Netherlands Journal of Geosciences / Geologie en Mijnbouw 80 (3-4): 305-314 (2001)

Seismic hazard analysis results for the Lower Rhine Graben and the importance of paleoseismic data

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Manuscript received: December 1997; accepted in revised form: December 1999

Abstract

Seismic hazard in low seismicity areas of Europe has traditionally been considered insignificant. However, in the light of the recently conducted paleoseismic studies along the Rhine Graben, a revision is required. Previously applied standard probabilistic seismic hazard assessment (PSHA) methods, using Poissonian approach for the earthquake occurrence, can now be substituted by renewal models where fault parameters such as the maximum magnitude, recurrence interval and the elapsed time since the last occurrence of a large earthquake, can be utilized. In this study, the application and the influence of the available paleoseismic data in the Lower Rhine Graben to seismic hazard analysis is demonstrated. The resulting hazard maps, when compared to the standard PSHA using Poissonian approach, indicate a more precise geographical distribution of the estimated seismic hazard levels. The influence of the paleoseismic data seem to be less important for return periods less than a 1000 years. Among the different input models, the highest values reach to 170 cm/sec^2 for a 1000 year return period using a combination of Poissonian and renewal models.

Keywords: Seismic hazard, paleoseismology, uncertainties, Lower Rhine Graben

Introduction

Potential of large earthquakes in stable continental regions such as northern Europe, has been a subject puzzling seismologists for many years. Earthquake hazard assessment for these apparently low seismicity areas has traditionally been evaluated on the basis of the instrumentally and historically recorded earthquakes, which indicates relatively low hazard levels. Reliability of such estimates is a matter of debate as the long-term potential of large earthquakes usually cannot be determined based on short observational periods generally less than a few hundred years. The deadly Killari (Latur, central India), earthquake of Sept.30, 1993 (m_b=6.3), is a reminder for us that large destructive earthquakes can practically occur almost anywhere, irrespective of past historical records. A significant improvement to this lack of knowledge can be achieved by extending the past observations into the geological time scale. Paleoseismic investigations can provide valuable information to bridge this gap, where the potential for large earthquakes can be quantified both in magnitude and recurrence period, based on the observation of prehistoric earthquakes (paleoearthquakes) in the geological record of particularly the Holocene (the last 10,000 years).

Although the importance of paleoseismology has been stressed since the early 1970s in North America (e.g. Wallace, 1970; Sieh, 1978), seismic hazard maps with integrated paleoseismic data did not appear until the 1980's. Today most of the earthquake prone countries consider paleoseismic data in seismic hazard analyses. In this study, the results from the recent paleoseismic investigations performed along the Lower

Rhine Graben are integrated into the probabilistic seismic hazard analysis using a combination of Poissonian and renewal models.

Paleoseismic investigations

The Roermond (Netherlands) earthquake (Camelbeeck and van Eck, 1994) of April 13, 1992 (M_W=5.3), has initiated a series of paleoseismic studies in the Lower Rhine graben region (Camelbeeck and Meghraoui, 1996; 1998; Vanneste et al., 1999; Meghraoui et al., 2000), which revealed that the occurrence of moderate to large earthquakes in northern Europe is likely. As a result, it was possible to identify active faulting in the Lower Rhine Graben. Holocene surface faulting was successfully correlated with historical and prehistoric earthquakes in trenches and in the scarp morphology. Near the town of Bree (Belgian Limburg), along part of the Feldbiss fault zone, the Bree fault, an average vertical displacement of 0.6m was estimated during the last coseismic event (690-980 A.D.) (Meghraoui et al., 2000). Assuming a fault width comparable to the thickness of the seismogenic layer at Roermond, the estimated seismic moment of this paleoearthquake is 4 x 10^{18}Nm., implying a moment magnitude of ca. 6.4. Furthermore, it was suggested three large earthquakes during the last 45 kyr, based on the three trenches excavated, coupled with analyses of geomorphic profiles, ground penetrating radar and electric tomography data across the 10 km long frontal Bree fault scarp. Within the framework of the PALEOSIS project, these initial studies were extended to the faults along the eastern boundary of the Lower Rhine Graben. Preliminary results from the Peel fault at Neer (the Netherlands) and Rurrand fault at Jülich (Germany), confirm the existence of significantly large earthquakes during the Quaternary.

One major limitation in paleoseismic studies is that the uncertainties related to the interpretation of the 'trench evidence' are not always documented in sufficient detail. In this study, the uncertainties associated with the paleoseismic data were treated systematically (Atakan et al., 2000a), prior to its application in the seismic hazard assessment.

Input data for the seismic hazard analysis

In order to demonstrate the influence of the paleoseismic data in estimating the seismic hazard, the results from the paleoseismic investigations performed along the Lower Rhine Graben were used in probabilistic seismic hazard analysis. Five different input source characterisations together with two different attenuation relations were used and as a result 10 seismic hazard maps are presented showing the peak ground acceleration (PGA) values for a 1000 year return period. The input parameters are summarized in Table 1 and the details are described below. In each of these models two different attenuation relations were applied. These are from Ambraseys et al. (1996) and Spudich et al. (1997), and are shown in Figure 1 for comparison.

The Ambraseys et al. (1996) relation is based on the European data and represents a more conservative estimate. A comparison between the recorded peak ground acceleration (PGA) values of the 1992 Roermond earthquake (Berger, 1994) and the attenuation relations for the two reported magnitudes (5.9 M_L and 5.3 M_W) is also shown. The agreement at distances between 50-250 km seem to validate the rele-

