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ON THE ASSESSMENT OF SEISMIC RISK IN THE NORTH SEA AREA

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1. The data

Figure 1 gives the area of which the seismicity has been considered for this study. It is situated between 50° and 71° N and 5° W and 15° E. All known earthquakes in the region with a magnitude of 5 and greater and/or a radius of perceptibility of at least 250 km are shown. The earthquake parameters are enlisted in Table A*). The table 5.2 in Husebye a.o. (1979) used as a base, was extended and completed with some data, mainly from the southern parts of the area in question.

The earthquakes seem to be concentrated in four regions, i.e. the U.K., the Netherlands/NW Germany zone incl. Belgium, Norway incl. Denmark and parts of Sweden, and the Atlantic Ocean inside depth contour of 500 m. The lack of epicenters in between these general concentrations is not caused by a lesser detection capability of the seismic station network for these regions, especially not for the later years. With the present station network earthquakes of magnitude 5 and higher will be recorded at any place inside the area under investigation. This than means that the North Sea area apparently does not act as an independent seismic unit as do the sub-regions indicated earlier. At its borders the North Sea area is affected or may be affected by the surroundig zones of relatively higher seismicity. And if the seismic risk in the North Sea block as outlined in figure 1 is to be determined, it should be realized that in fact marginal effects of the neighbouring sub-regions are considered.

The numbers of earthquakes in Table A rapidly decrease before the year 1850. For some regions this is more pronounced than for others according to the local density and development of human population. To be certain of homogeneity in time and space of the material the further discussion is based upon 100 years of data starting in 1878.

The following numbers of earthquakes occurred in the different sub-regions in this period:

*)see Annex

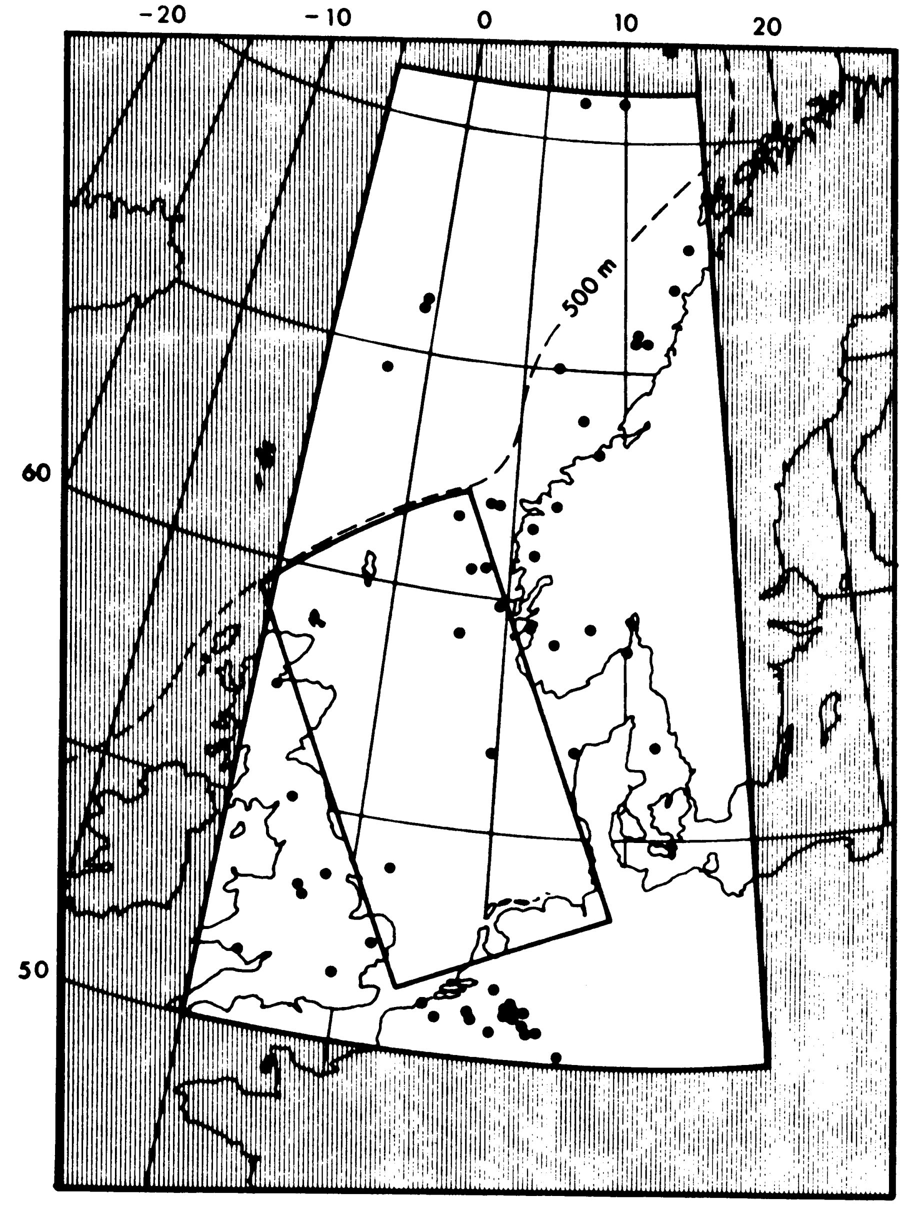

Figure 1 - The epicenter map with delineation of the area studied, inclusive the North Sea block.

