NAM

Special Report on the
earthquake density and activity rate following the earthquakes in Appingedam (M_L=1.8) and Scharmer (M_L=1.5) in August 2017

Datum September 2017

Editors Jan van Elk & Dirk Doornhof

Contents

1 Introduction

On Tuesday 29th August 2017 an earthquake of magnitude M_L = 1.8 occurred towards the centre of the Groningen gas field near Appingedam (Fig. 1). This earthquake contributed to the event rate statistic and caused the earthquake density monitoring parameter of the Measurement and Control Protocol (or Meet- en regelprotocol; MRP) to exceed the threshold for the “signaleringsniveau” of 0.25 events / ($km^2 \cdot 12$ months) for earthquakes larger than M_L=1.0 (Ref. 3 and 4). This is the first time the “signaleringsniveau” has been exceeded since the Meet- en Regelprotocol came into effect.

This report is issued as part of direct action taken by the operator in accordance with the appropriate alertness level being triggered.

This report assesses the characteristics of the Appingedam earthquake (M_L=1.8) as well as the group of events that collectively contributed to the threshold exceedance and the gas pressure development in the reservoir, providing context for the environment in which the seismicity occurred.

Figure 1 *Epicentre and magnitude of the Appingedam earthquake on 29th August 2017 as reported by KNMI. Note: UTC is the time standard commonly used across the world. The world's timing centres have agreed to keep their time scales closely synchronised - or coordinated - therefore the name Coordinated Universal Time. At the time of the Appingedam earthquake, there was a 2 hours difference between UTC and CEST (Central European Summer Time). The earthquake therefore took place at 7:40 UTC or 9:40 CEST.*

The day after the earthquake in Appingedam, on the 30th August 2017, an earthquake of magnitude M_L=1.5 was recorded with an epicenter near Scharmer. This earthquake raised the number of earthquakes with magnitude larger or equal to M_L=1.5 during the last 12-month period to 16. As a result, the “waakzaamheidsniveau” threshold for the monitoring parameter of activity rate was exceeded. This was set at 15 earthquakes of magnitude larger than or equal to M_L=1.5 during the previous 12 months. This is a lower monitoring level in the escalation structure of the Meet- en Regelprotocol, than the “signaleringsniveau” (Fig. 2). The epicenter of the Scharmer earthquake is located too far to the south to impact the earthquake density maximum, observed in the area between Appingedam and Loppersum.

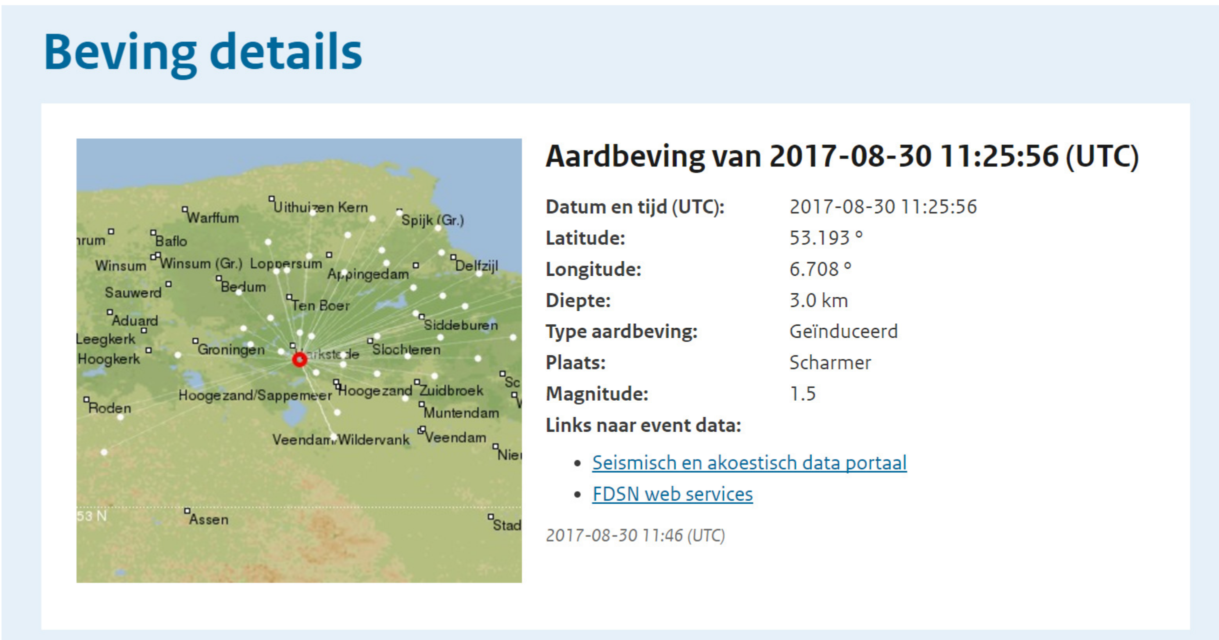


Figure 2 *Epicentre and magnitude of the Scharmer earthquake on 30th August 2017 as reported by KNMI.*

This report addresses the exceedance of both the “signaleringsniveau” (signaling level) by earthquake density after the Appingedam earthquake and the “waakzaamheidsniveau” (vigilance level) by the activity rate after the Scharmer earthquake. As both are related to the number of earthquakes, emphasis in this reports will be on the exceedance of the higher “signaleringsniveau”, as a result of the Appingedam earthquake.

In this document, reference will be made to the Meet- en Regelprotocol. As the original version of the protocol is written in Dutch, the text in the protocol has been translated in English. In this document, we’ll refer to this English translation. However, in case of conflict the Dutch text is leading.

2 Acknowledgements

In this report, we make use of assessments made by NAM, Rijswijk Laboratory (Shell) and Houston Laboratory (ExxonMobil). The methods used for the analysis of the relatively low magnitude earthquakes presented in this report are state-of-the-art and continuously further developed by staff working in these laboratories. These methods will be subject to further improvements in subsequent Special Reports prepared as part of the Meet- en Regelprotocol.

We are especially indebted to the staff at the Houston Laboratory (ExxonMobil), who are currently coping with severe flooding of their city in the aftermath of hurricane Harvey.

3 Operating the Meet- en Regelprotocol

Earthquake density is measured as the number of earthquakes with magnitude larger than M_L = 1.0 on the Richter scale per square kilometer per year. The applied calculation method is based on an internationally accepted method (quartic kernel function). Earthquake density is calculated using a 12-month rolling window. There are two important reasons for monitoring earthquake density; firstly, because it can indicate higher seismicity in the future (higher magnitudes) in a particular region, and secondly, because it indicates elevated local seismicity.

With the Appingedam earthquake (M_L = 1.8), the event density level exceeds 0.25 events / ($km^2 \cdot 12$ months) for earthquakes larger than M_L = 1.0, for a particular region. This threshold exceedance denotes the start of the decision escalation model as outlined in the second level (signalling level, yellow bar) of the Structure and Notification System of the MRP (Fig. 3). In principle, this level involves formulating direct actions, initially by the NAM Risk Coordination Team Earthquakes (RCT), which provides a brief analysis of the event and a set of accompanying measures within 48 hours, which can be implemented within a period of a few weeks. This involves using measures that have already been identified at alertness/vigilance level. Generally, a proposed measure has a regional nature. The impact of measures on safety will be discussed with SodM. In most cases, the measure will be implemented after consulting with GTS and GasTerra and, in some cases, after approval from the Minister of Economic Affairs.

The day after the earthquake in Appingedam, on the 30th August 2017, an earthquake of magnitude M_L = 1.5 was recorded with an epicenter near Scharmer. As the higher "signaleringsniveau" was already reached by the earthquake density parameter the day before, focus of this report will be on the analysis and response to the exceedance of the higher level by this last parameter.

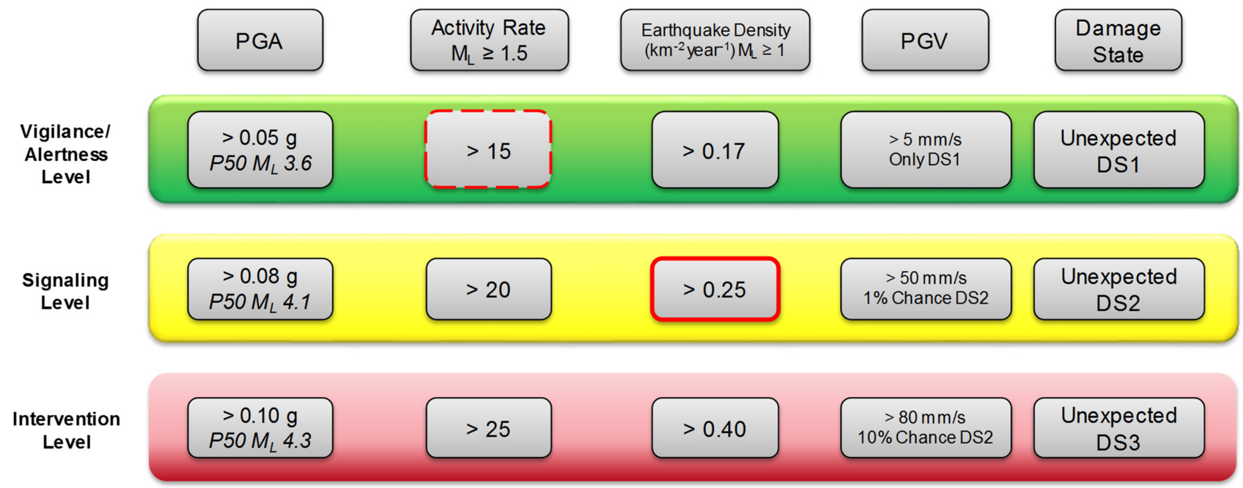


Figure 3 *Diagram showing the structure of the notification system. The second level (the signalling level) is the start of the decision escalation model as outlined in the yellow bar. The Appingedam M_L = 1.8 earthquake contributes to the exceedance of the value outlined in red. The Scharmer event M_L = 1.5 occurred on 30-08-2017 and contributed to the Activity Rate exceeding a vigilance level, outlined in dashed-red line.*

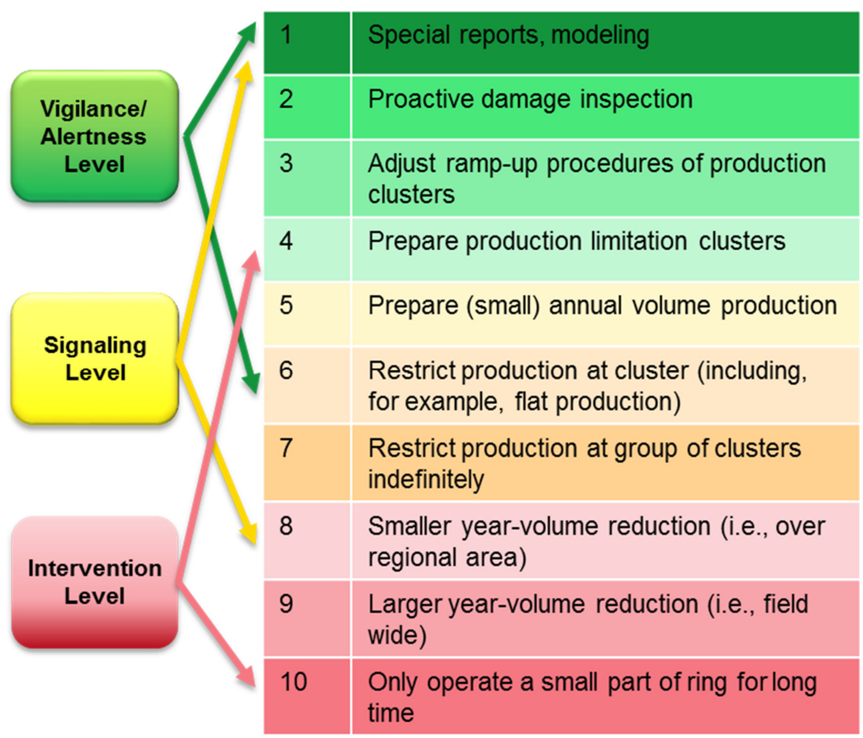


Figure 4 *The link between the notification and response system and the intended measures. The middle column shows the range of possible measures that can be taken; followed by the column with the evaluation framework and criteria used. Measures 1 to 8 will generally be implemented without the intervention of the Minister. Measures 9 and 10 will almost always require the Minister to intervene.*

4 Appingedam M_L = 1.8 earthquake overview

The Appingedam earthquake of 29th August 2017 (09:40 hrs CEST) was recorded by over 20 stations with clear P- and S waves arrivals (Fig. 5). The magnitude of the earthquakes was determined by KNMI to be M_L = 1.8 on the Richter scale.

