Measuring changes in earthquake occurrence rates in Groningen.

Update October 2016.

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by

Rakesh Paleja (PTI/CA); Stijn Bierman(PTI/CA)

Shell Global Solutions International B.V., Amsterdam

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Executive Summary

The Groningen field in the Netherlands is one of the largest on-shore gas producing field in western Europe. On 01/01/2014, gas production at a number of production clusters in a part of the gas field near the town of Loppersum was greatly reduced. The period following 01/01/2014 is referred to as the "post shut-in epoch". Of particular interest is the question whether there is evidence that EQ occurrence rates in four different regions of the field have changed following this reduction in gas production rates. To this effect, the period prior to this date is partitioned into a number of "pre shut-in" epochs such that the number of events in each pre-epoch is equal to the number of events in the post-epoch. Differences between the post-epoch and various pre-epochs in earthquake (EQ) occurrence rates were estimated for each of four different regions within the Groningen gas field using most recent catalogue that was downloaded on 29/09/2016 from the website of the Royal Dutch Meteorological Institute (KNMI).

The findings in this report (based on the most recent catalogue) are compared with the results as published in a report on the same topic which was published in June 2016. Thus, in the present report the results are based on a catalogue with approximately 3 months of additional monitored time compared to the report published in June 2016.

In the Loppersum region, the weight of evidence has shifted further towards a decrease in the rate at which earthquakes occur since 01/01/2014, such that we can now be confident that this decrease in event occurrence rate is not just due to random variations.

There is evidence that there are regional differences in event occurrence rate within the Groningen field. While the rate has decreased in Loppersum, in the Zuidwest region rates are higher in the post-epoch compared to a single pre-epoch which spans multiple years; Due to the relatively small number of event occurrences in this region it is not possible to determine whether the timing of changes in activity rate coincides with the changes in gas production rates.

For the other two regions (Oost and Eemskanaal) there is no evidence of changes in rates of event occurrences following January 2014 and the power of the statistical tests is low due to low numbers of events in these regions.

The monitoring (geophone) network has recently been upgraded which is expected to impact the magnitude of completeness M_c above which it can be assumed that all events will be detected and recorded in the earthquake catalogue. An initial analysis of temporal variations in M_c across the entire Groningen field is presented. The results indicate that M_c has been decreasing in recent years.

The overall field-wide (aggregated over all regions) changes in event occurrence rates are less pronounced compared to the regional contrasts. For events $M \geqslant 1.0$ there is evidence that the field-wide event occurrence rate has decreased in the post-epoch compared to the most recent pre-epochs (Appendix B). For events $M \geqslant 1.5$ there is no statistically significant difference.

More detailed conclusions are given below for the Loppersum and Zuidwest regions.

Results for the Loppersum area:

- **Earthquakes with** $M \geqslant 1.5$: There is good evidence that event occurrence rates were lower in the post-epoch compared to pre-epochs between January 2009 and November 2013. The average time between earthquakes (inter-event time) increased by an estimated $\Delta\nu(post - pre) = 33.9$ to 47.3 days in the post-epoch compared to these pre-epochs. These increases in average inter-event times were statistically significant at 95% level. When potential aftershocks are removed from the catalogue, there is still good evidence that the average

inter-event time has increased in the post-January 2014 epoch compared to the pre-epochs between August 2011 and November 2013.

- **Earthquakes with** $M \geqslant 1.0$: There is good evidence, regardless of whether potential aftershocks are retained or removed before statistical analysis, that there were fewer earthquakes with associated magnitudes $M \geqslant 1.0$ per unit of time in the period after 2014 (post-epoch) compared to the rates of earthquakes in pre-epochs between June 2011 and December 2013. The decrease in rate of earthquakes with associated magnitudes $M \geqslant 1.0$ may have been more pronounced than reported here, since the capability of the monitoring network to record events with magnitude $1.0 \leqslant M < 1.5$ is likely to have been better in the post-epoch compared to the pre-epoch.

Results for the Zuidwest area:

- **Earthquakes with** $M \geqslant 1.5$: The average inter-event time was lower in the post-epoch compared to the pre-epoch (March 2006 to February 2013) by $\Delta\nu(post - pre)$ = -106.4 days. This difference in average inter-event time is statistically significant at the 95% level. If potential aftershocks are removed, the difference in average inter-event time between the post and pre-epoch is non-significant at the 95% confidence level but significant at a lower (90%), level.
- **Earthquakes with** $M \geqslant 1.0$: There is an indication, regardless of whether potential aftershocks are retained or removed before statistical analysis, that there were more earthquakes with associated magnitudes $M \geqslant 1.0$ per unit time in the period after 2014 (post-epoch) compared to the rates of earthquakes in pre-epoch (September 2009 - December 2012) but care is required in the interpretation of this finding as this may have been partly due to improvements in the capability of the monitoring network to detect events with magnitudes below $M < 1.5$.
- Relatively few events have been recorded in this region and the statistical analysis is therefore performed only at a very coarse temporal resolution with one post-epoch (January 2014 to the present) and one pre-epoch which spans many years. We note that due to the relatively small number of event occurrences in this region, it is not possible to determine accurately when a change in activity rate has occurred. It is also possible that a gradual change in activity rate has occurred over the period of several years. It is unclear whether the timing of changes in activity rate coincides with the changes in gas production rates from 01/01/2014.

Amsterdam, October 2016.

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1.Introduction

Differences between epochs in earthquake (EQ) occurrence rates were estimated for each of four different regions within the Groningen gas field, using a catalogue that was downloaded on 29/09/2016 from the website of the Royal Dutch Meteorological Institute (KNMI). On 01/01/2014, gas production at a number of production clusters in a part of the gas field near the town of Loppersum was greatly reduced. Of particular interest is the question whether there is evidence that EQ occurrence rates have changed following this reduction in gas production rates. The period following 01/01/2014 is referred to as the "post shut-in epoch". The period prior to this date is partitioned into a number of epochs such that the numbers of events that occurred within each of these "pre shut-in" epochs is equal to the number of events observed in the post shut-in epoch. The findings in this report (based on the most recent catalogue) are compared with the results as published in a report on the same topic which was published in June 2016 (Paleja and Bierman [2016b]).

Thus, in the present report the results are based on a catalogue with approximately 3 months of additional monitored time compared to the report published in June 2016. The statistical methodology for estimating EQ occurrence rates for a given epoch, as well as differences in EQ occurrence rates between epochs, has been described in detail in Paleja and Bierman [2016a] and Paleja et al. [2015] and we refer to these two reports for mathematical notation and explanation of the methodology.