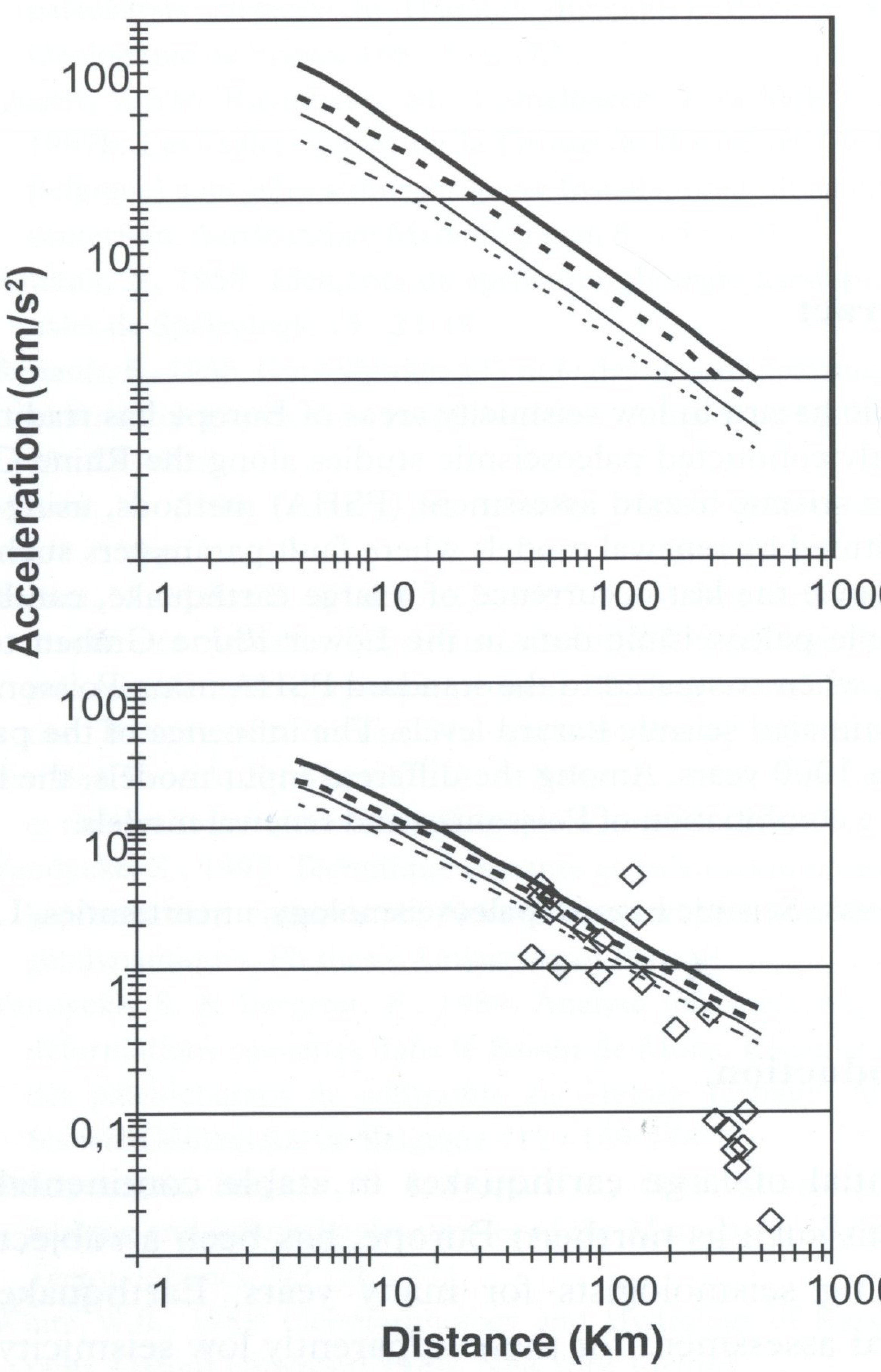

Fig. 1. Upper diagram shows the two attenuation relations used in this study. The solid lines are for Ambraseys et al., (1996) relationship and the stippled lines are for Spudich et al. (1997) relation. The thicker lines are for magnitude 7.0 and the thinner lines are for magnitude 6.0. The lower diagram shows a comparison of the recorded PGA values (for the largest of the horizontal components) of the 1992 Roermond earthquake (Berger, 1994) as diamonds and the two attenuation relations. The thicker lines are for Ambraseys et al., (1996) and the thinner lines are for Spudich et al. (1997). The solid lines are for magnitude 5.9 (M_L) and the stippled lines correspond to 5.3 (M_W). Note that the attenuation relations and the Roermond earthquake data points agree better for the distance range between 50 to 250 km, which is relevant to distances used in this study.