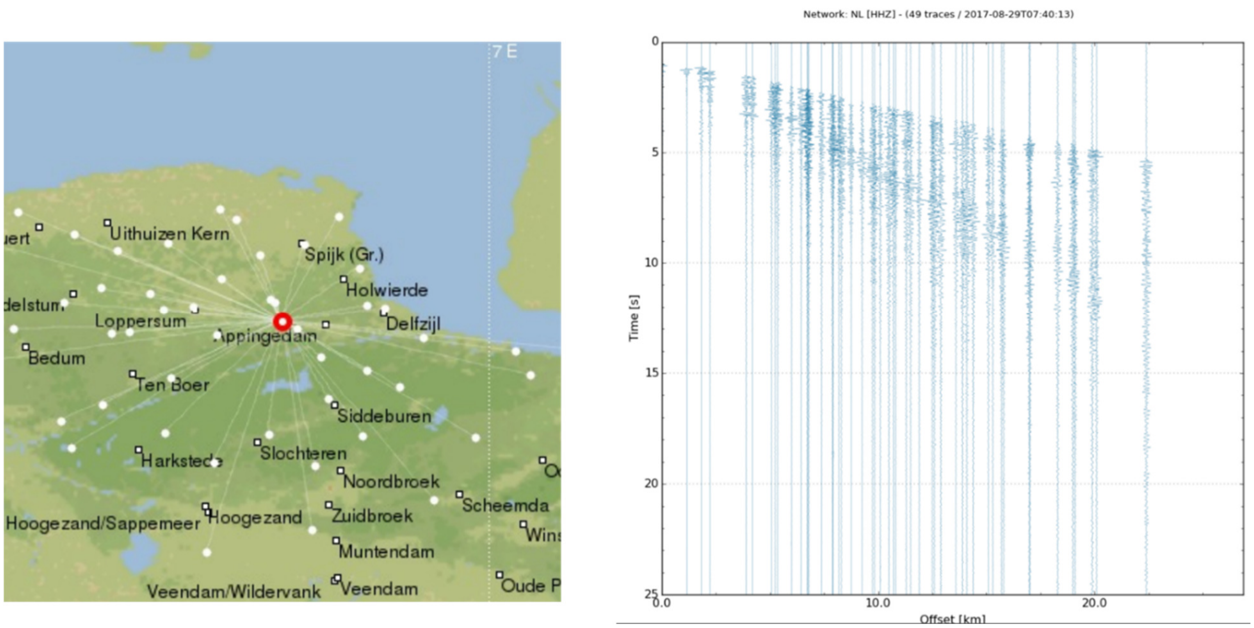
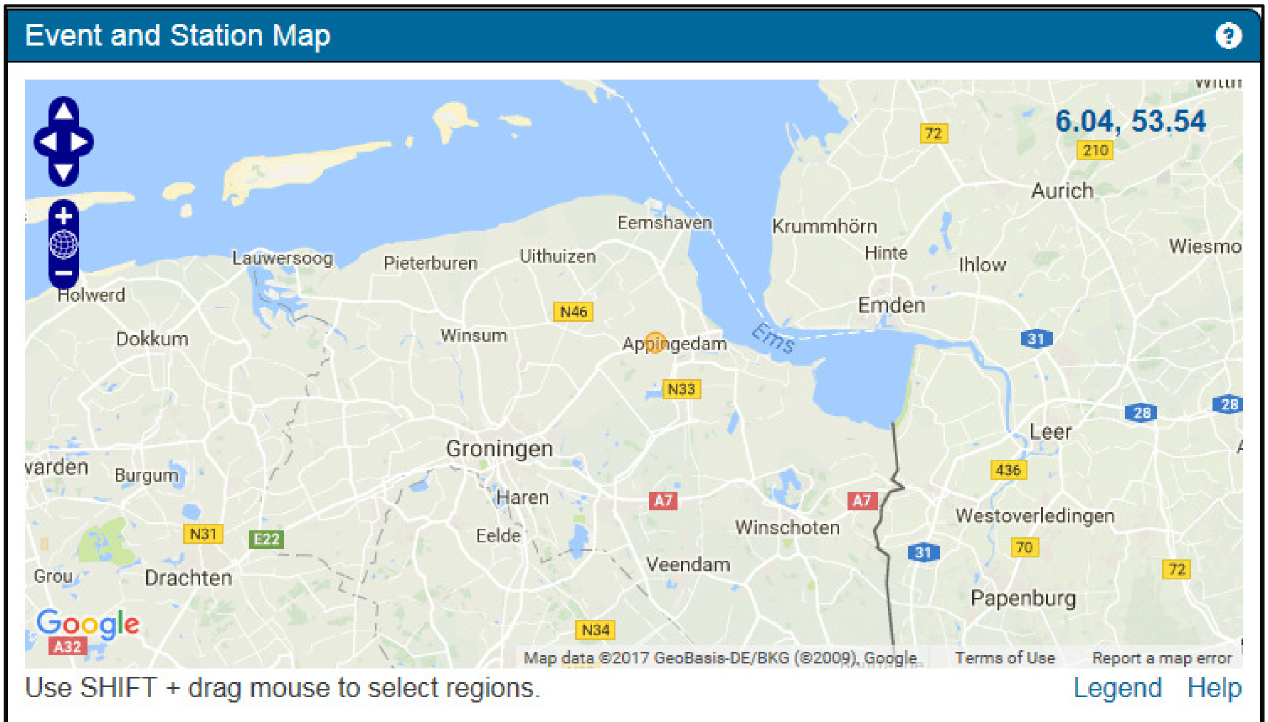


Figure 5 *Epicentre (left) and records (right) of the Appingedam earthquakes obtained by over 20 stations. The time record for each accelerometer response are shown against distance from the epicentre (horizontal) as measured and reported by KNMI. The amplitude of each record has been increased to be able to show noticeable response for each record. P- wave and S- wave arrivals can clearly be observed.*

Earthquakes of this magnitude occur regularly in the Groningen field and can only under very specific circumstances be felt at surface. As the Appingedam earthquake had a magnitude below M_L = 2.0, peak ground acceleration maps will not be made available in the Rapid Raw Strong Motion Data portal for The Netherlands operated by KNMI (Fig. 6). Please refer to the Appendix section for the review of the ground motion data of other events that contributed to the exceedance of the earthquake density signalling level threshold.



Event and Station List

Request: Freeze | Delete Stations | Save Stations | Delete Events

Events (1 event)

Origin Time	Mag.	Type	Lat.	Long.	Depth	Place
☑ 2017-08-29T07:40:13	1.8	MLn	53.3220	6.8220	3.0	Appingedam

Figure 6 Event and location data for the Appingedam earthquake.

Figure 7 shows the PGV values for all components of all stations that have recorded the Appingedam earthquake. The two outliers (highest values) correspond to two vertical PGV components, while the others are either vertical or horizontal velocities. All recorded ground motions are well below 2 mm/s. Based on the SBR guidelines, at these Peak Ground Velocity (PGV) no building damage is expected. Except for two measurements of vertical velocity, all recorded velocities are below 0.4 mm/s.

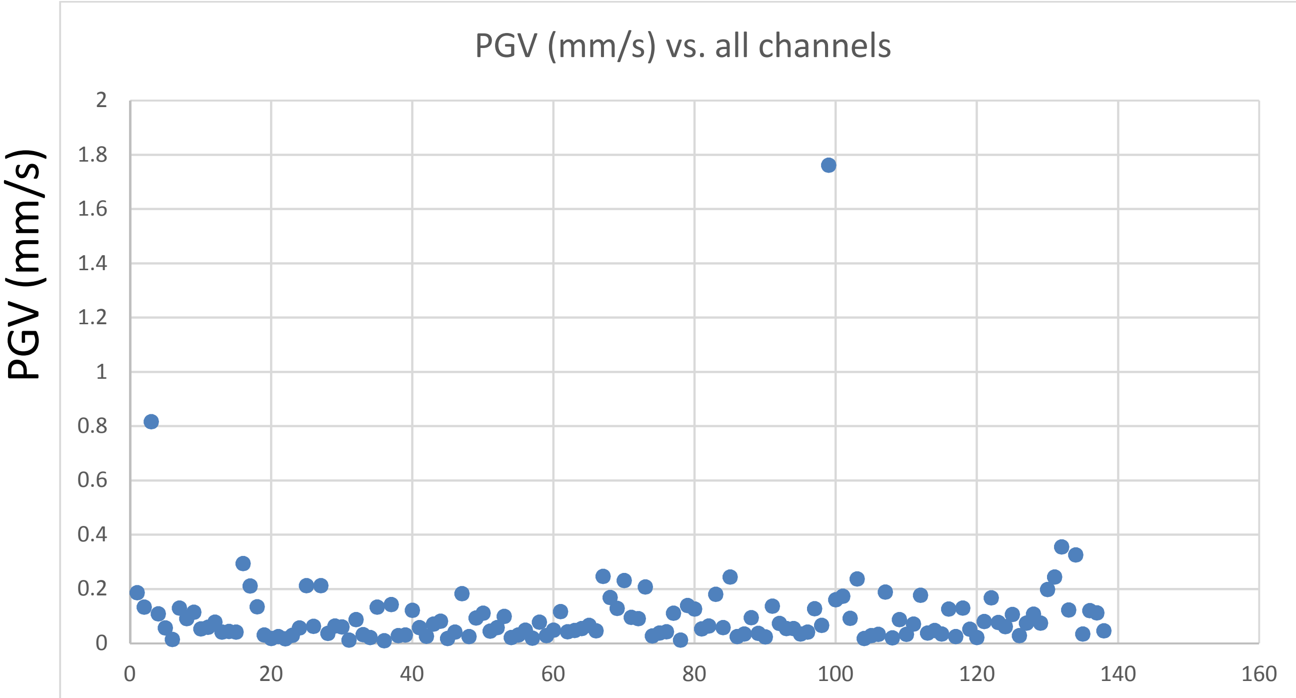


Figure 7 *The PGV values for all components of all stations where the Appingedam (M_L=1.8) was recorded. The two outliers (highest values) correspond to measurements in the vertical direction.*

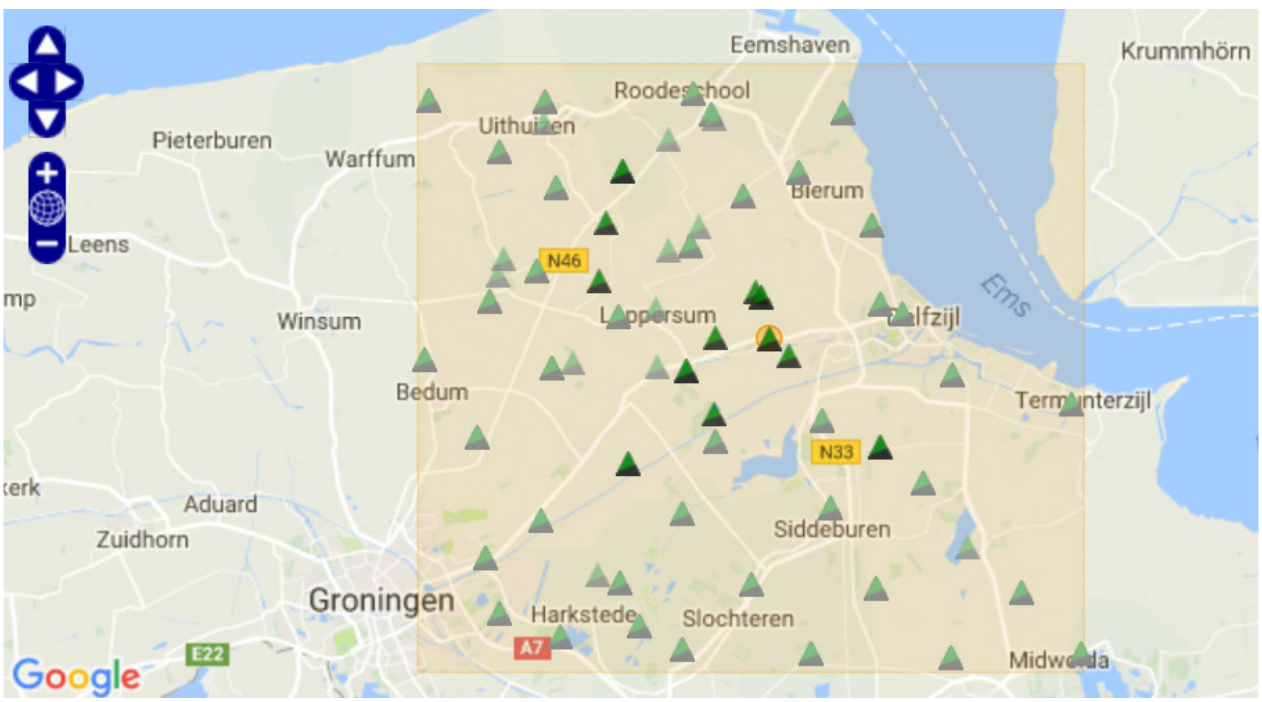


Figure 8 *Map of the 12 geophone stations where the best records of the Appingedam (M_L=1.8) were obtained with clear P- and S-wave arrivals.*

The earthquake was well recorded at many stations despite the relatively low magnitude. At twelve stations a clear S-wave was recorded (Fig. 8). The highest velocity was recorded by station G674 (Longitude 6.82 and Latitude 53.32). Figure 9 shows the short vertical acceleration measured by this station. This earthquake signal corresponds to the single highest velocity (almost 1.8 mm/s) observed as shown in figure 7.

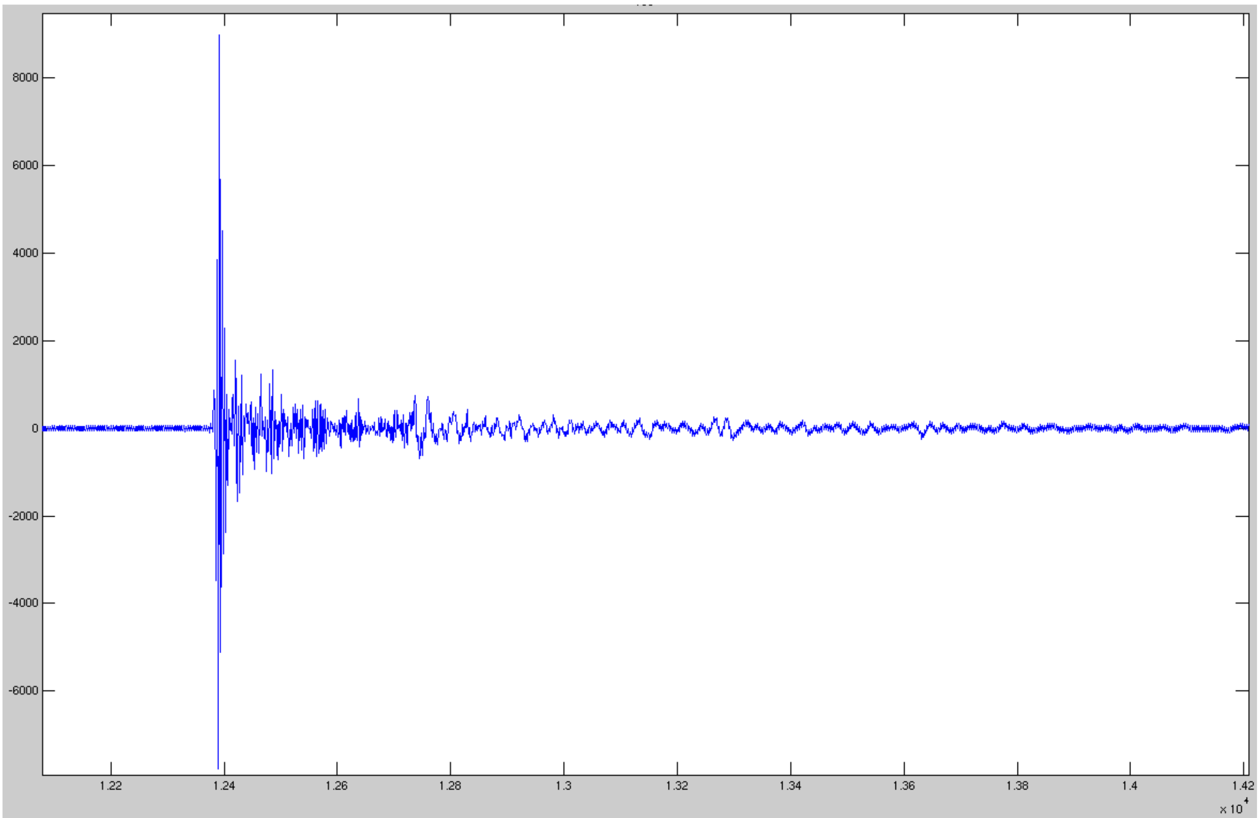


Figure 9 The vertical PGV recorded at station G674 (Longitude 6.82 and Latitude 53.32).

5 Schamer M_L = 1.5 earthquake overview

Figure 10 Epicentre and magnitude of the Scharmer earthquake on 30th August 2017 as reported by KNMI.

