Special Report on the M_L 2.6 Slochteren Earthquake of 27th May 2017

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Datum June 2017

Editors Jan van Elk & Dirk Doornhof

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Introduction

On Saturday 27 May 2017, an earthquake of magnitude M_L 2.6 occurred towards the south of the field near Slochteren (Figure 1). This report presents a preliminary assessment of the ground motion recordings from this earthquake, specifically addressing the question of whether the ground motions were consistent with the patterns observed in previous Groningen earthquakes or whether the recorded motions are in some way exceptional. This is followed by a discussion of the determination of the epicentre, the source mechanism and local pressure differences near the epicentre.

A key element of the seismic hazard and risk models for induced earthquakes in the Groningen field is a ground-motion model (GMM) that allows estimation of ground-motion amplitudes due to potential earthquake scenarios. The current GMM (Bommer *et al*., 2017a) has been derived using a database of 178 accelerograph recordings obtained from 22 earthquakes with local magnitude in the range from M_L 2.5 to M_L 3.6 (Figure 1).

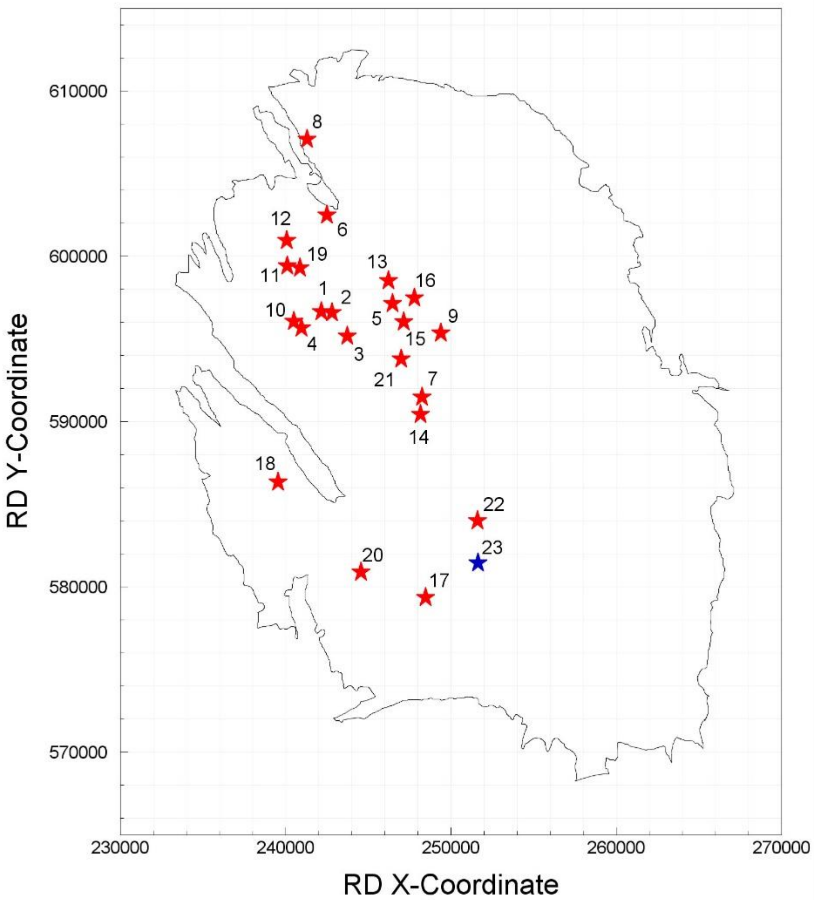


Figure 1. Epicentres of the 22 earthquakes in the current Groningen ground-motion database and the May 2017 Slochteren event (blue star)

Recorded PGA Values

Early reports of the earthquake noted that the largest value of horizontal peak ground acceleration (PGA) recorded in the earthquake was 0.035*g*. While this is smaller than the maximum value of 0.082*g* recorded in the 2012 Huizinge earthquake, at first glance it did appear large in comparison to previous earthquakes of a comparable magnitude. The value of 0.035g has been exceeded in five previous earthquakes, the smallest of which was of magnitude M_L 2.9.

To put this observation in context, Figure 2 shows all of the geometric mean (square root of the product of the two horizontal components) PGA values in the database plotted against magnitude, together with the Slochteren recordings. While there is a single recording that appears to be quite high in the Slochteren event, the overall pattern is generally consistent with that observed in previous earthquakes. One point that can be noted is that the Slochteren event produced a large number of recordings, a direct result of the expansion of the KNMI seismic monitoring network: we have identified 71 records with acceptably high signal-to-noise ratios for inclusion in the project database. This *is* exceptional: the largest previous harvest of useable recordings was 44 accelerograms from the M_L 3.1 Hellum in 2015 (Figure 3); prior to that no event had generated as many as 20 recordings. The large number of recordings of the Slochteren earthquake is a direct result of the extension of the KNMI seismic network with additional geophone and accelerometer stations. However, as shown in this report, the Slochteren values seem to be consistent with those from previous earthquakes, and if anything, trend a little on the low side: unlike the largest PGA value, the highest PGV does not stand out as being in any way unusual.

Figure 4 displays similar information to that shown in Figure 2, except now the data from different distance ranges are shown in separate plots, and the individual horizontal components (rather than their geometric mean values) are plotted. Once again, the single largest component does appear to stand out slightly but when looking at the more distal recordings, there is nothing exceptional about the Slochteren accelerations.

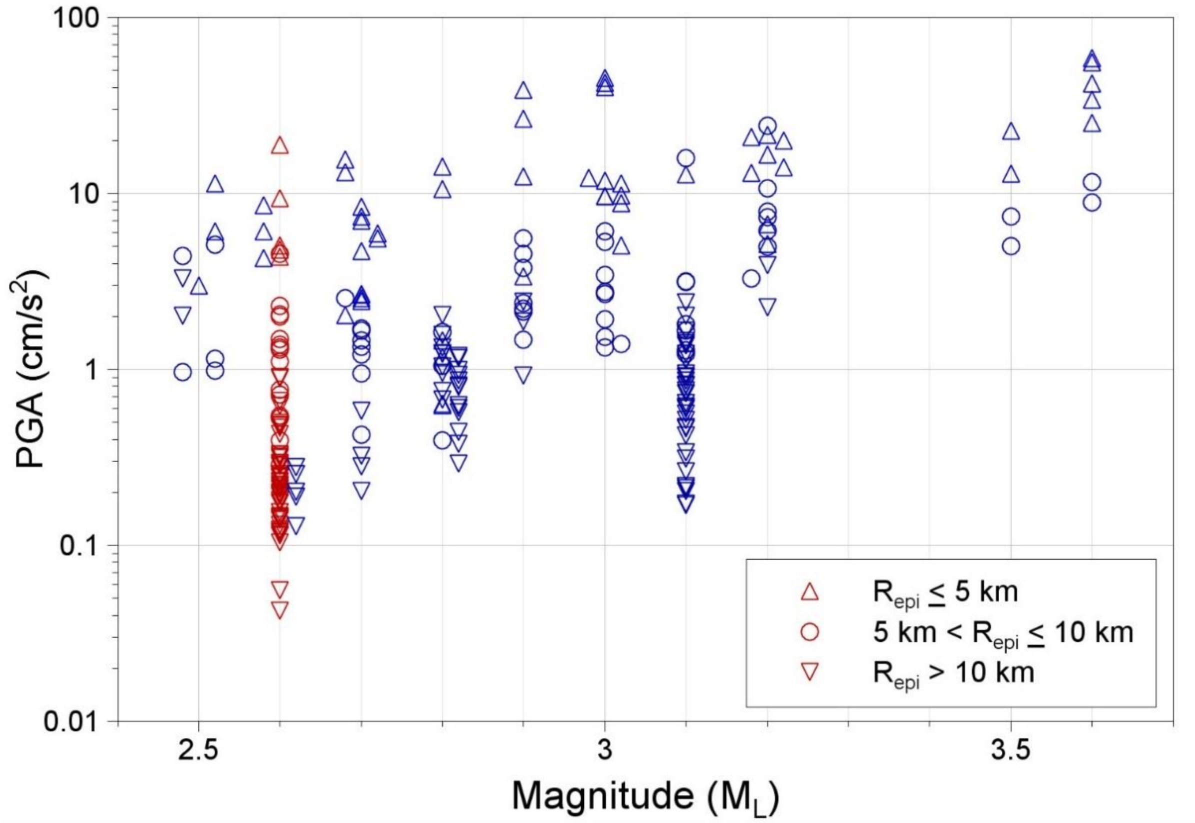


Figure 2. Geometric mean horizontal PGA values against magnitude in the Groningen database, with symbols indicating ranges of epicentral distance. The red symbols correspond to the May 2017 Slochteren event. Where two or more events have the same magnitude, the symbols are displaced slightly left and/or right for clarity.

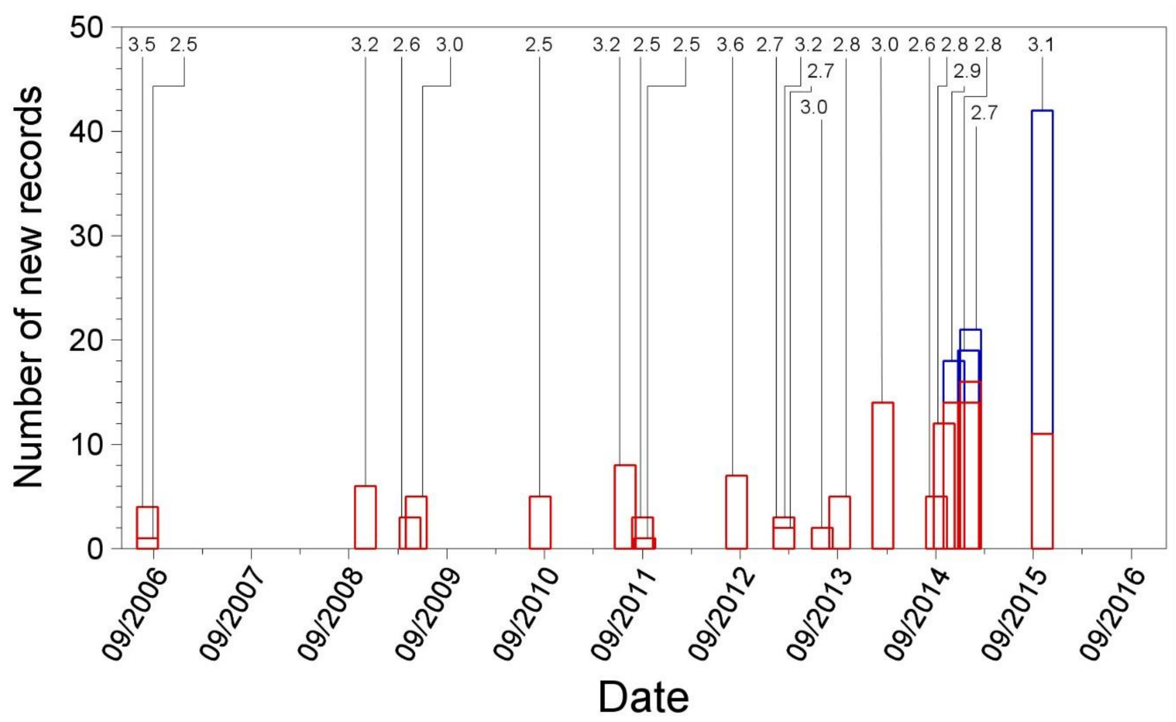


Figure 3. Histogram of accelerograms retrieved from earthquakes in the existing Groningen database, with red bars corresponding to the permanent network of KNMI (B-stations) and blue the new network of borehole geophones (G-stations). From Bommer *et al*. (2017c)

These observations suggest that there is, in general, nothing extraordinary about the peak accelerations recorded in the Slochteren earthquake, but there is a single record on which the values appear slightly larger than might be expected from previous observed trends. There are two posible explanations.