In the main body of the report, results are presented of statistical analyses of regional changes in event occurrence rates in the post-epoch compared to all pre-epochs. The post-epoch currently spans more than 2.5 years, and it is of interest to study potential changes in event occurrence rates within this post-epoch. This is possible only if the numbers of event occurrences are large enough to provide enough statistical power to detect potential trend changes. A more detailed analysis of changes in event occurrence rates in the period following January 2014 in the Loppersum region for events $M \geqslant 1.0$ is presented in Appendix A, as the numbers of event occurrences in this region were deemed to be sufficient for reliable statistical analysis. In Appendix B we present an analysis of overall field-wide changes in event occurrence rates. The monitoring (geophone) network has been upgraded from time to time and a major upgrade was carried out more recently. This is expected to impact the magnitude of completeness M_c above which it can be assumed that all events will be detected and recorded in the earthquake catalogue. An initial analysis of temporal variations in M_c across the entire Groningen field is presented in Appendix C.

2.Notation and Terminology

Here, a brief overview of notation is given. A full description of the methodology is given in Paleja and Bierman [2016a].

- The period from the 01/01/2014 up to and including the 29/09/2016 is referred to as the post shut-in epoch, or *post* for short in tables and graphs. The date 29/09/2016 was the date on which the earthquake catalogue (EC) as used in this study was downloaded from the KNMI website.
- The period prior to 01/01/2014 is partitioned into a number of epochs such that the numbers of events that occurred within each of these "pre shut-in epochs" are equal to the number of events observed in the post shut-in epoch.
- The number of EQ occurrences per unit time is also referred to as the "activity rate".
- M: the magnitude of an earthquake.
- M_c: the magnitude of completeness, defined as the lowest magnitude above which all of the earthquakes in the Groningen gas reservoir are detected and recorded in the earthquake catalogue.
- g: the vector with coordinates (easting and northing) of the epicenter of events.
- d: the time (date) of events.
- D: a user specified inter-event distance, used in catalogue declustering (see below).
- T: a user specified inter-event time, used in catalogue declustering (see below).
- Subscript q is used to denote the four regions of the Groningen field. The four regions are Loppersum, Oost, Eemskanaal and Zuidwest (see Figure 3.1 and Paleja and Bierman [2016a]).
- The EC, with or without aftershocks, is divided into four regional subsets with each subset containing events above a certain magnitude threshold. Two magnitude thresholds are considered in this report. These are M$\geqslant$ 1.5 and M$\geqslant$ 1.0 with and without aftershocks.
- The four regional EC subsets before 01/01/2014 are divided into k_q number of pre-epochs. Subscript j is the indicator of the pre-epoch ($j \in 1, 2, ...k_q$). The division of four EC subsets into k_q number of pre-epochs is such that the number of events in the $post^q$ and all the pre^q_j epochs are identical. This (i.e. the number of events in an epoch for each regional subset) is indicated by n_q.
- The subscript a_q is the indicator for epoch in the subset: $a_q \in \{post^q, pre^q_1, pre^q_2, ..., pre^q_{k_q}\}$
- $S_{\{a_q,q\}}$ is used to indicate the sum of inter-event times for epoch a_q with n_q number of events.
- The time difference between the date on which the EC was downloaded (29/09/2016) and the date of the last event in the four EC subsets is the "censored" observation time and is indicated by T^{cens}_q (see Paleja and Bierman [2016a]).
- The expected inter event time is denoted by the symbol ν. The difference in the expected inter event time between the $post^q$ epoch and pre^q_j epoch is indicated by $\Delta\nu(post - pre_j)$.
- The 95% Confidence Interval (CI) of $\Delta\nu(post - pre_j)$ is used to infer if the EQ occurrence rate in the *post* epoch is lower, higher or equal to the pre_j epoch. If the lower bound of the CI range is greater than 0, the EQ occurrence rate in the *post* epoch is lower than in the

pre_j epoch. If the upper bound of the CI is less than 0, the EQ occurrence rate in the *post* epoch is higher than in the pre_j epoch.

3.Description of regions

Differences between epochs in average inter-event times $\Delta\nu(post - pre)$ are estimated separately for subsets of the catalogue for events that occurred in each of the four different regions as shown in Figure 3.1.