The day after the earthquake in Appingedam, on the 30th August 2017, an earthquake of magnitude M_L = 1.5 was recorded with an epicenter near Scharmer. This earthquake raised the number of earthquakes with magnitude larger or equal to M_L=1.5 during the last 12-month (the activity rate) to 16. As a result, the “waakzaamheidsniveau” threshold for the monitoring parameter of activity rate was exceeded. This was set at 15 earthquakes of magnitude large than or equal to M_L = 1.5 during the previous 12 months. This is a lower monitoring level that the “signaleringsniveau” (Fig. 3). The epicenter of the Scharmer earthquake is located too far to the south to impact the earthquake density, observed in the area between Appingedam and Loppersum.

The activity rate is a global parameter over the Groningen field. However, it is primarily driven by the same earthquakes in the Appingedam and Loppersum area that have also contributed to the earthquake density in this area to exceed the threshold for the “signaleringsniveau”. As the activity rate exceeded the threshold to the lower “waakzaamheidsniveau”, emphasis in this report will be on analysis of the earthquake density. Analysis of the earthquakes in the Appingedam – Loppersum area will implicitly also address the exceedance of the field-wide activity rate.

Place	Date	Magnitude	Easting	Northing
Schildwolde	02-09-2016	2.1	252306	582249
Wirdum	01-11-2016	1.9	249653	591435
Wirdum	01-11-2016	2.2	249776	591994
Appingedam	20-11-2016	1.6	251641	595371
Loppersum	07-12-2016	1.8	247385	594953
Eems-Dollard	15-12-2016	1.6	257935	600178
Startenhuizen	15-02-2017	1.6	243298	599774
Onderdendam	06-03-2017	1.6	233873	594044
Zeerijp	11-03-2017	2.1	246483	596828
Woldendorp	04-04-2017	1.8	261993	588355
Scharmer	26-04-2017	2.0	243573	581189
Stedum	03-05-2017	1.5	244298	592557
Overschild	16-05-2017	1.7	249555	589652
Slochteren	27-05-2017	2.6	251654	581456
Appingedam	29-08-2017	1.8	250606	593792
Scharmer	30-08-2017	1.5	243274	579292

Table 1. List of events that contributed to the exceedance of the vigilance level for Activity Rate greater than or equal to M_L = 1.5 field-wide. The entries in blue denote the same events that also contribute to the Earthquake Density *threshold exceedance.*

6 Earthquake density

6.1 Development of Earthquake Density

Earthquake density is a parameter used in the Measurement and Control Protocol (Meet- en Regelprotocol). The threshold values in the current Measurement and Control Protocol are based on a historical analysis of $M \geq 1.0$ earthquakes (Fig. 11). The current exceedance of the “signalling level” is not unprecedented; This level was exceeded in several areas in recent history (Fig. 11).

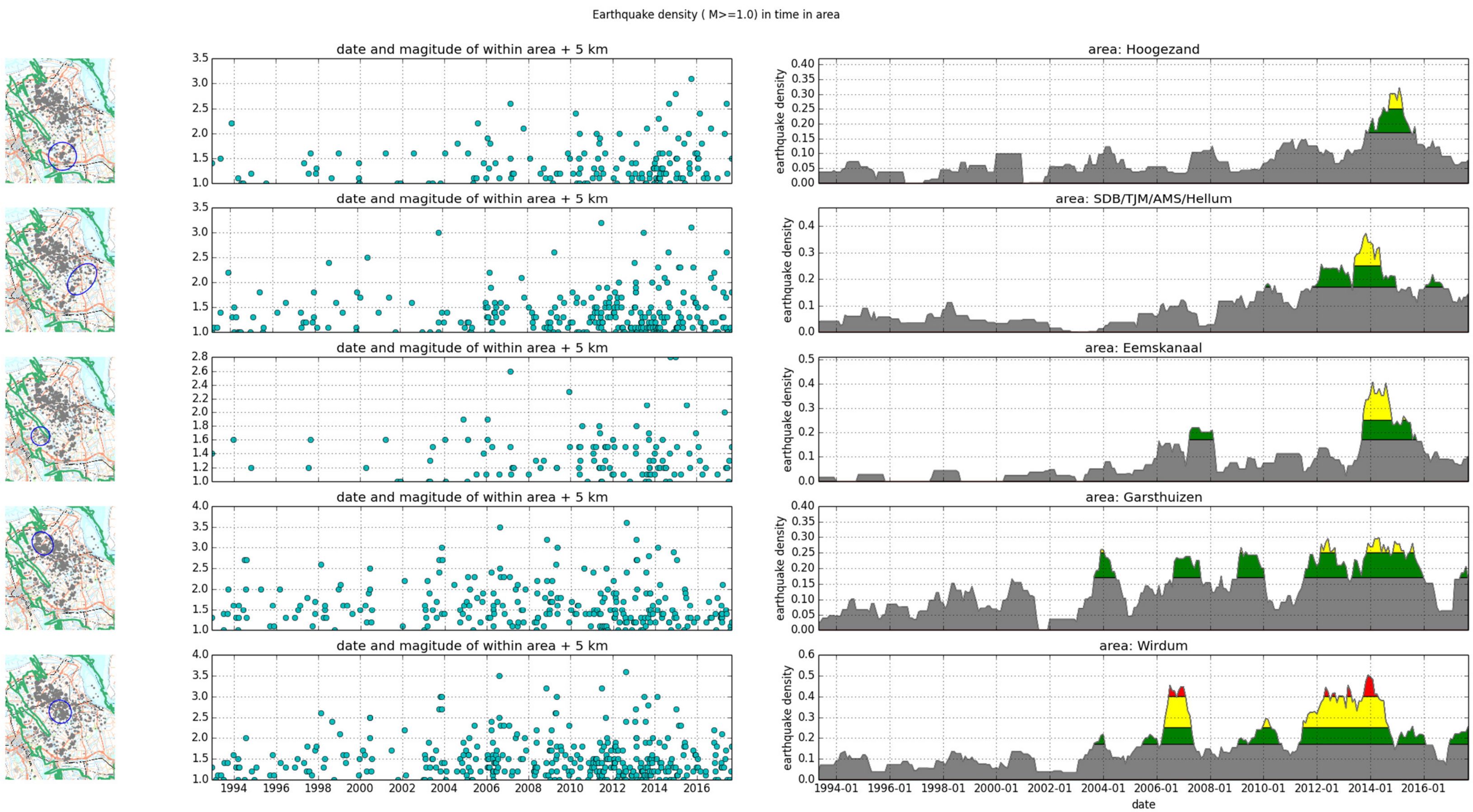


Figure 11 *The historical earthquake density around a number of areas (Figure taken from Meet- en Regelprotocol).*

6.2 Earthquakes contributing to threshold exceedance

The earthquakes with magnitude larger than or equal to $M_L = 1.0$, that have contributed to the highest earthquake density in the Groningen field in the area between Appingedam and Loppersum are listed in table 2.

Some observations can be made:

- The largest earthquake in this set, is the earthquake on the 11th November 2016 near Wirdum, which had a magnitude of $M_L = 2.2$.
- In total 16 earthquakes with magnitude larger than or equal to $M_L = 1.0$, have contributed to the highest earthquake density in the Groningen field in the area between Appingedam and Loppersum.
- Two earthquakes, the earthquake near Wirdum (1st November 2016) and near Zeerijp (11th March 2017) have a magnitude larger than or equal to 2 on the Richter scale.
- Three earthquakes took place on 20th November 2016 and two on the 1st November 2016.
- Six of the 16 earthquakes took place in November 2016 and two in December 2016.

Following the earthquakes near Wirdum and Garsthuizen, NAM published an assessment of the seismicity in March 2017 (Ref. 1). In this report an analysis of the seismicity is provided. This report covers the period until mid-March with 11 earthquakes of the 16 contributing to the currently observed highest earthquake density. In particular, it covers the two months period from November to December 2016, when 8 of the 16 earthquakes occurred.

During 2017, 8 earthquakes with magnitude larger than or equal to $M_L \geq 1$ have been recorded in the last 8 months. Figure 13 shows the earthquake density map after the Appingedam event. In case no further earthquakes with $M_L \geq 1$ are recorded, the density of earthquakes recorded during the previous 12 months will drop as illustrated in figure 14.

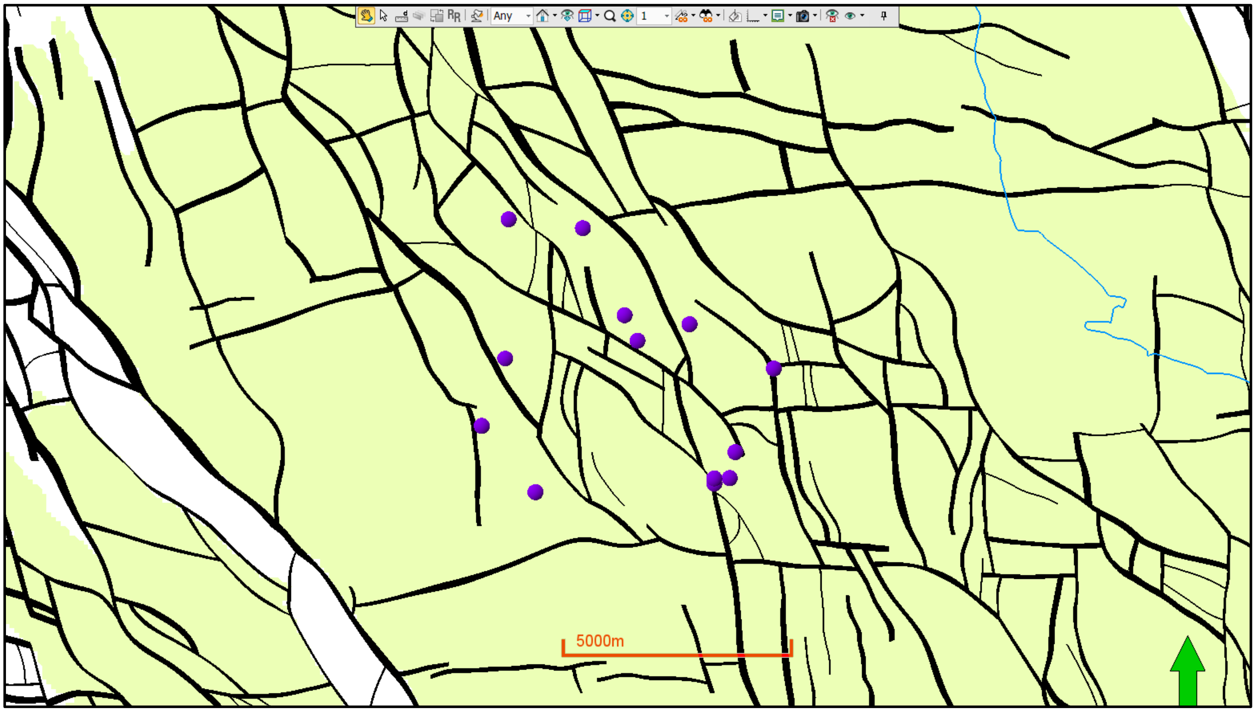


Figure 12 *Epicenters of largest earthquakes as determined by KNMI (purple dots) contributing to maximum earthquake density value in Loppersum region; events are overlaid on Petrel fault model.*

Place	Date	Magnitude	Easting	Northing
Wirdum	01-11-2016	1.9	249653	591435
Wirdum	01-11-2016	2.2	249776	591994
Eenum	08-11-2016	1.4	248788	594758
Ten Post	20-11-2016	1.0	245458	591132
Wirdum	20-11-2016	1.2	249322	591318
Appingedam	20-11-2016	1.6	251641	595371
Loppersum	07-12-2016	1.8	247385	594953
Wirdum	30-12-2016	1.0	249320	591429
Loppersum	25-02-2017	1.3	244804	594014
Wirdum	26-02-2017	1.4	247793	594516
Zeerijp	11-03-2017	2.1	246547	596941
Steendam	10-04-2017	1.3	251789	588027
Stedum	03-05-2017	1.5	244298	592557
Overschild	16-05-2017	1.7	249686	589766
Loppersum	25-07-2017	1.0	244881	597021
Appingedam	29-08-2017	1.8	250671	593905

Table 2 *List of the earthquakes that have contributed to the earthquake density in the Appingedam – Loppersum area. All earthquakes have a KNMI-assigned depth of 3km, approximately the depth of the gas reservoir.*

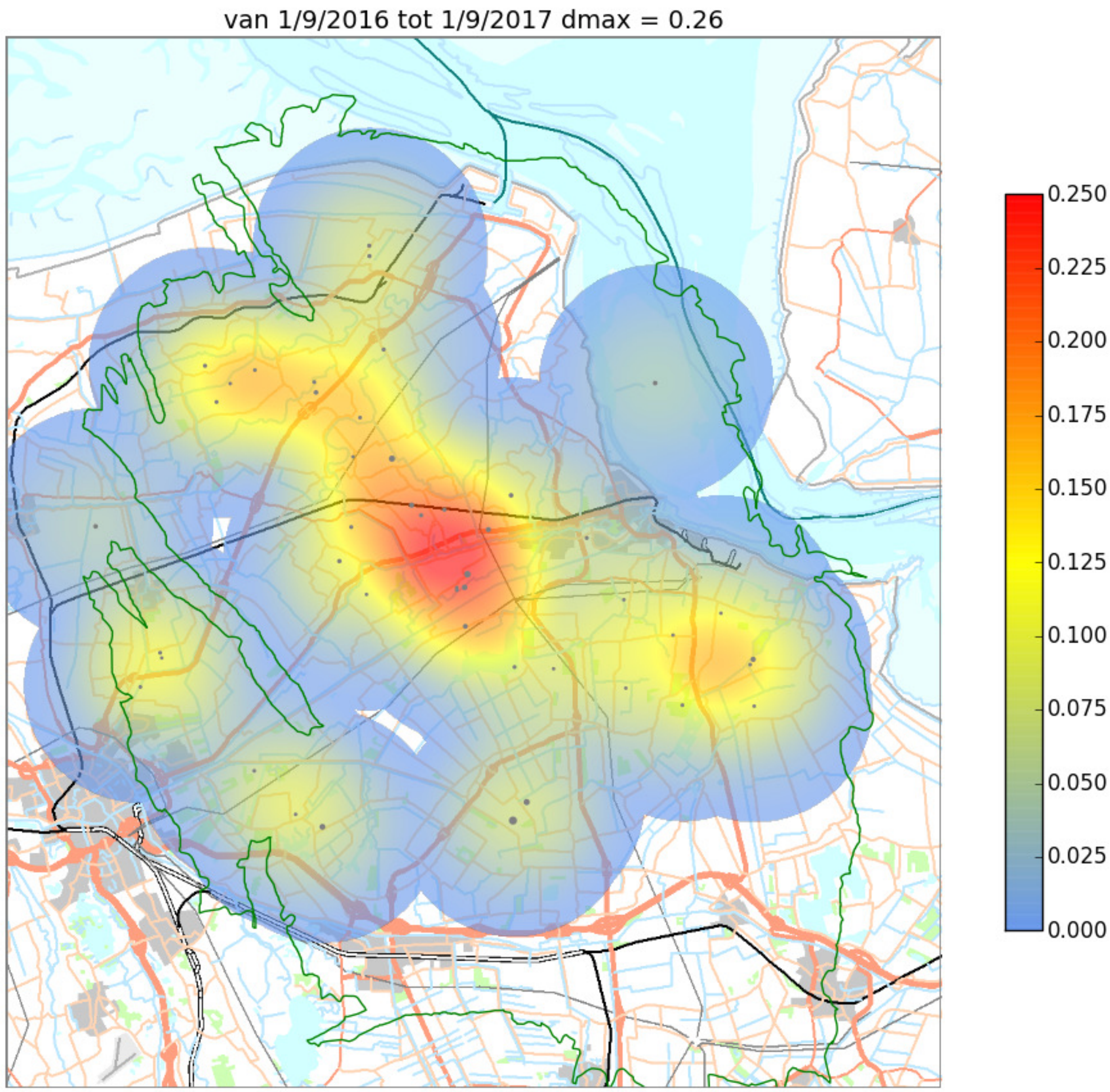


Figure 13 *Earthquake density map (M_L ≥1) after the Appingedam earthquake of 29th August 2017. Clearly the area with earthquake density exceeding 0.25 events/(km2 annum) between Appingedam and Loppersum can be seen.*

