

# Site specific hazard estimates for the LNG energy plant in the Europoort area

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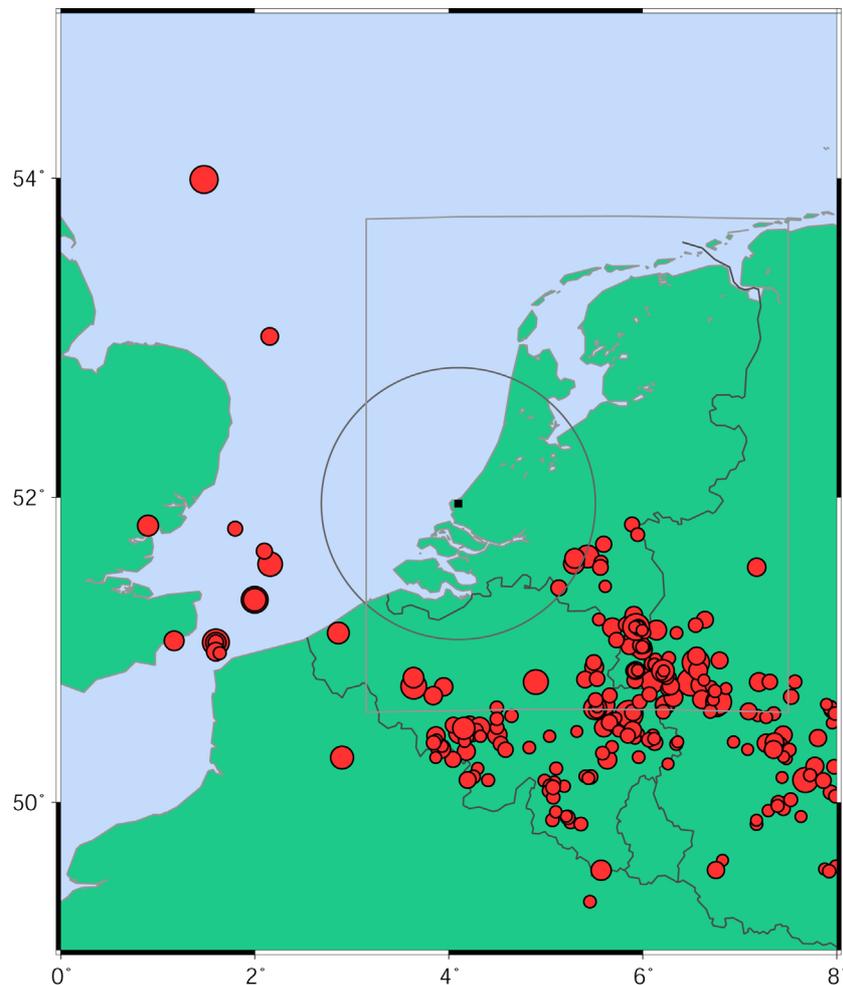
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## 1. Introduction

A new Liquid Natural Gas energy plant in the Europoort area, Port of Rotterdam (Figure 1) is planned for which a seismic hazard analysis is required. This report addresses the site specific seismic hazard as requested by Fugro.

For the seismic hazard we consider the natural seismicity within a radius of 100 km and slightly beyond and the induced seismicity within a radius of 10 km. Natural seismicity occurs on tectonic active zones with hypocenters usually at a depth of between 15 and 25 kilometres. Magnitudes can go up as high as  $M_L = 6.4$ . Induced seismicity may occur in the vicinity of the site, but would be relatively shallow, around 2-3 km depths and with magnitudes not much larger than 3.5. The signal characteristics of natural events and such induced events differ significantly.



**Figure 1.** Situation overview. The site of the LNG plant situated in the center and a circle with radius of 100 km illustrating the significance of the natural seismicity as depicted with red dots ( $M_L > 2.5$ ). The seismicity in the North Sea is scattered and mostly based on historical evidence and consequently imprecise. The seismicity in The Netherlands (Roer Valley), Belgium and Germany is based on a combination of historical and a significant amount of instrumental data and consequently more precise. The rectangular inlay refers to a more detailed seismicity map in Figure 2.

The geological quick scan performed by TNO (De Kleine, 2007) for FUGRO indicates a number of gas and/or oil exploration sites that may be capable of induced seismicity according to Van Eijs et al (2006). We will follow a conservative approach in which we assume that nearby oil and/or gas fields may generate induced seismicity in the same way as we observe in the northern part of The Netherlands. However, we would like to point out that, currently, we are unable to provide any reliable quantification of the probability of induced seismicity. Besides the fact that we did not record any seismicity until to date there are too many unknown parameters for a reliable quantification of this hazard.

The European guidelines (NEN-EN 1473, 2007) for the installation and equipment for liquid natural gas require hazard estimates in terms of an Operational Based Earthquake (OBE) and a Safe Shutdown Earthquake (SSE). We will follow their recommendations as close as possible.