The first option is whether this might be the result of site amplification effects at the recording station (G46) where the record was obtained. Figure 5 shows the geometric PGA values plotted against epicentral distance with different symbols to indicate the range of V_{S30} (time-averaged shear-wave velocity over the uppermost 30 metres) of the recording sites. Softer sites have lower V_{S30} values and in general will amplify the motions more. As can be immediately appreciated from the figure, there is no clear pattern of the softer sites producing markedly higher levels of acceleration, and the two highest values of PGA were obtained at one of the stiffest recording sites. The station G41 is the softest of the near-source stations (it yielded a maximum PGA more than six times smaller than the value obtained at G46, see Table 1).

The second option requires us to explore whether or not the larger observed PGA values are the result of effects such as rupture directivity and azimuth dependence reflecting the pattern of the seismic radiation from the earthquake source (Figure 6).

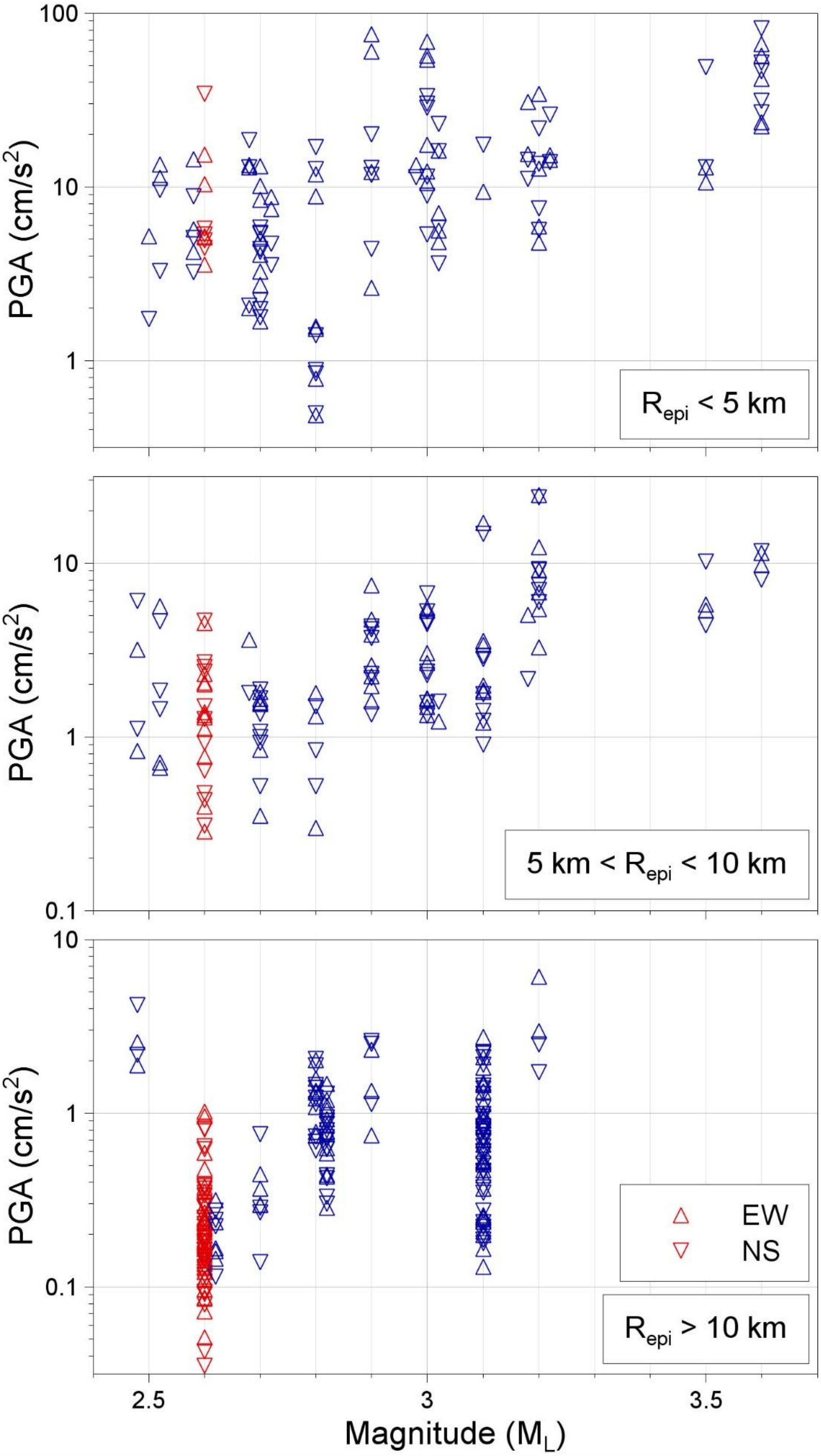


Figure 4. Individual horizontal PGA values against magnitude in the Groningen database, with symbols indicating ranges of epicentral distance. The red symbols correspond to the May 2017 Slochteren event. Where two or more events have the same magnitude, the symbols are displaced slightly left and/or right for clarity. Figure 4 displays similar

information to that shown in Figure 2. In this figure the data from different distance ranges are shown in separate plots, and the individual horizontal components (rather than their geometric mean values) are plotted.

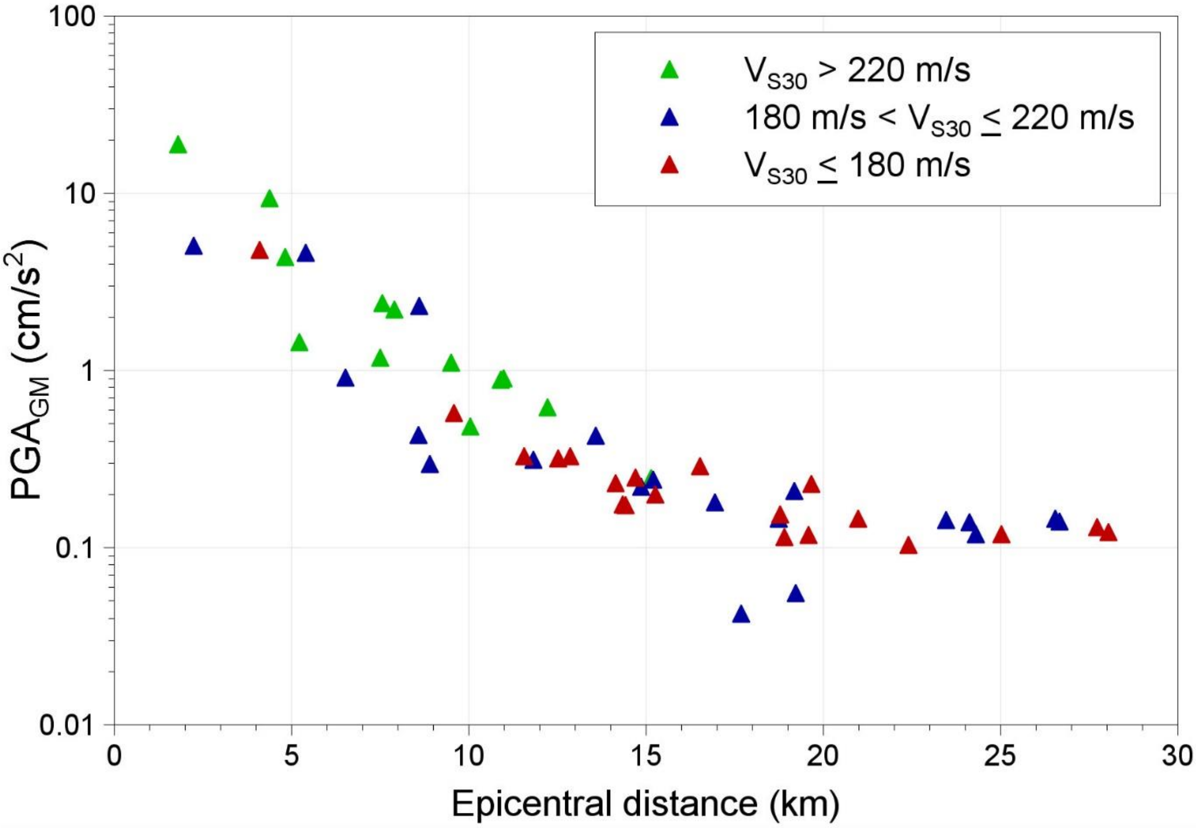


Figure 5. Geometric mean values of horizontal PGA against epicentral distance with symbols reflecting the V_{S30} class of the recording station

STAT	R_{epi} (km)	PGA_{max} (cm/s^2)	V_{S30} (Station)	Zone	V_{S30} (Zone)
G460	1.81	34.4	242.39	2824	254.8
G400	2.25	5.2	208.73	311	225.5
G410	4.11	5.1	171.07	1730	194.3
G500	4.38	15.4	255.81	2824	254.8
G450	4.82	5.3	262.96	3115	254.2
G350	5.24	1.5	255.43	3418	238.1
G510	5.40	4.7	190.29	1735	212.6

Table 1. Characteristics of the near-source recordings of the Slochteren earthquake in terms of larger horizontal PGA, epicentral distance, and the V_{S30} value as determined from velocity model for the field (Kruiver *et al*., 2017) and the mean values of V_{S30} for the site response zones (Rodriguez-Marek *et al*., 2017) in which each of the stations is located

