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# Macroseismic effects in Germany of the 1992 Roermond earthquake and their interpretation

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## Abstract

The Roermond earthquake of April 13, 1992, with a local magnitude of $M_L = 5.9$, belongs to the largest earthquakes which have been observed in the Lower Rhine Embayment in historical time. It was felt in central and western Europe over an area of about 600 000 km$^2$. The German territory forms much of the eastern part of that area. The most distant reports in Germany came from Kiel (450 km), Berlin (540 km) and Munich (520 km).

The epicentral intensity $I_0$ observed in the German-Netherlands border region was VII on the MSK-scale. For an $M_L = 5.9$ earthquake this $I_0$ is unusually low as compared to other large earthquakes in the Lower Rhine Embayment. Two factors are assumed to be mainly responsible for the low epicentral intensity: (1) the focal depth which is deeper than normal, and (2) the unusually strong absorption of seismic energy by a more than 1500 m-thick layer of soft Tertiary and Quaternary sediments within the Roer Valley Graben near the epicenter.

More than 2000 macroseismic reports from 600 different localities have been interpreted, resulting in detailed isoseismal maps for Germany. The following mean isoseismal radii have been determined: $r_7 = 6$ km, $r_6 = 42$ km, $r_5 = 102$ km, $r_4 = 179$ km, $r_3 = 322$ km, $r_2 = 440$ km. Based on these isoseismal radii the macroseismic focal depth has been determined with an iterative computer program based on the method of Sponheuer (1960). The uncorrected observed $I_0$ = VII gives a focal depth of about 26 km. However, if we correct $I_0$ for the influence of the sedimentary graben fill, resulting in a value of VII–VIII, the obtained depth is about 17 km. This corresponds better with the focal depth as determined instrumentally by various working groups.

## Introduction

The Roermond earthquake of April 13, 1992, belongs with its local magnitude of $M_L = 5.9$ (Ahorner 1994) to one of the largest earthquakes which have been observed in the Lower Rhine Embayment in historical time. It was felt in wide parts of central and western Europe over an area of about 600 000 km$^2$ (Fig. 1) of which Germany covers most of the eastern part. Shortly after the earthquake, the Department of Earthquake Geology of the University of Cologne started an investigation about the macroseismic effects in Germany. Many telephone calls reached the earthquake station at Bensberg in the hours and days after the earthquake. Questionnaires were sent to numerous persons and institutions and a call for information was published by the press. We obtained a response of more than 2000 useful reports with macroseismic observations from all parts of Germany. Additional information came from official reports and newspaper articles. The macroseismic database was augmented by personal visits to the epicentral region and to places where structural damage to buildings or geotechnical effects due to the earthquake could be studied. This paper presents the results of our macroseismic investigations, restricted mainly to observations from Germany and the adjacent areas.

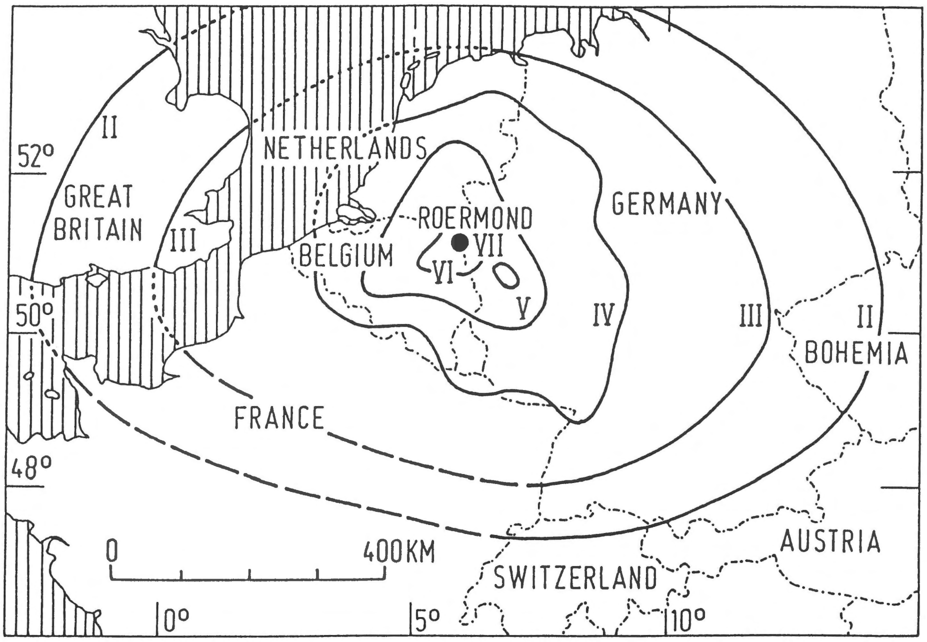

*Fig. 1.* Preliminary isoseismal map for the 1992 Roermond earthquake (Van Eck et al. 1993). Macroseismic observations from Germany, the Netherlands, Belgium, France, Great Britain and Bohemia have been combined. For a detailed multinational evaluation see Haak et al. (1994).