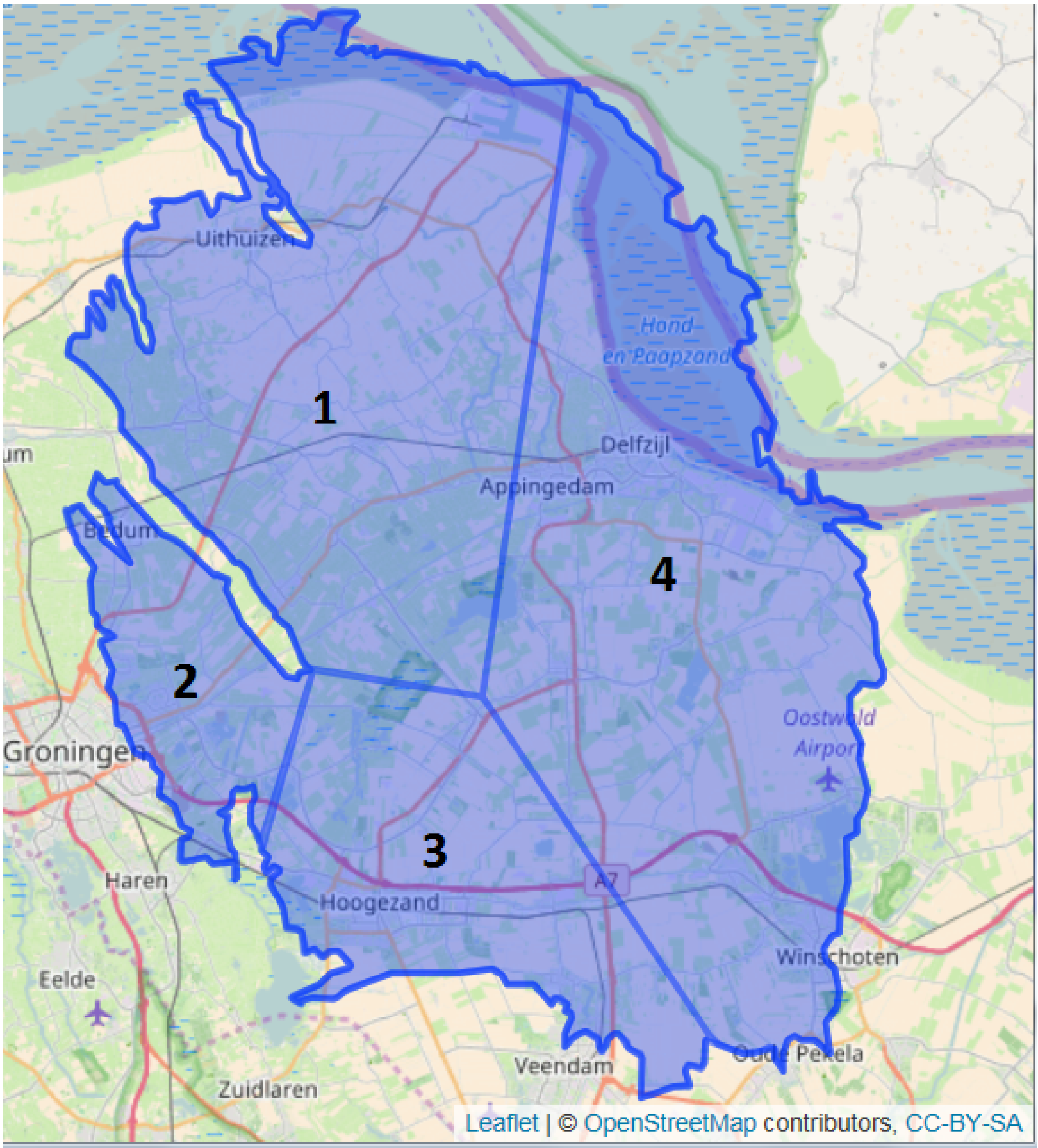

Figure 3.1: An outline of the Groningen gas field, with the four regions used in this report. 1: Loppersum region, 2: Eemskanaal region, 3: Zuidwest region, 4: Oost region. The background regional map is based on http://www.openstreetmap.nl/ . Blue boundaries are based on NAM information.

4. Identification of potential aftershocks

As described in the June report, aftershocks are identified using the window method proposed by Gardner and Knopoff (Gardner and Knopoff [1974]). Aftershocks, following a mainshock (d_o, g_o, M_o) are identified within space-time windows:

$$d_o < d < d_o + T, |g - g_o| < D, M < M_o \tag{4.1}$$

Where d, g and M are time, epicentre coordinates and magnitude of the potential aftershock respectively. D is set to 5 km while T is set to 5 days and M_o, the mainshock magnitude was 2.0. This means that an event of $M < 2.0$ within 5 days and a radius of 5 km from the mainshock (M_o $\geqslant$2.0) is considered to be an aftershock event.

5.Results based on all events (no potential aftershocks removed)

5.1. Results for events with associated magnitudes M⩾ 1.5, aftershocks retained

Start and end dates, numbers of event occurrences and durations of epochs are shown in Table 5.1 for the four regions. Estimates of differences in average inter-event times between the post-epoch and all pre-epochs are given in Table 5.2 and Figure 5.1 for all regions.

For the Loppersum region, the difference in the average inter event time between the post-epoch and the most recent pre-epoch (pre_9: 7/02/2013 to 15/11/2013; see Table 5.2) was estimated (95% confidence interval) at $\Delta\nu(post - pre)$ = 47.3 (19.5, 95.6) days. This difference in average inter-event time is 2.7 days larger than reported in our June report. A notable change in the results compared to the June report is that $\Delta\nu(post - pre)$ is now larger than 0 at the 95% level for pre-epoch pre_6 onwards (January 2009 - December 2013). In the June report statistically significant differences were estimated only for pre-epochs February 2013 onwards.

In the post-epoch a total of 15 events have been observed in the Zuidwest region. There is evidence that the event occurrence rate is higher in the post-epoch compared to the most recent pre-epoch (pre1: 05/08/2005 to 11/02/2013): $\Delta\nu(post - pre)$ = -106.4 (-258.0, -8.3) days. In our June report this was estimated at -113.8 (-263.9, -18.2) days.

Compared to our June report, there are no major changes in estimates for the Oost and Eemskanaal regions.

Table 5.1: Epoch definitions: Aftershocks retained.M⩾1.5

Loppersum Region					
Epoch	First EQ	Last EQ	T^{cens}, days	n_q, #	$S_{\{a_q,q\}}$, days
remainder	05/12/1991	04/11/1995	-	-	-
pre_1	29/02/1996	19/03/2000	-	16	1597.4
pre_2	16/05/2000	27/09/2003	-	16	1286.9
pre_3	24/10/2003	23/10/2005	-	16	757.1
pre_4	18/01/2006	23/10/2006	-	16	364.9
pre_5	26/01/2007	08/01/2009	-	16	807.5
pre_6	09/01/2009	25/04/2010	-	16	472.0
pre_7	03/05/2010	15/09/2011	-	16	508.0
pre_8	25/09/2011	19/01/2013	-	16	492.8
pre_9	07/02/2013	15/11/2013	-	16	299.9
post	03/02/2014	18/07/2016	72.6	16	1048.3
Oost Region					
Epoch	First EQ	Last EQ	T^{cens}, days	n_q, #	$S_{\{a_q,q\}}$, days
remainder	15/05/1995	03/12/1997	-	-	-
pre_1	24/12/1999	08/10/2011	-	13	5056.4
pre_2	09/11/2011	26/11/2013	-	13	781.0
post	15/03/2014	02/09/2016	26.4	13	1037.0
Zuidwest Region					
Epoch	First EQ	Last EQ	T^{cens}, days	n_q, #	$S_{\{a_q,q\}}$, days
remainder	23/11/1993	18/02/2005	-	-	-
pre_1	05/08/2005	11/02/2013	-	15	2914.6
post	11/03/2014	25/03/2016	187.9	15	1325.5
Eemskanal Region					
Epoch	First EQ	Last EQ	T^{cens}, days	n_q, #	$S_{\{a_q,q\}}$, days
remainder	23/08/1997	13/04/2006	-	-	-
pre_1	16/02/2007	21/06/2010	-	4	1529.9
pre_2	27/05/2011	07/01/2012	-	4	565.1
pre_3	05/02/2013	22/09/2013	-	4	624.3
post	26/01/2014	15/12/2015	288.7	4	1102.4