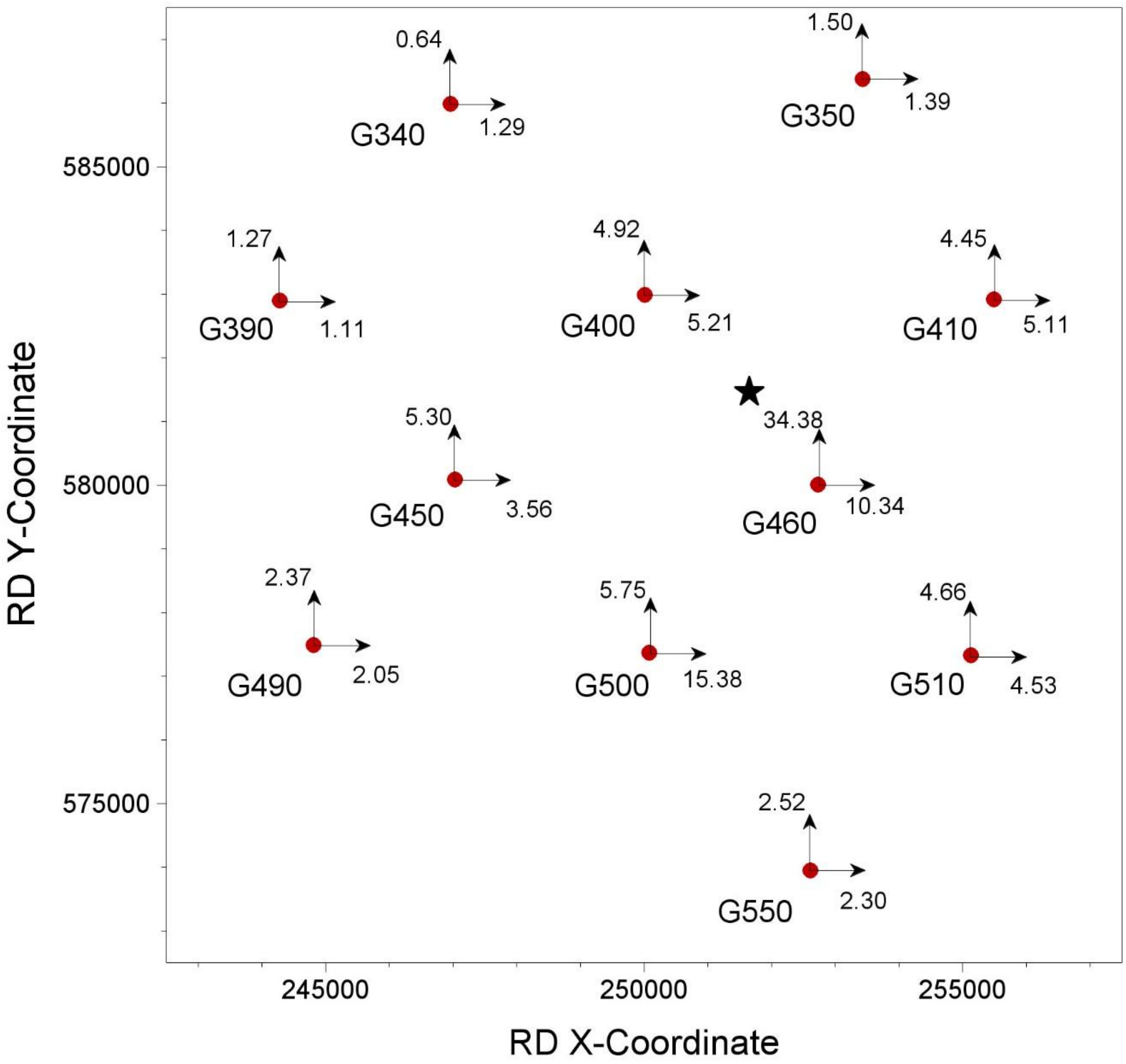


Figure 6. Accelerograph stations within ~8 km of the epicentre (*black star*) of the Slochteren earthquake, showing the PGA values (cm/s^2) on the NS and EW components

From Figure 6 it can be observed that the two highest PGA values are associated with highly polarised recordings, although it is also notable that the larger components have different orientations at the two stations. This observation is consistent with the finding that the Groningen recordings generally display appreciable orientation, as reflected in the high component-to-component variability. Comparison with the variability observed in recordings of tectonic earthquakes suggests that this is primarily a result of the short source-to-site distances of the recordings (Bommer *et al*., 2017b). This has been interpreted as being due to the recordings capturing the source radiation pattern, which becomes concealed at larger distances due to multiple travel paths of direct, reflected and refracted phases.

This component-to-component variability is consistent with earlier earthquakes in Groningen and fully accounted for in the seismic risk calculations through modification of the sigma values associated with the geometric mean component of motion in order to represent the arbitrary (or randomly-oriented) horizontal component of ground motion.

Recorded PGV Values

Peak ground velocity (PGV) is for building damage a more useful measure of ground-motion intensity than PGA, reflecting the energy content of the shaking. For the Groningen motions, it has been shown the PGV values correlate very well with response spectal accelerations at about 0.3 seconds, which reflects the loading experienced by many houses in the field and adjoining areas. Figure 7 shows the near-source recording stations, as for Figure 6, with the individual horizontal components of PGV (cm/s). The observed patterns are generally similar to those in Figure 6 for PGA, with the two highest components being associated with strongly polarised recordings obtained to the south of the epicentre.

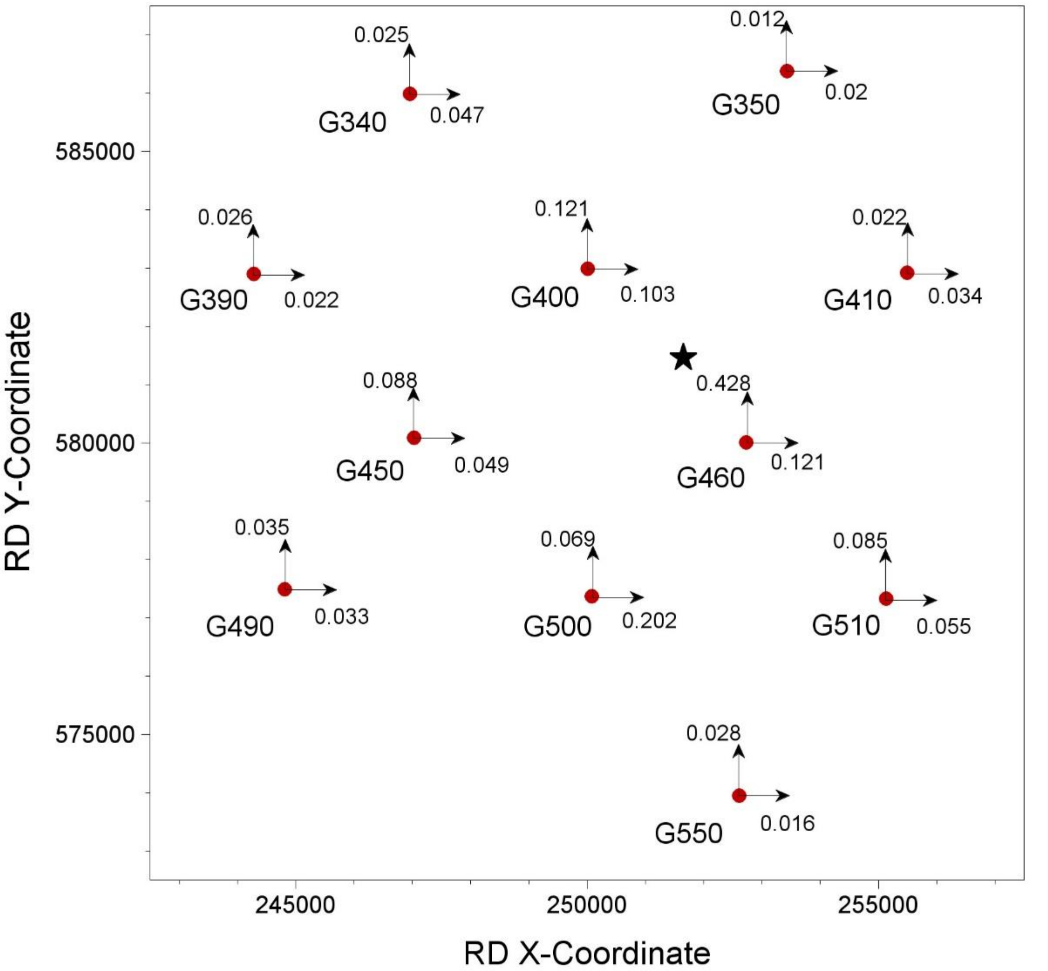


Figure 7. Accelerograph stations within ~8 km of the epicentre (*black star*) of the Slochteren earthquake, showing the PGV values (cm/s) on the NS and EW components

In terms of the actual amplitudes of PGV, these are compared with the 178 recordings accelerograms already included in the Groningen ground-motion database in Figure 8. The Slochteren values seem to be consistent with those from previous earthquakes, and if anything, trend a little on the low side. Unlike the largest PGA value, the highest PGV does not stand out as being in any way unusual.

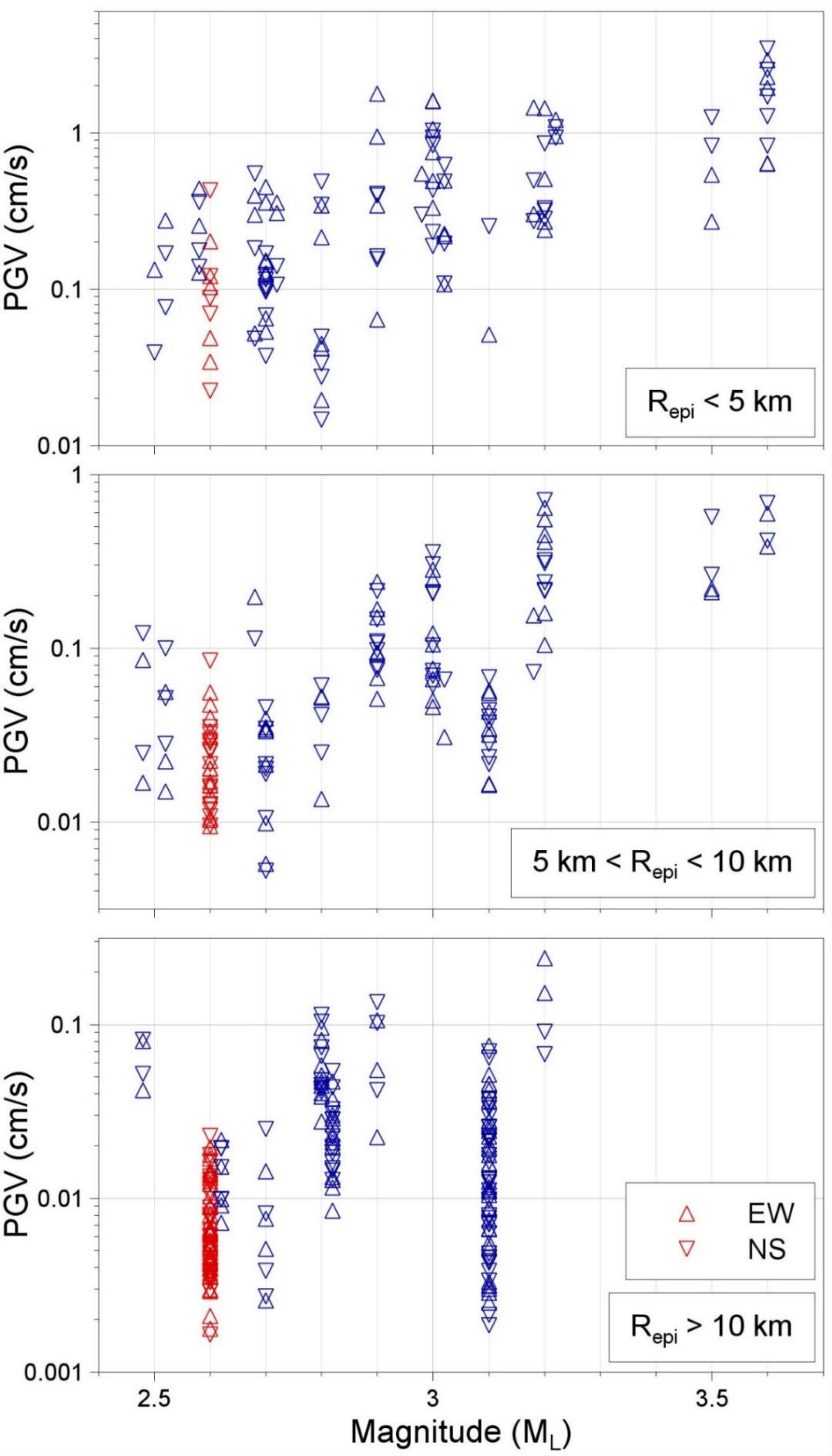


Figure 8. Individual horizontal PGV values against magnitude in the Groningen database, with symbols indicating ranges of epicentral distance. The red symbols correspond to the May 2017 Slochteren event. Where two or more events have the same magnitude, the symbols are displaced slightly left and/or right for clarity.