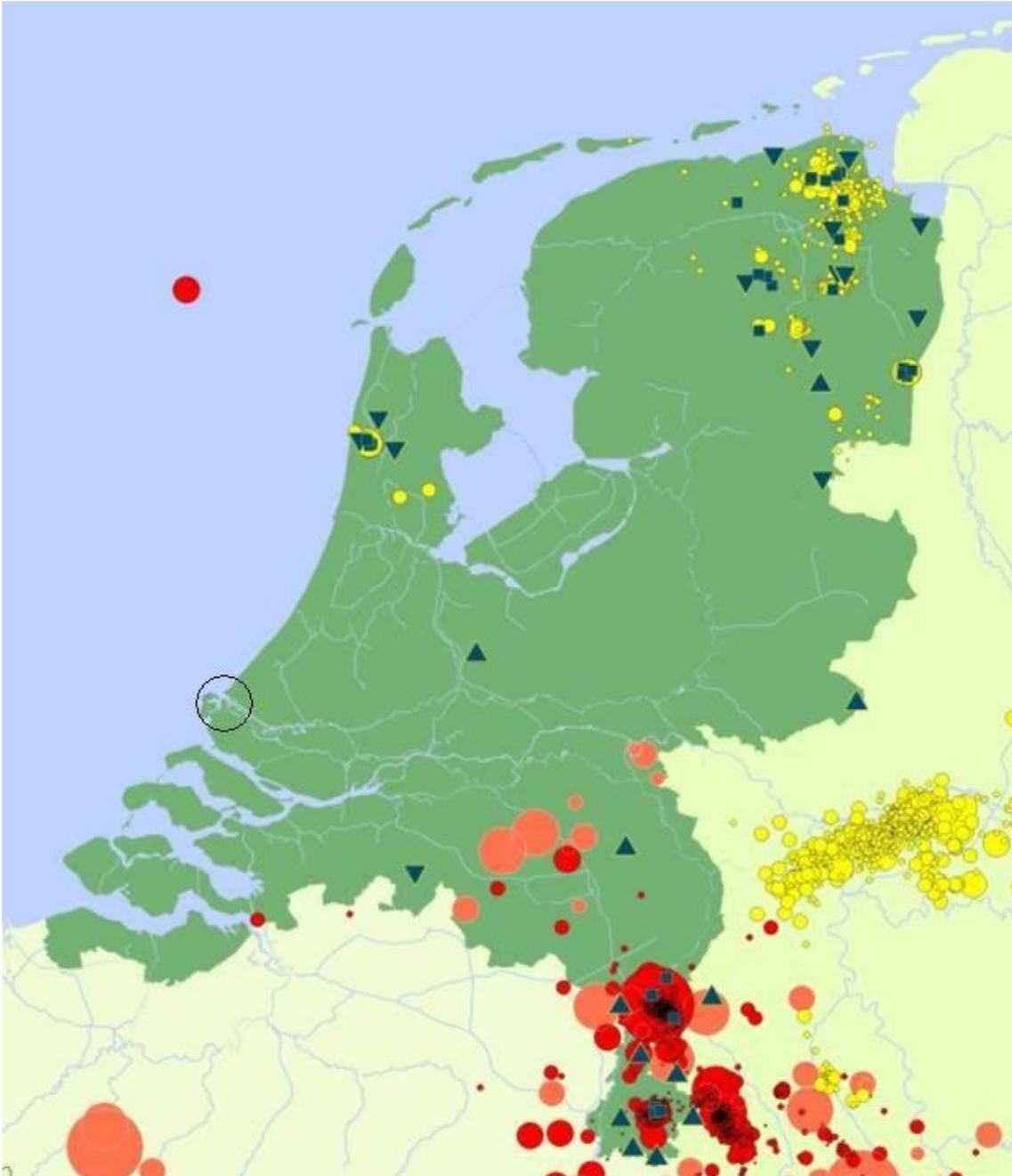
Consequently, in this report we provide site specific hazard estimates considering the impact of induced seismicity in the exploration fields close to the site and with a similar strength as in northern Netherlands and the impact due to a large natural earthquake at large distance. The time histories of nearby induced seismicity differ significantly from distant (100 km) medium-size earthquakes in duration, amplitude and frequency. Therefore we will provide relevant time histories and response spectra for both cases.

## 2. Seismicity

### *Natural seismicity*

We have neither historical nor instrumental evidence of seismicity in the direct vicinity of the investigated area within a radius of slightly less than 100 km. Natural seismicity has been observed and can possibly occur in a few regions at about 100 km distance and beyond (Figure 1). These regions include the Southern Anglo North Sea basin and possibly the Sole Pit basin in the North Sea, the Strait of Dover, the Roer Valley area in The Netherlands and Germany, a fault system in the Brabant Massif and the Hainaut region in Belgium. Of these regions we consider the Roer valley region to be most relevant (Figure 2). This region is closest to the site, defines an active graben system extending towards the northwest but with fading seismic activity, and has shown to produce significant earthquakes. In the Roer Valley region we observed a magnitude 5.8 ( $M_L$ ) earthquake on April 13, 1992 at about 150 km from the site of investigation. The Roer Valley has the potential of earthquakes up to magnitude 6.4, i.e. estimated  $M_{max}$  (unpublished analysis Dost et al. in 2007).