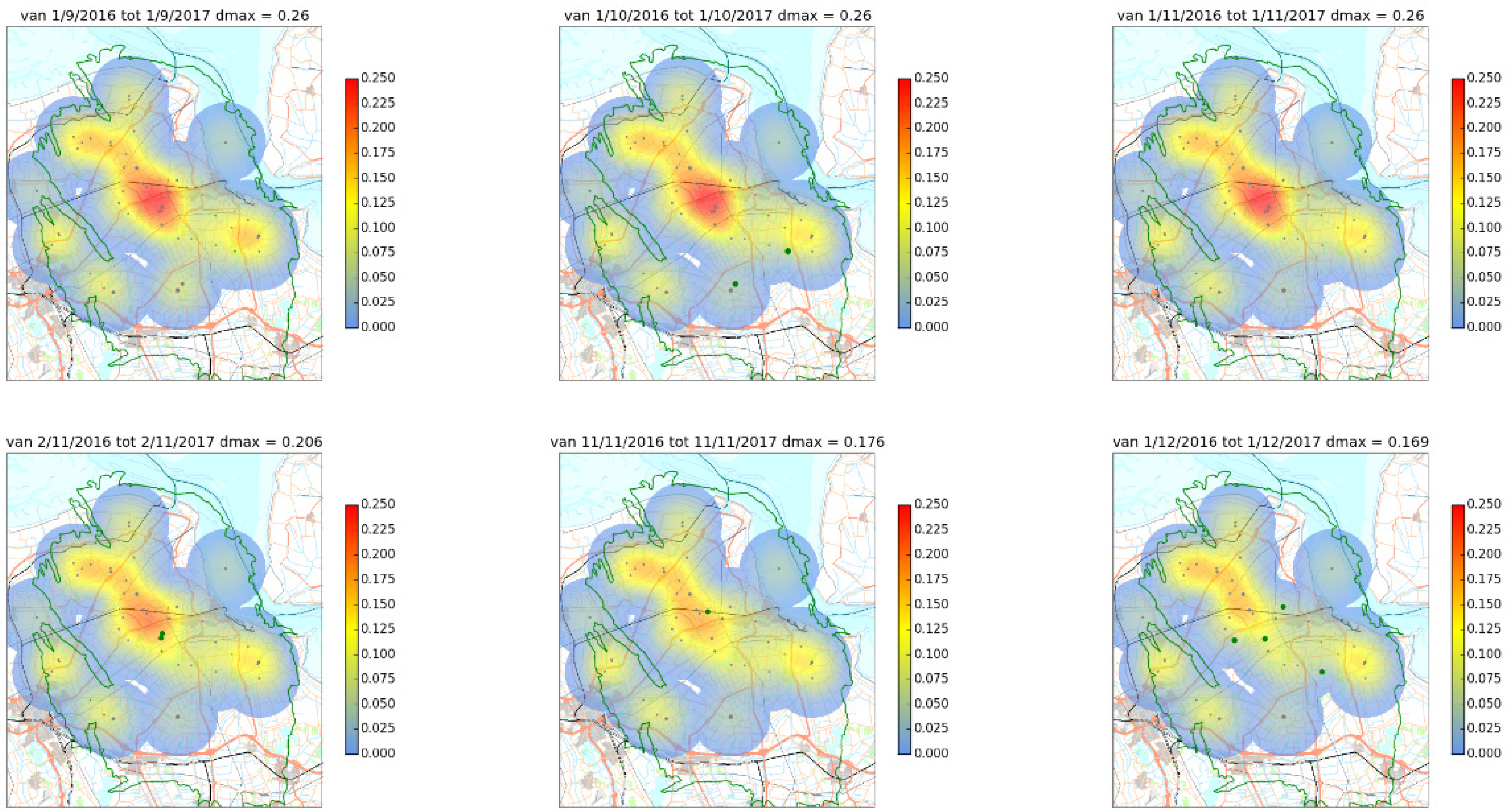


Figure 14 *Earthquake density maps after the Appingedam earthquake of 29th August 2017 in case no further earthquakes of magnitude* $M_L \geq 1$ are recorded. Below captions for each of the 6 maps.

Period from 1 September 2016 until 1 September 2017 with max. earthquake density 0.26 events/(km^2 year).

Period from 1 October 2016 until 1 October 2017 with max. earthquake density 0.26 events/(km^2 year).

Period from 1 November 2016 until 1 November 2017 with max. earthquake density 0.26 events/(km^2 year).

Period from 2 November 2016 until 2 November 2017 with max. earthquake density 0.21 events/(km^2 year).

Period from 11 November 2016 until 11 November 2017 with max. earthquake density 0.18 events/(km^2 year).

Period from 17 November 2016 until 17 November 2017 with max. earthquake density 0.17 events/(km^2 year).

6.3 Detailed analysis of the earthquakes in the Appingedam – Loppersum area

One method to compute a focal mechanism solution is based on the observation of the polarity of the first arrivals on as many azimuthally distributed stations as available. It is generally not trivial to determine the polarity of the first arrival of small magnitude earthquakes such as M_L = 1.8, due a low signal-to-noise ratio of the recorded signal. However, the Groningen region is unique in its dense seismic network coverage and these data render it possible to attempt such a task. Figure 15 shows the recorded data traces of the Appingedam earthquake at the 10 seismic stations closest to the epicentre (station locations shown in figure 16).

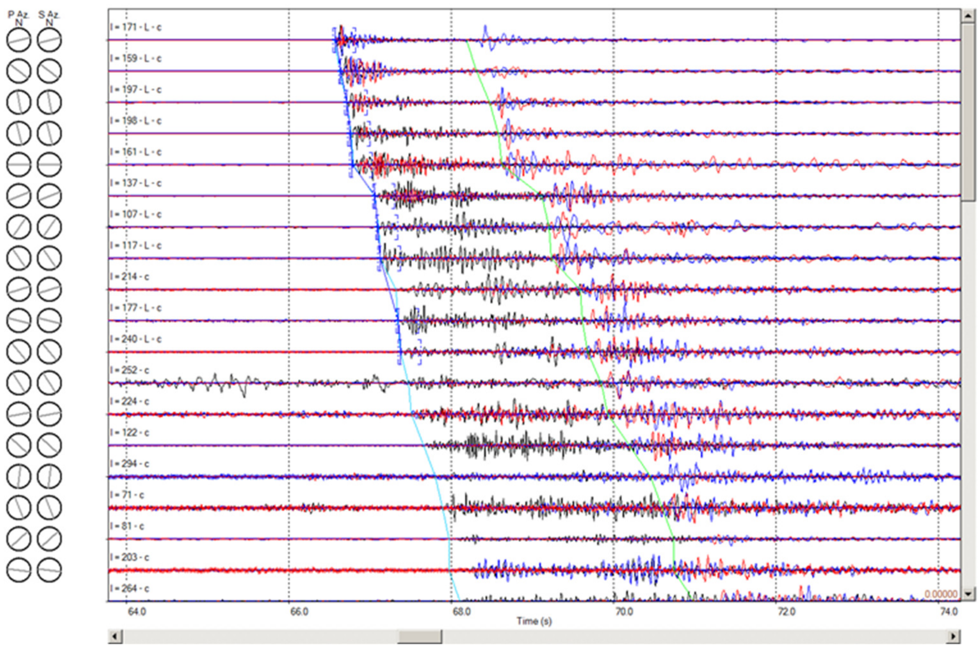


Figure 15 *Ray-traced moveout of the Appingedam ML = 1.8 earthquake. P arrival picks are best recorded on these 10 stations with epicentral distances within 6 km. Dark blue line shows manually picked P-wave arrival; light-blue is the theoretical P-arrival assuming KNMI event location; green is the theoretical S-wave arrival for the same location.*

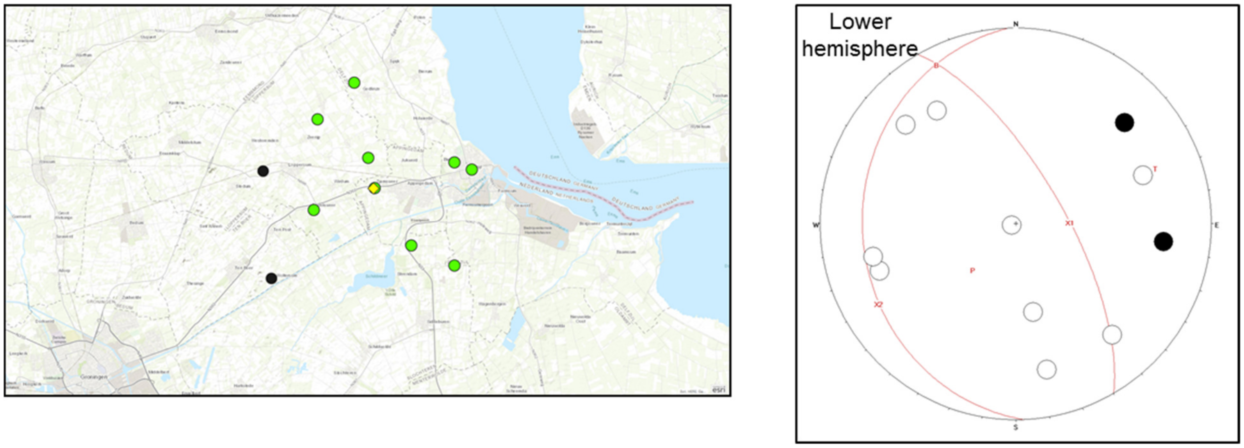


Figure 16 *Left: Yellow diamond represents the epicentral location of the Appingedam M_L = 1.8 event; circles show station locations; black circles are stations with compressional first motions and green are stations with tensional first motions. Right: focal mechanism solution indicates a normal fault with Strike = 330^o Dip = 70^o Rake = -100^o.*

Due to the relatively small magnitude (M_L = 1.8) and therefore a low signal-to-noise ratio of this event, it is challenging to determine with certainty all the polarities of the select P-arrivals used to compute the focal mechanism. Thus, the resulting mechanism contains one inconsistency (figure 16, right). Nevertheless, the final solution of a normal fault is in good agreement with the fault interpretations and also in line with the other focal mechanisms obtained with the same type of analysis for the Loppersum region (further detail provided in the appendix section; figure A4). The raytracing analysis also yields relocations of the events. For further detail please refer to the appendix section (figure A2).

We also obtain an independent assessment of the focal mechanisms and using a Full Waveform Inversion method (FWI) for the set of events that contributed to the exceedance of the 0.25 event /(km^2 year) density threshold. The results are shown in figure 17 and are remarkably consistent with the raytracing analysis method and in line with the local geology. The events are located at mapped faults at Rotliegend reservoir level. The focal mechanism is consistent with normal faulting.

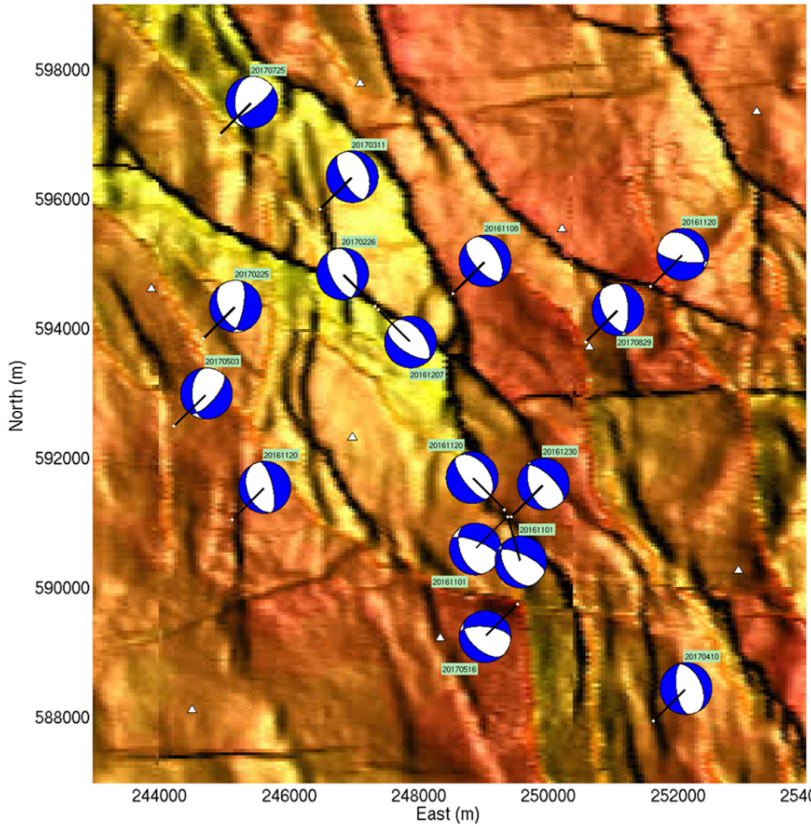


Figure 17 *Focal mechanism solutions for the group of earthquakes listed in table 2 resulting from the FWI method. For further detail please see table A1 in the Appendix.*

7 Reservoir analysis: Pressure & Production

Gas production from the production clusters in the direct vicinity of the Appingedam epicenter was within normal operating conditions, and there have been no extraordinary production changes[1] leading up to the seismic event on 29/8/2017 (Figures 16 and 17).

Figure 18 shows a three-dimensional view from the simulator, highlighting that the epicenter is within a densely faulted area (even though the dynamic simulator cannot physcially capture all 1100+ interpreted faults from seismic). The figure clearly brings out that there is no well control in the direct vicinity of the epicenter area to calibrate the simulation model in non-unique, and by default the predicted reservoir pressures has uncertainty. Still, good connectivity has been 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 across the suspect fault. 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. This can even better be observed in figure 23.