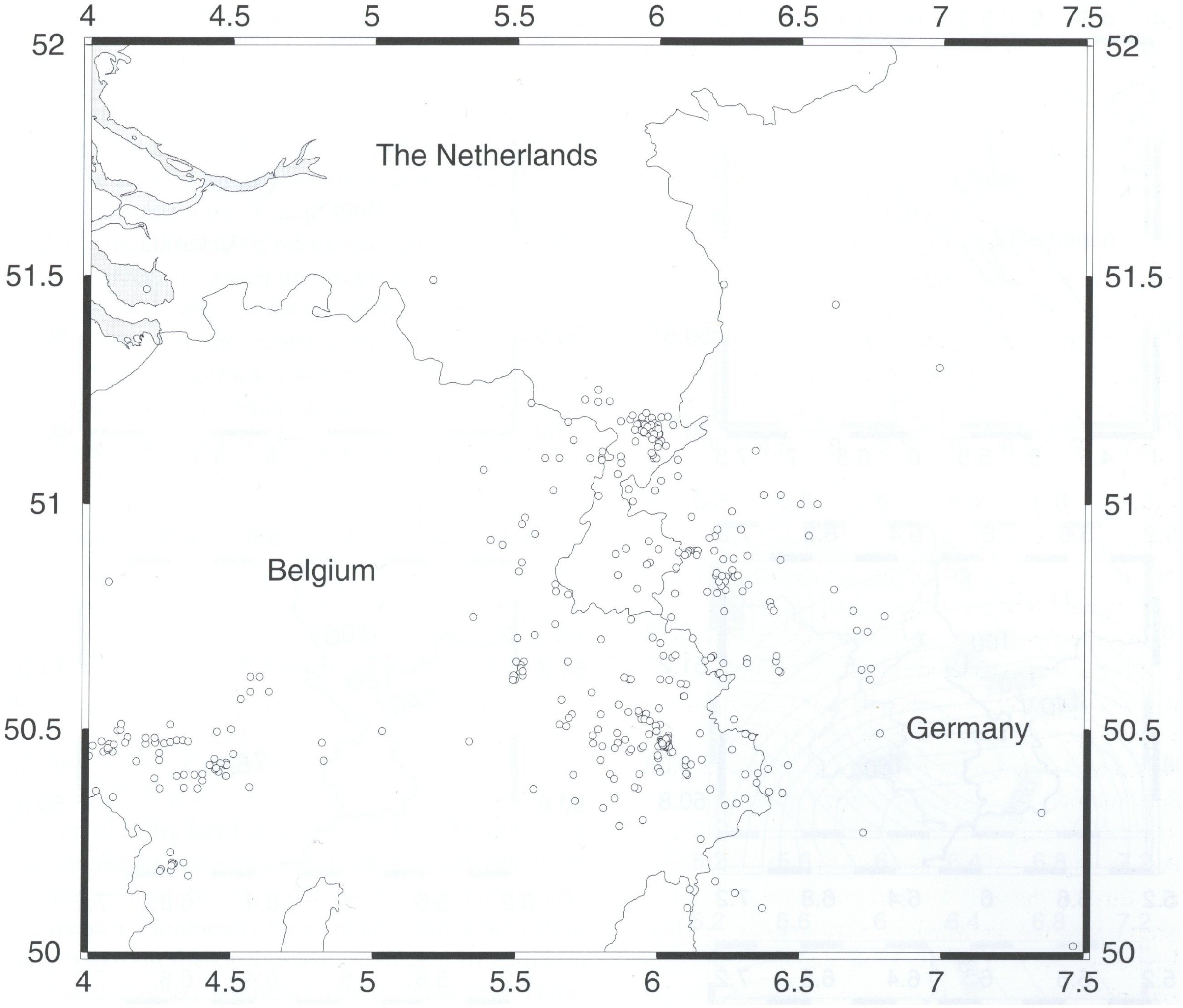

Fig. 2. Distribution of the seismicity in the study area based on a catalogue compiled from the Royal Observatory of Belgium for the last 50 years.

vance of the attenuation relations used in this study. The points that show higher PGA values are probably related to soft soil sites. The modelled PGA values for the epicentral area of the Roermond earthquake (Gariel et al., 1994) seem also to agree well with the predicted values based on the two attenuation relations used in this study. The earthquake catalogue used in the present paper is a compilation from the Royal Observatory of Belgium (Figure 2).

Regarding the definition of the earthquake sources two basic assumptions are used. The first one is based on a standard Poissonian assumption (Cornell, 1968) and the second is based on a renewal model (Schwartz, 1988; McGuire, 1993) assuming a 'characteristic earthquake' (Schwartz and Coppersmith, 1984; Youngs and Coppersmith, 1985). In the Poissonian model the earthquakes have no memory and it is assumed that the occurrence of a future earthquake is independent of the occurrence of a previous one. In the renewal model on the other hand, the time elapsed since the last event is incorporated recognising that the stress accumulation and release process on faults is cyclical (McGuire, 1993). It is assumed that the earthquakes occur in regular recurrence intervals and the time elapsed since the last earthquake can be used to compute the conditional probability of occurrence of a future earthquake from the same source. The latter model therefore has a better capacity to exploit the paleoseismic data and reflects the importance of dependent character of earthquake occurrence.

The five different source models and the associated input parameters used for each are described in following:

Model 1

Area sources based on a standard Poissonian assumption (Figure 3). Here the sources are similar to the ones used in previous probabilistic hazard analyses (e.g. de Crook, 1993; 1996; Grünthal et al., 1999).

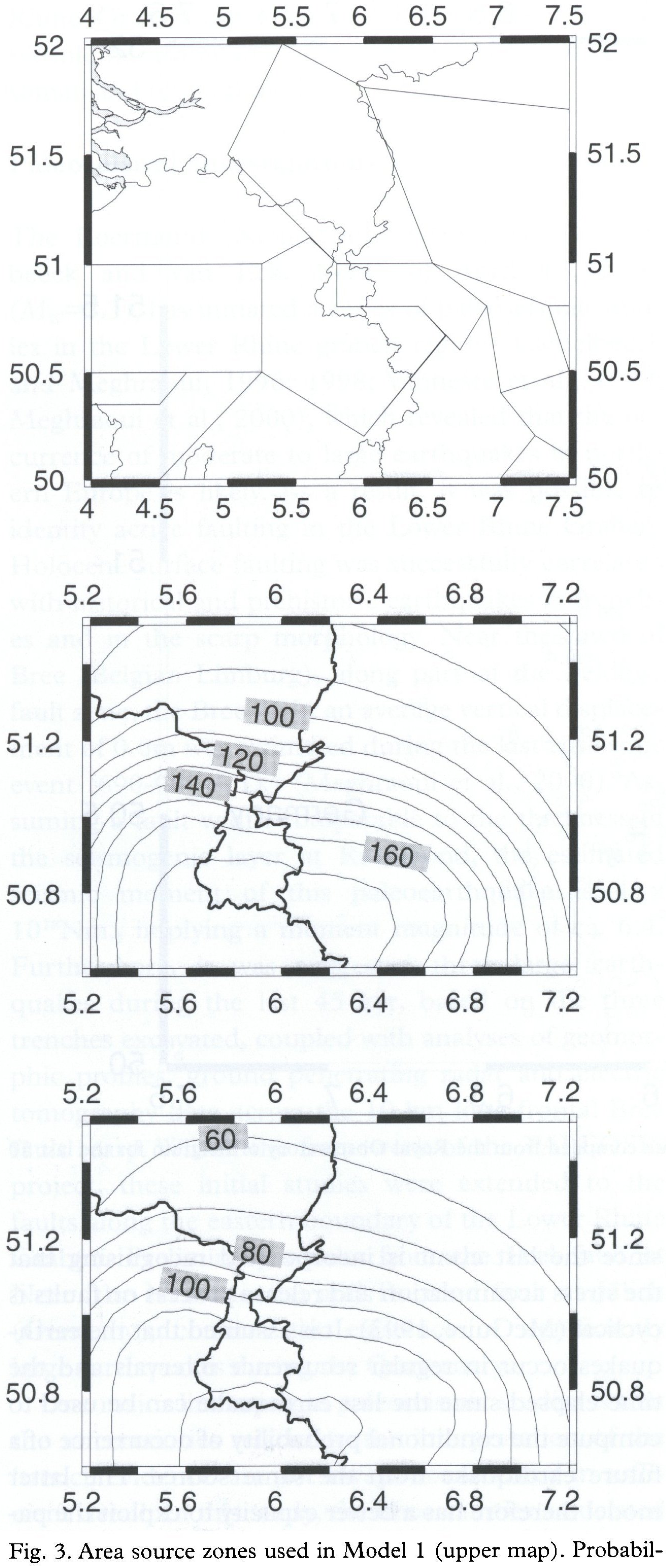

Fig. 3. Area source zones used in Model 1 (upper map). Probabilisitic seismic hazard in the Lower Rhine Graben expressed as peak ground acceleration (PGA, in cm/sec^2) contour maps for a 1000 year return period for bedrock conditions. The map shown in the middle corresponds to the Ambraseys et al. (1996) attenuation relation, whereas the lower map of the figure shows results using Spudich et al. (1997) relation.