A more formal comparison between the Slochteren PGV levels and those obtained in previous earthquakes can be made by calculating the residuals with respect to an empirical equation derived for the prediction of PGV in the Groningen field. This GMPE (ground-motion prediction equation) was derived through regression analyses on the recorded PGV values (Bommer *et al*., 2016b). This empirical model is particularly suitable for this purpose since it is well calibrated to the magnitude range of Groningen earthquakes, whereas the ground-motion models developed for hazard and risk modelling purposes (*e.g*., Bommer *et al.*, 2017b,c) are intended for application to larger magnitude earthquake scenarios. The empirical GMPE predicts PGV values as a function of only magnitude (M_L) and epicentral distance (R_{epi}) since the inclusion of V_{S30} was found not to bring any significant improvement to the fit.

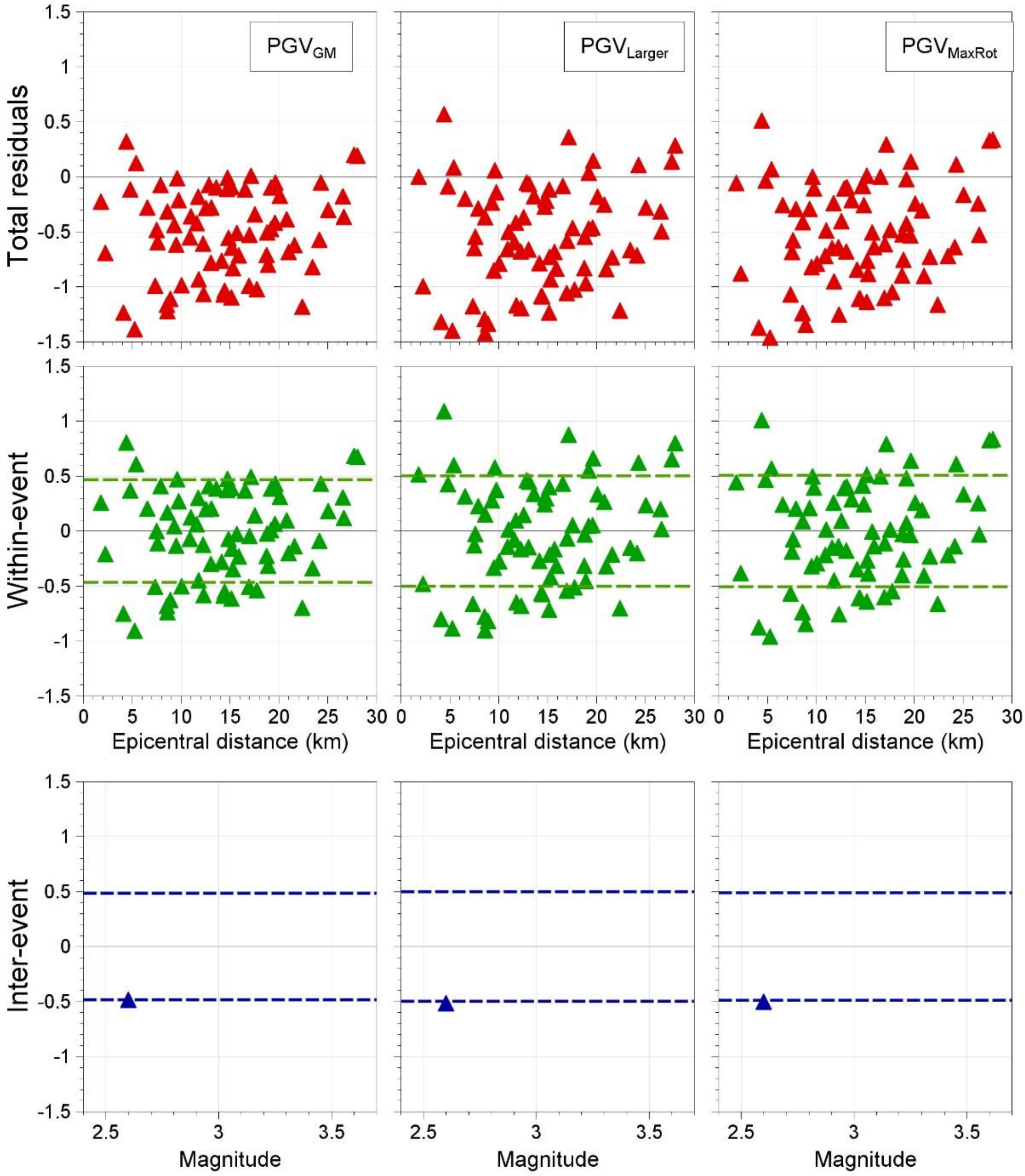


Figure 9. Total (*upper*), intra-event (*middle*) and inter-event (*lower*) residuals with respect to the empirical GMPEs for PGV from small-magnitude earthquake in Groningen. In the lower plots, the dashed lines indicate one standard deviation of the corresponding variability.

Figure 9 shows the total and within-event residuals plotted against distance and also the event term plotted against magnitude. The residuals are calculated and plotted for three different definitions of the horizontal component of motion: the geometric mean, the larger component (*i.e.*, V_{TOP}) and the largest component obtained by rotation. The same observations can be made for all three component definitions. The total residuals generally have negative values, which implies overestimation by the GMPE. There is considerable scatter exhibited by the intra-event residuals but this is not unusual in recordings from the Groningen earthquakes (or any other seismic events for that matter) and there is no discernible trend with respect to distance. However, the event term (the inter-event residual for this earthquake) is negative, showing that on average the motions from this earthquake were one standard deviation below the average level.

Finally, Figure 10 shows the geometric mean PGV values against distance, grouped by V_{S30} ranges. As for the PGA values, the highest values actually correspond to the stiffest sites whereas the amplitudes of the records from the softest sites do not exhibit large amplitudes in any persistent manner. On the other hand, the PGV values display a large spatial variability, but this is not uncommon in ground-motion recordings from tectonic earthquakes.

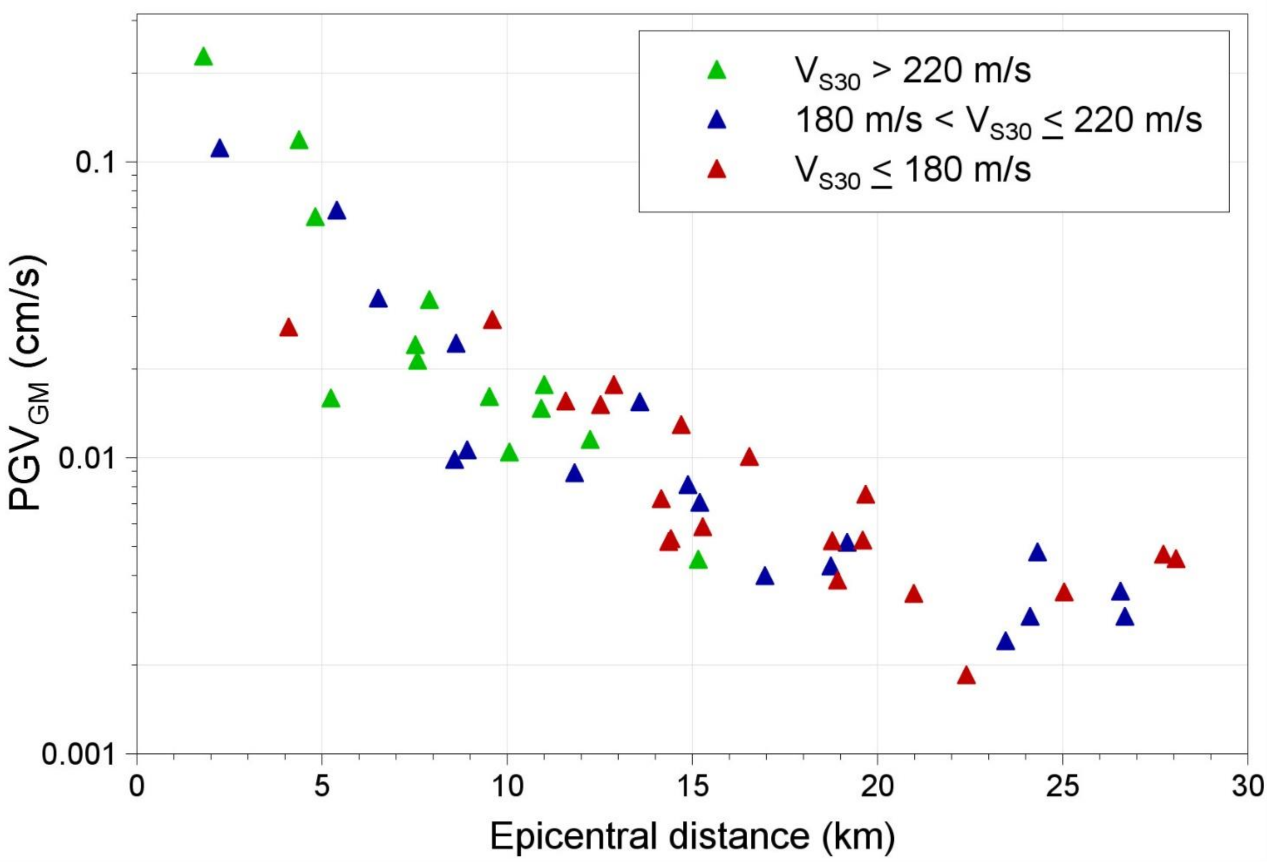
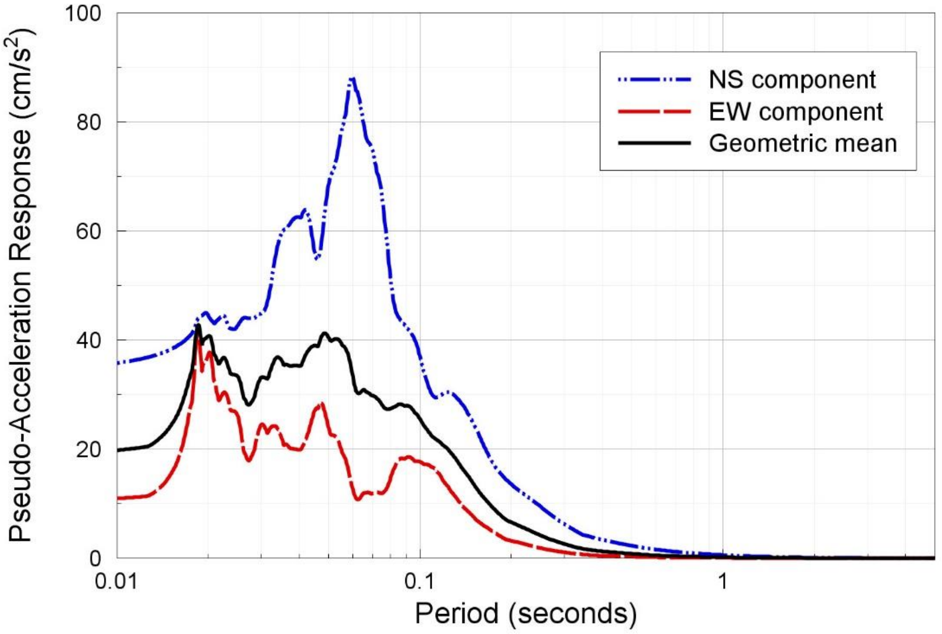


Figure 10. Geometric mean values of horizontal PGV against epicentral distance with symbols reflecting the V_{S30} class of the recording station

Acceleration Response Spectra

The 5%-damped response spectra of absolute pseudo-acceleration for the two strongest records (from stations G46 and G50) are shown in Figure 11. The spectral plots confirm the clear polarisation of these motions and also that this polarisation persists across nearly the entire the range of oscillator periods. The spectral shapes also indicate peaks below 0.1 s, which is consistent with the small magnitude of the earthquake. The high frequency content is also consistent with the observation that while the PGA values of these records appear to be slightly high, this does not hold for the PGV values.