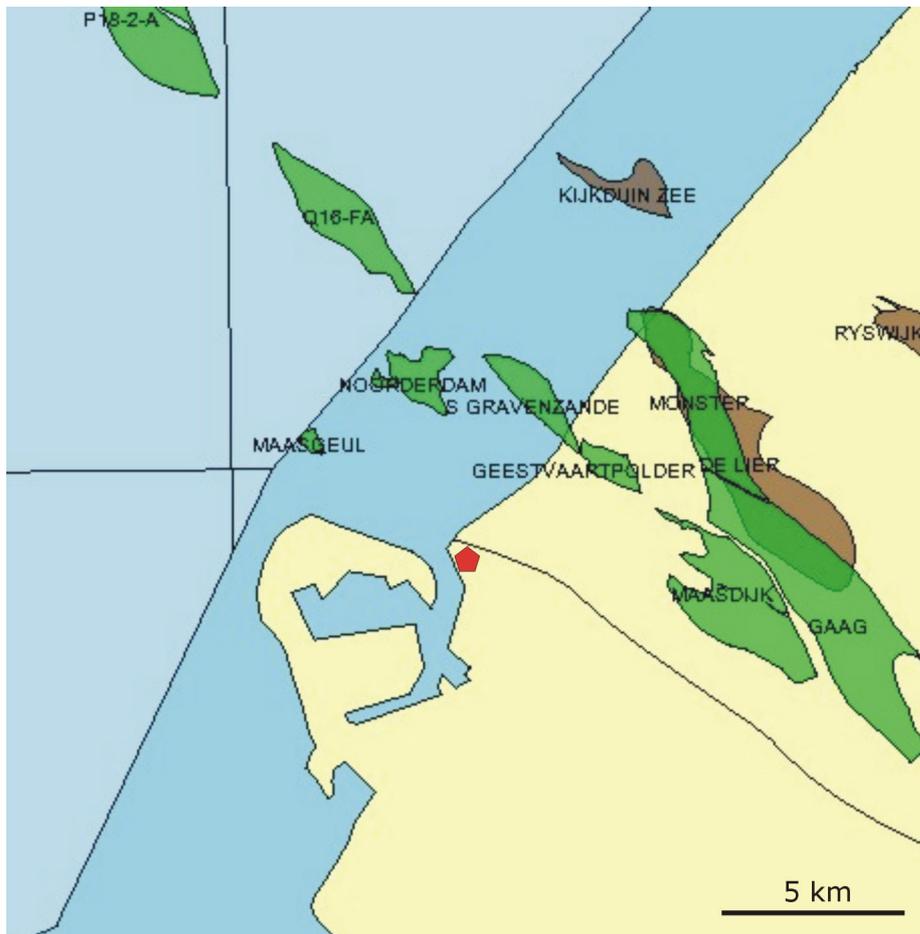
The seismicity in the fault system of the Brabant Massif and the Hainaut region in Belgium is more distant, less active and to the best of our knowledge not prone to earthquakes as large as those observed in the Roer Valley (Camelbeeck, 1994). The seismicity in the southern part of the North Sea is less well-known. Only few events are recorded from that area, the most notable being the 1931 ( $M_L = 5.7$ ) event, most probably at the northern tip of the Sole Pit Basin (PESGB, 2000; Bungum et al, 2000; Ambraseys, 1985). However, also the seismicity in the North Sea relevant for the LNG site is less and further away. Consequently, a potential strong earthquake in the Roer Valley at a distance of about 100 km from the site will represent the most serious natural earthquake threat to be considered for the OBE and SSE. This is also reflected in the seismic hazard map for the Netherlands as presented by De Crook (1996).



**Figure 2.** Observed seismicity in the Netherlands from 1600 to present (source KNMI). The yellow dots represent induced earthquakes, the red dots natural seismicity. The location of the new LNG plant site is indicated, situated in the center of the black circle. Blue triangles and squares indicate the stations in our current seismometer and accelerometer network.

### *Induced seismicity*

The TNO quick scan shows that the planned LNG site is located at a distance of approximately 5 to 6 km from the 's-Gravezande gas field and within a distance of 10 km of several other producing oil and gas fields (www.nlog.nl). Furthermore, the site is situated near the Noorderdam field, of which start of production is expected within the period 2007-2009, and the Maasgeul field, of which the start of production is yet unknown. The site and the hydrocarbon exploration fields are shown in Figure 3.



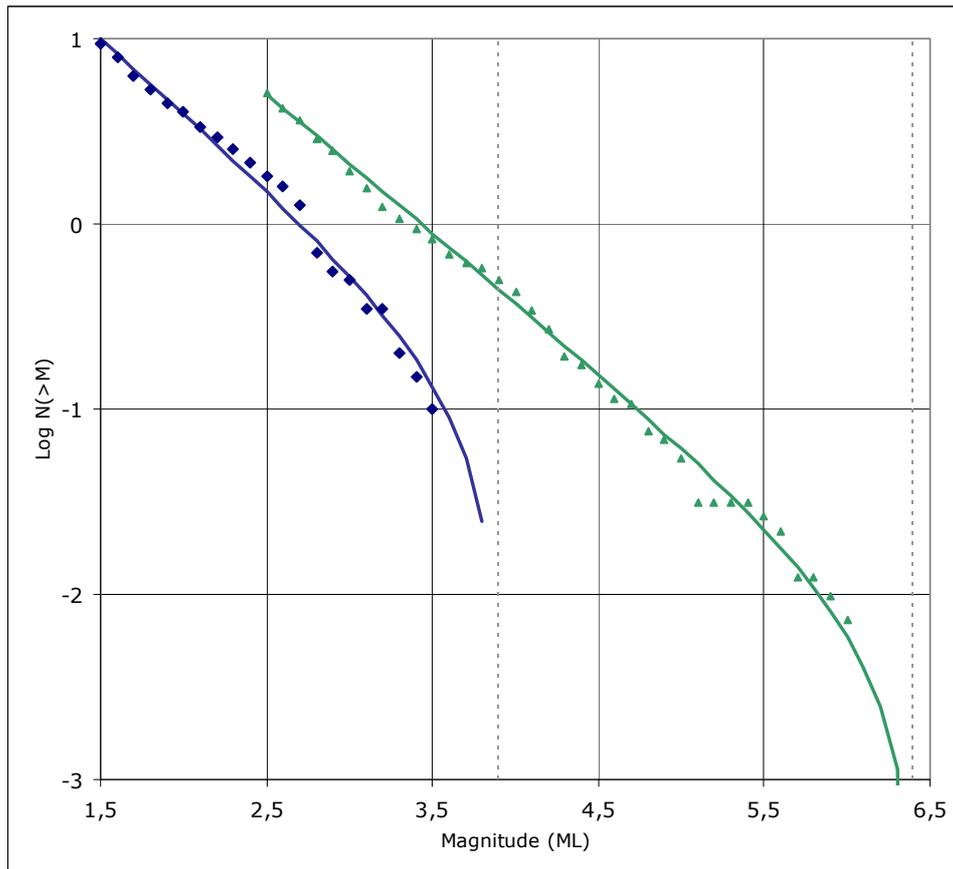
**Figure 3.** A detailed figure of the Europoort area with in red the location of the energy plant and in green and brown the hydrocarbon exploration fields in the vicinity. (Source: www.nlog.nl)