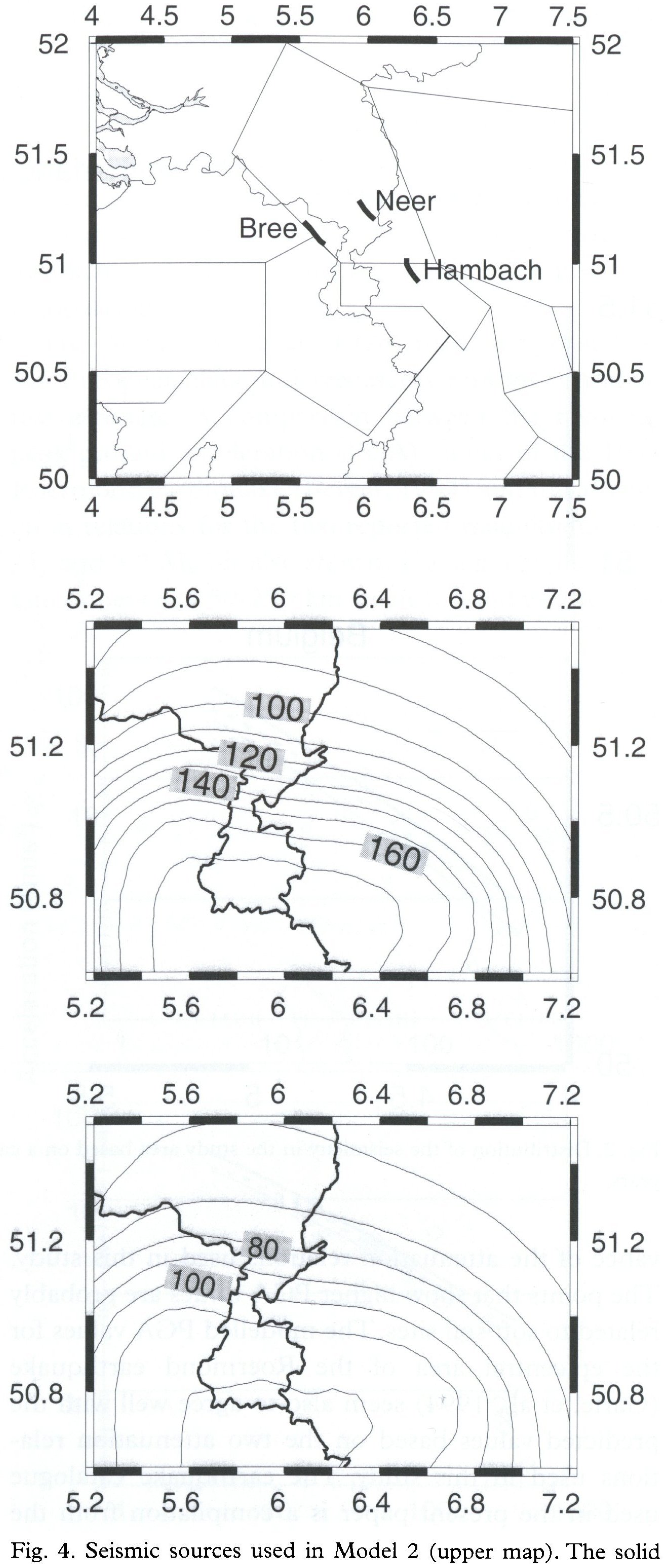

Fig. 4. Seismic sources used in Model 2 (upper map). The solid lines indicate the location of the three faults studied using paleoseismological investigations. Probabilisitic seismic hazard in the Lower Rhine Graben expressed as peak ground acceleration (PGA, in cm/sec^2) contour maps for a 1000 year return period for bedrock conditions. The map shown in the middle corresponds to the Ambraseys et al. (1996) attenuation relation, whereas the lower map of the figure shows results using Spudich et al. (1997) relation.

Based on the earthquake catalogue compiled by the Royal Observatory of Belgium (including the last 50 years which is complete for magnitudes larger than 3.0) a general b-value of 0.53 was obtained. In order to have a statistically valid b-value this is used for all the sources. The upper-bound magnitude and the activity rate are calculated separately for each source. The lower-bound magnitude applied is 4.0.

Model 2

Area sources are modelled as Poissonian and the same parameters are used as described in Model 1. The three fault segments (Bree, Neer and Hambach) that were studied by paleoseismological investigations are treated separately (Figure 4).

Here the earthquake occurrence along these fault (line) sources, are based on a renewal model. The parameters (recurrence interval, elapsed time and the magnitudes) for the renewal model are shown in Table 1. the magnitudes are based on the approximate length of the faults using the Wells & Coppersmith (1994) relation. For each fault a minimum magnitude and a maximum magnitude are assigned reflecting the uncertainty associated with the magnitude estimates. Here, the term 'minimum magnitude' should not be mixed with the lower-bound magnitude used for the hazard computations. Below the lower-bound magnitude it is assumed that there is not any significant earthquake hazard on engineering structures.

Model 3

Instead of using large area sources as in Model 2, the earthquake source zones are defined as extended line sources and are based on the Poissonian earthquake occurrence. Parameters for each line source are calculated based on the earthquake catalogue. In addition, the three studied segments (Bree, Neer and Hambach) are integrated as renewal model (Figure 5). Parameters for the renewal model are shown in Table 1.

Model 4

Feldbiss and Peel faults are modelled as line sources segmented as equal-length intervals corresponding approximately to the length of the Bree fault segment (Figure 6). Here, the earthquake occurrence is assumed as renewal model for all sources.