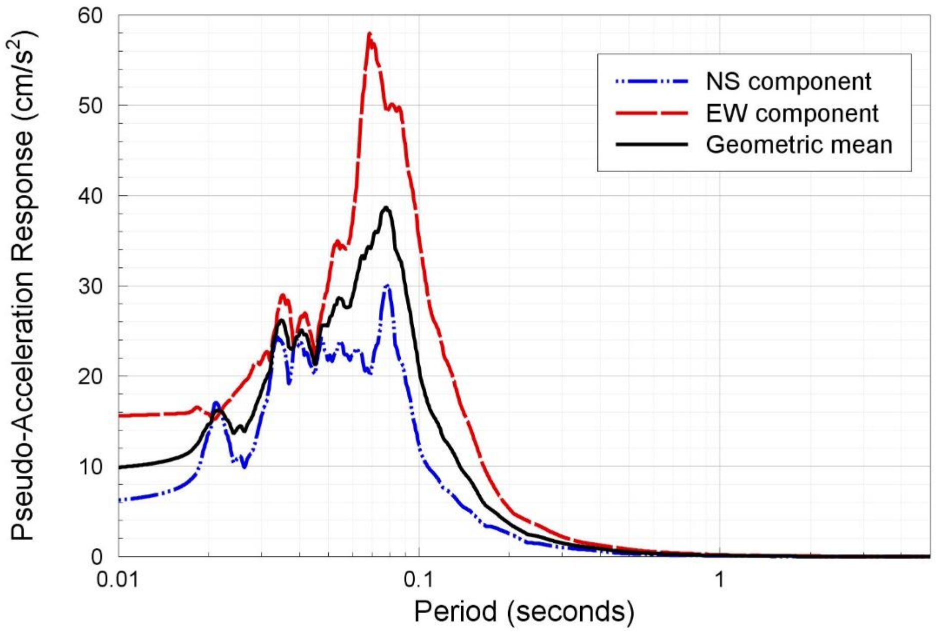


Figure 11. Acceleration response spectra (horizontal components and their geometric mean) for the recordings from the G46 (*upper*) and G50 (*lower*) stations.

Ground-Motion Durations

Figure 12 shows the horizontal acceleration and velocity time-histories from the strongest recording obtained at the G46 station, together with the Husid plots showing the build-up of Arias intensity (a measure of the energy content in the motion) over time. The time-histories show that the highest peak of both acceleration and velocity corresponds to a single spike in the motion.

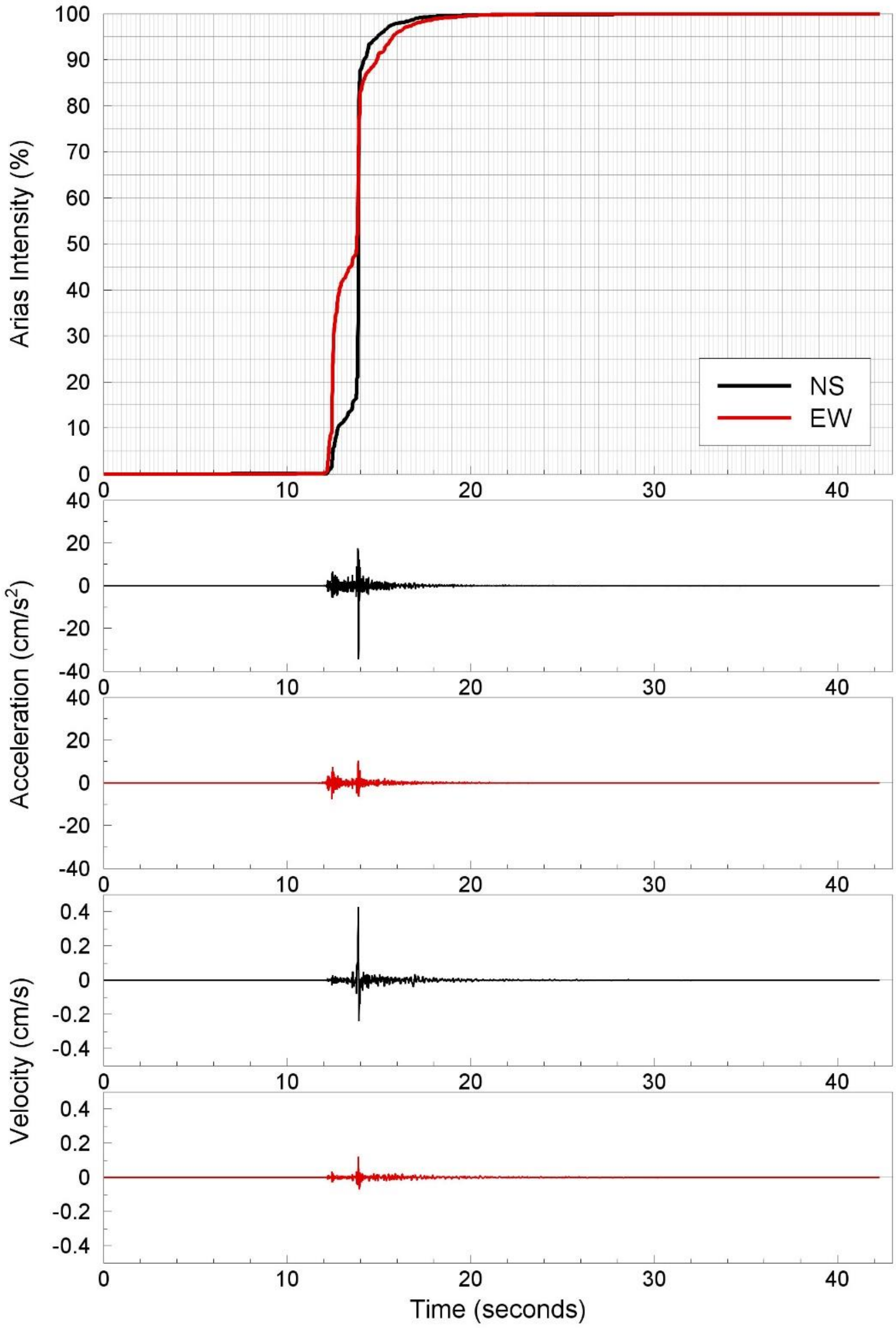


Figure 12. Horizontal acceleration and velocity components from the G46 station recordings of the Slochteren earthquakes and the Husid plots showing the distribution of the energy in the motion over time

The Groningen data show a strong negative correlation between PGA and the significant duration (measured as the time interval betweem the accumulation of 5% and 75% of the total Arias intensity), as shown in Figure 13. Such a correlation is expected because PGA decreases with increasing distance (as a result of geometrical spreading and attenuation of the seismic waves) whereas significant duration increases with distances as a result of the separation of the seismic waves and phases. However, it is also found that the residuals of PGA and duration with respect to predictive equations are also negatively correlated (Bradley, 2011). In other words, exceptionally high values of PGA will tend to be associated with unusually short durations, reflecting a conservation of energy. Figure 13 shows that the higher PGA values in the Groningen database—which are exclusively from records obtained at short epicentral distances—are associated with motions of very short duration (< 2 seconds).

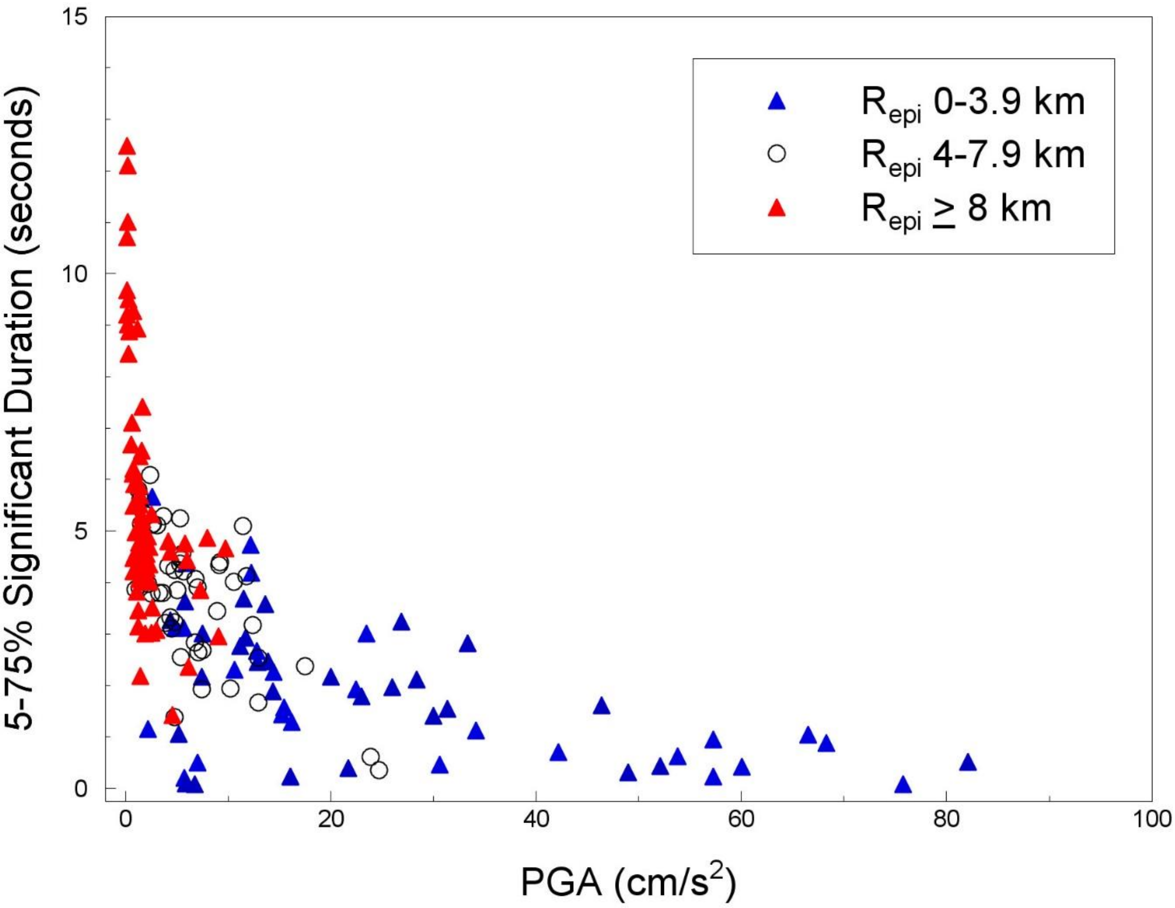


Figure 13. Individual component values of PGA and significant duration in the Groningen ground-motion database, showing the strong inverse relationship between these two parameters (Bommer *et al.,* 2016a)

Figure 14 shows a similar plot for the Slochteren recordings, which show exactly the same pattern, confirming that the higher PGA values are associated with very short duration motions.