Since 1986 the KNMI recorded more than 500 small earthquakes in the northern part of the Netherlands occurring in or close to gas reservoirs at about 3 kilometres depth. The magnitudes ( $M_L$ ) of these events range from -0.2 to 3.5 and the depth of the earthquakes coincides with faults at the upper boundary of the gas-reservoir. A more detailed description can be found in Van Eck et al. (2006). Up to now no events have occurred in the south-western part of the Netherlands due to the gas-extraction there. Consequently, we will perform our analyses on the dataset of earthquakes that occurred in the north-eastern part of the Netherlands, in Groningen and Drenthe. We assume herewith that if earthquakes are going to occur in the Europoort area they will have the similar characteristics. Obviously, there remains a subjective judgement of the degree of conservatism one want to apply in this context.

### 3. Quantification of the hazard parameters

#### Maximum magnitude

In figure 4 the green line depicts the frequency-magnitude relation for the natural seismicity in the Roer Valley region as obtained from the KNMI seismicity catalogue compiled from the data of the KNMI and surrounding observatories in Belgium and Germany. For a return period of about 5000 years (SSE) an  $M_L = 6.4$  earthquake can be expected. For a return period of about 500 years (OBE) an  $M_L = 6.2$  can be expected.



**Figure 4.** Annual cumulative frequency-magnitude relation for all events in the Northern part of the Netherlands (blue) and the southern part of the Netherlands (green). The observed data are represented in dots, the solid lines depict the best fit curves. The dotted lines depict the estimated maximum magnitudes.

The blue line in figure 4 depicts the frequency-magnitude relation for induced seismicity as obtained from our observations in the northern part of The Netherlands. The largest induced event we observed had a magnitude of 3.5. In van Eck et al. (2006) we show through some model simulations that the maximum possible magnitude is most possibly around  $M_L = 3.9$ . Following the standard seismicity modelling as used with natural seismicity an  $M_L = 3.9$  induced event is relevant for both the SSE and OBE. This seems to us the most conservative approach. The largest induced event we have observed until now in the northern Netherlands with significant reservoirs had a magnitude 3.5. Considering the fact that no induced seismicity has been observed in the Europoort area even the  $M_L = 3.5$  seems to be a conservative estimate. Currently we propose this least conservative option, however, the LNG operators will need to weight the degree of conservatism against other constraints.

*Peak Ground Acceleration of induced events*

In Van Eck et al. (2006) we show in a probability hazard analysis that in the vicinity of a seismic active exploration field Peak Ground Accelerations (PGA) of 0.15g and 0.25g may be exceeded with associated annual probabilities of 0.1 and 0.01 respectively. However, as described in the same paper, large uncertainties are associated with these estimates. The fact that no seismicity has been observed in the exploration fields in the vicinity of the Europoort introduces even larger uncertainties. Moreover, as shown in the Appendix these accelerations are generally characterized by short durations and a single strong acceleration pulse.

*Peak Ground Acceleration of natural events*

A probabilistic seismic hazard analysis presented by De Crook (1993; 1996) indicates that for the Europoort area an Intensity V may be exceeded for annual probabilities within the range of 0.001 to 0.0001. Intensity V corresponds to a Peak Ground Acceleration of around 22 cm/sec<sup>2</sup> or 0.02g. However, the conversion from Intensity to PGA includes a significant variance.

#### 4. Ground motion time histories

Ground motion time histories are provided for the specified site and are based on observed accelerations (Table 1) due to induced seismicity in the North of the Netherlands and a velocity recording of the Roermond earthquake recorded at station BUG, a German high quality station 100 km from the epicentre. These are appropriate representative ground motion time histories for the LNG site as argued in sections 2 and 3. The three component waveform seismograms are provided in Appendix A.

**Table 1.** Observed ground accelerations for an  $M_L = 5.8$  natural event and an  $M_L = 3.5$  induced event.

Figures	Event date	Magnitude ( $M_L$ )	Station	Delta (km)	Comments
Appendix A1	1992-04-13	5.8	BUG	100	Velocity sensor
Appendix A2, A3, A4	2006-08-08	3.5	't Zand 2	4	Accelerometers
			't Zand 1	6	
			Hoeksmeer	9	

