 27 43.1	19.32	-26.17	0	6.2		142		
15- 2-38	6 57 11.1	19.33	-26.21	0			76		
13- 5-38	2 53 24.0	56.77	-33.84	0			23		DELETED
23- 5-38	8 12 23.0	-2.55	-28.88	0			45		
25-11-38	0 7 3.0	46.18	-34.04	0			35		
5- 3-39	15 11 51.8	23.09	-69.38	0	5.5		29		
12- 6-39	4 5 8.5	20.51	-65.83	0	6.2		158		
18- 6-41	11 9 10.4	52.54	-34.05	0	6.2		191		DELETED
15- 8-41	6 9 23.1	19.29	-26.36	0	6.7		189		
6- 7-43	13 13 55.4	31.49	-40.88	0			35		DELETED
17- 8-44	18 2 44.4	46.15	-29.51	0			19		DELETED
31-12-47	5 30 39.8	47.64	-30.55	0			34		DELETED
17- 9-47	17 46 59.0	-2.29	-22.06	0			81		DELETED
9- 7-49	18 44 43.4	32.47	-70.58	0	5.7		105		
17-11-50	15 57 41.7	6.93	-36.37	0			40		DELETED
1-12-50	14 51 0.3	13.86	-47.26	0	7.2		270		
5- 4-52	0 26 33.9	-28.18	-5.86	0			19		
9- 4-52	8 8 8.7	42.36	-34.34	0			12		
20-10-52	1 4 53.9	56.96	-57.20	0			54		
16-11-52	15 4 57.7	1.40	-28.96	0			45		DELETED
27- 9-53	6 5 24.8	13.60	-57.84	0	6.0		165		
27- 2-55	16 36 60.0	7.62	-42.56	0	6.0		32		
1- 3-55	1 46 13.1	-19.81	-36.75	0	6.0		106	2	
6-10-55	10 55 40.2	33.53	-48.05	0	5.5		43		
17- 7-56	15 19 39.0	40.92	-27.13	0			42		DELETED
29- 7-58	21 37 22.1	3.67	-26.64	0	6.2		167		
1- 4-59	0 34 18.3	27.56	-20.83	0	6.2		235		
2- 9-59	9 31 37.7	19.96	-65.12	0			46		DELETED
20- 5-62	15 1 15.0	20.53	-65.88	0			69		

APPENDIX 3

Relocation of Atlantic Intraplate Earthquakes 1913-1963

The epicentres located within the Atlantic intraplate region by the International Seismological Summary (ISS) were relocated for several reasons. ISS locations prior to 1930 are based on seismic wave travel time tables which were considerably revised by the Jeffreys-Bullen tables subsequently used. Earthquakes prior to 1954 are located without the aid of the digital computer and the results may not represent the optimal solution from the data; in particular, they are frequently assigned to the location of an earlier event in the same general region. Finally, all the ISS epicentres lack error limits which can be a useful guide when deciding whether an earthquake has been mislocated from an active plate boundary into the intraplate region.

Initially, it was decided to follow present day policy of locating the teleseismic earthquakes using P-wave arrival time data alone. These data were collected for events reported by the ISS within the intraplate region shown in Figure 1. The earthquakes were relocated using the computer program described by Douglas, Lilwall and Young (1974). This program uses standard techniques (e.g. Bolt, 1960) and P-wave arrival time data. Time differences (or residuals) between observed and calculated arrival times for an initial approximate location are first computed. The initial approximation is then corrected by least squares minimisation of the residuals. This procedure is repeated until further corrections become negligible, usually after three or four iterations. Using only P-wave data, however, it was found that many less well recorded events, apparently acceptably located by the ISS, could not be relocated, giving unstable solutions. Closer examination of the ISS data reveals that dependence on arrival time data for phases later than P is frequently necessary in order to obtain a solution. Data were, therefore, collected for other phases reported by the ISS, the most important being direct S-wave arrivals. Other phases collected were the P and S-wave surface reflections PP, PPP, SS and SSS, and the core reflections PcP, ScS and PcS. Data were limited to the epicentral distance range 0-100°.