The magnitude vs fault-length relations are based on Wells & Coppersmith (1994). In total, 18 fault segments are identified and used in the computations. The parameters for the three faults studied through paleoseismological investigations (Bree, Neer and Hambach) are shown in Table 1. For the remaining line sources we have used the recurrence period that is associated with the studied segment. The elapsed time is kept constant for all and 3000 years is applied.

Model 5

Same as Model 4, assuming longer but equal length

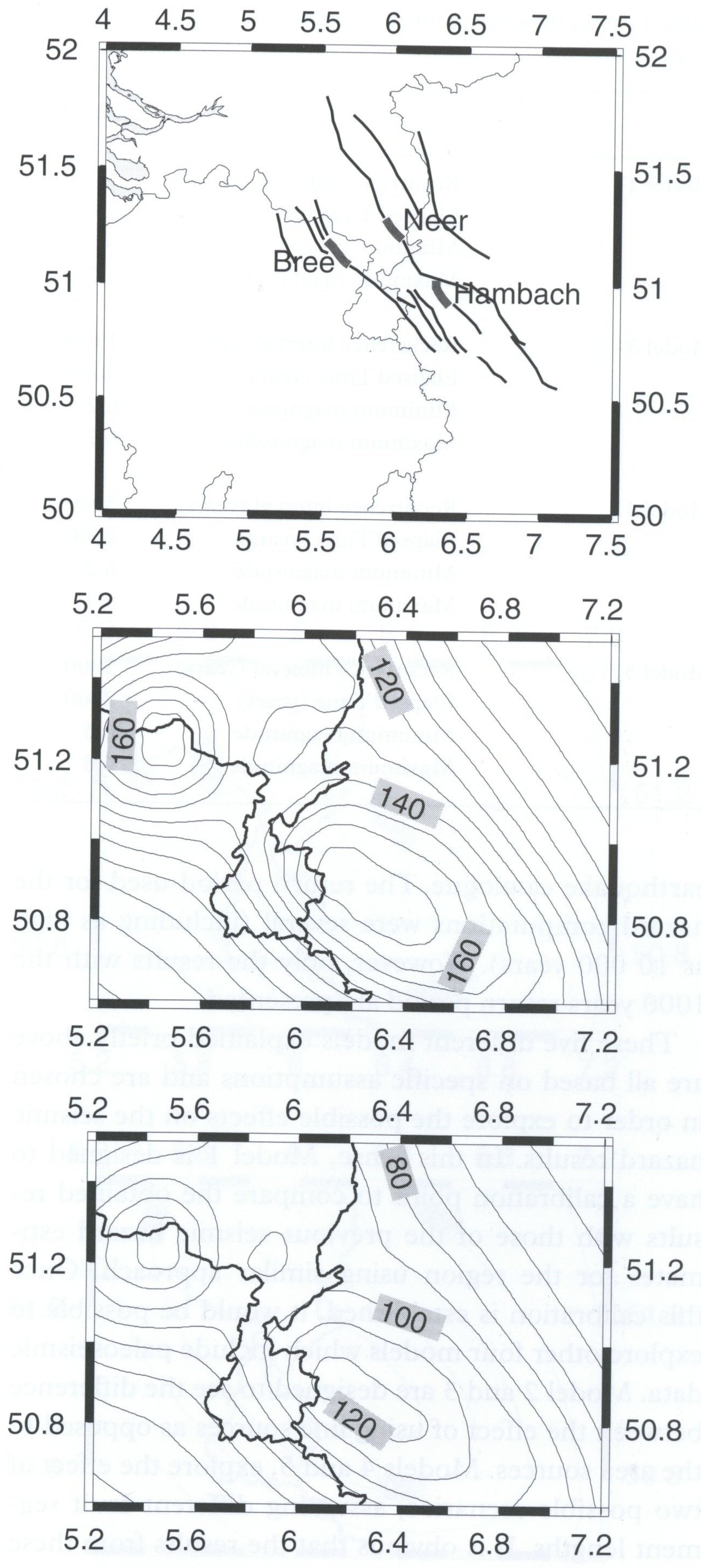

Fig. 5. Seismic sources used in Model 3. Note that the seismic sources are assumed to follow the existing active faults in the region. Probabilisitic seismic hazard in the Lower Rhine Graben expressed as peak ground acceleration (PGA, in cm/sec^2) contour maps for a 1000 year return period for bedrock conditions. The map shown in the middle corresponds to the Ambraseys et al. (1996) attenuation relation, whereas the lower map of the figure shows results using Spudich et al. (1997) relation.

segments with neighbouring faults joined (Figure 7). Here in total 9 line sources are used.

Parameters for the background (i.e. areas not covered by the line- or area sources) are maximum magnitude 6.0 and the b-value is kept as the general value obtained for the area. Activity rate is based on the

Table 1. Input parameters for the renewal models used in the seismic hazard computations (see text for the parameters used in the Poissonian model).

		NEER	BREE	HAMBACH
Model 2	Recurrence interval (years)	15000	15000	15000
	Elapsed Time (years)	5000	1250	5000
	Minimum magnitude	6.2	6.2	6.2
	Maximum magnitude	6.7	6.7	6.7
Model 3	Recurrence interval (years)	15000	15000	15000
	Elapsed Time (years)	5000	1250	5000
	Minimum magnitude	6.2	6.2	6.2
	Maximum magnitude	6.7	6.7	6.7
Model 4	Recurrence interval (years)	5000	7000	7000
	Elapsed Time (years)	2000	1250	2000
	Minimum magnitude	6.2	6.2	6.2
	Maximum magnitude	6.4	6.4	6.4
Model 5	Recurrence interval (years)	5000	7000	7000
	Elapsed Time (years)	2000	1250	2000
	Minimum magnitude	6.6	6.6	6.6
	Maximum magnitude	6.8	6.8	6.8

earthquake catalogue. The return period used for the hazard computations were several (including as high as 10 000 years). However, only the results with the 1000 years return period are presented.

These five different models explained briefly above are all based on specific assumptions and are chosen in order to explore the possible effects on the seismic hazard results. In this sense, Model 1 is designed to have a calibration point to compare the obtained results with those of the previous seismic hazard estimates for the region using similar approach. Once this calibration is established, it would be possible to explore other four models which include paleoseismic data. Model 2 and 3 are designed to see the difference between the effect of using line sources as opposed to the area sources. Models 4 and 5, explore the effect of two possible scenarios, assuming different fault segment lengths. It is obvious that the results from these last two models can only have a comparative value (relative to each other), since complete paleoseismic information covering all the faults in the entire Lower Rhine Graben does not exist. All parameters are kept similar in models 4 and 5 except the length of the faults (hence the upper bound magnitudes).