Delta = Epicentral distance in kilometres

##### *Ground motion due to induced events.*

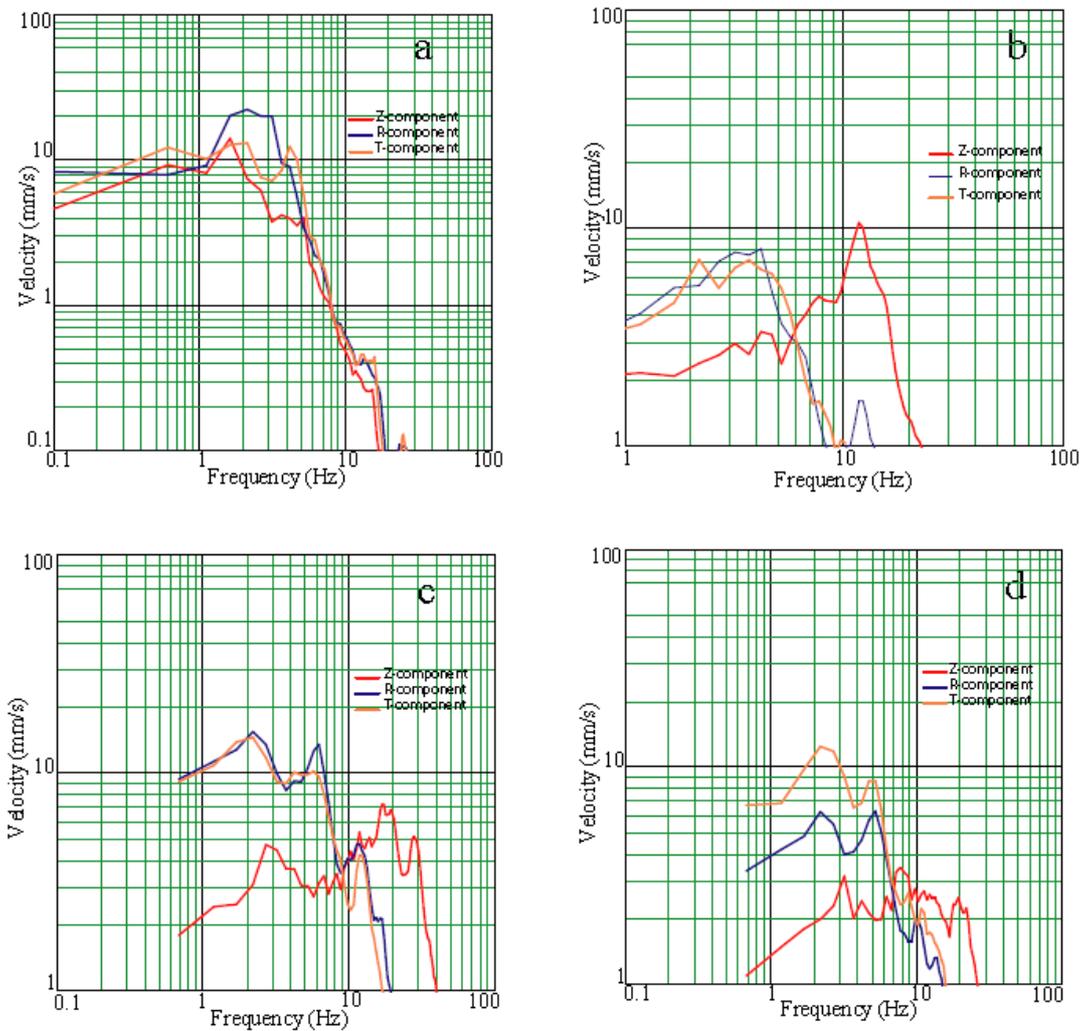
The observed ground motion acceleration records have been selected from three accelerometer observations of an  $M_L = 3.5$  event in the northern part of the Netherlands. As shown in Appendix A the PGA may reach 20 milli g.

##### *Ground motion due to natural events.*

The argumentation for our selection of the earthquake size and its associated probabilities is given in chapter three. Observed Peak Ground Velocity (PGV) for the Roermond earthquake, recorded at approximately 100 km distance, is around 20 – 30 cm/sec. The recommended maximum amplitude distant-events,  $M_L = 6.2$  and 6.4 should be scaled with a factor of 2.5 and 4.0 respectively. To obtain the scaling factors we use the relation  $M_L \sim \log A$  (Lee and Stewart, 1981) and assume little frequency variation between the events of magnitudes between 5.8 and 6.4. Within the range of uncertainties due to focal mechanism, attenuation and source zone this is a reasonable assumption. The PGV obtained from the recording are somewhat larger than expected from the PGV prediction to be exceeded (section 3). This illustrates again the large uncertainties involved in the hazard estimates for the site.

## 5. Relative Response Spectra

The response spectra with 5% damping have been calculated for all three components (vertical, radial and transverse component) of the distant (100 km) natural earthquake and the induced event at three different distances (Figure 5).



**Figure 5.** Three component relative response spectra for four design earthquakes: a) Distant earthquake ( $\Delta = 100$  km;  $M_L = 5.8$ ); b) Induced event ( $\Delta = 9$  km;  $M_L = 3.5$ ); c) Induced event ( $\Delta = 4.4$  km;  $M_L = 3.5$ ); d) Induced event ( $\Delta = 6$  km;  $M_L = 3.5$ ). The response spectra are computed for 5% damping.

## 7. Conclusions and discussion

### *Site effect considerations*

The observed accelerations are recorded on the surface and, consequently, they include a local site effect. None of the accelerometers are situated in the free field. In most cases they are situated on the ground or cellar floor of small buildings. Currently, we have not yet explored in detail the effect of these locations, but from preliminary experiments we expect them to be minor. The spectra of the natural event recorded at station BUG can be considered as including only a negligible site effect as the station is a properly installed seismograph station.

### *Instrumental corrections*

The instrument response for the accelerometers is flat for accelerations between 0.3 and 30 Hz (Dost and Haak, 2002). Therefore, no instrumental corrections have been applied beyond the amplification. All amplitudes are given in milli g. The seismometer is a flat response velocity sensor between 1 and 20 seconds. Therefore also in this case we did not apply instrumental corrections other than the amplification. The amplitudes in Appendix A1 are given in m/sec.

### *Deliverables*

We provide 12 relevant ground motion histories for dynamical modelling and 12 relative response spectra for 5% damping. These ground motion histories and spectra are based on one actual 3C regional recording of a large natural earthquake at 100 km distance, the Roermond earthquake of April 13, 1992 and three 3C regional acceleration records at different epicentral distances (respectively 4.4, 6 and 9 km) from an induced event in the northern part of The Netherlands. The ground motion due to the Roermond earthquake needs to be scaled in amplitude with a factor 2.5 to simulate an  $M_L = 6.2$  event with return period of 500 years and a factor 4.0 to simulate an  $M_L = 6.4$  event with a return period of 5000 years. We believe, however, that these factors are close to the uncertainties introduced by source mechanism, i.e. radiation pattern, rupture process and propagation effects.