	N	M
U.K.	10	4.8 - 6.0
Neth. s.l.	8	$4\frac{3}{4}$ - 5.8
Norw. s.l.	19	$4\frac{1}{2}$ - 6.4
Atl. Oc.	7	5.0 - 6.0
Total	44	$4\frac{1}{2}$ - 6.4
North Sea block	6	$4\frac{1}{2}$ - 6.0

Table 1 - 100 years of earthquakes in the North Sea region.

2. The magnitude-frequency distribution and recurrence times

The frequency distribution of the total material and for that of the North Sea block is shown in figure 2. The curve for all data has a normal course: for higher magnitudes M the numbers N are falling off more rapidly, and for smaller magnitudes a tendency exists for a linear relation between log N and M; according to:

$$\log N = A - B.M,$$

where B - the inclination of the curve - equals a value of 0.75. The B-value equals the one found by Husebye and Ringdal (1976) for Scandinavian earthquakes and also that used by Ritsema (1966) for the earthquakes of the lower Rhine Graben inclusive the Netherlands. The curve for the North Sea block only can be considered tentative with the small number of available data. As lower boundary condition it has been assumed here that the B-value for small magnitudes tends to the same value of 0.75 as that for the whole region. The numbers and recurrence times of the earthquakes of a certain magnitude or higher in the two blocks of figure 1 are given in Table 2. For the four sub-regions the approximate numbers of shocks per 100 years are given in the Table 3, under the assumption that the B-value for the lower magnitude end of the frequency distribution equals that of the total material. It goes without question that these numbers too are less reliable than those of the total material, because of less complete documentation for smaller regions or a too small time-window. It should be remarked also that for the Atlantic Ocean sector a smaller B-value than 0.75 is possibly more appropriate. Because of the small number of data, however, no definite conclusion is given here.

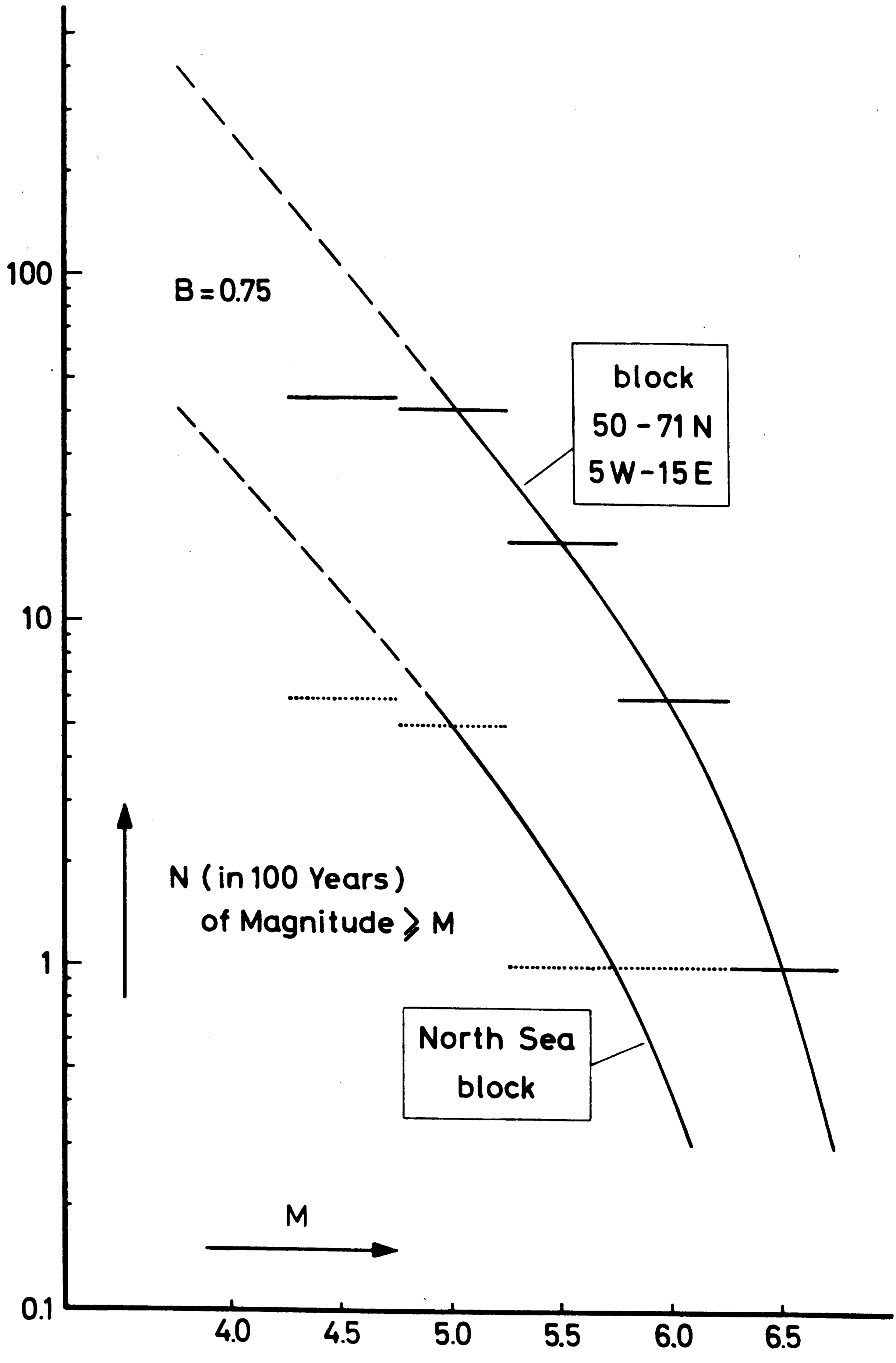

Figure 2 - The accumulated frequency - magnitude distribution for the total material, and for the North Sea region in itself.