The program was adapted to use these additional phases and a procedure to weight data incorporated. Weighting is necessary because of the pooling of relatively high quality P arrival times with lower quality arrival times for later phases and, in addition, to reduce the effect of arrival times with large reading errors. The ith equation of condition for the ith arrival time reading was, therefore, weighted by a factor ω_i depending on its residual r_i as follows:

$$\omega_i^2 = \frac{\sigma_p^2}{\sigma^2}\left[\frac{1.0}{1.0+\mu\ \exp(r_i^2/2\sigma^2)}\right] \tag{14}$$

$$\sigma = \sigma_p \text{ for P readings}$$

$$\sigma = \sigma_L \text{ otherwise}$$

σ_p and σ_L are the variances of the P and later arrivals respectively. The part of equation 14 in square brackets weights out readings with large residual r_i by the method of uniform reduction suggested by Jeffreys (1961) for this type of data. Following Bolt (1960) the constant μ was set to 0.02. The ratio σ_p/σ allows for the difference in standard deviations of the P and later arrivals. These were assumed to be 3s and 9s respectively but, for the larger events, they were revised using the distribution of observed residuals.

The use of additional arrival time data together with the program adaptation described above enables stable epicentre locations for all but one of the ISS events for which arrival time data are available. The relocations are listed in Appendix 2. Examination of these relocations results in the deletion of 60% of the events initially suspected as being intraplate. Relocated epicentres for these events have either moved out of the intraplate region or have confidence limits which overlap the edge of this region. These deletions reduce the apparent level of intraplate activity by a factor of two to three.

It is useful to check whether the relocation procedure has given genuine improvements in location in addition to providing error limits for use in the validation of the intraplate earthquakes. A way to test this is to assume that all the earthquakes are mislocated from the nearest point on an active plate boundary. If this assumption is correct, then the change in distance to the nearest point gives a lower bound on the improvement or degradation of the epicentre. Figure 11 presents histograms showing the number of events as a function of the distance change. Positive distance changes imply relocation towards the plate margin, negative values the converse. The histogram for all the earthquakes is skewed to positive shifts with a mean change of +72 km. The distribution for the inferred intraplate earthquakes shows little skew and a mean change of only +6 km; as expected if they are correctly identified. Perhaps the best measure of epicentre improvement is obtained by removing the intraplate events from the total to give the third histogram in Figure 11. This distribution has an average of +114 km with 79% of the events moving towards the plate boundary and explains why so many of the ISS intraplate locations have been deleted in Appendix 2.