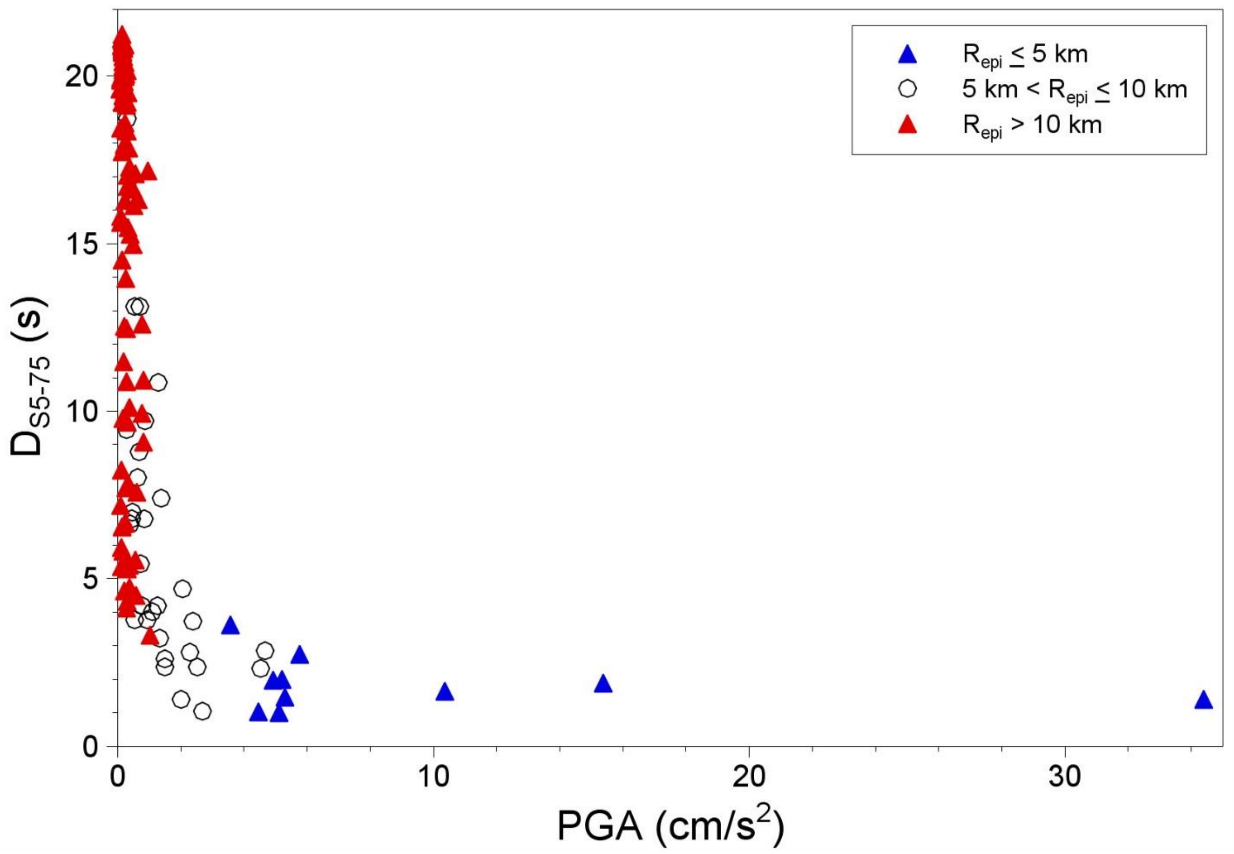


Figure 14. Individual component values of PGA and significant duration for the recordings of the Slochteren earthquake

Results Full-Wave Form Inversion

An independent assessment of the location and focal mechanism solution of the Slochteren M2.6 event was obtained through the application of two different approaches: the Full Wavefield Inversion (FWI) and the Ray-Based method. Both methods were performed on a select subset of data recorded by the closest KNMI stations located within 9 km of the KNMI-determined epicenter location (stations marked as black triangles in figure 15). Event location results from both FWI and Ray-Based method show virtually co-located epicentral locations with that estimated by the KNMI: the differences are within several 10's of meters (figure 15; brown dot KNMI location, black dot location based on FWI). Full Wavefield modeling shows the best fitting event depth solution is within the reservoir interval.

The focal mechanism solutions obtained by FWI and the Ray-Based method are remarkably consistent (within 10° in strike and dip, and within 30 in rake) and indicate a normal fault striking in the North-South general direction. This type of mechanism is in general agreement with several faults in the immediate vicinity of the hypocenter. Given the intrinsic uncertainty in the location of faults and the earthquake epicenter of a few tens of meters and the densely populatied fault map, there are several candidate faults with a normal sense of slip that could host this event.

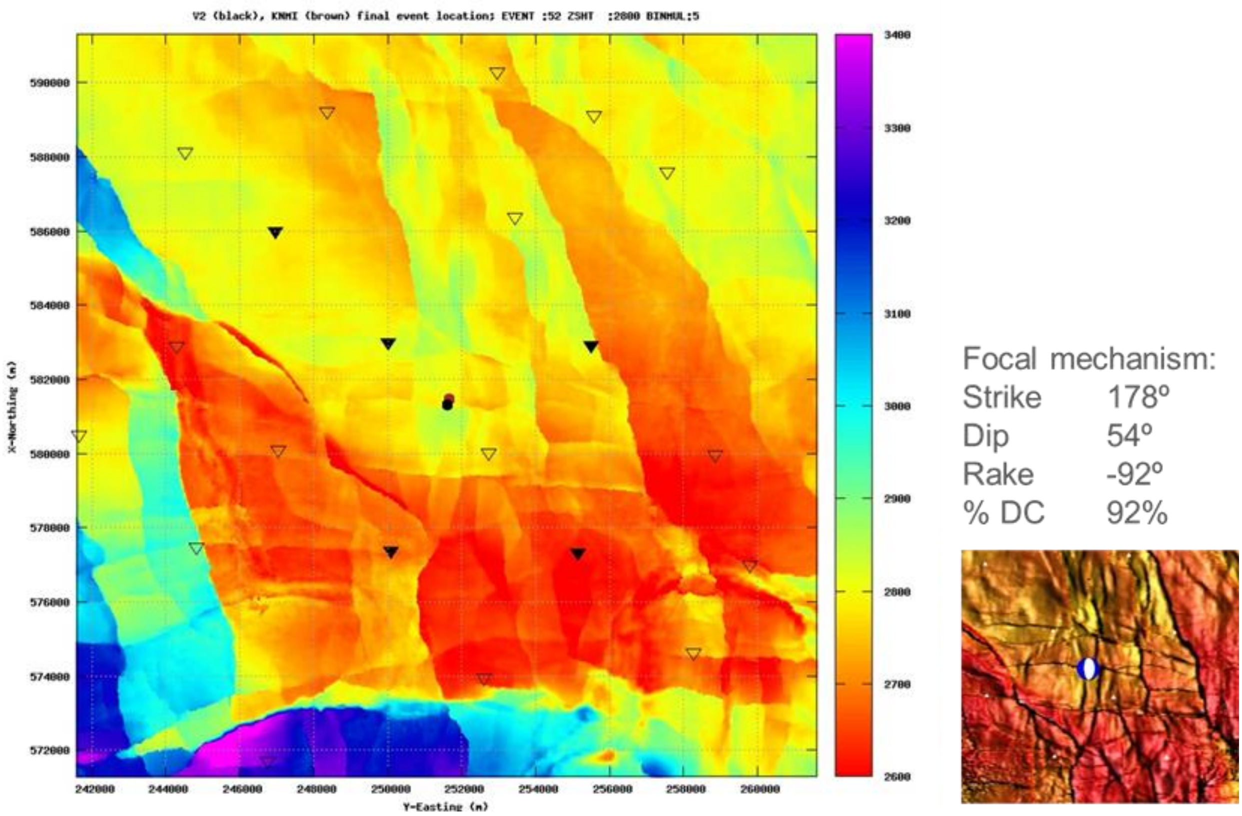


Figure 15. Left: depth map outlining the top of the Rotliegend reservoir. KNMI Slochteren event location (brown circle) and the NAM location (black circle) are virtually co-located. Triangles denote KNMI seismometer locations. Dark triangles are stations used in the NAM location algorithm. Right: moment tensor solution and its location with respect to the faults mapped based on the seismic data interpretation. Moment tensor shows normal slip motion on a North-South striking fault.

Gas production and reservoir pressure

Gas production from the wells in the vicinity of the epicenter of the Slochteren earthquake is shown in figures 16 and 17. These indicate that production from these clusters has been within normal operating conditions, and there were no extraordinary production changes leading up to the seismic event on 27/5/2017.

Figure 18 shows a three-dimensional view from the reservoir simulator, highlighting that the epicenter is within a densely faulted area (even though the dynamic simulator cannot capture all 1100+ faults interpreted from seismic). As evidenced by figures 16 and 18, there is no well producing from the area in the direct vicinity of the epicentre. The calibration of the simulation model is in this area of the field well-constrained, with good connectivity established within the area based on 50+ years of production history.

Figure 19 shows that away from the production clusters the predicted reservoir pressure changes are very gradual, due to the dampening effect of a highly compressible fluid (gas) in a porous medium. This highly gradual change in reservoir pressure is also clearly visible from figures 20 and 21, showing pressure along a cross-section through the reservoir at various times. Figure 22 gives the pressure trend in time for the gridblocks near the fault, which possibly hosted the earthquake. The onset of the field-wide North-South pressure trend can be observed in line with the start of the regional production caps in January 2014.

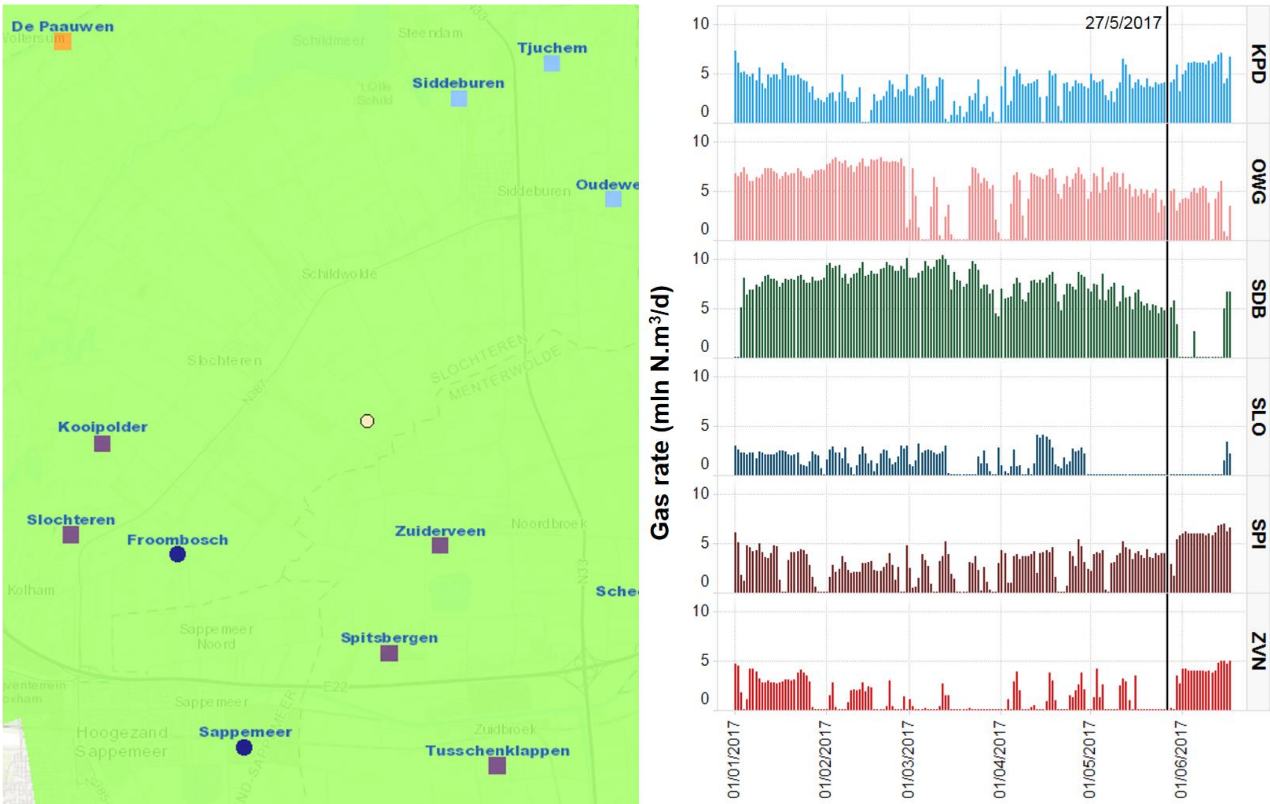


Figure 16. Daily production rates of clusters in the vicinity of the epicenter (yellow circle). The abbreviation of the clusters; KPD = Kooipolder, OWG = Oudeweg, SDB = Siddeburen, SLO -= Slochteren, SPI = Spitsbergen and ZVN = Zuiderveen.