Table 5.2: Results: Aftershocks retained.M⩾1.5

Loppersum Region		$\Delta\nu$(Post-Pre), days		
Epoch	$\nu, days$	p= 0.025	p=0.5	p= 0.975
pre_1	106.2	-109.2	-34.2	24.6
pre_2	86.1	-79.2	-15.0	40.4
pre_3	50.4	-23.0	18.3	69.2
pre_4	24.3	14.2	43.2	91.5
pre_5	53.7	-27.9	15.3	66.3
pre_6	31.5	4.2	36.2	85.6
pre_7	33.9	1.4	33.9	82.7
pre_8	32.9	2.4	35.0	84.2
pre_9	20.0	19.5	47.3	95.6
post	65.5	-	-	-
Oost Region		$\Delta\nu$(Post-Pre), days		
Epoch	$\nu, days$	p= 0.025	p= 0.5	p= 0.975
pre_1	421.4	-647.9	-313.6	-144.1
pre_2	65.0	-39.0	19.9	90.8
post	79.8	-	-	-
Zuidwest Region		$\Delta\nu$(Post-Pre), days		
Epoch	$\nu, days$	p= 0.025	p=0.5	p= 0.975
pre_1	208.3	-258.0	-106.4	-8.3
post	88.4	-	-	-
Eemskanaal		$\Delta\nu$(Post-Pre), days		
Epoch	$\nu, days$	p= 0.025	p=0.5 0.975	
pre_1	511.0	-1107.2	-108.2	601.8
pre_2	187.6	-241.9	136.2	837.2
pre_3	207.7	-290.7	119.6	823.4
post	275.6	-	-	-

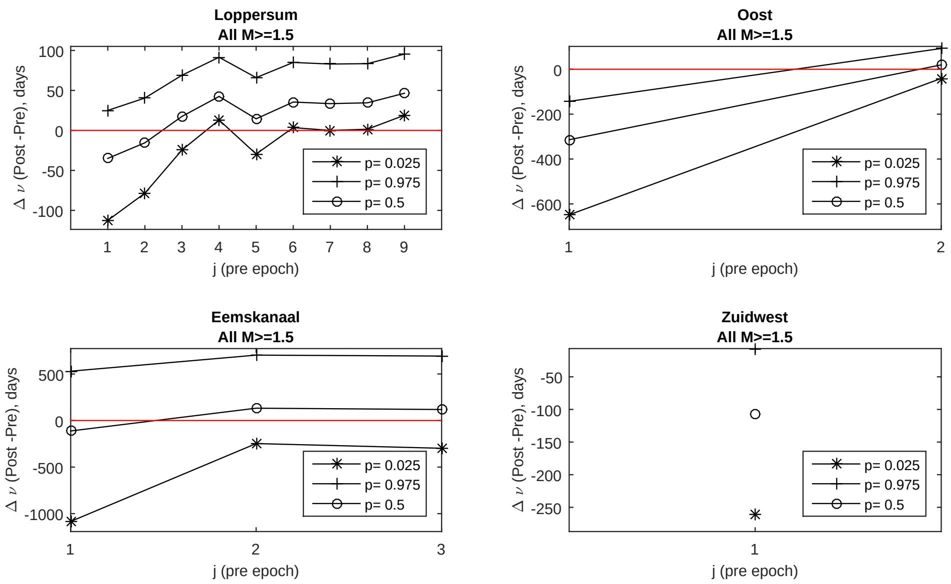

Figure 5.1: $\Delta\nu(post - pre)$ for $M \geqslant 1.5$ with aftershocks retained. x-labels indicate the pre-epoch number. See Table 5.1 for the dates.

5.2. Results for events with associated magnitudes M$\geqslant$ 1.0, aftershocks retained

Start and end dates, numbers of event occurrences and durations of epochs are shown in Table 5.3 for all regions. Estimates of differences in average inter-event times between the post-epoch and all pre-epochs are given in Table 5.4 and Figure 5.2.

In the post-epoch a total of $n_q = 43$ events with associated magnitudes $M \geqslant 1.0$ occurred within the Loppersum region (compared to 40 events in our June report). The differences in the average inter-event time between the post-epoch and the two most recent pre-epochs (pre_6 and pre_7: from 27/06/2011 to 23/12/2013) are statistically significant at the 95% level at $\Delta\nu(post - pre) =$ 12.0 (4.7, 21.4) days for epoch pre_7 (similar to estimate given in our June report) and $\Delta\nu(post - pre)$ = 13.8 (6.9, 23.0) days for pre-epoch pre_6 (2.5 days more compared to the estimate reported in our June report).

In the post-epoch a total of 36 events have been observed in the Zuidwest region (one more event compared to our June report). There is evidence that the activity rate in the post-epoch is higher compared to the activity rate in the first (and only) pre-epoch (pre_1: 13/04/2007 to 22/12/2013): $\Delta\nu(post - pre) = -40.6$ (-70.2, -19.1) days.

Compared to our June report, there are no major changes in estimates for the Oost and Eemskanaal regions.

Table 5.3: Epoch definitions: Aftershocks retained.M⩾1.0

Loppersum Region					
Epoch	First EQ	Last EQ	T^{cens}, days	n_q, #	$S_{\{a_q,q\}}$, days
remainder	05/12/1991	27/06/1993	-	-	-
pre_1	10/07/1993	08/05/1999	-	43	2141.7
pre_2	10/08/1999	30/10/2004	-	43	2001.6
pre_3	13/11/2004	27/09/2006	-	43	697.5
pre_4	06/10/2006	04/05/2009	-	43	949.5
pre_5	07/05/2009	24/06/2011	-	43	780.6
pre_6	27/06/2011	15/08/2012	-	43	418.8
pre_7	16/08/2012	23/12/2013	-	43	494.2
post	03/02/2014	28/08/2016	31.9	43	1011.0
Oost Region					
Epoch	First EQ	Last EQ	T^{cens}, days	n_q, #	$S_{\{a_q,q\}}$, days
remainder	12/02/1993	25/10/2006	-	-	-
pre_1	10/01/2007	15/11/2011	-	34	1846.9
pre_2	31/01/2012	08/12/2013	-	34	753.8
post	16/01/2014	21/09/2016	7.4	34	1025.9
Zuidwest Region					
Epoch	First EQ	Last EQ	T^{cens}, days	n_q, #	$S_{\{a_q,q\}}$, days
remainder	11/12/1992	21/03/2007	-	-	-
pre_1	13/04/2007	22/12/2013	-	36	2467.9
post	02/01/2014	18/06/2016	102.0	36	1011.1
Eemskanal Region					
Epoch	First EQ	Last EQ	T^{cens}, days	n_q, #	$S_{\{a_q,q\}}$, days
remainder	23/08/1997	08/04/2000	-	-	-
pre_1	18/03/2001	23/07/2008	-	12	3028.4
pre_2	20/09/2008	23/12/2011	-	12	1247.6
pre_3	07/01/2012	29/09/2013	-	12	646.3
post	04/01/2014	28/05/2016	123.9	12	1095.2

Table 5.4: Results: Aftershocks retained.M⩾1.0

Loppersum Region		$\Delta\nu$(Post-Pre), days		
Epoch	$\nu, days$	p= 0.025	p=0.5	p= 0.975
pre_1	51.0	-45.7	-26.3	-11.3
pre_2	47.7	-41.6	-23.1	-8.6
pre_3	16.6	-1.1	7.3	17.0
pre_4	22.6	-8.8	1.4	11.7
pre_5	18.6	-3.6	5.4	15.2
pre_6	10.0	6.9	13.8	23.0
pre_7	11.8	4.7	12.0	21.4
post	23.5	-	-	-