## Isoseismal maps

The macroseismic database concerning the Roermond earthquake consists of more than 2000 observations from 600 different localities spread over the whole country. The database includes information about the places of the observations (name and geographical coordinates of the village), the number of observations and the obtained macroseismic intensity I (mean value and standard deviation). The intensity determinations were made following the MSK-scale as described by Grünthal (1993).

An overview of the regional distribution of localities of the macroseismic data base is given in Fig. 2. This map has been used to draw isoseismals for Germany and the adjacent areas (Figs 3–5).

The most distant places in Germany where the earthquake was felt are the island of Wangerooge (320 km), Kiel (450 km), Berlin (540 km), Regensburg (500 km), Munich (520 km) and the Allgäu region (560 km). The mean radius of perceptibility (intensity II) is about 440 km. The following mean isoseismal radii have been determined for the eastern part of the area: $r_7 = 6$ km, $r_6 = 42$ km, $r_5 = 102$ km, $r_4 = 179$ km, $r_3 = 322$ km, $r_2 = 440$ km.

Intensity V effects were observed as far as Luxembourg, Frankfurt, Siegen and in some isolated places, for example around Kassel. Such islands with intensity V can be explained by local site conditions. The inner isoseismals show a distinct elongation in southeast direction.

An increased intensity, due to soil amplification, is clearly observed within the Middle Rhine Valley from Bonn to Koblenz. Intensity VI was reached within the Rhine valley at places with up to 30 m thick sedimentary deposits, whereas at places outside the valley on Devonian rock only intensity V was observed. The increased intensity along the Middle Rhine Valley correlates quite well with the recorded ground motion at three seismic stations in and around the Neuwied Basin, which have nearly the same epicentral distance (about 150 km) and the same azimuth. At the stations Burg Eltz (BGG) and Köppel (KOE), located outside the Middle Rhine Valley on firm rock, a maximum ground acceleration of 22 and 8 cm/s$^2$, respectively, have been measured, whereas at the station Mülheim-Kärlich (KKW), located inside the Neuwied Basin on soft soil, the recorded peak ground acceleration reached values up to 44 cm/s$^2$ (Ahorner 1993).