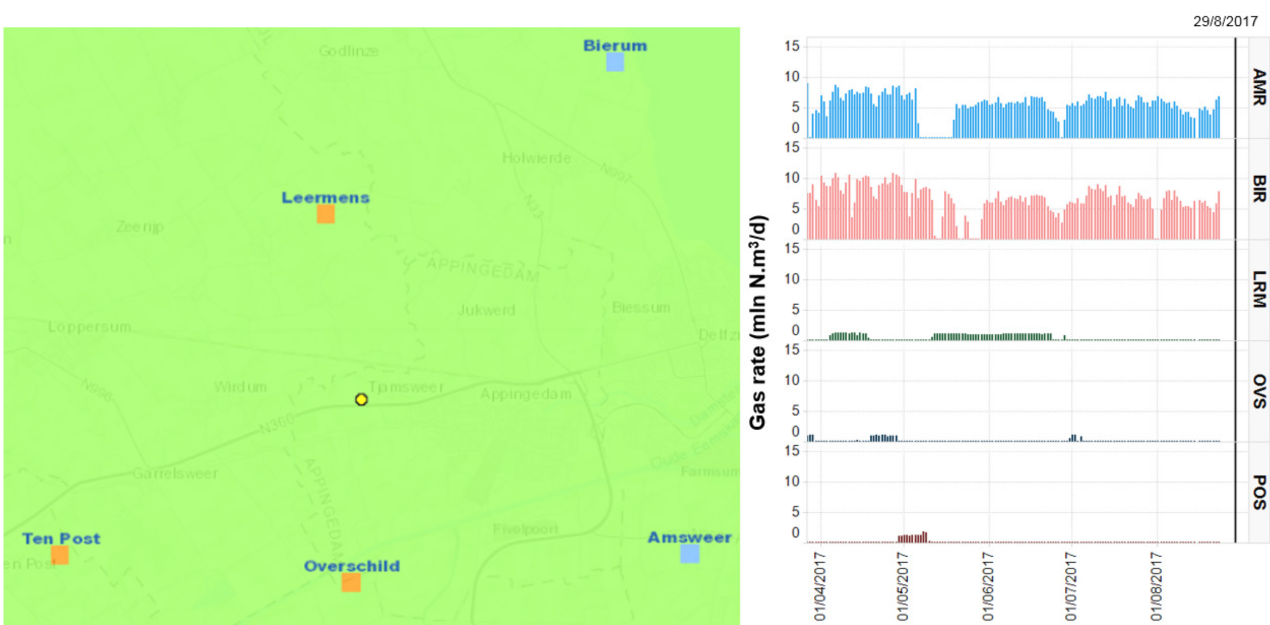


Figure 16 Daily production rates of clusters in the vicinity of the epicenter (yellow circle).

[1] Note that at the time of writing, the corporate daily production database was updated up to and including 23/8/2017. Given that it a pressure transient initiated at a production cluster would take some 2-4 weeks to reach the epicentre, the conclusions in this analysis are not affected by the missing 6 days.

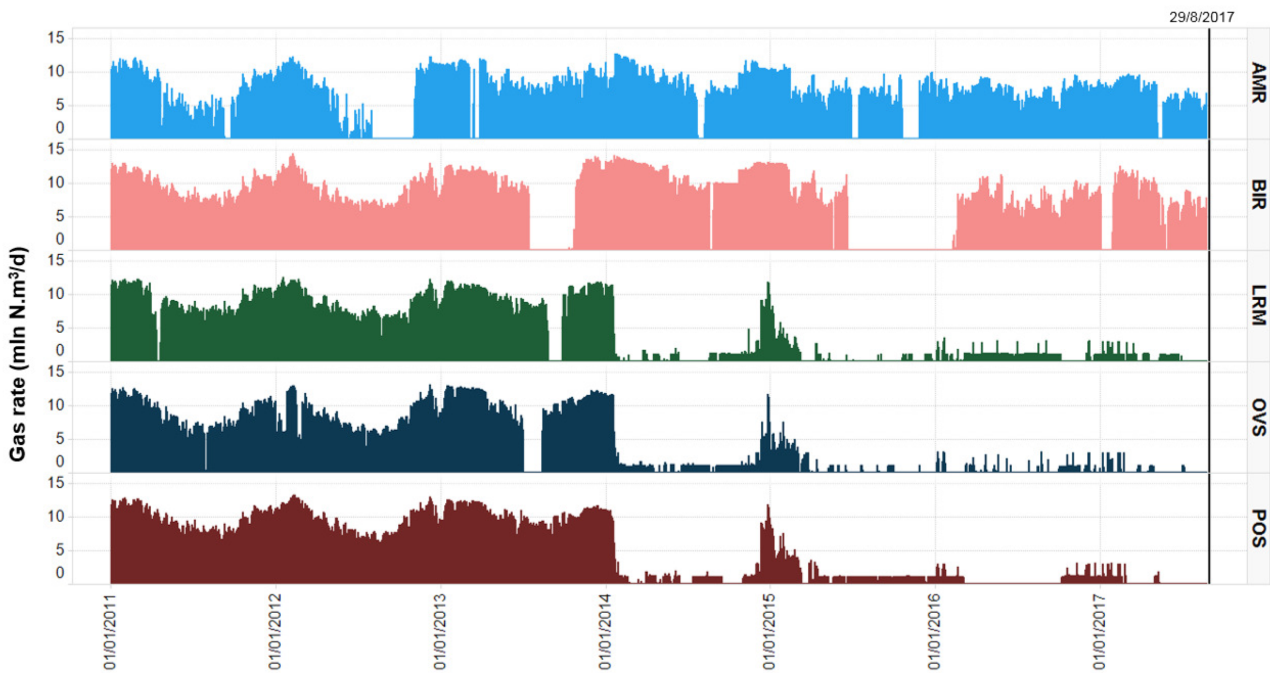


Figure 17 *Longer term trend in daily production rates of clusters in the vicinity of the epicentrum*

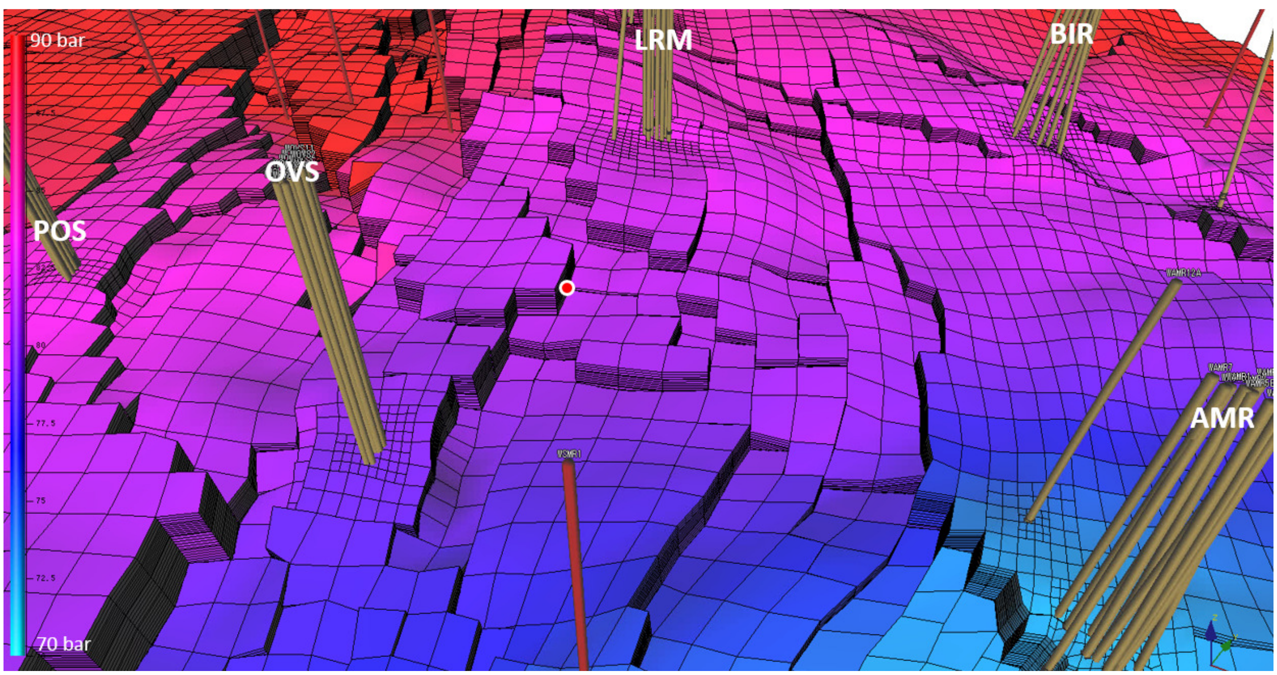


Figure 18 *3D visualisation of reservoir pressure (31/8/2017) from the full field model (V4) in the top of the Slochteren formation. Colorscale clipped at 90 bar. Approximate epicenter location is indicated as a red circle.*

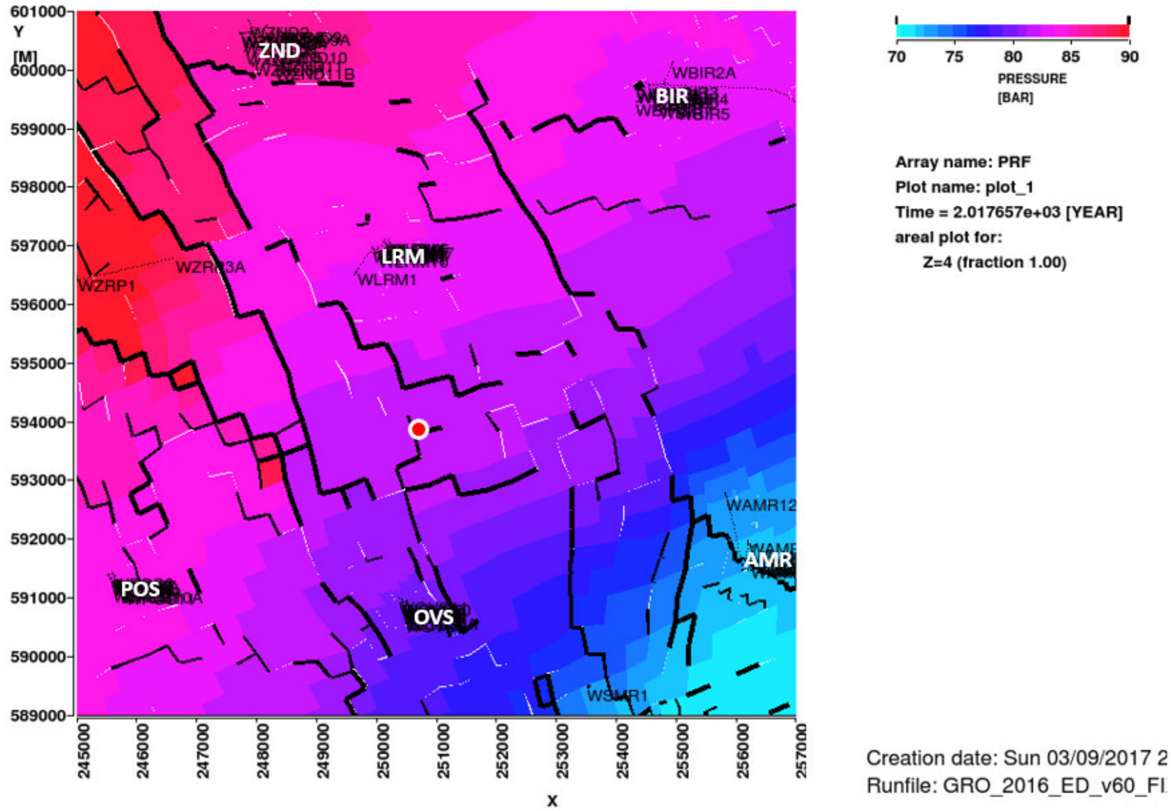


Figure 19 *Reservoir pressure (31/08/2017) from the full field model (V4) in the top of the Slochteren formation. Colorscale clipped at 90 bar. Approximate epicenter location is indicated as a red circle.*