Oost Region		$\Delta\nu$(Post-Pre), days		
Epoch	$\nu, days$	p= 0.025	p= 0.5	p= 0.975
pre_1	55.9	-49.2	-24.0	-4.3
pre_2	22.8	-4.6	8.1	22.5
post	30.2	-	-	-

Zuidwest Region		$\Delta\nu$(Post-Pre), days		
Epoch	$\nu, days$	p= 0.025	p=0.5	p= 0.975
pre_1	70.5	-70.2	-40.6	-19.1
post	28.1	-	-	-

Eemskanaal		$\Delta\nu$(Post-Pre), days		
Epoch	$\nu, days$	p= 0.025	p=0.5	p =0.975
pre_1	275.3	-394.3	-162.8	-31.3
pre_2	113.5	-112.9	-12.6	79.3
pre_3	58.8	-22.7	37.7	123.1
post	91.3	-	-	-

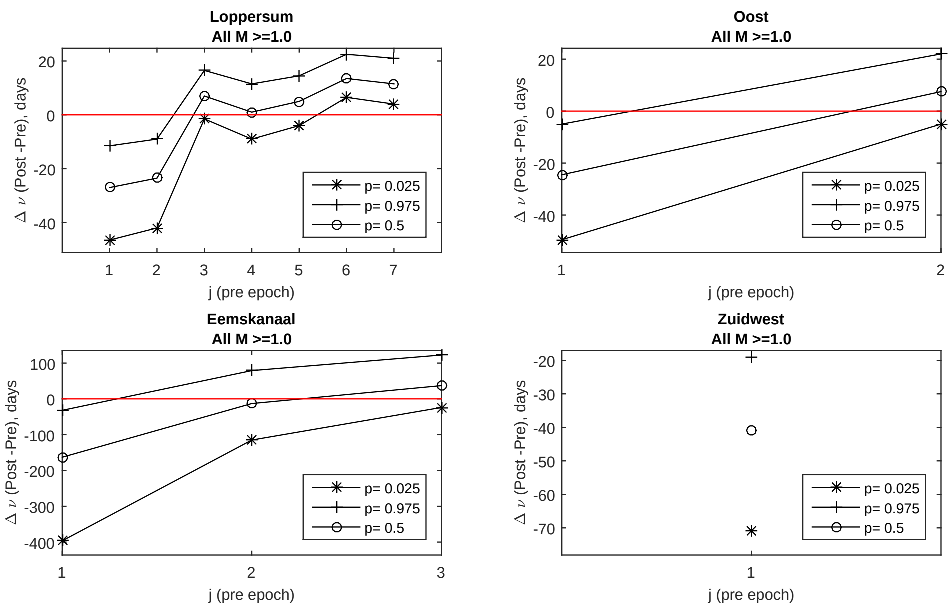

Figure 5.2: $\Delta\nu(post - pre)$ for $M \geqslant 1.0$ with aftershocks retained. x-labels indicate the pre-epoch number. See Table 5.3 for the dates.

6.Results based on a catalogue with potential aftershocks removed

Potential aftershocks were removed using the Gardner and Knopoff method described in Chapter 4. The main shocks were identified by indicator '1' in column F in Figure 6.1. The associated after-shocks are identified by indicator '0' in the same figure. There are in total 25 potential aftershocks paired with 21 main shocks (column G in figure 6.1). We note however that no main shock/after shock sequence has been observed between the June report and the current report. We also note that a large sequence of 6 events is observed in February 2013. The choice to include or exclude this sequence of potential aftershocks has a relatively large influence on the conclusions of the statistical analyses.

A	B	C	D	E	F	G
date	mag	place	RD_X	RD_Y	MS	Cluster
30/07/1994	2.7	Middelstum	237624.8	596779.0	1	1
30/07/1994	1.3	Middelstum	234203.2	598279.6	0	1
11/06/2000	2	Loppersum	246620.2	596608.6	1	2
12/06/2000	2.5	Loppersum	245238.6	595691.8	0	2
24/10/2003	3	Hoeksmeer	248666.4	590748.1	1	3
26/10/2003	1.2	Hoeksmeer	248380.2	591744.4	0	3
10/11/2003	3	Stedum	241805.5	593958.6	1	4
10/11/2003	1.4	Westeremden	243088.9	596653.7	0	4
21/03/2006	2.4	Ten Post	246184.8	591479.6	1	5
23/03/2006	2.2	Overschild	247758.8	589394.7	0	5
08/08/2006	3.5	Westeremden	242221.2	596749.1	1	6
08/08/2006	2.5	Westeremden	242889.2	596650.0	0	6
23/10/2006	2.3	Garsthuizen	244905.3	599247.8	1	7
26/10/2006	1.4	Oldenzijl	242664.2	601655.3	0	7
17/02/2007	2.6	Harkstede	242871	583069.0	1	8
17/02/2007	0.9	Harkstede	241533.4	583156.1	0	8
01/02/2009	2.2	Westeremden	245063.5	597914.9	1	9
04/02/2009	1.7	Garsthuizen	245163.1	599697.9	0	9
16/04/2009	2.6	Appingedam	252159.3	592821.4	1	10
20/04/2009	1.5	Wirdumerpolde	249730.9	590880.3	0	10
03/05/2010	2.3	Spijk	249664	601009.4	1	11
05/05/2010	1.6	Oosternieland	247299	602855.7	0	11
27/06/2011	3.2	Garrelsweer	248315.7	591631.8	1	12
27/06/2011	1.4	Appingedam	247666.3	590728.7	0	12
27/06/2011	1.1	Appingedam	249311.2	591873.9	0	12
15/08/2012	2.4	Leermens	249405.9	597219.3	1	13
16/08/2012	1.2	Zeerijp	245858.2	598152.6	0	13
16/08/2012	3.6	Huizinge	240566.5	596162.7	1	14
17/08/2012	0.6	Middelstum	239271.9	597809.5	0	14
07/02/2013	2.7	Zandeweer	240174.2	599495.3	1	15
07/02/2013	3.2	Zandeweer	240146.4	601053.2	0	15
11/02/2013	2	Garrelsweer	248062	590959.0	1	16
11/02/2013	1.8	Garrelsweer	247072.7	590383.3	0	16
15/02/2013	2	Wirdum	248814.1	593422.7	0	16
18/02/2013	0.7	Leermens	247883.2	596744.2	0	16
20/07/2013	2.4	Oosterwijtwerd	249338.5	593878.3	1	17
20/07/2013	1.9	Wirdum	247472.9	593841.9	0	17
21/07/2013	0.7	Overschild	247750.2	589839.8	0	17
01/09/2014	2.6	Froombosch	248551.5	579502.7	1	18
01/09/2014	1.6	Froombosch	250282.4	579870.6	0	18
30/12/2014	2.8	Woudbloem	244579.7	580985.6	1	19
30/12/2014	0.8	Luddeweer	246184.4	584466.5	0	19
30/10/2015	2.3	Meedhuizen	257223.8	589809.5	1	20
30/10/2015	0.9	Meedhuizen	257545.3	590373.0	0	20
25/02/2016	2.4	Froombosch	248172.1	578382.2	1	21
29/02/2016	0.3	Froombosch	247975.9	578155.8	0	21