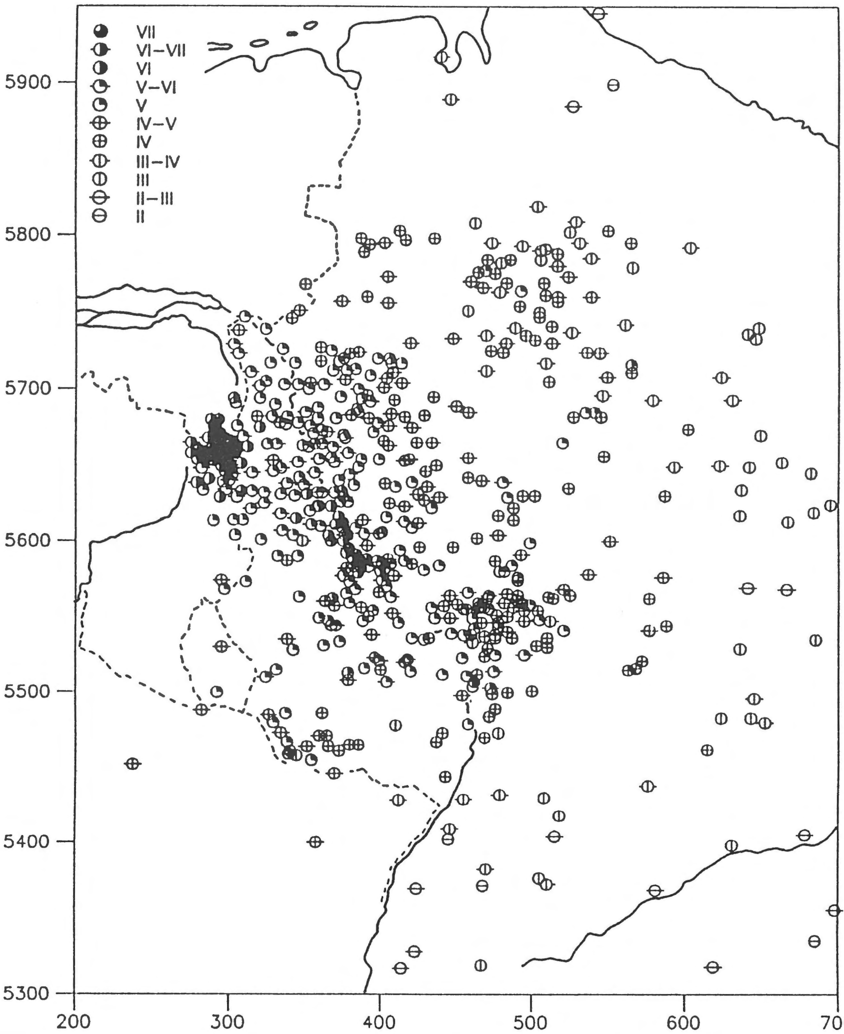

*Fig. 2.* The distribution of macroseismic observations, mainly in western and central Germany. Intensities (II–VII) are given in MSK-scale units. UTM-coordinates (km) Zone 32U.

## Detailed description of macroseismic effects

### *Damage in the epicentral area*

The Roermond earthquake reached $I_0$ = VII in the German-Netherlands border region near the epicenter. The maximum intensity was observed in a relative small area of 92 km$^2$ which is elongated in NW-SE direction and shifted eastward with respect to the instrumental epicenter (Fig. 5). This can be explained by the specific geometry and the dynamics of the earthquake source (Ahorner 1992, 1993).

The places most affected by the earthquake were Roermond, Herkenbosch, Heinsberg, Oberbruch and Dremmen (hatched area in Fig. 5). Small cracks in walls and plaster, pieces of plaster falling down, cracks in chimneys, and parts of chimneys falling down were predominantly observed. A few single buildings were heavily damaged.

The largest damage in Germany was observed near Heinsberg in the districts Oberbruch and Dremmen. In Oberbruch more than 100, in Dremmen about 30, and in the surrounding villages about 50 buildings were significantly damaged. At some buildings the uppermost part of the gable wall fell down and large cracks occurred in walls. Three houses were in danger of collapsing and had to be torn down. Eight buildings were uninhabitable after the earthquake and had to be temporarily evacuated. Many walls and chimneys were in danger of falling down. The roof of the Marienkloster

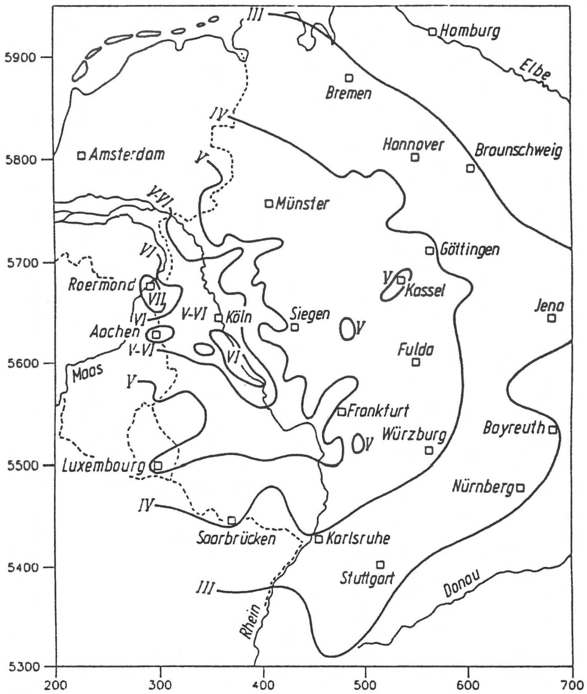

*Fig. 3.* Isoseismal map for Germany and the adjacent areas based on observations shown in Fig. 2. Geographical coordinates as in Fig. 2.

in Dremmen collapsed partly. In nearly all cases where significant damage occurred, the buildings were structurally of inferior quality. First estimates of damage to public buildings in the district of Heinsberg reached approximately 500 000 DM. For private houses and industrial facilities the damage was by far larger.