The hazard computations were performed using the CRISIS99 software (Ordaz, 1999), for a grid of 21 x 10 points (i.e. 210 points) and the results are contoured and presented without any additional smoothing, except the extrapolations done during the computational procedures. It should be noted here that the hazard is computed for a rectangular area which covers basically the border area between Belgium, the Netherlands and Germany (see Figures 3-7), which is smaller than the area used for the definition of the seismic sources. CRISIS99 uses standard probabilistic approach (as in Cornell, 1968) and has the same capabilities as the well-known programs, such as the EQRISK (McGuire, 1976) and SEISRISK III (Bender and Perkins, 1987). In addition it is possible to compute the conditional probability of occurrence for a renewal model using the time elapsed since the last occurrence of a 'characteristic earthquake'. Source geometry can be modelled either as Poisson or 'characteristic earthquake' process. In the first, magnitude frequency relations are smoothly truncated Gutenberg-Richter curves, whereas for the second, the program assumes Gaussian distribution of magnitudes. Hazard computations are performed simultaneously for several ground motion measures, for instance, a_{max} (acceleration), v_{max} (velocity) and several spectral ordinates. Required attenuation laws are given in the form of tables containing the median values of the ground motion measures as a function of magnitude and focal distance. Spatial integrations are performed using a recursive triangularization algorithm optimising the number of calculations (i.e. it integrates with more points for the nearest sources and less points for distant sources).

Seismic hazard results in the Lower Rhine Graben

Results are presented in 10 different PGA (in cm/sec^2) contour maps for bedrock conditions for a

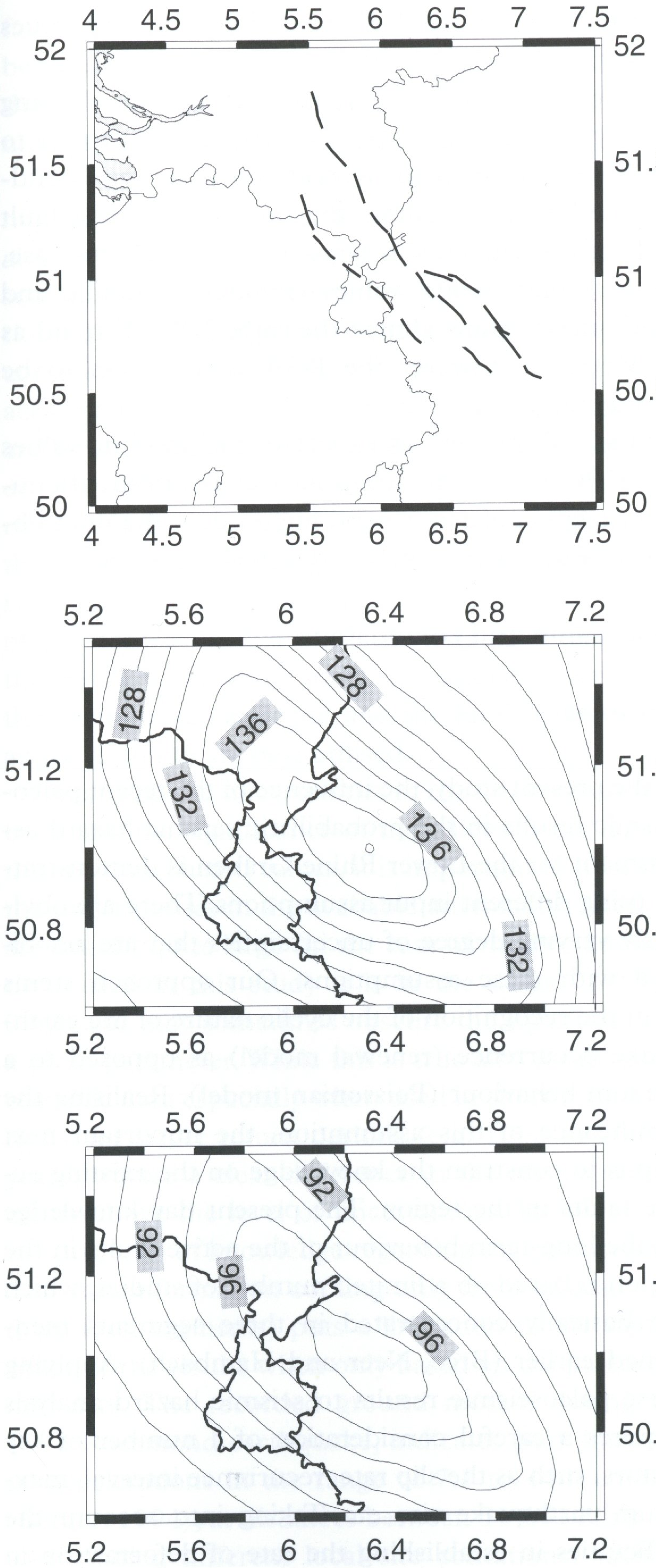

Fig. 6. Seismic sources used in Model 4. The two boundary faults of the Roer graben, Feldbiss and Peel faults are modeled with segment sizes similar to that of the Bree fault. Probabilisitic seismic hazard in the Lower Rhine Graben expressed as peak ground acceleration (PGA, in cm/sec^2) contour maps for a 1000 year return period for bedrock conditions. The map shown in the middle corresponds to the Ambraseys et al. (1996) attenuation relation, whereas the lower map of the figure shows results using Spudich et al. (1997) relation.