	total area		North Sea block	
M	N per 100 years	recurrence time in years	N per 100 years	recurrence time in years
≥ 6.5	1	~100	-	> 1000
≥ 6.0	5½	18	0.4	250
≥ 5.5	17	6	1.8	55
≥ 5.0	43	2.3	4.6	22
		extrapolated		
≥ 4.5	105	1	11	9
≥ 4.0	260	4½ month	28	3.6

Table 2 - The magnitude-frequency distribution and the recurrence times for the two considered areas, based upon the available material of the past 100 years.

M	U.K.	Neth. s.l.	Norw. s.l.	Atl. Oc.
≥ 6.5	0.4	0.1	0.4	0.1
≥ 6.0	1.9	0.6	1.7	0.7
≥ 5.5	5.7	2.5	5.6	2
≥ 5.0	15	7	15	5
≥ 4.5	38	16	40	12
≥ 4.0	~100	38	~100	30

Table 3 - The numbers of earthquakes per 100 years in the four sub-regions.

3. Attenuation

For the determination of earthquake risk,data on attenuation in the regions concerned are required. Since the region of the North Sea has a structure that from the surrounding sub-regions is most comparable to that of the Netherlands s.l., it seems justified to use existing information on attenuation from this particular region. It concerns the decay of Intensity values with epicentral distance for some earthquakes in the sub-region. and especially that for the 1932 Uden earthquake in Eastern N-Brabant.

Figure 3 shows the intensity decay for some earthquakes of this sub-region as brought together by Ahorner (1976). Table 4 compiles the intensity decrease with epicentral distance used in this particular sub-region.

Intensity MMS or MSK scale	5 (in km)
I_{max}	0
$I_{max} - \frac{1}{2}$	10
$I_{max} - 1$	20
$I_{max} - 1\frac{1}{2}$	30
$I_{max} - 2$	40
$I_{max} - 2\frac{1}{2}$	55
$I_{max} - 3$	75
$I_{max} - 3\frac{1}{2}$	105
$I_{max} - 4$	140
$I_{max} - 4\frac{1}{2}$	185
$I_{max} - 5$	240
$I_{max} - 5\frac{1}{2}$	300

Table 4 - The intensity decrease with epicentral distance in the sub-region of the Netherlands s.l. (after Ahorner 1976).