Detailed information about the damage ratios to buildings in the epicentral region is given by Pappin et al. (1994).

### *Damage at larger distances*

At distances larger than 20 km from the epicenter the earthquake caused only slight damage corresponding to intensity VI. Predominantly small cracks in chimneys and walls and plaster falling off walls and ceilings were observed. At some isolated places, for example in Aachen and in Euskirchen, a few chimneys fell down.

Strong damage corresponding to intensity VI and locally even to VI–VII occurred along the Middle Rhine Valley from Bonn to Koblenz. In Bonn more than 60 private and public buildings were damaged. Chimneys collapsed and walls cracked. All over the town damage to plaster was observed.

### *Damage to churches*

In Germany more than 150 churches were damaged, predominantly around Heinsberg, but also in regions as far as Cologne, Bonn and Koblenz (Fig. 6). The most prominent example is the cathedral in Cologne where six finials broke out off their embeddings. One finial fell from the top of a 60 m-high stair-tower. The stone, weighing about 500 kg, struck a hole in the roof of the southern transept and was shattered on a false ceiling about 40 m below. Repair costs were estimated to 50 000 DM.

In Fig. 6 we have classified damage to churches into three different categories: slight, moderate and heavy. Slight damage corresponds to fine cracks in plaster, fall of small pieces of plaster and the loosening of pinnacles or comparable construction parts. Moderate damage corresponds to small cracks in walls and vaults, cracks between church tower and nave and the falling of pinnacles. Heavy damage corresponds to large and deep cracks in walls and vaults, and damage to load-bearing parts. Slight and moderate damage to churches occurred mainly in regions with macroseismic intensities between V–VI and VI. Heavy damage to churches occurred mainly in regions with macroseismic intensities larger than VI.

### *Casualties*

About 21 persons were injured in the region of Heinsberg (population about 37 000), mostly by falling parts of chimneys and roofing tiles. Some people were slightly injured by shattering window glass. Three persons had to be treated in hospital. In Bonn one 79 year old woman died because of a heart attack probably due to a shock caused by the earthquake. Even in more distant towns like Euskirchen (82 km) or Langenfeld (71 km) some persons were slightly injured.

### *Geotechnical effects*

The most prominent geotechnical effects caused by the Roermond earthquake have been described from Leeuwen, Montfort and Brunssum in the Netherlands (Nieuwenhuis 1994, Davenport et al. 1994, Alkema et al. 1994, Maurenbrecher et al. 1994). In Germany only small landslides have been reported, mostly from shore lines of artificial lakes located at distances of

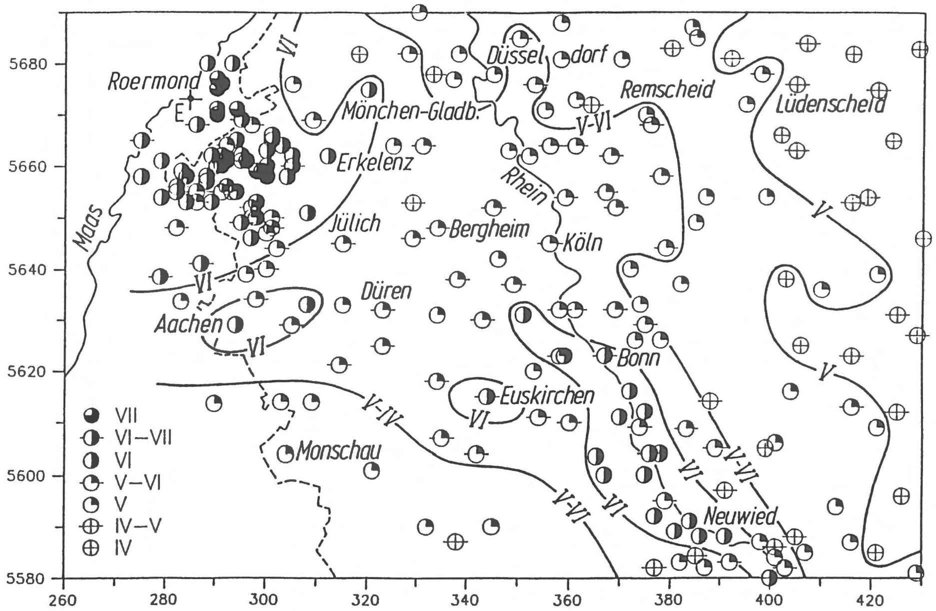

*Fig. 4.* Detailed isoseismal map for the Lower Rhine Embayment and the Middle Rhine Valley. E = epicenter of the Roermond earthquake. Geographical coordinates as in Fig. 2.