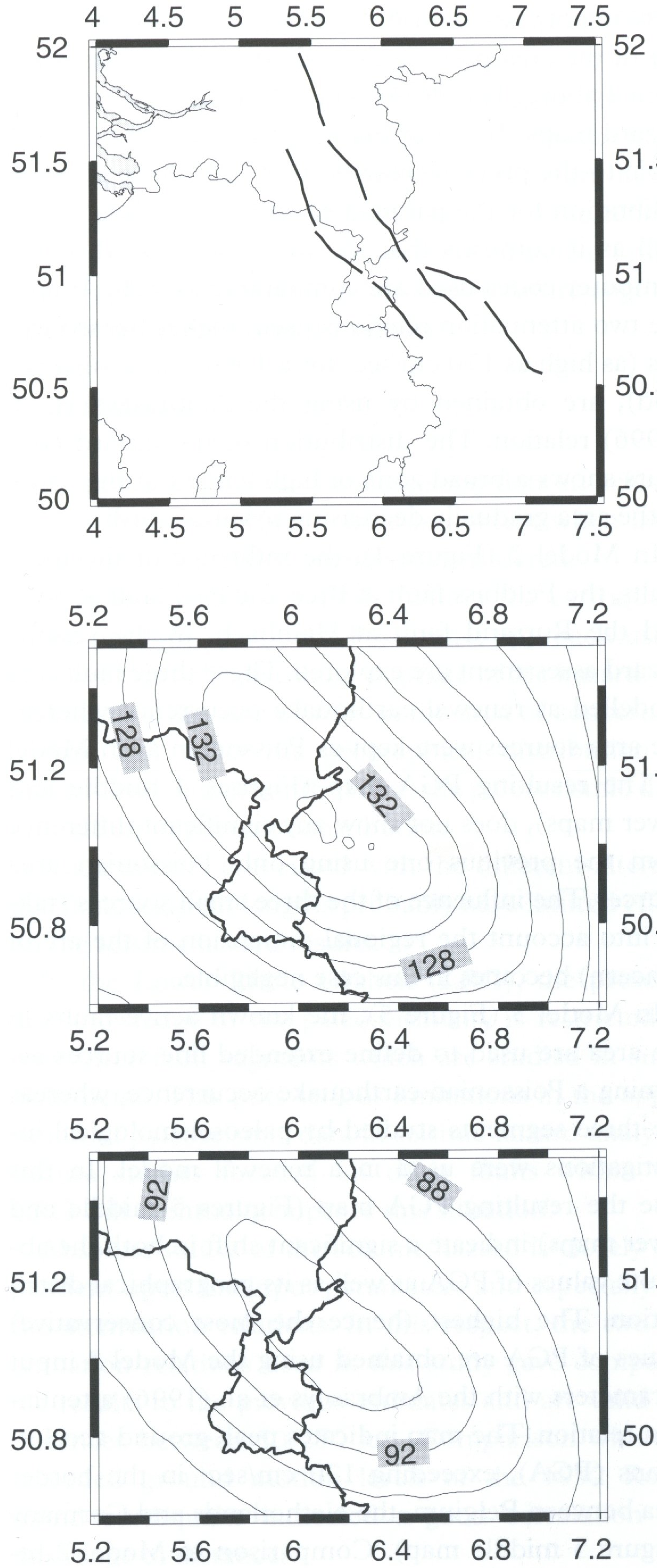

Fig.7. Seismic sources used in Model 5. This is the same as Model 4, where the segment lengths are assumed to be longer. Probabilisitic seismic hazard in the Lower Rhine Graben expressed as peak ground acceleration (PGA, in cm/sec^2) contour maps for a 1000 year return period for bedrock conditions. The map shown in the middle corresponds to the Ambraseys et al. (1996) attenuation relation, whereas the lower map of the figure shows results using Spudich et al. (1997) relation.

1000 year return period (shown in Figures 3-7). The influence of the paleoseismic results becomes more significant when longer return periods are used (Atakan et al., 2000b).

In Model 1 (Figure 3), the area source zones were defined taking into account the previous seismic hazard assessment performed for the region (e.g. de Crook, 1993; 1996; Grünthal et al., 1999), which were mainly based on the seismotectonic understanding of the area prior to the paleoseismic results mentioned above. The PGA values shown in the resulting hazard maps shown in Figure 3 are therefore comparable to the previous results. This provides a sense of calibration for the parameters used in the analysis as well as it confirms that the methods applied in the computer codes used are comparable as well. Among the two attenuation relations used, higher hazard values (as high as 170 cm/sec^2 for a 1000 year return period), are obtained by using the Ambraseys et al. (1996) relation. The distribution of the hazard contours shows a broad zone of high hazard in the south of the area gradually decreasing towards north.

In Model 2 (Figure 4), the influence of the three faults, the Feldbiss fault at Bree, the Peel fault at Neer and the Rurrand fault at Hambach, in the seismic hazard assessment are explored. These three faults are modelled as renewal earthquake occurrence whereas the area sources were kept as Poissonian as in Model 1. The resulting PGA map (Figures 4 middle and lower maps), does not show any significant difference from the previous one using only Poissonian area sources. The influence of the three small sources (taken into account the regional dimension of the are of concern) becomes in this case negligible.

In Model 3 (Figure 5), the known active faults in the area are used to define extended line sources assuming a Poissonian earthquake occurrence, whereas the three segments studied by paleoseismological investigations were used in a renewal model. In this case the resulting PGA map (Figures 5 middle and lower maps) indicate a significant shift in both the absolute values of PGA as well as its geographical distribution. The highest (hence the most conservative) values of PGA are obtained using the Model 3 input parameters with the Ambraseys et al. (1996) attenuation relation. The map indicates peak ground accelerations (PGA), exceeding 170 cm/sec^2 in the border area between Belgium, the Netherlands and Germany (Figure 5 middle map). Comparison to Model 2 results indicate a clear shift in the geographical distribution of the hazard.

In Model 4 (Figure 6), the two major boundary faults of the Lower Rhine Graben, the Feldbiss and the Peel/Rurrand faults are used as line sources with equally spaced segments of a length equivalent to that of the Bree. This results in total 18 segments and the behaviour of each segment is assumed to be characteristic following a renewal model. The corresponding PGA maps (Figures 6 middle and lower maps), indicate peak values reaching 140 cm/sec2 with a NW-SE trend similar to the general trend of the faults. As opposed to the Model 3 the hazard is more smoothly distributed in Model 4. In general the absolute values are slightly lower than the previous model results.

In Model 5 (Figure 7), the assumption of using equally spaced segments of ca 10 km (equivalent to the Bree fault segment) is modified, this time extending the length to almost the double assuming fault rupture on segments as large as 20 km. In this case, the resulting hazard values (Figures 7 middle and lower maps), show almost the same NW-SE trend as in Model 4, however the PGA values seem to be slightly reduced.