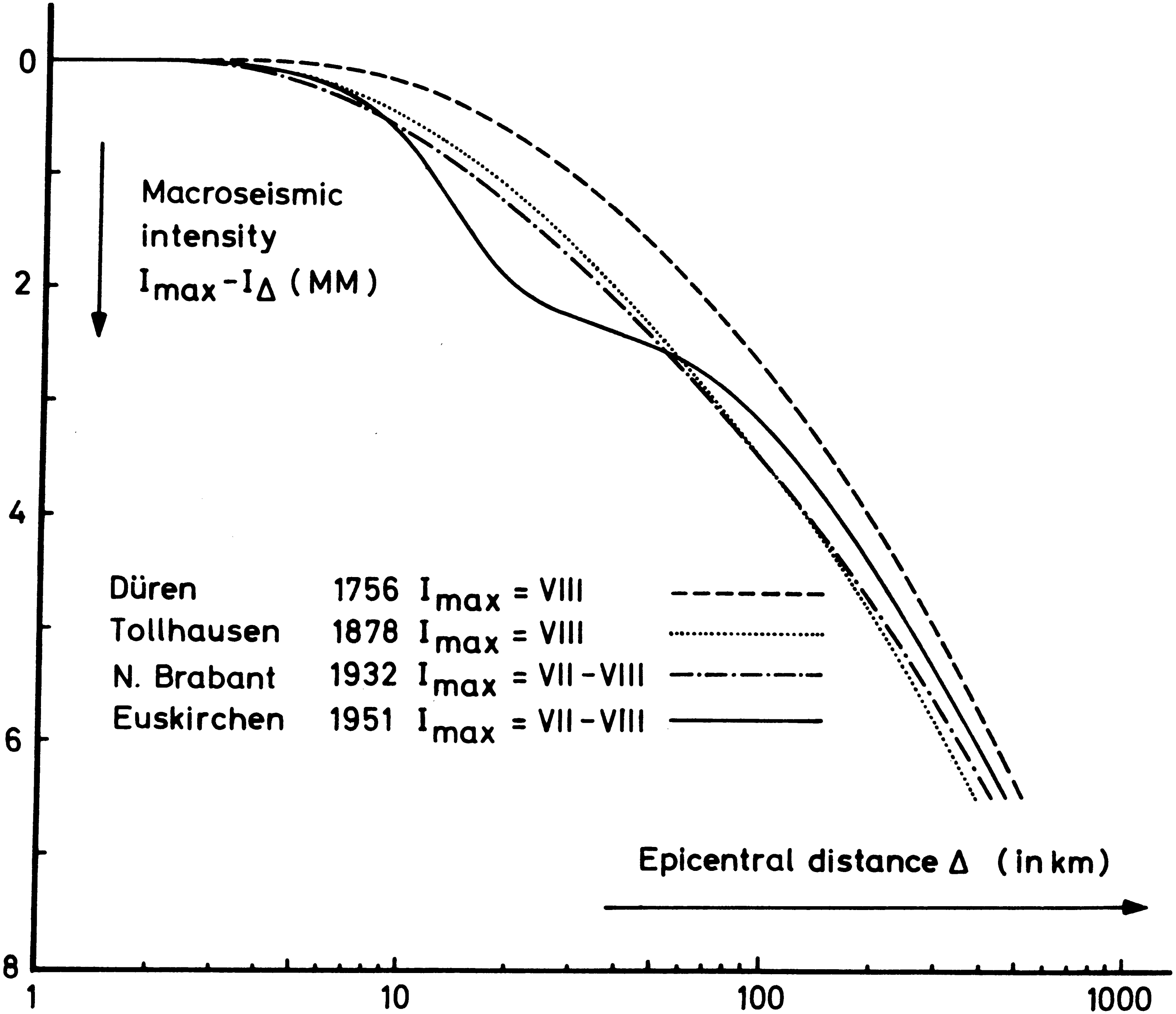

Figure 3 - Attenuation curves for the MM-intensity values of earthquakes of the sub-region Netherlands s.l. (after Ahorner, 1976).

4. The magnitude-intensity relation

For quite a few earthquakes of Table A no I_{max} values are known. This is a difficulty inherent to areas covered by sea. The by far greatest majority of the earthquakes in the region have their foci within the earth's crust at, say, 10-15 km (see also Husebye a.o. p. 73 (1979), Ritsema (1966) and Karnik (1969). It is fair than to assume that a certain relation does exist in the region between magnitude M and the intensity I_{max} which can be assumed to be valid for all earthquakes of Table 1, including those for which no I_{max} values have been reported. From the earthquakes of Table A with both M and I_{max} data an empirical relation is found shown in Table 5, including the extrapolation to lower magnitudes.

M	I_{max}
6½	VIII +
6	VII - VIII
5½	VII -
5	VI
4½	V +
4	IV - V
3½	IV -
3	III

Table 5 - The relation between magnitude M and maximal Intensity I_{max}

5. The intensity-acceleration relation

The empirical relation between intensity I and groundacceleration a is not unique. Figure 4 shows the measured a-values as a function of the observed intensity I at the accelerometer-site in 40 years of recording (from Ambraseys 1974). There is a tendency for higher a-values at higher intensities, but the dispersion is enormous, mostly more than a factor 10, sometimes of the order of a factor 100! This means that in an area affected by, say, intensity VII, the acceleration may very from about 0.01 to 0.5 g. Assuming that the sites of accelerometer posts used in the data set of figure 4 were randomly distributed in the intensity zones it is possible to determine the chance that in zone intensity VII the value of the acceleration exceeds 0.1 g, or 0.2 g etc. This has be done for each intensity class, and the result is shown in figure 5, giving for each intensity zone the probability that a certain value of acceleration is exceeded. Numerical values read from the figure 5 are enlisted in Table 6.

Intensity I	Percentage observations of acceleration a						
	a= $<\frac{1}{10}$ g	$\frac{1}{10} - \frac{2}{10}$g	$\frac{2}{10} - \frac{3}{10}$g	$\frac{3}{10} - \frac{4}{10}$g	$\frac{4}{10} - \frac{5}{10}$g	$>\frac{5}{10}$g	
VIII	38%	24	18	10	4	6	%
VII-VIII	53	22	12	6	3½	3½	%
VII	69	16	7	4	2	2	%
VI-VII	80	12	4	2	2	-	%
VI	88	8	2	1	1	-	%
V-VI	92	6	1	1	-		%
V	95	4	1	-			%
IV-V	97	3	-				%
IV	98½	1½	-				%
III-IV	99½	½	-				%
III	100%	-					%

Table 6 - The relation between intensity I and acceleration a.