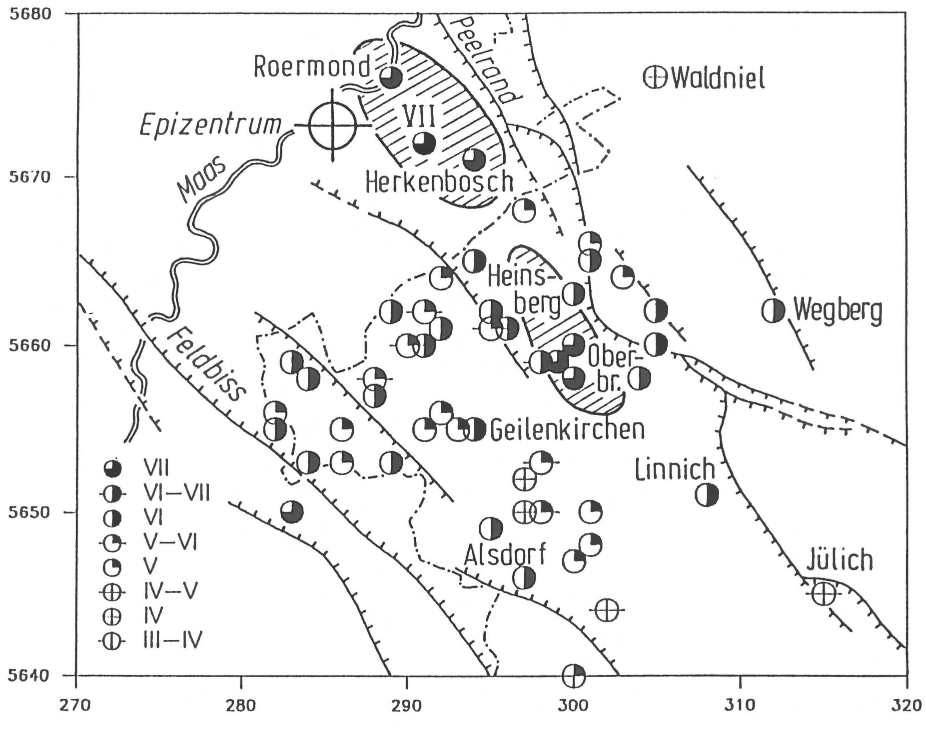

*Fig. 5.* Distribution of macroseismic intensities near the epicenter of the Roermond earthquake (Epizentrum). Lines with barbs on the downthrown side denote active faults (Peelrand = Peel Boundary Fault). Geographical coordinates as in Fig. 2.