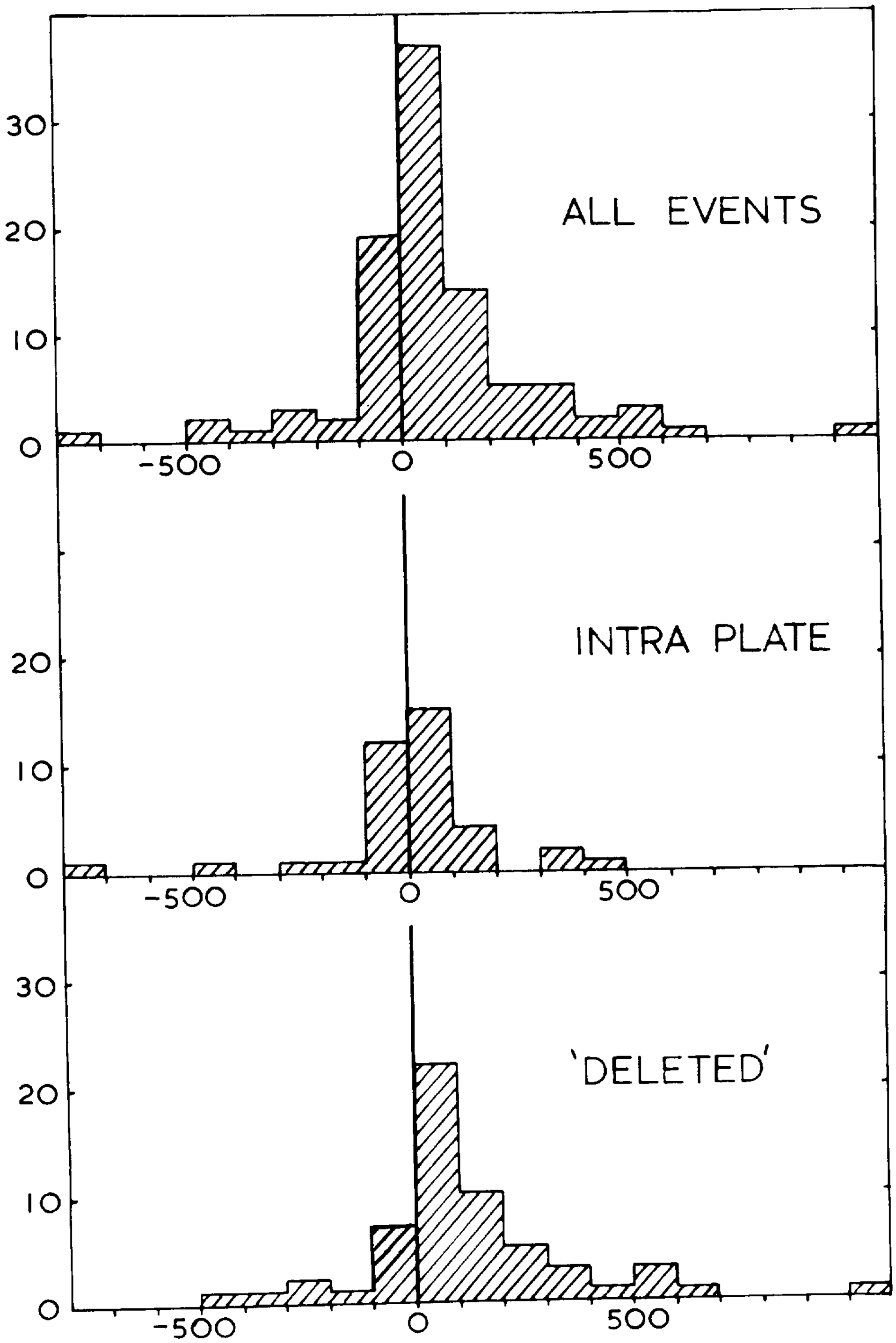

Figure 11. Histograms showing the change in distance from the nearest active plate boundary on relocation (in km) of the ISS epicentres to those given in Appendix 2. Positive values indicate movement toward the plate boundary. Note that the designated intraplate events show little net change while overall there is a movement towards the Boundary which is greatly enhanced when the intraplate events are deleted.

APPENDIX 4

Application of Extreme Value Statistics

Given a set of earthquake magnitudes over a given time period, the extremes of the magnitude distribution are obtained by dividing the period into equal intervals and taking the largest value in each. Table 3 lists the annual extremes for the 1964-1979 Atlantic oceanic intraplate data (excluding events in the active region D) and also the 1963-1978 world oceanic intraplate data listed in Bergman and Solomon (1980). M_s values were compiled from m_b using Equation 7.

YEAR	Atlantic		World	
	Max M_s	P_i	Max M_s	P_i
1963	-	-	5.1	0.22
1964	5.3	0.78	6.3	0.72
1965	4.9	0.66	6.0	0.53
1966	3.7	0.28	4.2	0.03
1967	4.4	0.41	5.5	0.34
1968	4.6	0.59	5.5	0.28
1969	3.9	0.34	4.8	0.16
1970	3.3	0.22	6.8	0.90
1971	6.4	0.97	6.4	0.78
1972	4.4	0.47	5.7	0.41
1973	3.3	0.16	6.2	0.66
1974	5.1	0.72	6.6	0.84
1975	3.0	0.10	4.4	0.10
1976	4.4	0.53	6.0	0.47
1977	5.3	0.84	7.1	0.97
1978	5.8	0.90	6.1	0.59
1979	3.0	0.03	-	-

Table 3 - Annual extreme magnitudes (M_s) for Atlantic and world oceanic intraplate earthquakes. P_i are estimates of the probability that the observed extreme will not be exceeded and are computed using Gringorten's (1963) plotting rule. The world data is taken from Bergman and Solomon (1980).

If the extremes show an upper magnitude limit, then the theory of extremes (Gumbel, 1958; Fisher and Tippett, 1928) predicts that the probability $P(X < x)$ that an extreme X will be less than x is given by equation 8 on page 18.