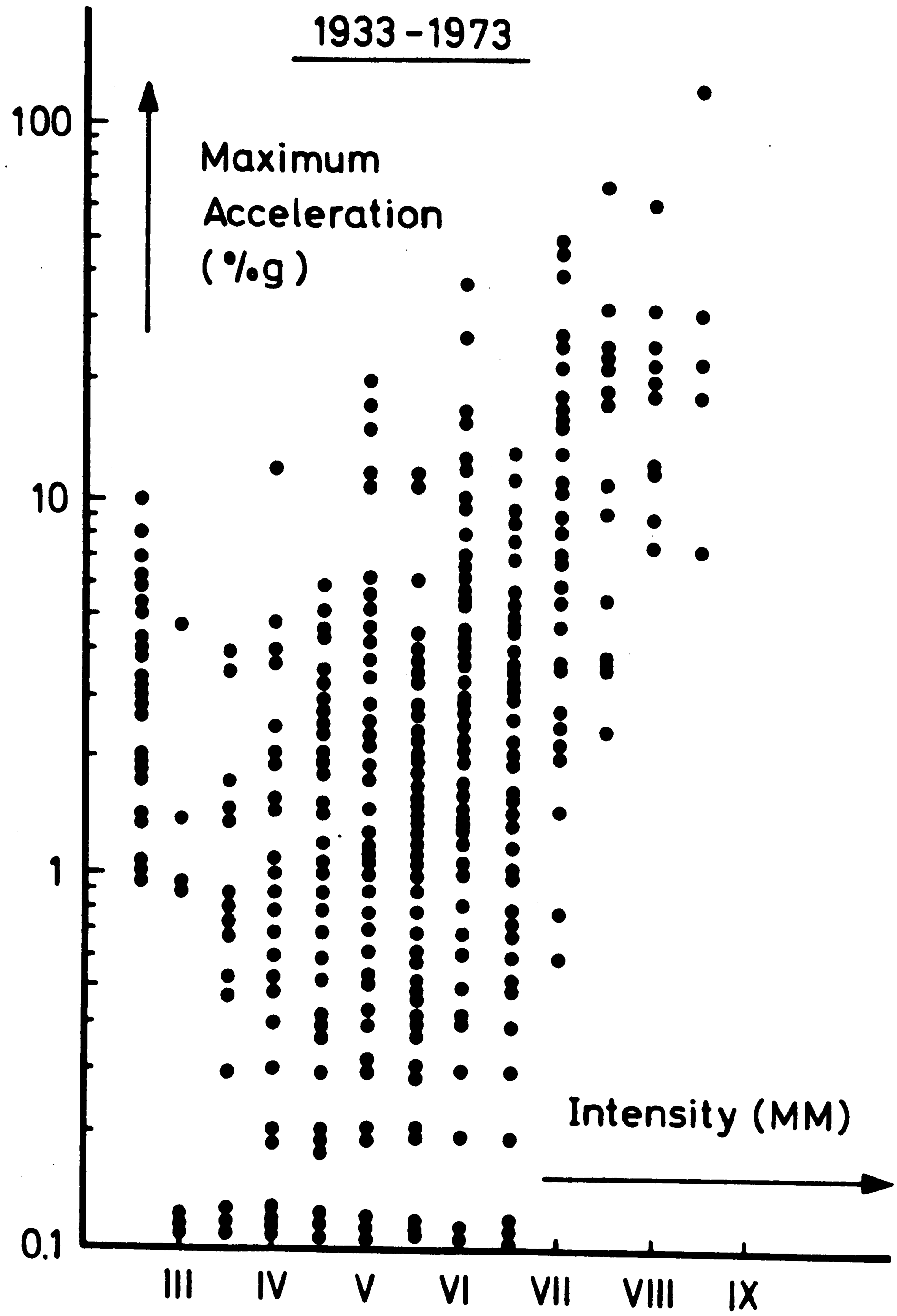

Figure 4 - The recorded maximum accelerations versus reported Intensities (after Ambraseys, 1974).