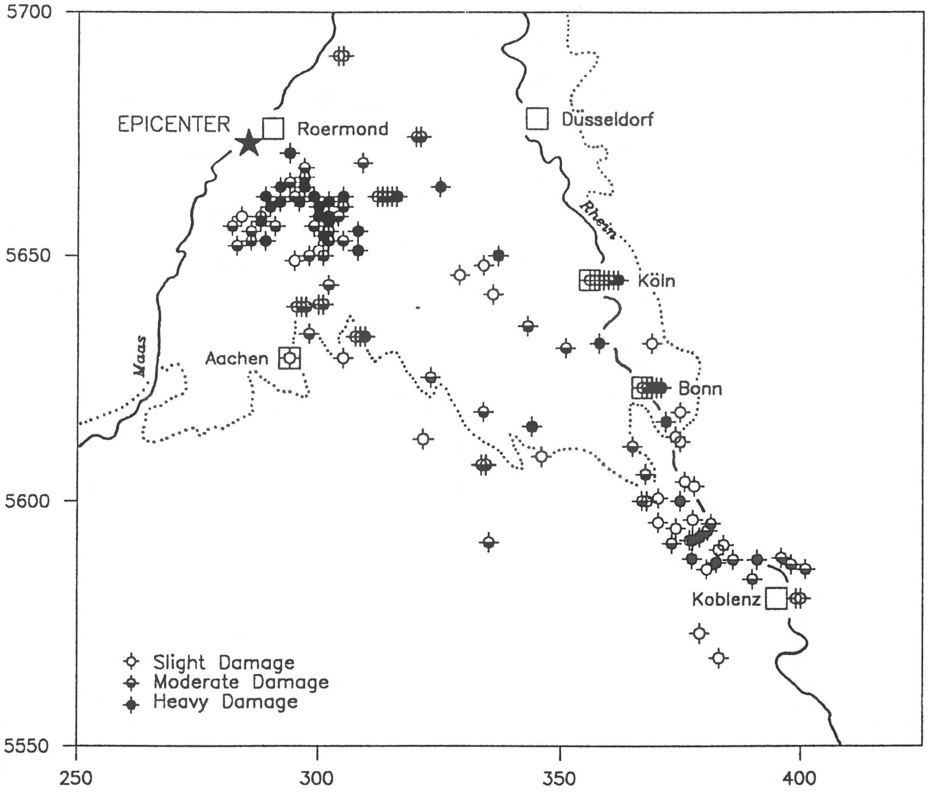

*Fig. 6.* Locations of churches damaged by the Roermond earthquake, mainly those in Germany. Dotted line indicates the contours of the Rhenish Massif. Geographical coordinates as in Fig. 2.

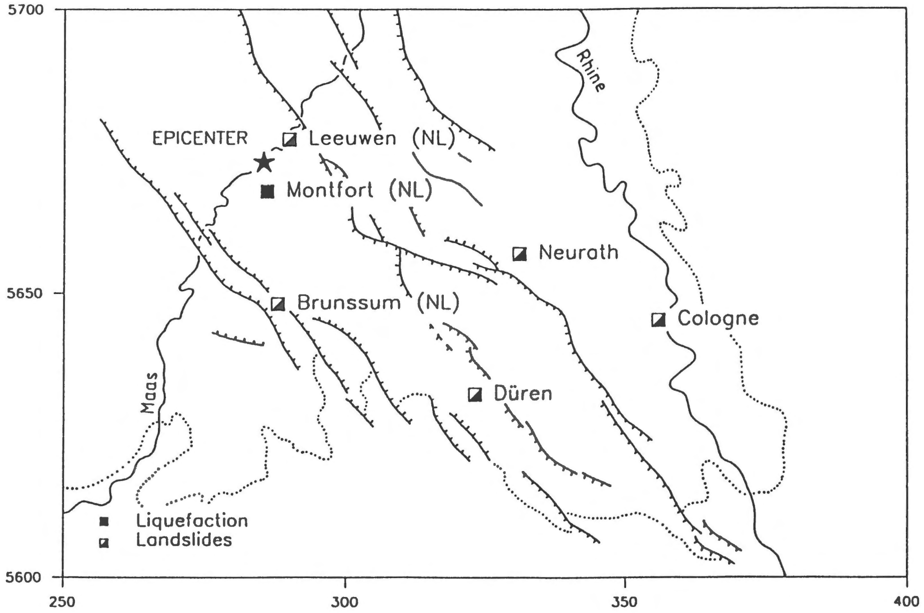

*Fig. 7.* Map of geotechnical effects triggered by the Roermond earthquake. Lines with barbs on the downthrown side denote active faults. Dotted line indicates the contours of the Rhenish Massif. Geographical coordinates as in Fig. 2.

15 to 75 km from the epicenter (Fig. 7), i.e. (1) the 'Baggersee' near Heinsberg, (2) the 'Badesee' near Düren, (3) the 'Neurather See' near Grevenbroich and (4) the 'Fühlinger See' north of Cologne.

At some geological fault zones in the lignite mining district of the Lower Rhine Embayment near Bergheim, installed extensiometers and water-tube tiltmeters recorded accelerated creep movements at the time of the earthquake.

## Corrected epicentral intensity

For an $M_L = 5.9$ earthquake the observed $I_0$ = VII is unusually low as compared with other strong historical earthquakes in the Lower Rhine Embayment (Meidow 1994). We assume that two factors are mainly responsible for the low epicentral intensity, (1) the focal depth which is deeper than normal, and (2) the unusually strong absorption of seismic energy by a layer of more than 1500 m soft sediments within the Roer Valley Graben near the epicenter. The energy absorption due to extremely low Quality factors (Q) of the sedimentary layer exceeds the counteracting dynamic amplification if the absorbing layer is very thick (Budny 1984).