In all five models, as expected, the absolute values of the PGA using the Ambraseys et al. (1996) attenuation relation are in general higher than the ones obtained using the Spudich et al. (1997) relation.

Discussion and conclusions

Discussion

In the present study, the influence of the recent paleoseismic results in the probabilistic seismic hazard assessment for the Lower Rhine Graben is demonstrated using different input assumptions. There are obviously varying degree of uncertainties that are associated with these assumptions. Our approach stems from the recognition of the cyclic nature of the earthquake occurrence (renewal model) as opposed to a random behaviour (Poissonian model). Realising the significance of this assumption, the important next step is to constrain the knowledge on the existing active faults in the region. The present day knowledge on the long-term behaviour of the active faults in the region is based on a limited number of studies, which are basically concentrated in three segments mentioned earlier (Bree, Neer and Hambach). Applying these paleoseismic results to seismic hazard analysis requires a careful consideration of a number of key factors, such as the slip rate, recurrence interval, maximum earthquake size etc. Taking into account the difficulties in establishing the rate of deformation in all other possible faults in the area, the most appropriate application would be the one used in Model 3. In this model the paleoseismic data is incorporated using a renewal model only for the three segments, where detailed studies were performed. The remaining segments are modelled as poissonian. The resulting hazard map (Figure 5) represents a realistic estimate for the region, which is in accordance with the present-day knowledge of the active tectonics of the area. The two other models (Models 4 and 5), on the other hand, where the paleoseismic results obtained in the three studied segments were extrapolated to other segments of the Feldbiss and the Peel/Rurrand faults, were designed to see the effect of the difference between the length of the fault segments. It is obvious that the absolute hazard values obtained from these models (4 and 5) are of limited value.

The fact that the paleoseismic data provides a much longer time record as opposed to the short catalogue time intervals used (30-50 years) in the Poissonian approach, is important to stress. The computational procedure applied in the renewal models (i.e. conditional probabilities) does indeed take this into account and hence reflect a better estimate of the hazard level. This however, becomes only visible for larger return periods (>1000 years). For short return periods (which is covered by the catalogue time span), the Poissonian assumption of earthquake occurrence is probably sufficient and provides a robust estimate of the hazard. In this sense, the Model 3 represents the best alternative in which the available data from the earthquake catalogue and the knowledge on the active tectonics are best utilised.

Regarding the uncertainties in the attenuation relations and the significance of the paleoseismic data in the absolute hazard values, it is important to note that the uncertainties in the available attenuation relations are usually quite large (in the case of the two attenuations used in this study it is in the range of 0.5 to 0.62) and may sometimes obscure the significance of a given parameter. While this is true also for the paleoseismic data especially when used in short return periods, for larger return periods (e.g. 1000 to 10 000 years) we see a clear difference in the results significantly above the level of uncertainties. However, the existing level of knowledge regarding the paleoseismic data (i.e. information coming only from basically the three fault segments) puts a limitation to the significance of the results when only based on the paleoseismic data. The recorded ground motion during the 1992 Roermond earthquake, indicates peak horizontal accelerations in the range of 7.1 to 44.0 cm/sec^2 (Berger, 1994), at distances between 51-151 km's (also including different local site conditions, such as soft soil sites). At shorter distances there were not any acceleration data that can be directly compared with the seismic hazard results obtained in this study. However, Gariel et al. (1994) estimated acceleration levels based on strong ground motion modelling using the aftershock data. Their results indicated 57-175 cm/sec^2 in the epicentral area. Assuming that these modelling results are correct, the obtained seismic hazard values in this study, corresponding to a 1000 years return period, which are in the range of 80 to 170 cm/sec^2, are comparable.

As a conclusion the most conservative estimates of the hazard in the region were obtained using the Model 3 parameters with the Ambraseys et al. (1996) attenuation. When these results are compared to the previous hazard estimates for the region (e.g. de Crook, 1993; 1996; Grünthal et al., 1999), the most significant change is the distribution of hazard in the region following a NW-SE trend similar to the general trend of the graben and the associated active faults. This needs to be taken into account in future applications of these results in the region.

Conclusions

The significance of the paleoseismic data in seismic hazard analysis becomes more important when large return periods (>1000 years) are considered.

For shorter return periods (within the earthquake catalogue time span), the Poissonian approach using area sources provide robust estimate of the hazard.

Delineating the active faults in the area of concern, is critical and effect the geographical distribution of hazard levels significantly. Here, the paleoseismic data provide an important contribution.

Uncertainties associated with the different alternative fault segment lengths probably have limited effect on the seismic hazard results.

In the Lower Rhine Graben (LRG), the present-day knowledge of the paleoseismicity is restricted to only three fault segments which are studied in sufficient detail. This puts serious limitations in the application of paleoseismic data in seismic hazard analysis. Future studies focused on other faults within the LRG will eventually improve this situation.

Absolute values of the seismic hazard is closely dependent upon the input parameters and especially on the attenuation relations. In this respect, the two attenuation relations used in this study gave comparable results to the previous estimates and are valid for distances between 50-250 km. Comparison with the recorded ground motion levels of the 1992 Roermond earthquake indicated a good correlation for this range of distances.

The best estimates of seismic hazard for the region are obtained, when both models (Poissonian and renewal) are used, which combine both the earthquake catalogues and the paleoseismic data. The highest seismic hazard is obtained in this case reach 170 cm/sec^2 in the border area between Belgium, the Netherlands and Germany for a 1000 year return period.

Obviously, possible consequences of a potentially large earthquake in this highly populated and industrialized region of Europe is a major concern as is indicated by the previous seismic hazard studies (e.g.

Rosenhauer and Ahorner, 1994; van Eck & Davenport, 1994; de Crook, 1993; 1996; Grünthal et al., 1999). In order to be able to establish the true seismic hazard potential, a systematic search through detailed paleoseismic investigations needs to be performed along the entire Rhine Graben.

Acknowledgements

Results presented in this study were obtained within the framework of the project PALEOSIS supported by the Environment and Climate Programme – European Commission DG XII (Contract No. ENV4-CT97-0578; DGIL-ESCY). We thank Mario Ordaz of the UNAM, Mexico for providing the CRISIS99 software. Review of the two anonymous referees have improved the manuscript significantly.

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