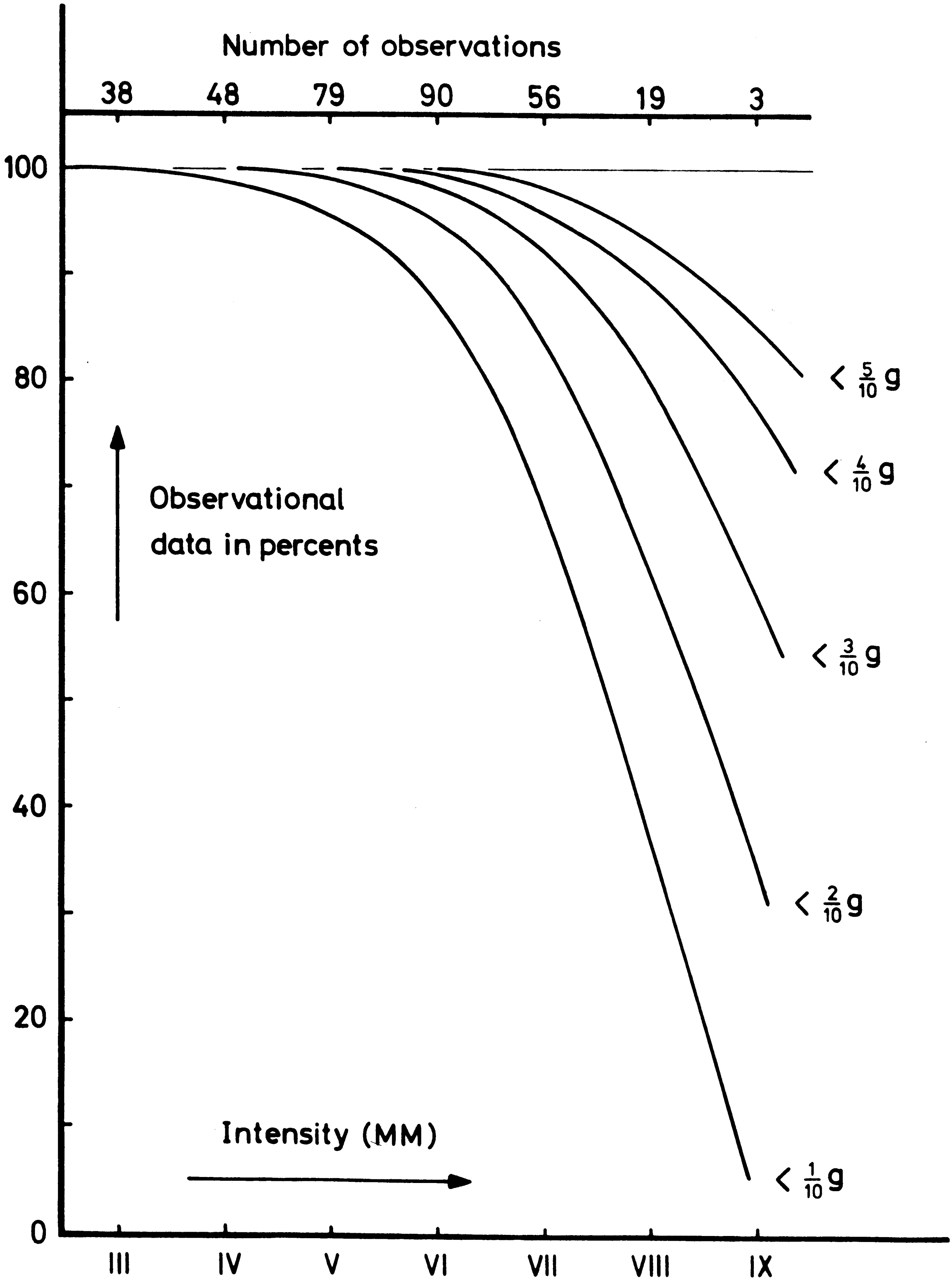

Figure 5 - The percentage of given values of acceleration observations in different intensity zones (from Ritsema, 1975).

6. Results

With the empirically determined relations between N, M, I_{max}, r, I and a it is possible now to calculate the areal surface which is affected by a certain intensity I in the course of a specific time-span of, say,1000 years in each of the chosen sub-regions of the studied area. And, taking into account the areal extent of the geographical blocks under consideration, it is possible than to calculate the recurrence time of the occurrence of a certain value of acceleration anywhere in the blocks. This has been done here for two blocks; that of the total region under consideration ($S = 255 \times 10^4$ km^2) and that of the North Sea proper as indicated in the figure 1 ($S = 59 \times 10^4$ km^2). The results are given in Table 7 and figure 6.

According to these calculations than the recurrence time for an earthquake generated acceleration smaller than 1/10 g is 300 years in the North Sea area against 180 years in the whole region. Accelerations ⩾ 3/10 g occur once in 670.000 years in the North Sea area, once in 250.000 years when the total investigated area is considered.

	total region	North Sea block
$< \frac{1}{10}g$	0.18	.30
$\frac{1}{10} - \frac{2}{10}g$	7.7	13.4
$\frac{2}{10} - \frac{3}{10}g$	56.8	113.9
$\frac{3}{10} - \frac{4}{10}g$	255.	666.
$\frac{4}{10} - \frac{5}{10}g$	332.	770.
$> \frac{5}{10}g$	1060.	4.240.

Table 7 - The recurrence time for earthquake accelerations a in the North Sea area as compared to that for the total investigated region (Unit = 1000 years)