In order to correct the damping effect of the sedimentary graben fill on the macroseismic intensity a correction term $\Delta I$ has been determined. The following formula is based on theoretical considerations concerning the relationship between macroseismic intensity and seismic ground motion influenced by absorption and impedance contrast as described by Schneider (1975) and others.

$$\Delta I = 3.3 \log \left( \sqrt{\frac{v_0 \rho_0}{v_1 \rho_1}} e^{-\alpha\, m} \right) \quad \text{with } \alpha = \frac{\pi f}{v_1 Q} \quad (1)$$

where $v_0$ and $\rho_0$ are the mean shear wave velocity (in m/s) and the density of the basement (in kg/m$^3$), respectively, $v_1$ and $\rho_1$ are the mean shear wave velocity and the density of the sedimentary layer, respectively, $\alpha$ is the absorption coefficient, f is the frequency (in Hz), and m is the thickness of the sedimentary layer (in m). The dominant resonance-frequencies for sedimentary layers of more than 500 m thickness in the Lower Rhine Embayment are distinctly lower than 1 Hz according to Budny (1984) and dynamic amplification can therefore be neglected for the macroseismic effects in the epicentral region of the Roermond earthquake. Based on *in situ* measurements of the dynamic properties of soft soil of the Lower Rhine Embayment by Budny (1984) we used $v_0 = 2900$ m/s, $\rho_0 = 2700$ kg/m$^3$, $v_1 = 600$ m/s, $\rho_1 = 2000$ kg/m$^3$ and a Q-value of 30 for the sedimentary layer as the appropriate geological model for the epicentral region. The thickness of the sedimentary layer was set to m = 1500 m according to Geluk et al. (1994). For dominating frequencies between 4 and 6 Hz, which are thought to cause the bulk of the macroseismic effects to the predominant building type in the epicentral region, an intensity decrease in the range of 0.2 to 0.9 (mean 0.5) degree on the MSK-scale was found (Fig. 8). Consequently, a correction term of $\Delta I = -0.5$ was used to eliminate the influence of the graben fill on the macroseismic intensity near the epicenter.

## Macroseismic focal depth

The macroseismic focal depth of the Roermond earthquake was calculated by means of an iterative computer program, developed at our institute and based on the intensity-attenuation law of Sponheuer (1960) (equation 1 in Meidow 1994), which has been desdribed in detail by Schneider (1975) and others. The uncorrected observed epicentral intensity $I_{0(obs.)}$ = VII gives a focal depth of about 26 km (Fig. 9). If we correct the epicentral intensity in order to avoid the damping effect of the sedimentary graben fill and take a value of $I_{0(corr.)}$ = VII–VIII, the resulting focal depth is h = 17 km (Fig. 9). This value corresponds better with the instrumental focal depth determinations by various working groups (Camelbeeck et al. 1994).

## Discussion

The macroseismic observations of the Roermond earthquake in Germany are showing a significant damping effect of thick soft sediments in the Roer Valley Graben near the epicenter. Although this earthquake with its local magnitude of 5.9 belongs to one of the largest seismic events in the Lower Rhine Embayment in historical time, its macroseismic effects at the surface were relatively small. The observed epicentral intensity does not greatly exceed degree VII on the MSK-scale. These observations indicate that if the epicentral region of an earthquake is located on top of a thick (more than 500 m) soft sedimentary layer, the seismic energy will be damped so much that the macroseismic intensity will decrease about half a degree on the MSK-scale. This damping effect can be proven using crude