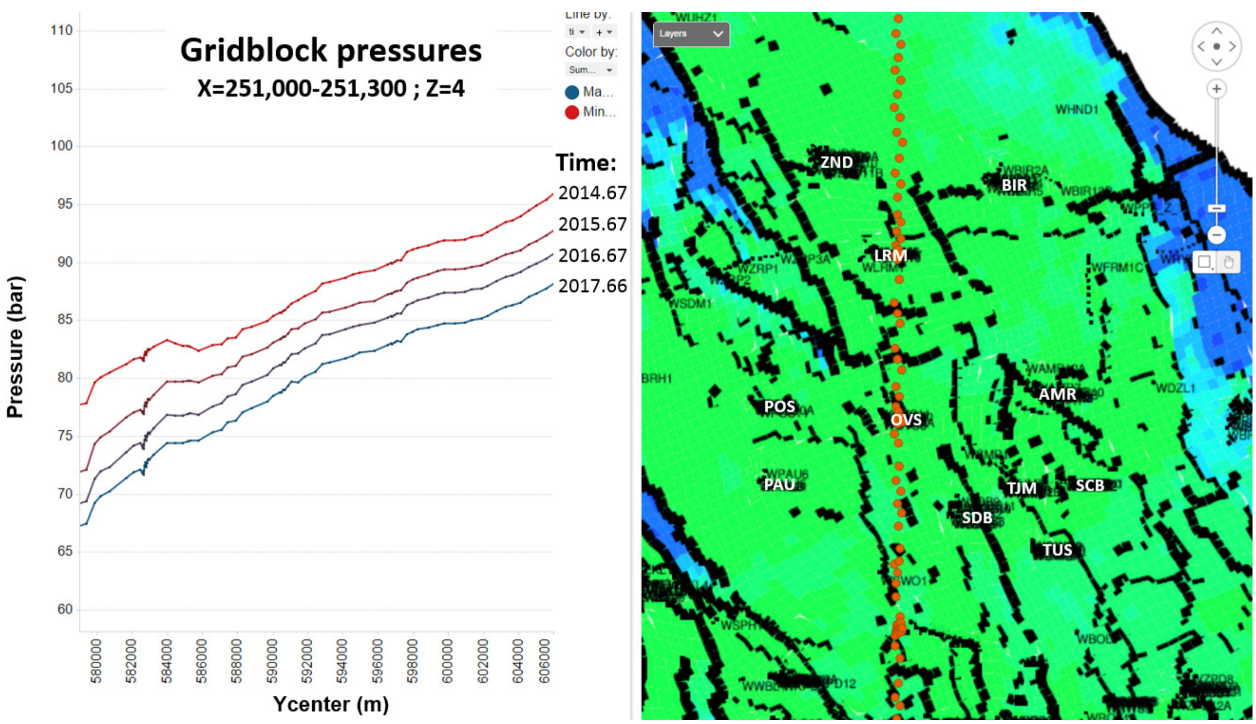


Figure 20 *Pressure cross-section for X=251,000-251,300 at yearly intervals*

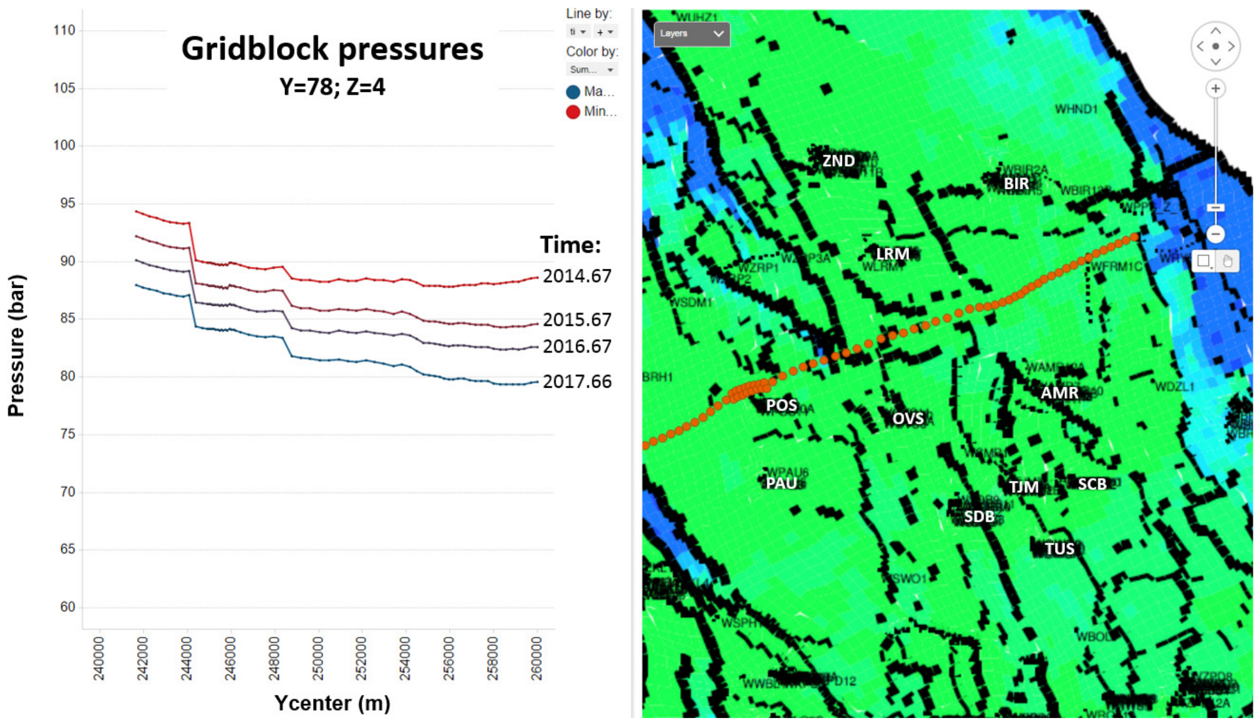


Figure 21 *Pressure cross-section for gridblock Y=78, at yearly intervals*

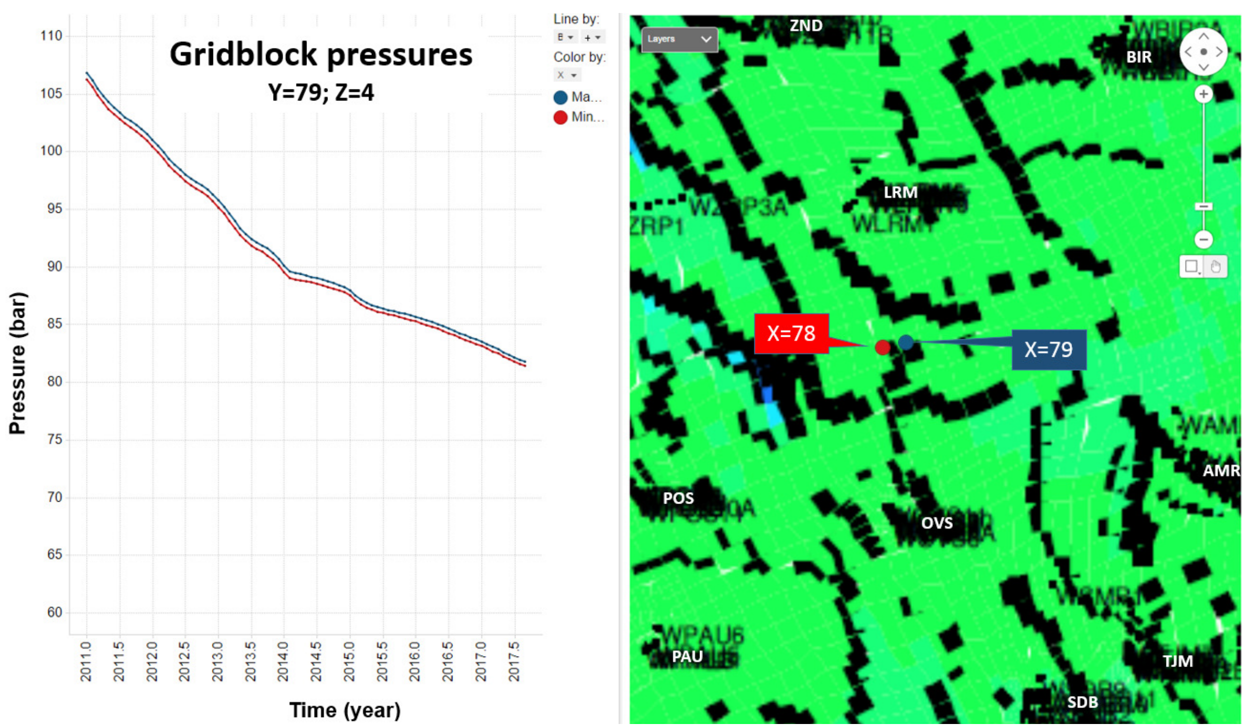


Figure 22 *Gridblock pressures in time*

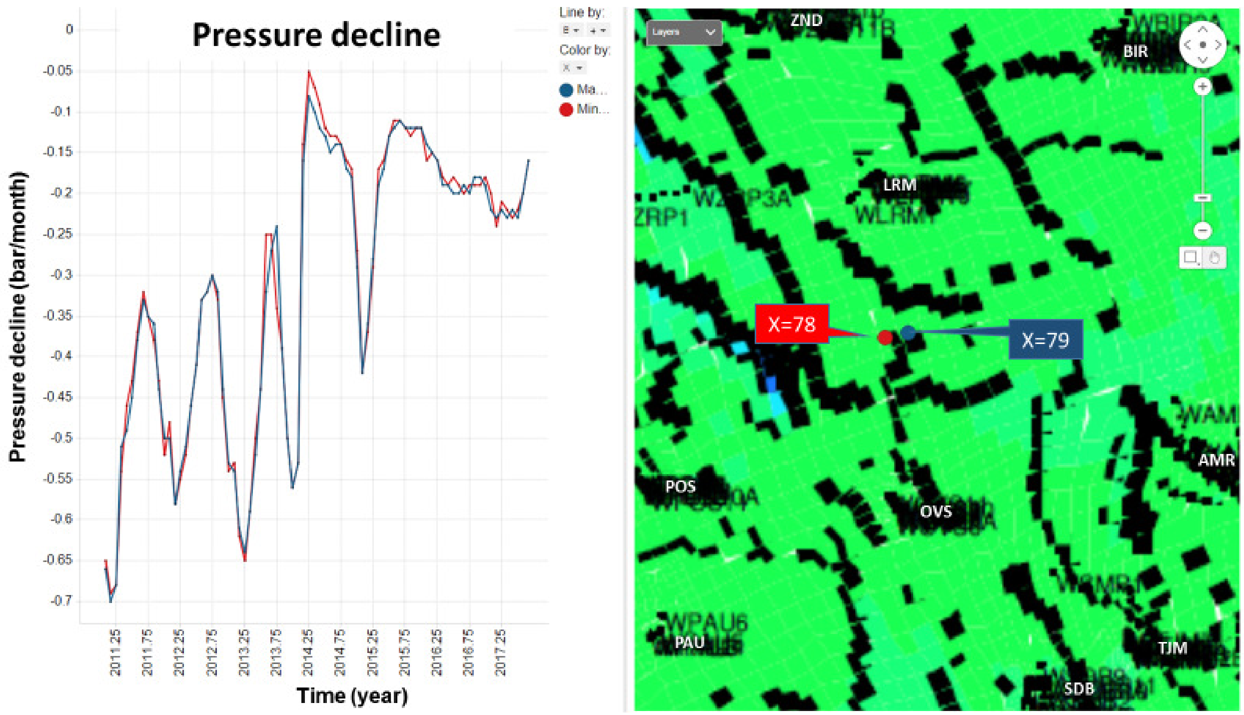


Figure 23 Gridblock pressures-decline (in bar/month) in time

8 Discussion of causes and consequences of earthquake density exceedance

The main reason why the earthquake density measure has been adopted in the Meet- en Regelprotocol 2017 (Ref. 3), is that it functions as a potential early warning of earthquakes of a higher magnitude and that it may point out unexpected or interesting patterns of concentration of earthquakes around specific faults or other subsurface features.

In line with the Wirdum report (Ref. 1), it is concluded here, however, that no special pattern has been observed: no new faults have become active, nor can earthquakes be confidently associated with one fault or one fault-system, nor is there any sign of an escalating pattern. The event is not associated with any anomalous PGV or anomalous number of damage claims either. It is also important to realize that the exceedance of this earthquake density value is nothing new per se; this has happened several times during recent history (see Fig. 11).

In the Wirdum report (Ref. 1), it was hypothesized that the somewhat higher level of seismicity could be related to a local pressure decline that was picking up with respect to the total field pressure decline at large (the field has very few no-flow boundaries). The current earthquake observations do follow the general observation that for a given pressure decline some areas in the Groningen field show somewhat more seismicity. This is in turn probably related to a combination of higher HC column thickness and/or higher fault-density (see also Ref. 1) of some areas compared to others.

The earthquake density exceedance (in this case) does not seem to be sensitive to the threshold magnitude value adopted in the Meet- en Regelprotocol 2017 Protocol. The equivalent earthquake density probably would have been exceeded even if the threshold value had been chosen based on M≥1.5 (with an adjusted threshold value); 6 out of the 16 events contributing to the threshold exceedance (M≥1.0), were events with M≥1.5. Therefore, it is unlikely that we are looking at an artefact which only depends on the chosen lens of the Meet en Regelprotocol 2017 protocol, i.e. one that depends on magnitude threshold only.

The only reservation that can be made is that what we are looking at is the result of statistical variation. As was done in the Wirdum report (Ref. 1), it was pointed out that random statistical variations may also drive fluctuation of earthquake density values and that, consequently, the significance of this pattern may be limited (given the low number of samples available to apply statistics). In general, quite a few events are required to convincingly show that an event is not the product of “normal” random variations. Therefore, these statistical patterns and analyses are routinely reported in yearly reports, grouping a number events and not on a one-by-one basis. Although it cannot be ruled out that it is statistical variations that drive this, it is assumed in the remainder of this document that the pattern is significant and that production measures will need to be considered, if not already in place.

9 Discussion of Production Measures

This discussion of production measures closely follows references 1 and 3. Figure 24 is reproduced from Ref. 3 to illustrate the palette of measures, the severity of exceedance and the context.

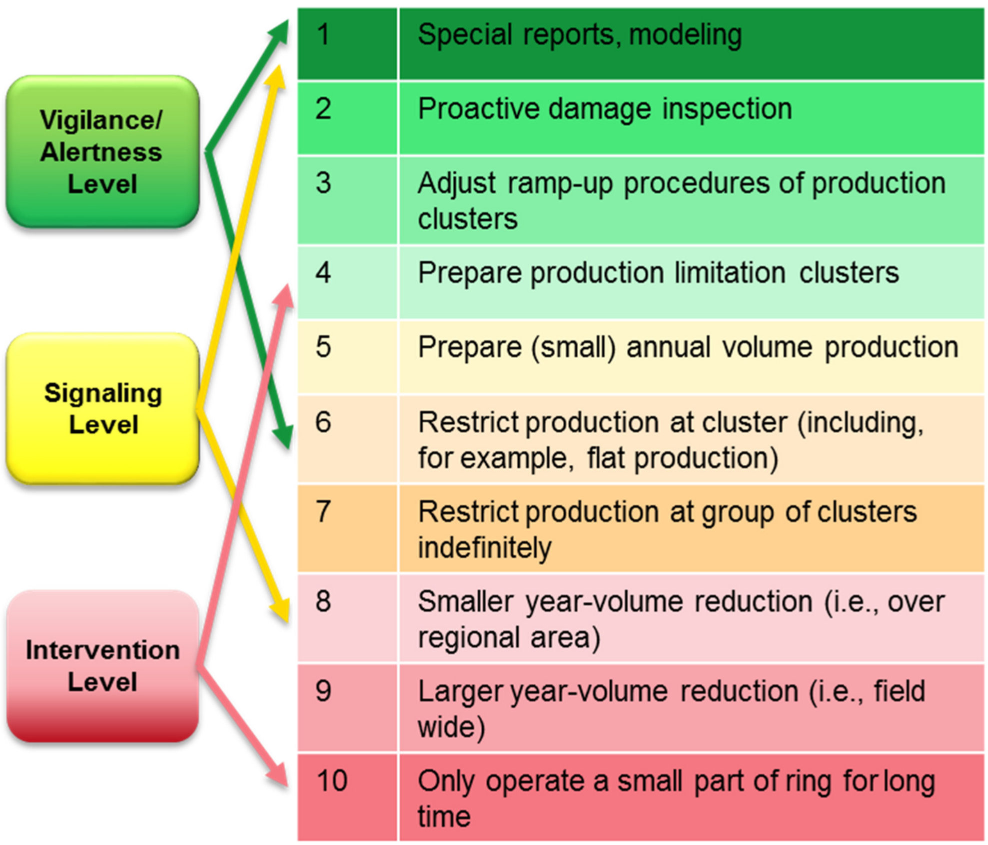


Figure 24 Range of measures, severity of the event and context (reproduced from Ref 3)

The earthquake density in the Appingedam – Loppersum area has exceeded the signalling level following the Appingedam earthquake of 29th August 2017. Therefore, following the Meet-en Regelprotocol 2017, the range of production measures varies from making changes to the way clusters are operated (e.g. adjust ramp-up procedures, measure 3) to making small reductions in the total field volume produced (measure 8), Ref. 3. In general, an exceedance of the signalling level of earthquake density, would steer any production measures toward local/regional adjustments (in contrast, an exceedance of the equivalent "activity rate threshold" would in general require a field-wide adjustment). Adjustment of the ramp-up procedures is already planned for but is probably insufficient a measure to expect a strong effect from. A second measure, also planned for, is an attempt to further flatten production at a regional level (avoiding strong production fluctuations). The third measure, a reduction in volume (by 10%, to 21.6 Bcm, from gas year 17/18 onwards) is already planned for as per the 24/5/2017 Wijzigingsbesluit, and its effect may start to become visible from 2018 onwards. Therefore, at this moment it is proposed to assess the effect of those three measures and it is not proposed to take an additional measure even if we stay on this signalling level for several months (evaluation around June 2018). Only if the next level for earthquake density is exceeded (intervention level, it would take about 7 additional events with hypocentre near the area of the current maximum earthquake density, to reach this level), additional measures will be prepared (e.g. (fully) closing-in Loppersum clusters). Obviously, if the earth-quake density exceeds the signaling level in a different area - unrelated to Loppersum (e.g. Eemskanaal) – additional measures will be considered.