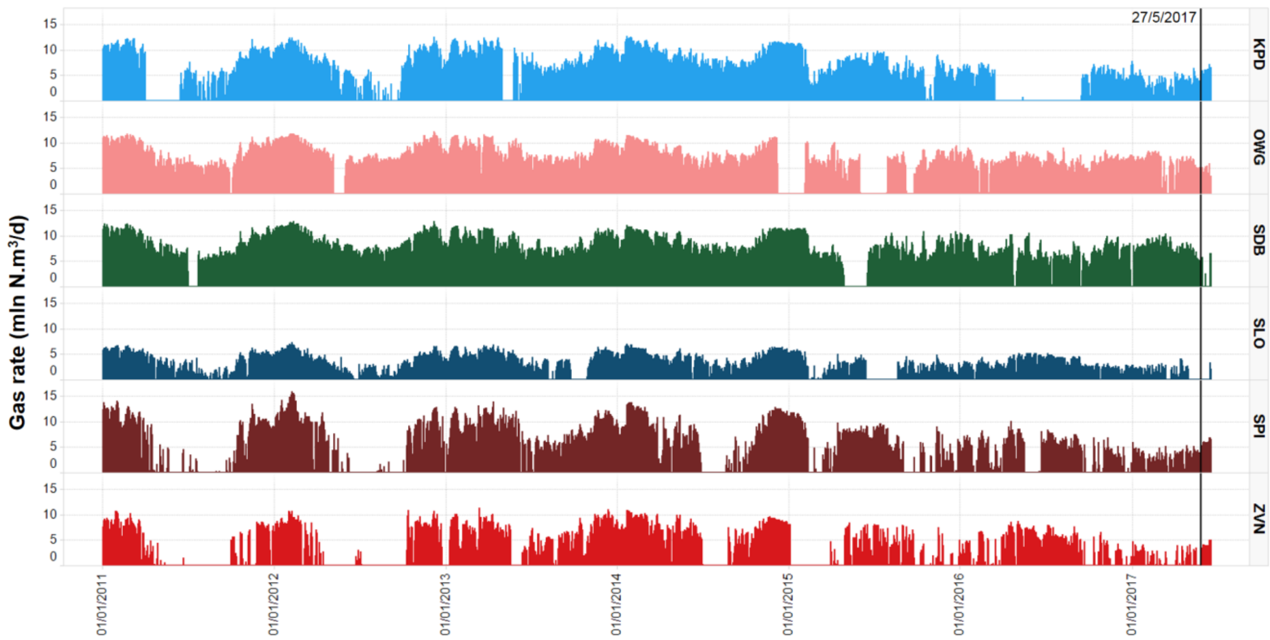


Figure 17. Longer term trend in daily production rates of clusters in the vicinity of the epicenter

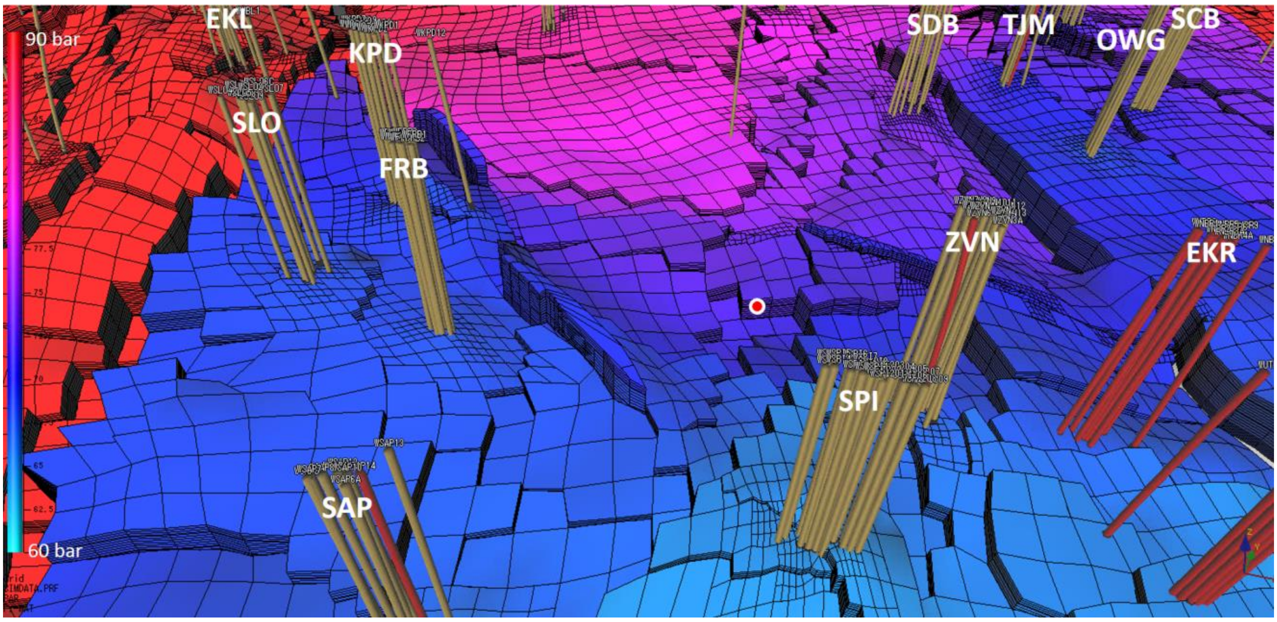


Figure 18. 3D visualisation of reservoir pressure (31/12/2016) from the full field model (V4) in the top of the Slochteren formation. Colorscale clipped at 90 bar. Approximate epicenter location is indicated as a red circle.

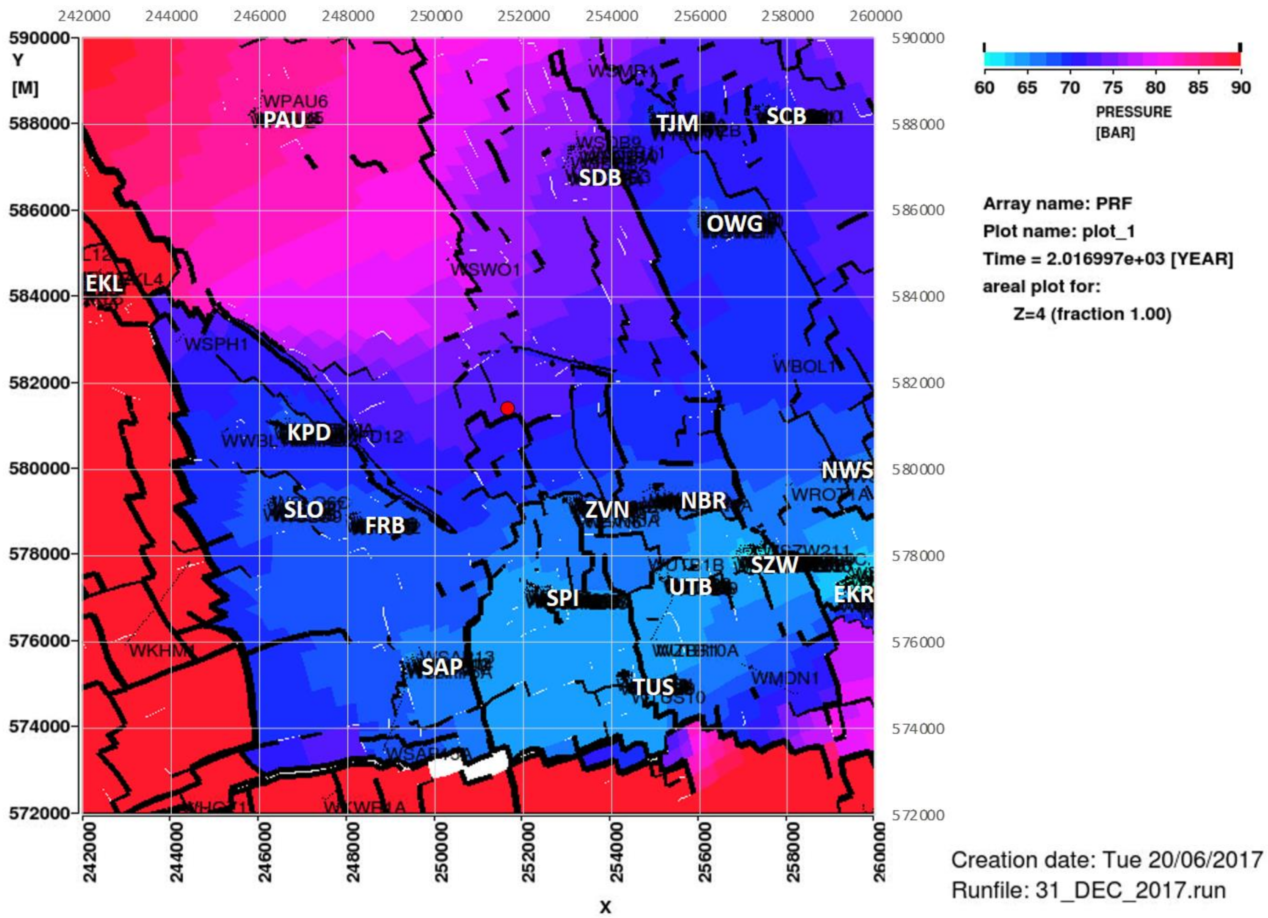


Figure 19. Reservoir pressure (31/12/2016) from the full field model (V4) in the top of the Slochteren formation. Colorscale clipped at 90 bar. Approximate epicenter location is indicated as a red circle.