Figure 6.1: Clusters of potential Main Shocks and Potential aftershocks, as identified using the Gardner and Knopoff method (see chapter 4). Column F shows main potential main shocks (indicated by '1') and potential aftershocks caused by this main shock (indicated by '0'). Each horizontal colored strip (Green or Amber) indicates one group of a main shock and its aftershock(s). The event at Wirdum (marked in red) dated 15/02/2013 can be considered as both a main shock and an aftershock.

6.1. Results for events with associated magnitudes M⩾ 1.5, aftershocks removed

Start and end dates, numbers of event occurrences and durations of epochs are shown in Table 6.1 for all regions. Estimates of differences in average inter-event times between the post-epoch and all pre-epochs are given in Table 6.2 and Figure 6.2 for all regions.

In the post-epoch a total of $n_q = 16$ events with associated magnitudes M⩾ 1.5 occurred within the Loppersum region, with aftershocks removed (one additional event compared to our June report). An increase in average inter-event time in the post-epoch is estimated compared to the seven most recent pre-epochs (pre_3 through to pre_9: from 30/01/2003 to 15/11/2013) although the 95% CI includes zero for several of these pre-epochs. For the two most recent pre-epochs (pre_8 and pre_9), the differences in average inter-event time are statistically significant at the 95% confidence level, with $\Delta\nu(post - pre_8)$ = 45.5 (17.1, 94.1) days (compared to 40.3 (11.1. 89.4) days in our June report) and $\Delta\nu(post - pre_9)$ = 33.7 (0.4, 82.6) (compared to 33.4 (-0.2, 82.5) days in the June report).

In the post-epoch a total of 14 events have been observed in the Zuidwest region (equivalent to the number of events in our June report). The difference in average inter-event time is estimated at $\Delta\nu(post - pre_1)$= -102.6 (-265.1, 2.0) days and is thus not statistically significant at the 95% confidence level. We note that these results should be regarded with caution due to the small sample size which results in a low statistical power.

Compared to our June report, there are no major changes in estimates for the Oost and Eemskanaal regions.

Table 6.1: Epoch definition: Aftershocks removed.M⩾1.5

Loppersum Region					
Epoch	First EQ	Last EQ	T^{cens}, days	n_q, #	$S_{\{a_q,q\}}$, days
remainder	05/12/1991	22/09/1993	-	-	-
pre_1	22/12/1993	15/02/1998	-	16	1606.6
pre_2	19/04/1998	23/01/2003	-	16	1803.0
pre_3	30/01/2003	26/11/2004	-	16	673.0
pre_4	09/01/2005	22/04/2006	-	16	511.9
pre_5	16/06/2006	18/05/2008	-	16	757.4
pre_6	19/05/2008	29/09/2009	-	16	498.5
pre_7	04/12/2009	29/07/2011	-	16	668.9
pre_8	31/08/2011	21/06/2012	-	16	327.4
pre_9	15/08/2012	15/11/2013	-	16	512.4
post	03/02/2014	18/07/2016	72.6	16	1048.3
Oost Region					
Epoch	First EQ	Last EQ	T^{cens}, days	n_q, #	$S_{\{a_q,q\}}$, days
remainder	15/05/1995	03/12/1997	-	-	-
pre_1	24/12/1999	08/10/2011	-	13	5056.4
pre_2	09/11/2011	26/11/2013	-	13	781.0
post	15/03/2014	02/09/2016	26.4	13	1037.0
Zuidwest Region					
Epoch	First EQ	Last EQ	T^{cens}, days	n_q, #	$S_{\{a_q,q\}}$, days
remainder	23/11/1993	05/08/2005	-	-	-
pre_1	04/03/2006	11/02/2013	-	14	2746.7
post	11/03/2014	25/03/2016	187.9	14	1325.5
Eemskanal Region					
Epoch	First EQ	Last EQ	T^{cens}, days	n_q, #	$S_{\{a_q,q\}}$, days
remainder	23/08/1997	13/04/2006	-	-	-
pre_1	16/02/2007	21/06/2010	-	4	1529.9
pre_2	27/05/2011	07/01/2012	-	4	565.1
pre_3	05/02/2013	22/09/2013	-	4	624.3
post	26/01/2014	15/12/2015	288.7	4	1102.4

Table 6.2: Results: Aftershocks removed.M⩾1.5

Loppersum Region		$\Delta\nu$(Post-Pre), days		
Epoch	$\nu, days$	p= 0.025	p=0.5	p= 0.975
pre_1	107.2	-112.4	-35.0	24.5
pre_2	120.0	-132.2	-47.3	14.8
pre_3	44.9	-15.0	23.4	73.7
pre_4	34.1	0.7	33.7	83.2
pre_5	50.5	-23.4	18.2	69.0
pre_6	33.2	2.0	34.5	84.2
pre_7	44.5	-14.9	23.7	74.3
pre_8	21.8	17.1	45.5	94.1
pre_9	34.1	0.4	33.7	82.6
post	65.5	-	-	-
Oost Region		$\Delta\nu$(Post-Pre), days		
Epoch	$\nu, days$	p= 0.025	p= 0.5	p= 0.975
pre_1	421.9	-649.5	-314.7	-145.4
pre_2	65.0	-39.5	19.8	91.7
post	79.8	-	-	-
Zuidwest Region		$\Delta\nu$(Post-Pre), days		
Epoch	$\nu, days$	p= 0.025	p=0.5	p= 0.975
pre_1	211.5	-265.1	-102.6	2.9
post	94.7	-	-	-
Eemskanaal		$\Delta\nu$(Post-Pre), days		
Epoch	$\nu, days$	p= 0.025	p=0.5	p =0.975
pre_1	508.0	-1092.0	-106.7	611.2
pre_2	188.7	-251.0	136.1	839.1
pre_3	208.3	-300.6	120.8	835.4
post	275.6	-	-	-