This distribution is variously described as Gumbel or Fisher-Tippett type 3 (FT3). If there is no upper limit, then the form reduces to equation 9. The double exponential form is described as Gumbel or Fisher-Tippett type 1 (FT1).

The problem is to estimate from the observed data values of the constants u, α, k and u, α for the two distributions respectively and to ascertain whether the FT3 distribution (implying an upper limit) gives a significantly better fit than FT1. The method of maximum likelihood was used to estimate the parameters since, unlike curve fitting methods, it does not need independent estimates of the values of P_i corresponding to each of the observed extremes x_i. To obtain estimates of these parameters, the likelihood L defined below must be maximised for the N extremes x_i. For the FT3 distribution the likelihood is:

$$L_3 = \prod_{i=1}^{N} \frac{1}{\alpha}\left[1 - k(x_i - u)/\alpha\right]^{\frac{1}{k}-1} \exp-(1 - k(x_i - u)/\alpha)^{\frac{1}{k}} \tag{15}$$

and for the FT1 distribution:

$$L_1 = \prod_{i=1}^{N} \frac{1}{\alpha} \exp\left[-(x_i - u)/\alpha + \exp(-(x_i - u)/\alpha)\right] \tag{16}$$

where in each case the expression after the product sign is the probability density function obtained by differentiating the cumulative forms 8 and 9. Methods of maximising the likelihood functions are described elsewhere (Carter and Challenor, 1981; NERC, 1975) and the results obtained with the oceanic intraplate data are given in Table 4. As expected, the results obtained using the 3 parameter FT3 give higher maximum likelihoods than the 2 parameter FT1. Whether the difference is significant can be tested using the likelihood ratio λ which is equal to 1.0 for no difference and becomes small for larger differences.

$$\lambda = \frac{L_1}{L_3} \tag{17}$$

The ratio can be tested for significance since -2 Log λ is distributed as χ^2 (Wilkes, 1938). For the Atlantic data this statistic equals 0.73 which is not significant while for the world data it is 5.29 which is significant at the 97.5% level. These results are illustrated in Figure 10 where the curves for the two distributions 8 and 9 obtained using the parameters given in Table 4 are plotted using the negative double logarithm of P as abscissa. Since P is the annual probability of x not being exceeded then 1-P is the annual probability of x being equalled or exceeded and, therefore, the return periods (given along the top of Figure 10) are given by 1.0/(1-P). The data points for the observed extremes are plotted using estimates of P using Gringorton's (1963) plotting rule. For the ith of N extremes ranked in ascending order an estimate of P_i is:

$$P_i = \frac{i - 0.44}{N + 0.12} \tag{18}$$

This rule is applicable to the FT1 distribution but not necessarily the FT3.

	Distribution Constants			Max Likelihood	$-2\ \mathrm{Log}(L_1/L_3)$	Significance
	U	α	k	L		
Atlantic FT1	3.94	0.86	-	1.61×10^{-10}	0.73	60%
Events FT3	4.05	0.93	0.23	2.32×10^{-10}		
World FT1	5.37	0.83	-	6.74×10^{-10}	5.29	97.5%
Events FT3	5.61	0.88	0.53	9.50×10^{-9}		

Table 4 - Results obtained by applying the method of maximum likelihood to the two sets of extremes given in Table 3. The constants u, α and k are for equations 8 and 9 and the curves are plotted in Figure 10. The likelihood ratio statistic $-2\ \log(L_1/L_3)$ is distributed as χ^2 with one degree of freedom and only for the world data is the difference between the two distributions FT1 and FT3 significant (last column).

It is clear that for the world data the FT3 distribution appears to be a much better fit. The upper limit, given by $u + \alpha/k$ is magnitude (M_s) 7.3.

The extreme value data gives a useful check on the b value in equation 7 since the FT1 distribution can be derived directly from the form of this equation (see Karnik, 1971). In particular:

$$b = 1.0/2.3\alpha \tag{19}$$

For the Atlantic data $\alpha = 0.86$ giving $b = 0.51$. This agrees fairly well with the value 0.44 in equation 7.