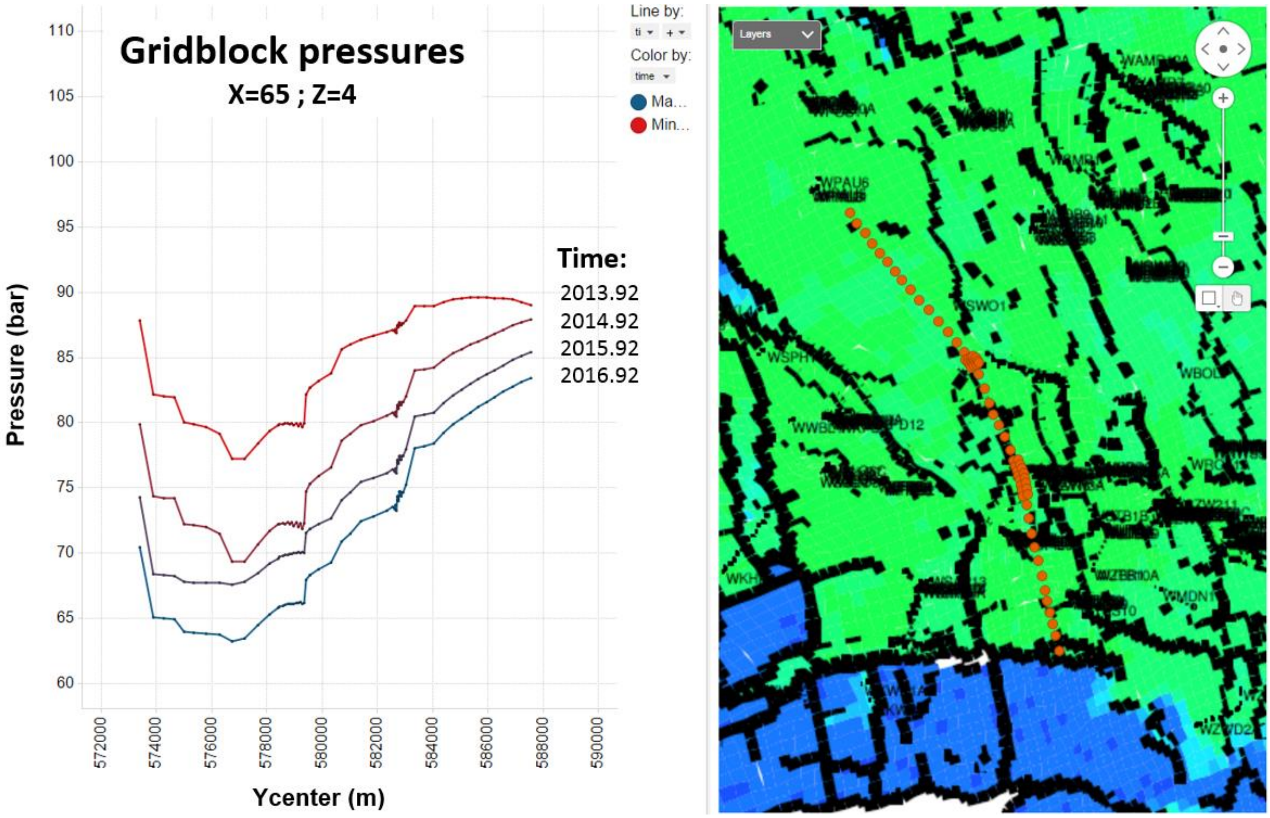


Figure 20. Pressure cross-section for gridblock X=65, at yearly intervals

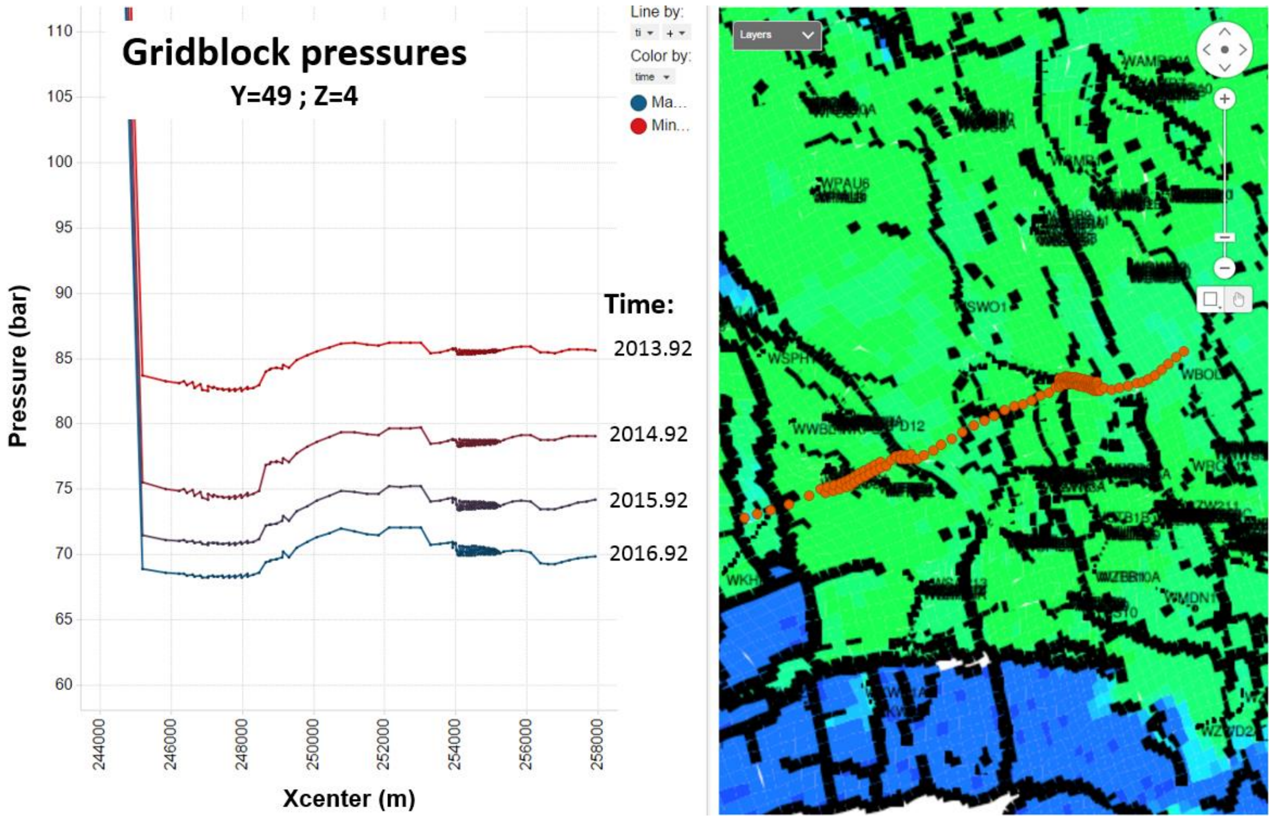


Figure 21. Pressure cross-section for gridblock Y=49, at yearly intervals

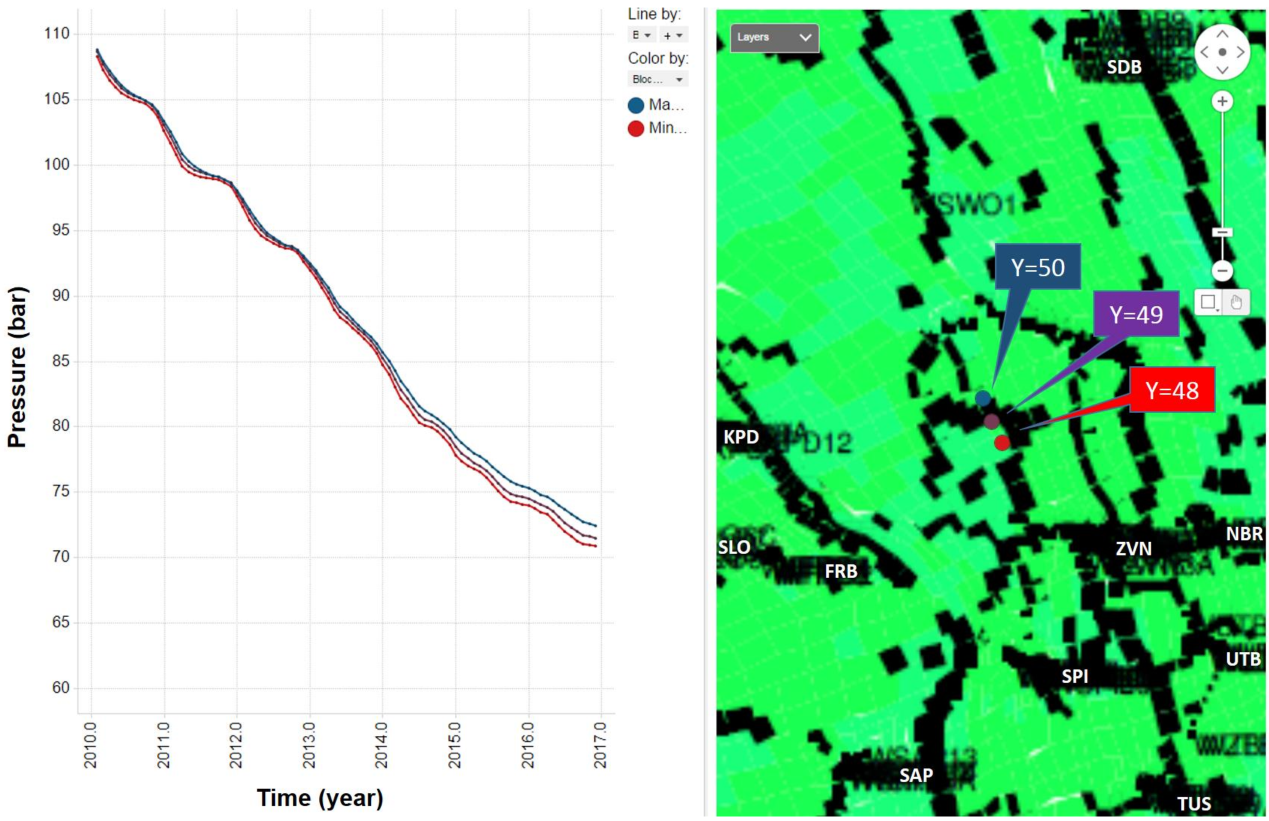


Figure 22. Gridblock pressures in time

Conclusions

The ground-motion recordings from the recent M_L 2.6 earthquake near Slochteren are consistent with previous ground motions recorded in the Groningen field. The general level of the motions, in terms of PGV, are appreciably lower than average but within the general distribution indicated by the 178 records in the database used to derive the current predictive models deployed in the seismic hazard and risk assessment.

The only sense in which the Slochteren ground motions are in any way ‘exceptional’ is that the event has been recorded on a larger number of accelerographs than any previous earthquake, as a direct result of the expansion of the KNMI seismic monitoring network in the Groningen field. As a consequence of the denser instrumental coverage, the ground motion field is more richly sampled than in previous earthquakes, thereby increasing the chances of capturing higher—and lower—epsilon values in terms of peak motions that diverge from the median predictions.

In the measurement and control document (Ref. 9) the choice has been made to base interventions and reports on a measured value of PGA rather than a calculated max value (at the epicentre). This choice has been made for reasons of speed (a measured PGA is immediately available) and for reasons of clarity (no ambiguity of calculation method). An obvious disadvantage of this is that we may (very seldom) be confronted with PGA values that initially seem at odds with equivalent measurements in the past, whereas this will often be related to proximity of the earthquake to a measurement-station, like has happened in this case of Slochteren.

On the basis of these simple analyses, nothing emerges that indicates a need for modifications to the current models for estimating ground motions due to Groningen earthquakes. Moreover, the Slochteren earthquake recordings will now be added to the database used in the development of the V5 GMM since they enrich the dataset and in particular the spatial density of the available recordings.

The epicenter of the Slochteren earthquake has been determined by three different methods (KNMI method, Full-Wavefield Inversion and the Ray-Based method). The results of these methods agree very well. The focal mechanism solutions obtained by FWI and the Ray-Based method are remarkably consistent (within 10° in strike and dip, and within 30 in rake) and indicate a normal fault striking in the North-South general direction. This type of mechanism is in general agreement with several faults in the immediate vicinity of the epicentre.

Evaluation of the production from the clusters in the vicinity of the epicentre of the Slochteren earthquake during the period prior to the earthquake shows, no exceptional changes in production took place. Similarly, an analysis of the reservoir pressure in the epicentrl area, which was located at considerable distance from any of the clusters, showed only very gradual pressure changes.

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