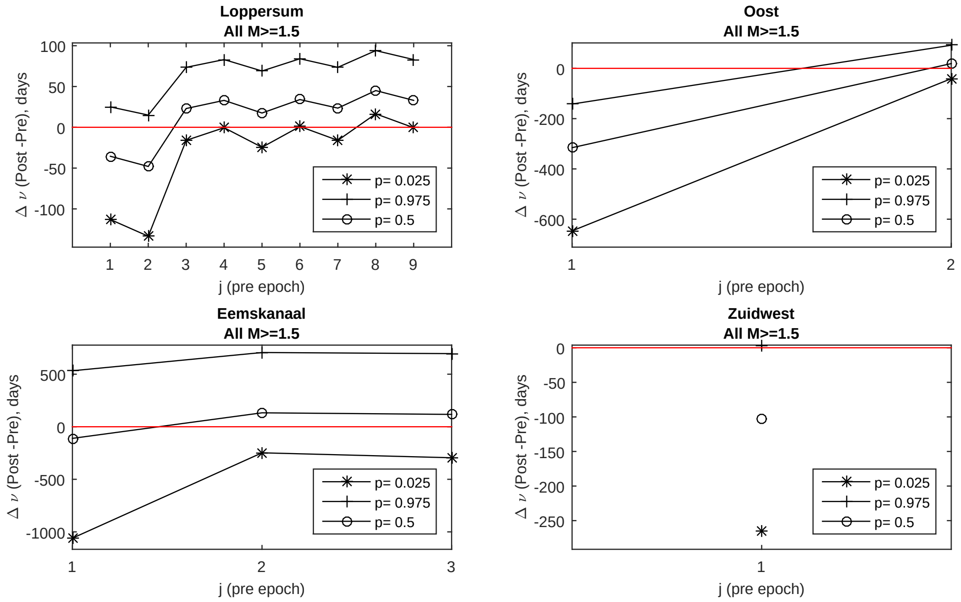

Figure 6.2: Results for $\Delta\nu(post - pre)$ for $M \geqslant 1.5$ with aftershocks removed. x-labels indicate the pre-epoch number. See Table 6.1 for the dates.

6.2. Results for events with associated magnitudes M⩾ 1.0, aftershocks removed

Start and end dates, numbers of event occurrences and durations of epochs are shown in Table 6.3 for all regions. Estimates of differences in average inter-event times between the post-epoch and all pre-epochs are given in Table 6.4 and Figure 6.3 for all regions.

A total of 43 events occurred occurred in the Loppersum region (compared to 40 events in our June report). The difference in the average inter event time between the post-epoch and the most recent pre-epochs (pre_6: from 19/05/2011 to 23/12/2013) was estimated (95% confidence interval) at $\Delta\nu(post - pre)$ = 11.0 (3.6, 20.3) days (compared to 9.9 (2.3, 19.4) days in our June report and $\Delta\nu(post - pre)$ = 13.7 (6.8, 22.8) days for epoch pre_5 (compared to 12.6 (5.6, 21.8) days in our June report).

A total of 35 events occurred occurred in the Zuidwest region (compared to 34 in our June report). The difference in the average inter event time between the post-epoch and the pre-epoch (pre_1 from 30/09/2007 to 22/12/2013 was estimated at -41.0 (-71.7, -18.7) days (compared to -40.3 (-70.3, -18.8) days in our June report).

Compared to our June report, there are no major changes in estimates for the Oost and Eemskanaal regions.

Table 6.3: Epoch definitions: Aftershocks removed.M⩾1.0

Loppersum Region					
Epoch	First EQ	Last EQ	T^{cens}, days	n_q, #	$S_{\{a_q,q\}}$, days
remainder	05/12/1991	29/04/1997	-	-	-
pre_1	19/06/1997	03/06/2003	-	43	2225.9
pre_2	08/06/2003	19/04/2006	-	43	1051.1
pre_3	22/04/2006	23/12/2008	-	43	978.9
pre_4	01/01/2009	07/05/2011	-	43	864.9
pre_5	19/05/2011	03/07/2012	-	43	423.2
pre_6	27/07/2012	23/12/2013	-	43	537.3
post	03/02/2014	28/08/2016	31.9	43	1011.0
Oost Region					
Epoch	First EQ	Last EQ	T^{cens}, days	n_q, #	$S_{\{a_q,q\}}$, days
remainder	12/02/1993	25/10/2006	-	-	-
pre_1	10/01/2007	15/11/2011	-	34	1846.9
pre_2	31/01/2012	08/12/2013	-	34	753.8
post	16/01/2014	21/09/2016	7.4	34	1025.9
Zuidwest Region					
Epoch	First EQ	Last EQ	T^{cens}, days	n_q, #	$S_{\{a_q,q\}}$, days
remainder	11/12/1992	13/04/2007	-	-	-
pre_1	30/09/2007	22/12/2013	-	35	2445.3
post	02/01/2014	18/06/2016	102.0	35	1011.1
Eemskanal Region					
Epoch	First EQ	Last EQ	T^{cens}, days	n_q, #	$S_{\{a_q,q\}}$, days
remainder	23/08/1997	08/04/2000	-	-	-
pre_1	18/03/2001	23/07/2008	-	12	3028.4
pre_2	20/09/2008	23/12/2011	-	12	1247.6
pre_3	07/01/2012	29/09/2013	-	12	646.3
post	04/01/2014	28/05/2016	123.9	12	1095.2

Table 6.4: Results: Aftershocks removed.M⩾1.0

Loppersum Region		$\Delta\nu$(Post-Pre), days		
Epoch	ν, *days*	p= 0.025	p=0.5	p= 0.975
pre_1	53.0	-48.5	-28.4	-12.7
pre_2	25.0	-11.7	-0.9	9.8
pre_3	23.3	-9.4	0.8	11.1
pre_4	20.6	-6.0	3.5	13.5
pre_5	10.1	6.8	13.7	22.8
pre_6	12.8	3.6	11.0	20.3
post	23.5	-	-	-
Oost Region		$\Delta\nu$(Post-Pre), days		
Epoch	ν, *days*	p= 0.025	p= 0.5	p= 0.975
pre_1	55.9	-49.3	-24.1	-4.7
pre_2	22.8	-4.6	8.0	22.4
post	30.2	-	-	-
Zuidwest Region		$\Delta\nu$(Post-Pre), days		
Epoch	ν, *days*	p= 0.025	p=0.5	p= 0.975
pre_1	71.9	-71.7	-41.0	-18.7
post	28.9	-	-	-
Eemskanaal		$\Delta\nu$(Post-Pre), days		
Epoch	ν, *days*	p= 0.025	p=0.5	p= 0.975
pre_1	275.1	-394.0	-163.0	-32.2
pre_2	113.5	-114.8	-12.7	79.3
pre_3	58.8	-22.7	37.5	123.4
post	91.3	-	-	-