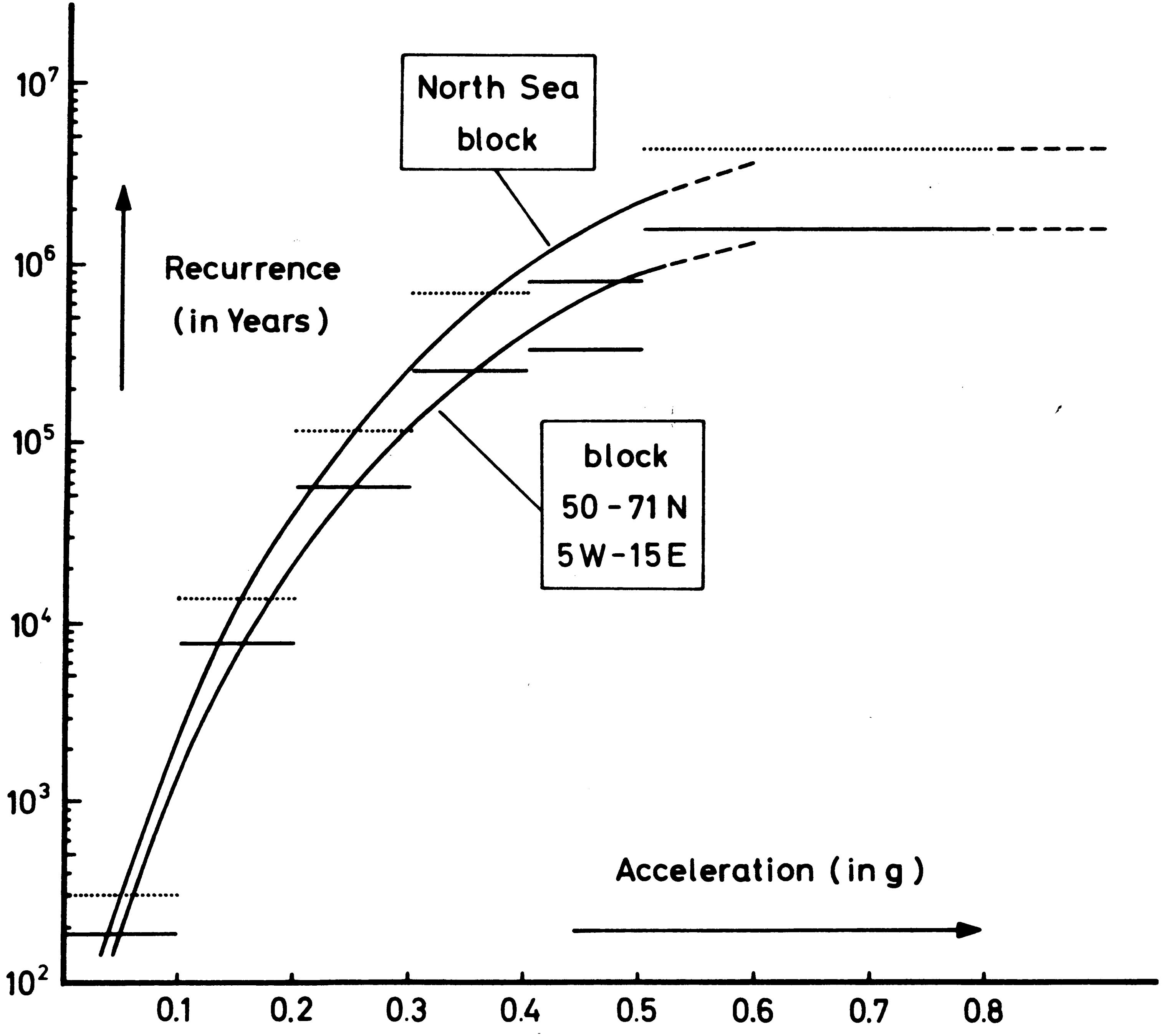

Figure 6 - The recurrence time for earthquake accelerations in the two considered regions.

7. Remarks

Some points should be realised in evaluating the results of this study:

7.1. The used data base of 100 years very probably is homogeneous for magnitudes ⩾ 5.0. It is questionable, however, if the data base is long enough for a complete description of the seismicity. The lower the seismicity is, the longer the required time base is.

7.2. We have assumed in the foregoing a homogeneous distribution of earthquake foci all through the regions in question. This is obviously untrue. It has been pointed out already that the known data of the region naturally fall into four groups, that of the UK epicenters (including the Doggersbank earthquake of M 6.0 in 1931), that of the Netherlands (inclusive Belgium and NW Germany), that of Norway, Sweden, Denmark (inclusive some westerly epicenters in the north-eastern North Sea) and the Atlantic Ocean shocks at waterdepths greater than 500 m. It seems more appropriate thus to describe the seismicity of these 4 sub-regions separately. The remaining (greater) part of the North Sea than should be devoid of any seismic activity of M ⩾ 5, which means that the conclusions drawn from the present evaluation are conservative with respect to this central and northern part of the North Sea. It may also be concluded that for the places where in the West and in the East seismically more active regions border the North Sea area the found recurrence times in Table 8 actually are too great.

7.3. The uncertainties in the (N,M)-relations used are obvious from the figure 2. The assigning of intensity values to seabottom earthquakes of which the magnitude is known also is more or less arbitrary. Much depends on the depth of the individual earthquake-sources and on the structure of the earth's crust at the epicenters, both factors being unknown in detail. The used attenuation or intensity decrease with distance (fig. 3) also is not determined at the place where we should like to know its values. According to local structure important differences may occur in such attenuation curves. The relation intensity-acceleration (fig. 4) is that with the greatest uncertainties. It is clear that the acceleration in a zone of certain intensity very strongly depends on local factors and consequently may vary within wide limits. Some of this uncertainty has been taken into account by the way this data-set has been used in the present study. But it goes without question that a factor of at least two in the ultimate results of Table 8 is quite plausible and acceptable.

7.4. We have considered here only the larger events of M $\geqslant$ 5. Data of smaller magnitudes are lacking for the region of the North Sea proper. It could well be that small seismic events in the region will correlate well with one of the known structural features in the underground (Ziegler, 1978). This than could give an indication on the probability of future occurrence of larger events in these general areas. The study of local seismicity in the North Sea area, therefore, should be of great importance. The setting-up of a local seismic network for the countries around the North Sea, including seabottom seismometers in the general area should be supported where possible.

7.5. Any addition to the knowledge of structural features in the underground of the North Sea basin also is to be welcomed. It is gradually been realized that old fault-zones sometimes can be re-activated, especially in intraplate conditions such as exist in the present general area. On comparable structures in the coastal areas of the Eastern USA earthquakes have occurred unexpectedly in otherwise quite areas with magnitude of around 7, higher than historical records indicate for the region of the North Sea. Such high magnitude events, therefore, cannot be ruled out completely for the region under consideration, although no evidence can be produced indicating any significant probability for the future occurrence of such an event.

7.6. Recently evidence has been found for the local occurrence of extremely high accelerations even higher than g in relatively small earthquakes (Mexicali earthquake of 15 October 1979 with magnitude 6.7 and recorded acceleration of 1.7g). It seems possible that extreme acceleration values so now and than do occur in otherwise modest earthquakes. It seems difficult to assign a probability factor to such occurrences, so that no allowance is made for such events. It should be realised however that such occurrences cannot categorically be excluded.

7.7. Peak-accelerations used in the foregoing are not always per definition the most dangerous for structures. It has been found that also the duration of the signal is of paramount importance. This factor has not been taken into account since up till now hard data to be used for such an exercise are scarce.

7.8. It can be concluded that the results, brought together in the table 7 and figure 6, should be considered with the necessary reserve. And because of the limited time that could be used for its preparation, the present study on the general lines of the seismicity of the region should in no way be considered as the ultimate work on the subject.