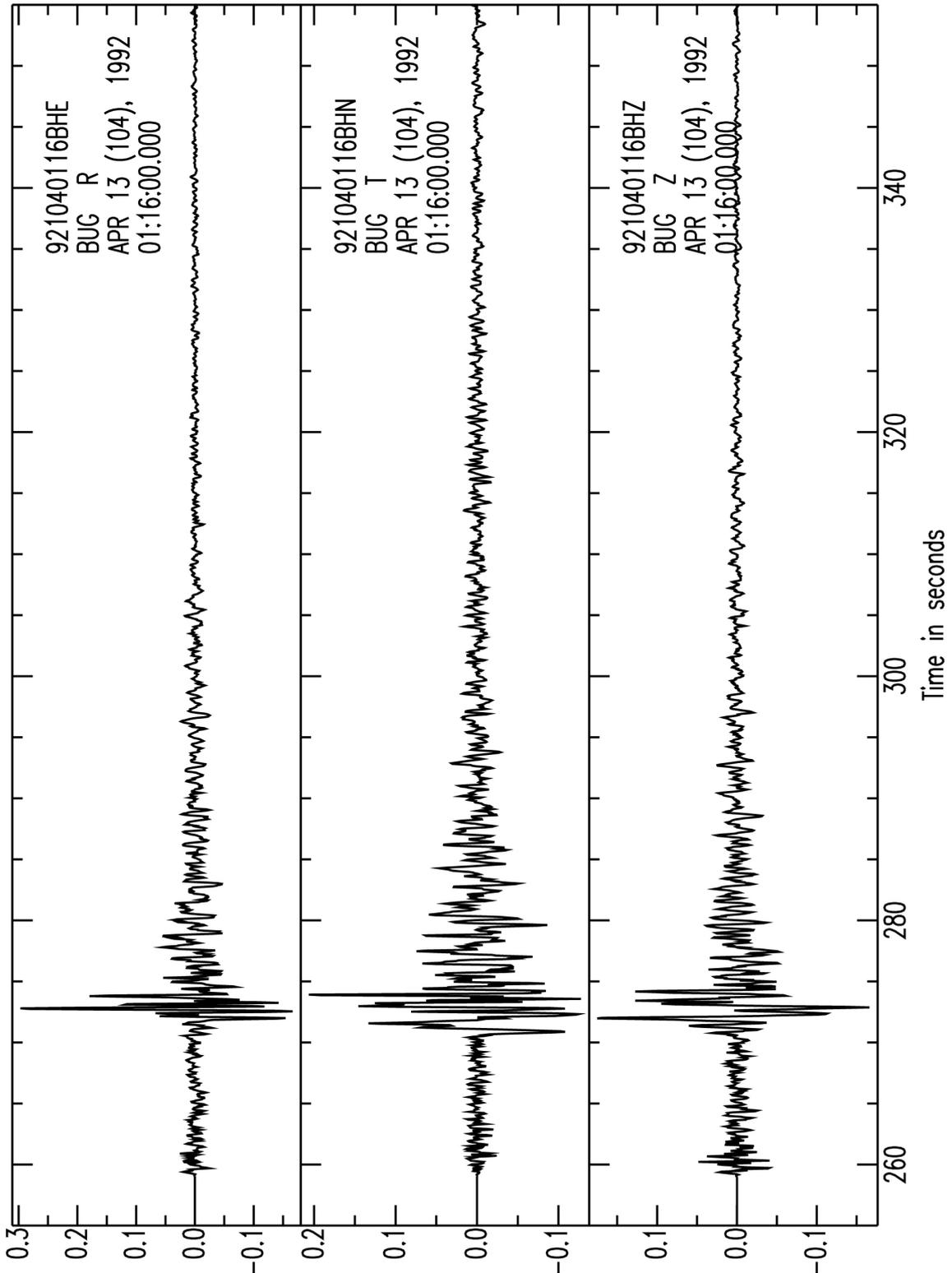
### *Additional comments*

The acceleration records are from shallow nearby induced events as expected from the existing hydrocarbon exploration fields and are characterized by small short pulses. The form and amplitude of those pulses may depend significantly on the source radiation pattern in relation to the source-site path. Observations have shown that within 6-8 km distance this can give rise to significant uncertainties very well ranging in between a factor 2 - 4 or, closer to the epicentre, more. A detailed discussion of the uncertainties can be found in Van Eck et al. (2006).