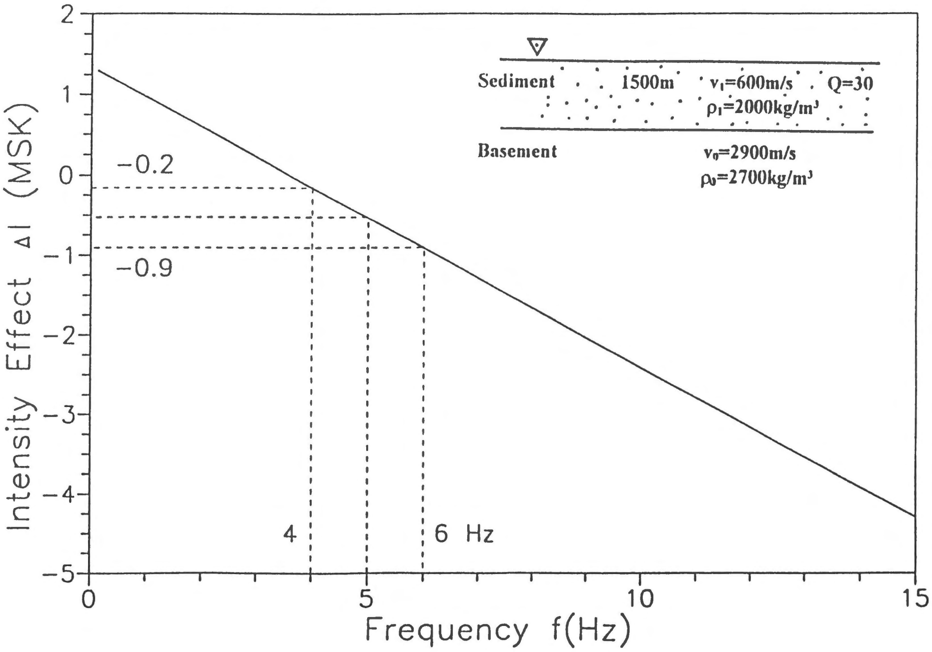

*Fig. 8.* Damping effect in a simplified model (eq. 1) of the 1500 m-thick sedimentary graben fill. $v_1$, $v_2$: S-wave velocities; $\rho_1$, $\rho_0$: density; Q: Quality factor. For dominating frequencies between 4 and 6 Hz an intensity decrease corresponds to a correction term of $\Delta I = -0.5$ degree on the MSK-scale.

theoretical considerations concerning propagation and absorption of seismic energy in a soft layer with low Q.

On the other hand, relatively larger macroseismic intensities can be observed where sedimentary layers have only small thicknesses (up to 100 m). This is generally the case in the border regions of the Lower Rhine Embayment, e.g. in the areas of Aachen, Düren, Euskirchen and Bonn, and in the Middle Rhine Valley where the Roermond earthquake caused heavy damage to buildings at large distances from the epicenter. This special site effect can be confirmed by the instrumentally recorded peak ground accelerations at seismic stations situated in the Middle Rhine Valley (Neuwied Basin) and in the neighbouring Rhenish Massif.

The shape of the isoseismals is strongly influenced by local site conditions. Other effects controlling the general shape of the isoseismals may originate, for instance, from the focused energy release of the earthquake source in southeast direction due to geometry and dynamics of the focal mechanism as described by Ahorner (1993, 1994).

One special point in our investigation was the analysis of damage to churches, especially historical ones. Damage categories 'slight to moderate' and 'heavy'

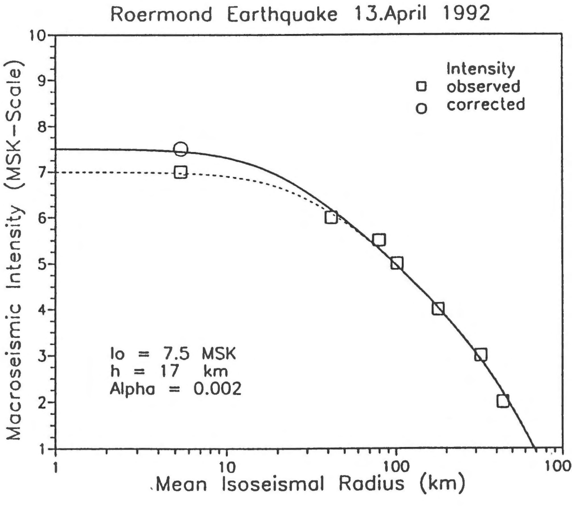

*Fig. 9.* Intensity attenuation in the eastern part of the area of perceptibility of the Roermond earthquake. Squares indicate the observed intensities. Circle indicates the corrected epicentral intensity incorporating the damping effects of the sedimentary graben fill (Fig. 8). A focal depth of 26 km is determined using the uncorrected intensity ($I_0 = 7.0$ MSK; data fit with broken line). A focal depth (h) of 17 km is determined using the corrected intensity ($I_0 = 7.5$ MSK; data fit with solid line). Alpha: attenuation constant in the intensity-attenuation law of Sponheuer (1960).

could be correlated with intensities V–VI and VII, respectively. Although this correlation is presently not very convincing, it may be improved by the observations of future earthquakes. We may then obtain a useful tool for the reconstruction and reinterpretation of historical earthquakes in the Lower Rhine Embayment.

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