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8. References

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Annex

DATE				EPICENTER		DEPTH	MAGNI-	INTEN-SITY	FELT RADIUS
Year	Month	Day	Hour	Lat	Long	(km)	TUDE	MM-Scale	(km)
1979	Dec	26	03.57	55.1N	2.8W	10	4.8	VI	275
1977	Apr	6	19.31	61.6N	2.5E	-	5.0		
1975	Jan	20	10.47	71.7N	14.2E	-	5.0		
1967	Aug	21	13.41	57.0N	4.9E	-	5.2		
1962	Dec	15	03.48	67.5N	14.2E	-	5	VI	235
1959	Jan	29	23.24	70.9N	7.3E	-	5.8		
1958	Aug	6	17.16	59.5N	6.0E	-	5.1	VI	300
1958	Jan	23	13.35	65.0N	6.5E	-	5.5		
1955	Jun	3	11.39	61.9N	4.0E	-	5.0		
1954	Jul	7	00.48	59.8N	4.8E	-	4.9	VI+	350
1951	Mar	14	09.47	50.6N	6.7E	8.5	5.2	VIII	370
1950	Mar	8	04.27	50.6N	6.7E	7	5.0	VII	230
1946	May	11	18.39	66.0N	0.5W	-	5.1		
1946	May	11	16.25	66.0N	0.5W	-	5.0		
1938	Jun	11	10.57	50.8N	3.6E	24	5.8	VII-VIII	340
1938	Mar	11	16.08	61.9N	4.2E	-	4.8	V+	268
1935	Jul	17	00.04	65.5N	11.5E	-	5.6		
1934	May	20	19.04	64.5N	2.0W	-	5.6		
1933	Mar	23	18.48	51 N	2.9E	-	$4\frac{3}{4}$	V	300
1932	Nov	20	20.24	51.7N	5.6E	8-9	5.0	VII	380
1931	Jun	7	00.25	54.0N	1.4E	(70)	6.0	(VIII)	600
1929	Jun	10	23.03	71.0N	10.0E	-	6.0		600
1927	Jan	24	05.18	59.0N	3.0E	-	5.1	VI	440
1926	Jan	5	23.37	50.7N	6.6E	22	5	VI	260
1924	Jul	25	19.36	72.5N	16.0E	-	5.6		
1913	Aug	4	07.38	61.4N	5.8E	-	4.9	V+	270
1913	Jul	19	15.50	64.0N	8.0E	-	5.0		200
1907	Jan	27	04.58	65.5N	11.0E	-	$5\frac{1}{2}$	VI	315
1907	Jan	14	13.03	65.5N	11.0E	-	5	V+	250
1906	Jun	27	09.45	51.6N	4.0W	30	5.3	VIII	237
1905	Apr	23	01.37	53.5N	0.9W	40	5.4	VII	119
1904	Oct	23	10.26	59.2N	10.5E	55	6.4	VIII	560
1904	Jul	3	15.21	53.0N	1.7W	20	5.2	VII	142

DATE year	Month	Day	Hour	EPICENTER Lat	Long	DEPTH (km)	MAGNI-TUDE	INTEN-SITY MM-scale	FELT RADIUS (km)
1903	Mar	24	13.30	53.0N	1.7W	25	5.5	VII+	150
1901	Sep	18	01.24	57.4N	4.1W	30	5.8	VIII	240
1895	Feb	4	23.40	61.9N	7.0E	-	5	VI+	250
1892	May	15	14.51	60.9N	6.0E	-	5½	VII+	240
1889	May	30	20.21	49.2N	1.7W	-		VII	200
1886	Oct	24	23.30	60.5N	4.0E	-	4½	IV	300
1884	Apr	22	9.18	51.9N	0.9E	-	5½	VIII	300
1881	Nov	18	23.14	50.8N	6.1E	13	4.9	VI	220
1879	Sep	25	00.15	59.0N	7.0E	-	4½	IV	250
1878	Aug	26	8.50	50.9N	6.5E	9	5.4	VIII	370
1878	Jan	28	11.53	49.2N	1.7W	-		VI	310
1866	Mar	9	01.15	63.2N	9.0E	-	6	VII	400
1865	May	7	13.21	60.5N	3.0E	-	5½	VI	400
1846	Jul	29	21.24	50.1N	7.7E	10	5.4	VII	280
1841	Apr	3	02.16	57.0N	8.0E	-	5½	VII+	250
1834	Sep	3	19.15	59.3N	8.5E	-	5½	VI	400
1828	Feb	23	08.30	50.7N	4.9E	17	5.4	VII-VIII	220
1819	Aug	31	15.00	66.5N	13.0E	-	6	VII	500
1762	Jul	31	13	50.7N	6.7E	-		V-VI	170
1759	Dec	22	01.00	57.0N	11.5E	-	6	VII	500
1756	Febr	18	07.45	50.8N	6.5E	16	6	VIII	460
1755	Dec	26	23.56	50.8N	6.3E	11	5½	VII-VIII	210
1692	Oct	28	14.15	50.8N	4.8E	-		V-VI	300
1692	Sep	20	08	50.8N	4.8E	-		VI-VII	290
1692	Sept	18	14.15	50.8N	4.8E	27	6	VII-VIII	430
1690	Dec	18		50.8N	6.2E	60	5	VI-VII	210
1640	Apr	4	03.15	50.8N	6.6E	-	5¼	VII-VIII	250
1580	Apr	6	18	51.5N	0.2W	-		VII	550
1456	Aug	26	02	50.6N	5.6E	-	(5)	(VII)	450

Table A - The data list of earthquakes.