The exceedance of the “alertness/vigilance” level for (field wide) activity rate following the Scharmer earthquake on the 30th August 2017, would normally trigger a report and a consideration and potentially preparation of production measures. However, given the intended decrease of production volume (10% decrease, as per Wijzigingsbesluit), it is proposed to wait to see the effects of this measure before any new measures are proposed. Only if the next level (signalling level) is exceeded, additional measures will be considered and prepared (e.g. further reduction of production volume).

The fact that two signal-parameters are exceeded at the same time (albeit at different levels), does in this case not require additional production measures; they are essentially driven here by the same process and an intended reduction in production volume is already in place.

9.1 Earthquake Density Values Looking Ahead

A significant number of earthquakes that contribute to the elevated earthquake density occurred in November 2016 and February 2017.

Between now (the occurrence of the Appingedam M_L = 1.8 event) and November 2017, it would take 7 more earthquakes in centre of the Loppersum region to bring the earthquake density up to the Meet- en Regelprotocol intervention level of 0.40 events per km^2 per year (Fig. 26). As we move past November the earthquake density starts to subside significantly. November is a unique month in that at least 5-7 events from 2016 contribute to the current maximum earthquake density value and surrounding region in Loppersum. In the scenario in which 7 earthquakes with hypocentre near the current maximum earthquake density occur, the density will quickly increase to 0.4 events/(km^2 year), but will then decay again as the events from last November cycle out of the 12 months window.

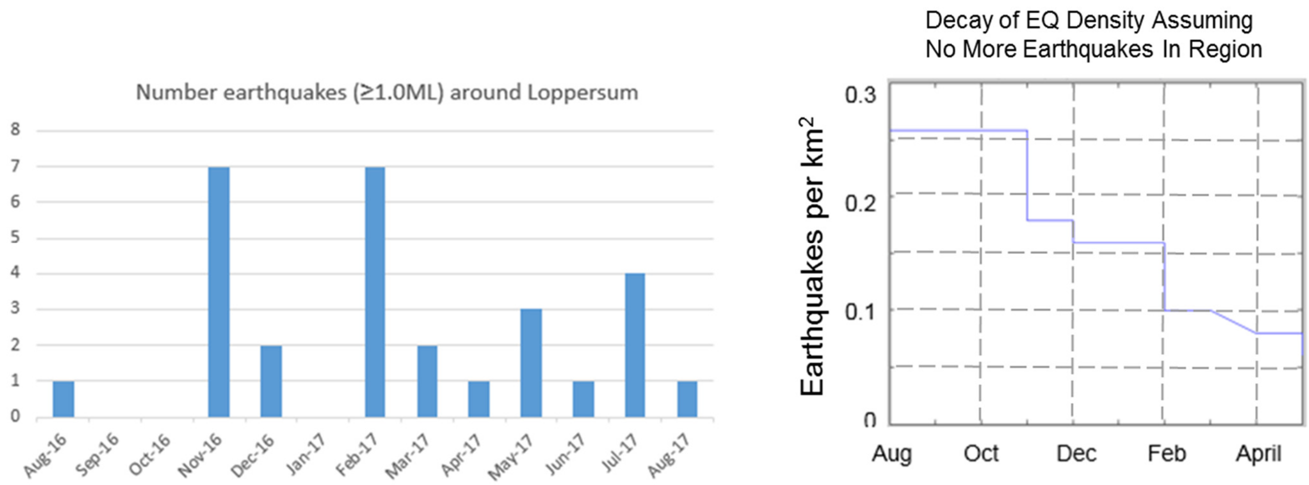


Figure 25 *Left: bar chart shows the number of earthquakes greater than ML1.0 in the Loppersum area. Right: the decay of earthquake density per 12 months computed assuming no additional events occur. The notable drop in density corresponds to November 1st pair of events from 2016.*

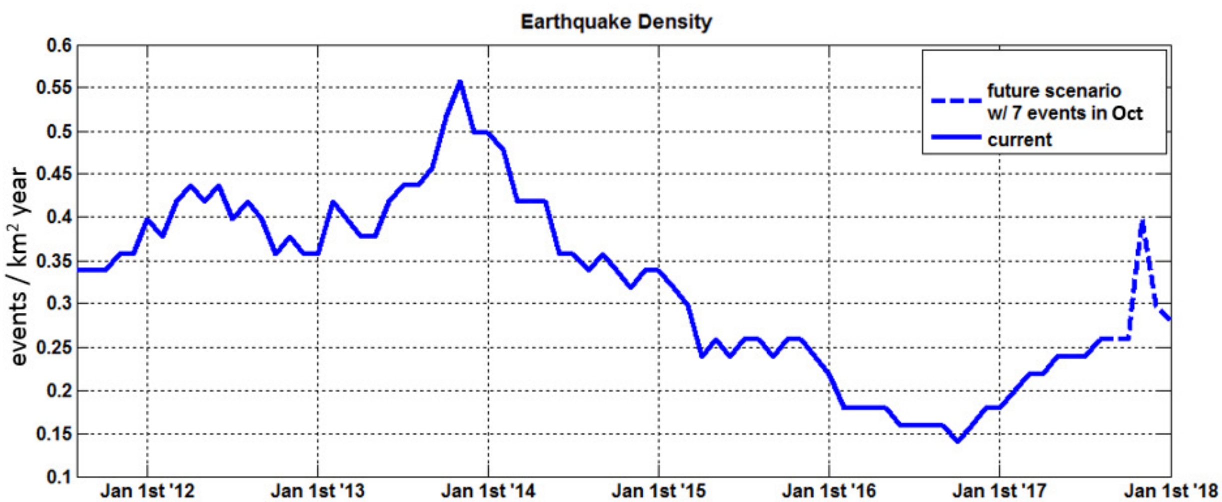


Figure 26 *Model scenario showing that approximately 7 events greater than or equal to M_L = 1.0 would need to occur between now and November within 5 km of the current maximum earthquake location for the next signalling level of 0.40 events/(km^2 year) intervention threshold to be exceeded.*

10 References

This is a chronological list of the documents references in this report.

1. Rapportage recente aardbevingen Wirdum en Garsthuizen 2016/2017, NAM, March 2017
2. Ground Motions from the ML 2.6 Slochteren Earthquake of 27th May 2017, Julian J Bommer, Michail Ntinalexis, Ewoud van Dedem, Jelena Tomic, Leendert Geurtsen and Jeroen Uilenreef, June 2017
3. Meet- en Regelprotocol Groningen veld, NAM, June 2017
4. Measurement and Control Protocol Groningen field, NAM, June 2017
5. Appendix bij het Meet- en Regelprotocol Groningen – Cases, NAM, June 2017
6. Appendix to the Measurement and Control Protocol Groningen – Cases, NAM, June 2017
7. Technisch Addendum bij het Meet- en Regelprotocol Groningen, NAM, June 2017
8. Technical Addendum to the Measurement and Control Protocol Groningen, NAM, June 2017

12 Appendix

The following material provides further technical content and background referred to in the main body of text.

12.1 Earthquake Density Overview

Earthquake density is measured as earthquakes per km2 per year; it is calculated over a 5 km radius Kernel filter on a 50 m grid over the field area using all events ≥ 1.0 ML. From Jan-2014 through Nov-2016 the maximum field wide earthquake value has been decreasing. More recently it has been increasing; it exceeded the 0.25 events km-2 year-1 M&CP signalling threshold on 28-Aug-2017.

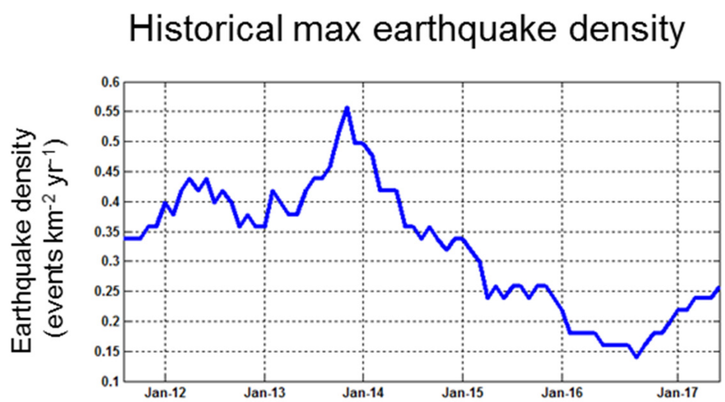


Figure A1. A chart showing the maximum earthquake density for each month going back the past 5yrs in the Loppersum Area.

12.2 Earthquake Relocation Results

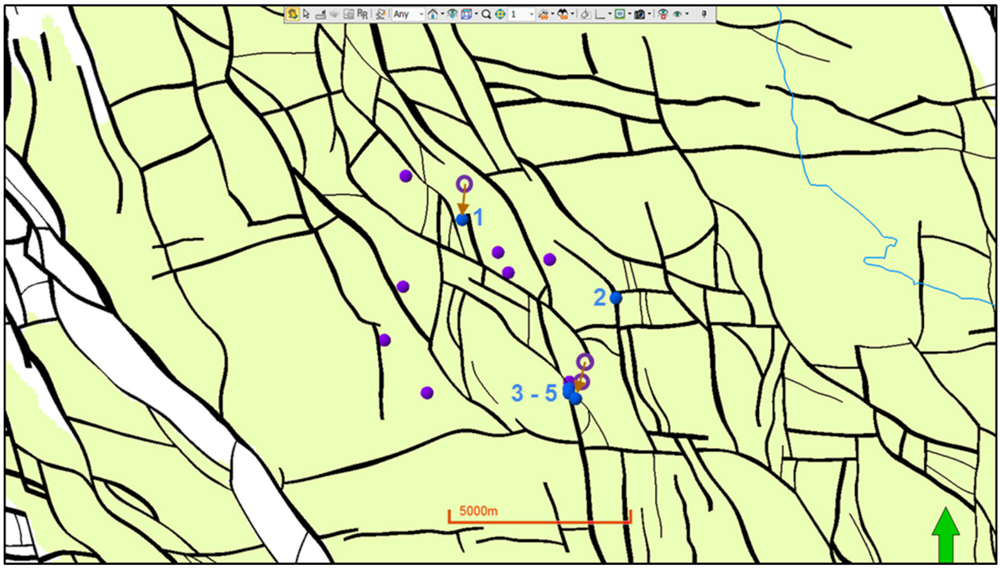


Figure A2. *Relocations using the ray-tracing method focus on stations within 6 km of the event to improve location accuracy. Event numbering: (1) Zeerijp M_L = 2.1; (2) Appingedam 1.8; (3) Wirdum M_L = 1.2; (4) Wirdum M_L = 2.2; (5) Wirdum M_L = 1.9; Note clustering of Wirdum events (3 - 5) and location change of Zeerijp event (1) onto mapped faults. Largest lateral shifts are Zeerijp M_L = 2.1 (1 km South) and Wirdum M_L = 1.9 (1 km SSW). These lateral shifts are not expected to change the maximum earthquake density.*

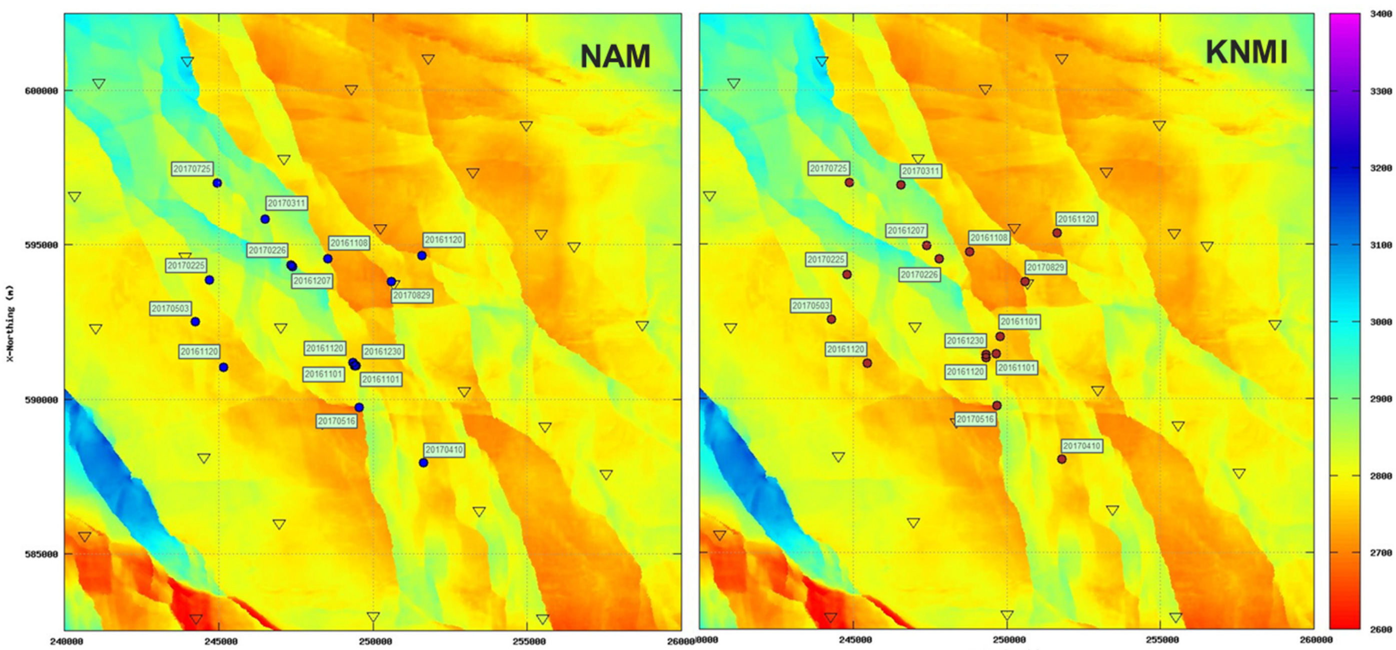
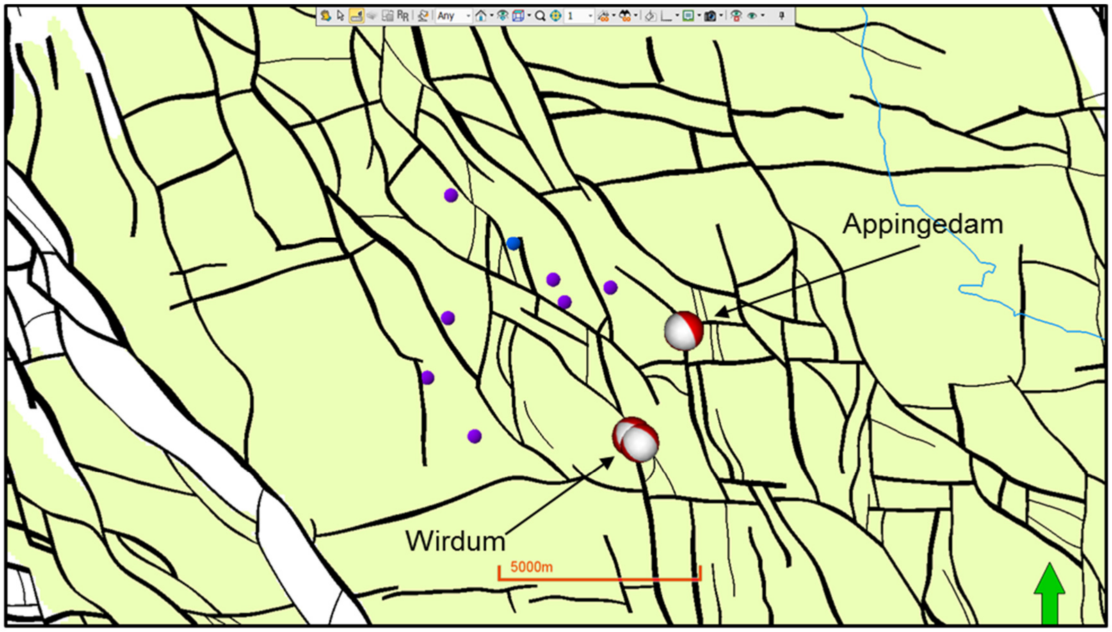