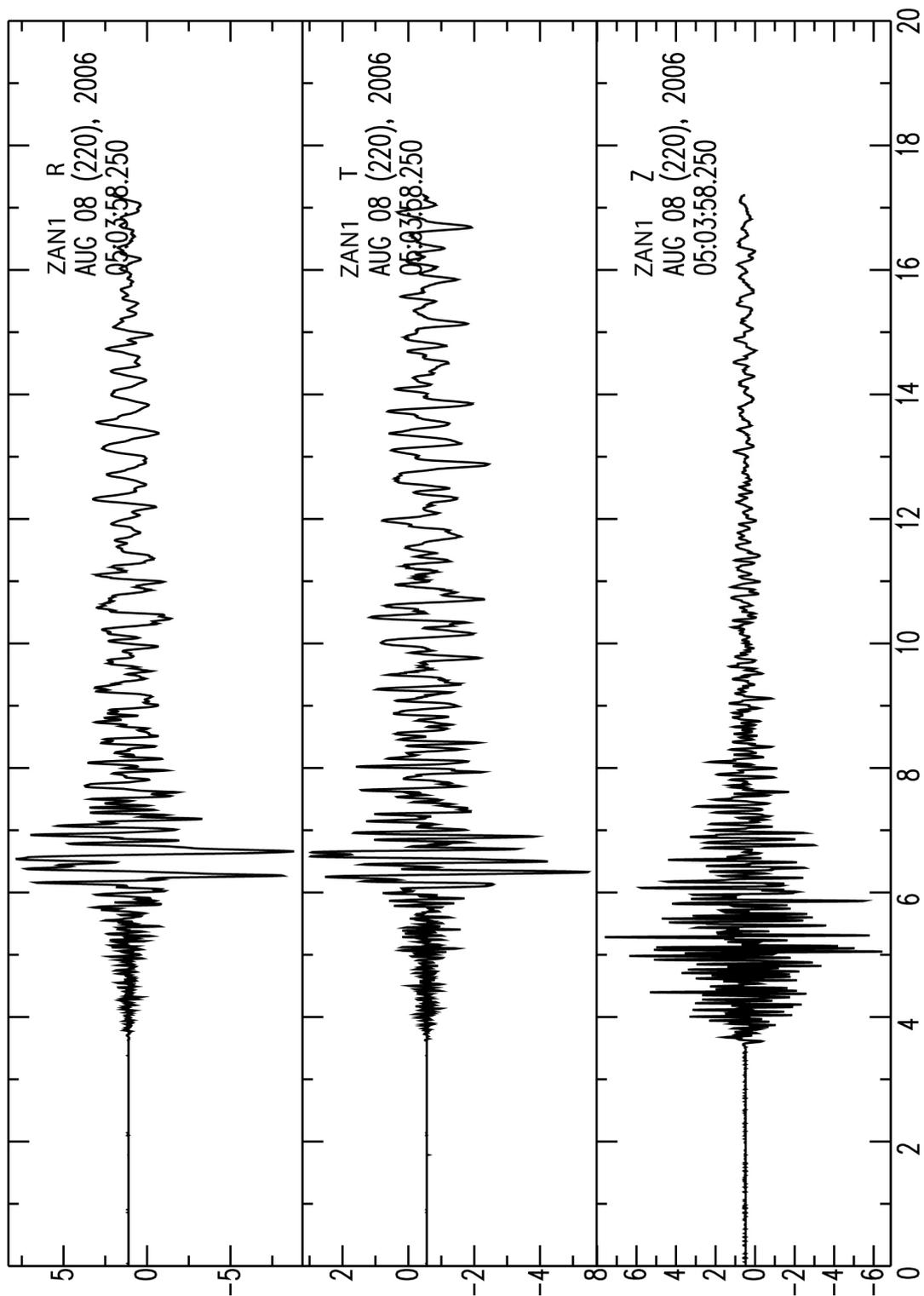
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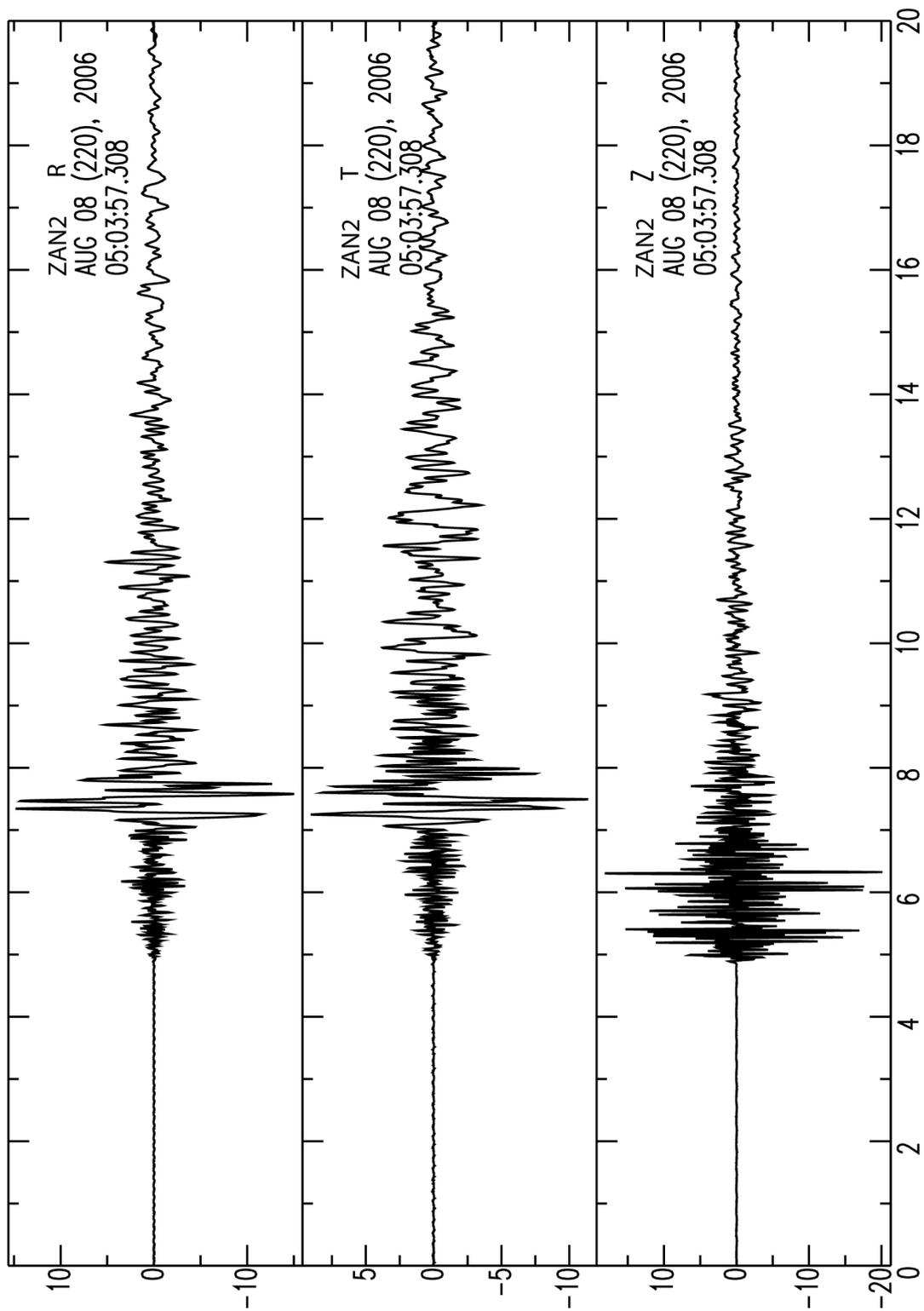
## **Appendix A.** Ground motion time series