Figure A3 *Relocations of the events listed in table 2 from the FWI method (left) and comparison to the locations published by KNMI (right). The FWI method results in quake relocations closer to known faults.*



- Focal mechanisms derived from picked P-arrival first motions; to determine focal mechanism clear P-arrival first-motions on at least 6 stations are required; preferably 10 or more

Figure A4 Focal mechanisms derived from the P-arrivals for Wirdum M_L = 1.9, M_L = 2.2, and Appingedam M_L = 1.8 earthquakes.

Date	Time	Location	M_L KNMI	Northing (m)	Easting (m)	Depth (m)	Strike (°)	Dip (°)	Rake (°)	ISO (%)	DC (%)	CLVD (%)	Cluster *	# contr
20161101	001229	Wirdum	1,9	591100	249400	2950	286	54	-119	9	71	20	10	7
20161101	005746	Wirdum	2,2	591100	249400	2950	296	67	-106	7	84	9	10	7
20161108	112318	Eenum	1,4	594550	248550	2900	138	53	-100	4	85	11	11	6
20161120	152008	Ten Post	1,0	591050	245150	3000	346	63	-86	12	85	3	-	7
20161120	175841	Wirdum	1,2	591200	249350	2800	143	60	-90	8	82	10	-	7
20161120	185757	Appingedam	1,6	594650	251600	2900	100	65	-108	8	71	21	-	8
20161207	015250	Loppersum	1,8	594300	247400	3050	123	51	-103	8	67	25	12	6
20161230	030554	Wirdum	1,0	591100	249450	2900	314	57	-107	10	84	6	10	7
20170225	053247	Loppersum	1,3	593850	244700	3050	12	61	-69	8	88	4	-	7
20170226	213949	Wirdum	1,4	594350	247350	2950	153	51	-100	5	90	5	12	8
20170311	125248	Zeerijp	2,1	595850	246500	3100	149	57	-97	7	85	8	-	10
20170410	001719	Steendam	1,3	587950	251650	2950	172	56	-81	6	85	8	-	8
20170503	111554	Stedum	1,5	592500	244250	2950	41	58	-65	10	90	0	-	5
20170516	013126	Overschild	1,7	589750	249550	2700	277	56	-112	5	92	3	-	6
20170725	150008	Loppersum	1,0	597000	244950	3000	53	67	-66	6	88	6	-	7
20170829	074013	Appingedam	1,8	593800	250600	2900	358	54	-71	12	82	6	-	5

Table A1 Focal mechanism results from the FWI method.

12.3 Earthquake Ground Motions

The recent earthquakes that contributed to the density threshold exceedance in the Loppersum area, range in magnitude from M_L = 1.0 to M_L = 2.2. The maximum measured peak ground acceleration from these events was 7.8 cm/s^2 and occurred during a ML 2.2 event on 1st November 2016 near Wirdum. PGA thresholds in the Meet- en Regelprotocol are 49 cm/s^2 for vigilance level, 78 cm/s^2 for signalling level and 98 cm/s^2 for intervention level.

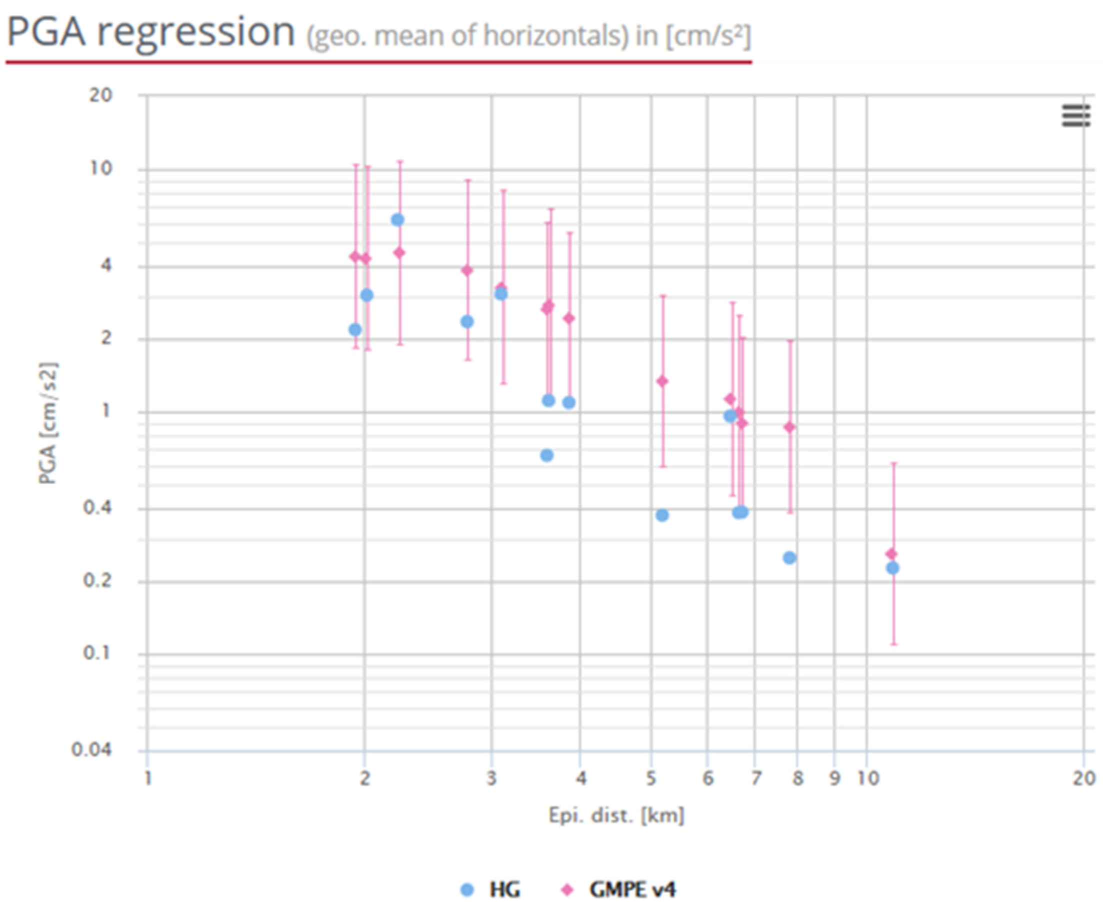


Figure A4. Measured PGA (blue) and predicted ground acceleration from GMPE v4 (red). Source KNMI.

To better understand the extent of ground motions we simulated the largest event that occurred in the Loppersum region during the past year, the 11th January 2016, M_L = 2.2 near Wirdum. The event was simulated to a bedrock surface using the measured focal mechanism solution for rake, dip and strike (see slide X). The waveform modelling results are consistent to 1st order with what is predicted by GMPE v4 at bedrock surface.

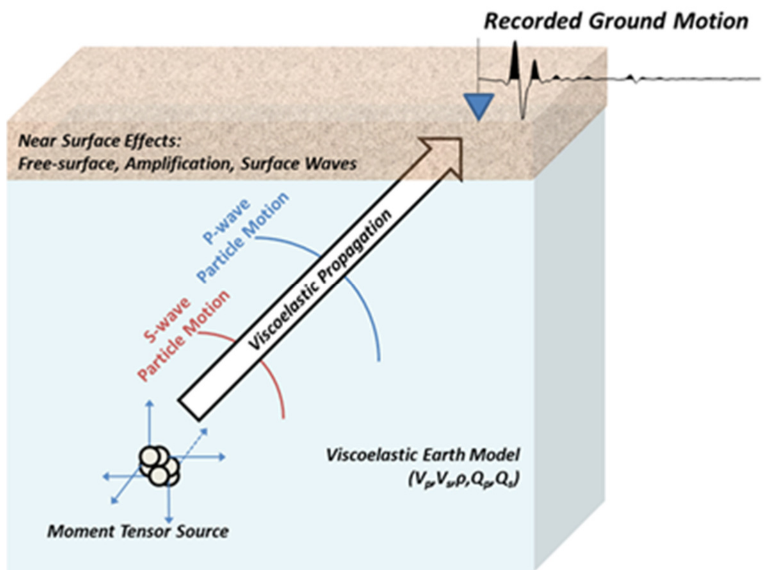


Figure A5 *Schematic describing ground motion modelling from the earthquake source at depth to the recorded ground motion at the surface.*

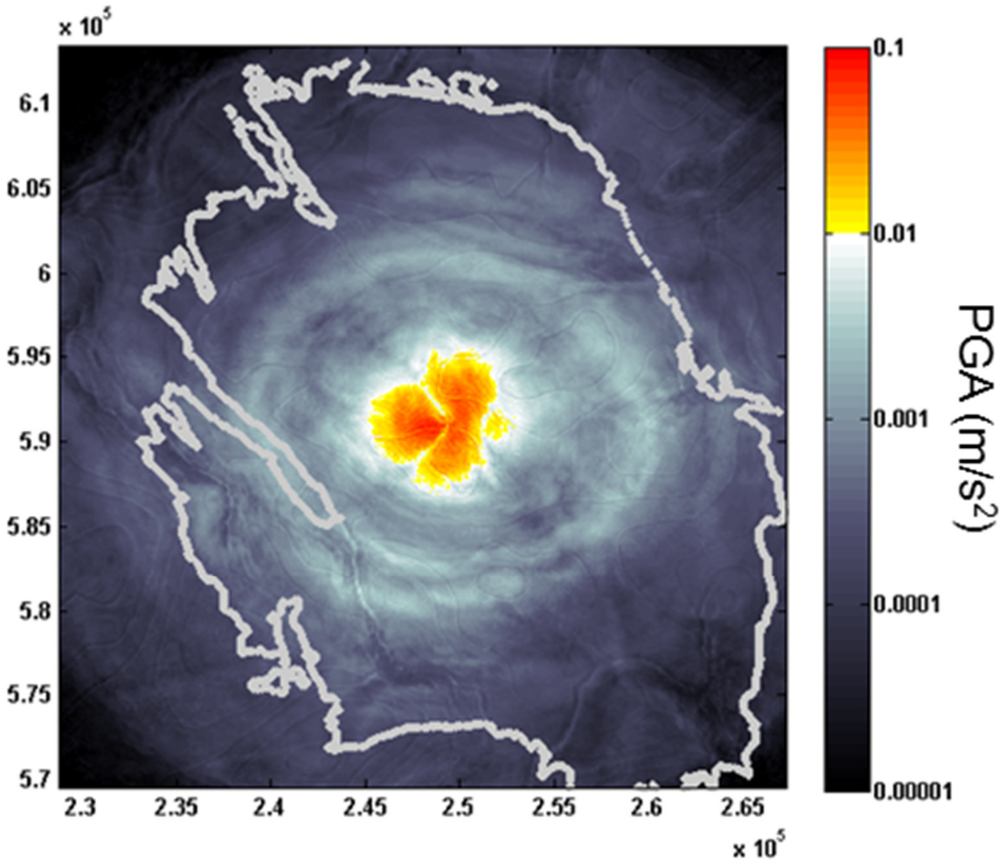


Figure A6 *Peak ground acceleration at the bedrock surface for Wirdum ML2.2 event.*

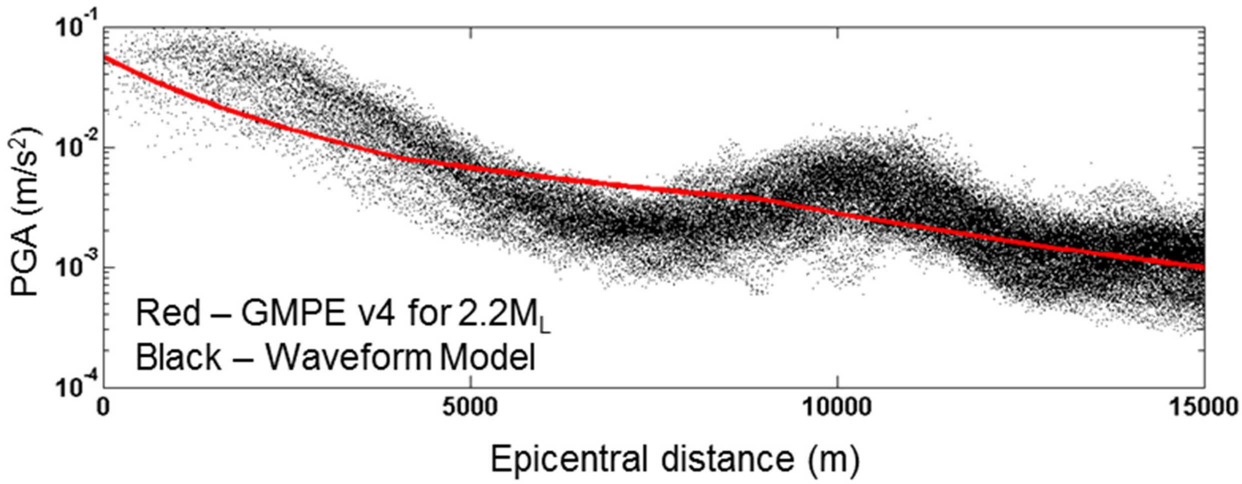


Figure A7 *Waveform modeling results (black dots) for the Wirdum M_L = 2.2 event show consistency with the GMPE V4 for an M_L = 2.2 event.*