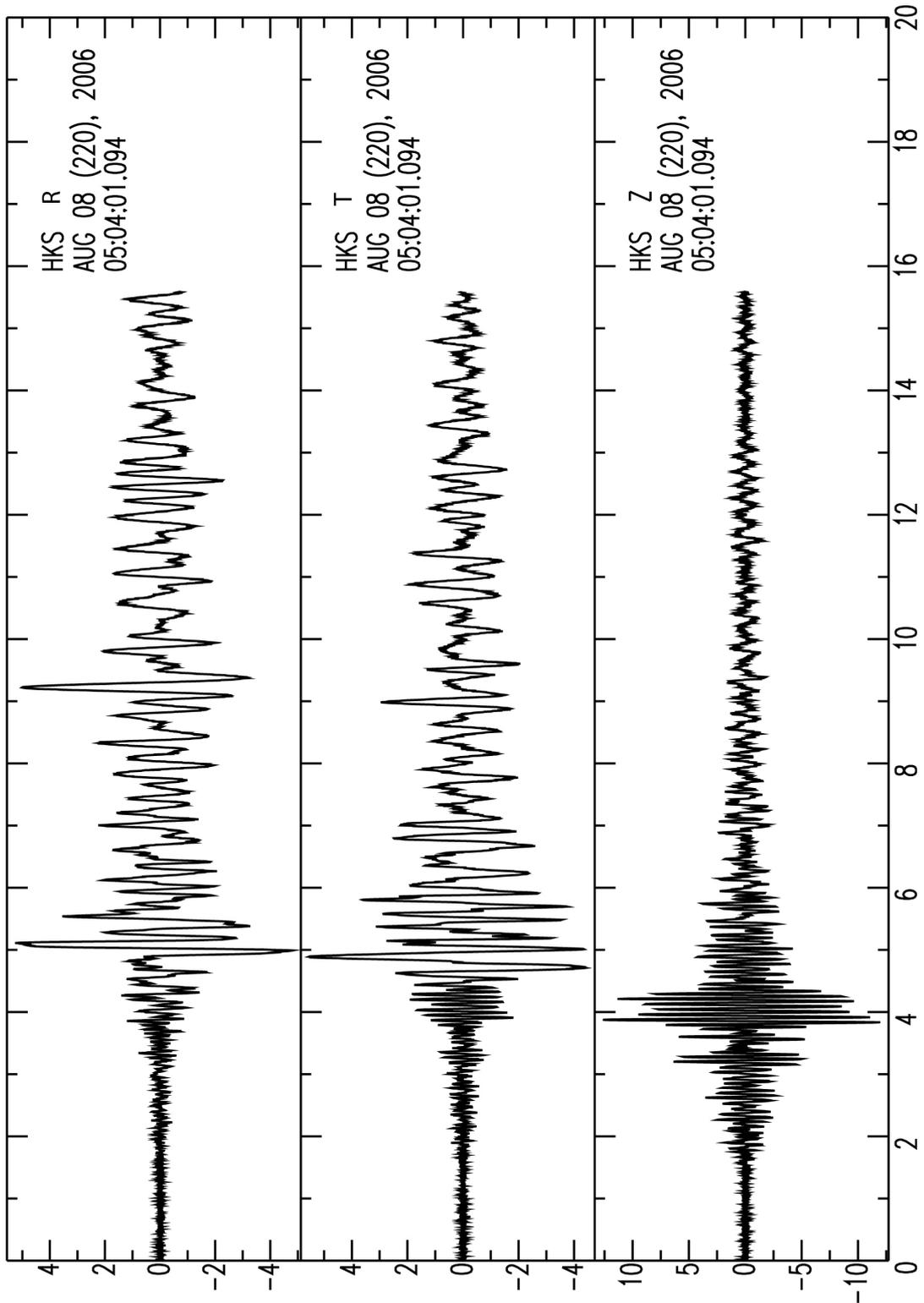
**Figure A1.** Velocity time series for a magnitude  $M_L = 5.8$  earthquake at 100 kilometres epicentral distance from the site. The amplitude is in m/sec. This signal is a true event (Roermond 1992 event) recorded at station BUG in Germany (GR seismograph network). The x-axis shows time in seconds. The components are from left to right; radial, transverse and vertical.



**Figure A2.** Three component acceleration time series for a magnitude  $M_L = 3.5$  earthquake at 4.4 kilometres epicentral distance. The amplitudes are in milli g. Time is given in seconds. The components are from left to right the radial, transverse and the vertical component. The records are based on true records of an  $M_L = 3.5$  event in the Northern Netherlands.



**Figure A3.** Three component acceleration time series for a magnitude  $M_L = 3.5$  earthquake at 6.0 kilometres epicentral distance. The amplitudes are in milli g. Time is given in seconds. The components are from left to right the radial, transverse and the vertical component. The records are based on true records of an  $M_L = 3.5$  event in the Northern Netherlands.



**Figure A4.** Three component acceleration time series for a magnitude  $M_L = 3.5$  earthquake at 9.0 kilometres epicentral distance. The amplitudes are in milli g. Time is given in seconds. The components are from left to right the radial, transverse and the vertical component. The records are based on true records of an  $M_L = 3.5$  event in the Northern Netherlands.