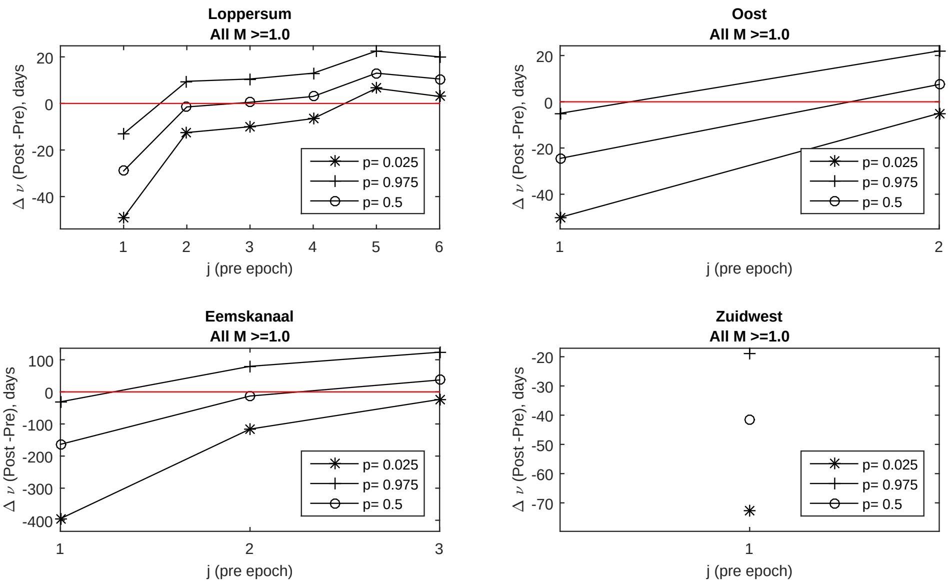

Figure 6.3: Results for $\Delta\nu(post - pre)$ for $M \geqslant 1.0$ with aftershocks removed. x-labels indicate the pre-epoch number. See Table 6.3 for the dates.

7.Conclusions

Differences between epochs in earthquake (EQ) occurrence rates were estimated for each of four different regions within the Groningen gas field using the latest catalogue that was downloaded from the KNMI website on 29/09/2016.

The results of the statistical analyses as presented in this report are similar to the results as presented in the report published in June 2016. However, the weight of evidence has shifted further towards a decrease in the rate at which earthquakes occur in the Loppersum area since 01/01/2014, such that we can now be confident about this decrease in event occurrence rate. Furthermore, there is evidence that there are regional contrasts in EQ occurrence rate within the Groningen field. While the rate in the post-epoch has decreased in Loppersum, in the Zuidwest region rates were higher in the post-epoch compared to a single pre-epoch which spans multiple years; Due to the relatively small number of event occurrences in this region it is not possible to determine whether the timing of changes in activity rate coincides with the changes in gas production rates. For the other two regions (Oost and Eemskanaal) there is no evidence of changes in rates of event occurrences following January 2014, but the power of the statistical tests is low due to low numbers of events in these regions. The monitoring (geophone) network has been upgraded from time to time and a major upgrade was carried out more recently. This is expected to impact the magnitude of completeness M_c above which it can be assumed that all events will be detected and recorded in the earthquake catalogue. An initial analysis of temporal variations in M_c across the entire Groningen field is presented. The results indicate that the magnitude of completeness has been decreasing in recent years, with an M_c of approximately 1.2 in the period 2003-2009 compared to approximately 0.6 in more recent times. These estimates are preliminary, and we recommend that more work is done on this subject.

More detailed conclusions are given below for the Loppersum and Zuidwest regions.

Results for the Loppersum area:

- **Earthquakes with** $M \geqslant 1.5$: There is good evidence that event occurrence rates were lower in the post-epoch compared to pre-epochs between January 2009 and November 2013. The average time between earthquakes (inter-event time) increased by an estimated $\Delta\nu(post - pre) = 33.9$ to 47.3 days in the post-epoch compared to these pre-epochs. These increases in average inter-event times were statistically significant at the 95% level. When potential aftershocks are removed from the catalogue, there is still good evidence that the average inter-event time has increased in the post-January 2014 epoch compared to the pre-epochs between August 2011 and November 2013.
- **Earthquakes with** $M \geqslant 1.0$: There is good evidence, regardless of whether potential aftershocks are retained or removed before statistical analysis, that there were fewer earthquakes with associated magnitudes $M \geqslant 1.0$ per unit of time in the period after 2014 (post-epoch) compared to the rates of earthquakes in pre-epochs between June 2011 and December 2013. The decrease in rate of earthquakes with associated magnitudes $M \geqslant 1.0$ may have been more pronounced than reported here, since the capability of the monitoring network to record events with magnitude $1.0 \leqslant M < 1.5$ is likely to have been better in the post-epoch compared to the pre-epoch.

Results for the Zuidwest area:

- Relatively few events have been recorded in this region and the statistical analysis is therefore performed only at a very coarse temporal resolution with one post-epoch (January 2014 to the present) and one pre-epoch which spans many years. There is evidence that there were more earthquakes per unit of time in the post-epoch compared to the pre-epoch. We note that no additional events have been recorded in the EQ catalogue since the June 2016 report on this topic.

- **Earthquakes with** $M \geqslant 1.5$: The average inter-event time was lower in the post-epoch compared to the pre-epoch (March 2006 to February 2013) by $\Delta\nu(post - pre)$ = -106.4 days. This difference in average inter-event time is statistically significant at the 95% significance level. If potential aftershocks are removed, the difference in average inter-event time between the post and pre-epoch is (marginally) non-significant at the 95% confidence level.
- **Earthquakes with** $M \geqslant 1.0$: There is an indication, regardless of whether potential aftershocks are retained or removed before statistical analysis, that there were more earthquakes with associated magnitudes $M \geqslant 1.0$ per unit of time in the period after 2014 (post-epoch) compared to the rates of earthquakes in pre-epoch (September 2009 - December 2012) but care is required in the interpretation of this finding as this may have been partly due to improvements in the capability of the monitoring network to detect events with magnitudes below $M < 1.5$.
- We note that due to the relatively small number of event occurrences in this region, it is not possible to determine when a change in activity rate has occurred. It is also possible that a gradual change in activity rate has occurred over the period of several years. It is unclear whether the timing of changes in activity rate coincides with the changes in gas production rates at the 1st of january 2014.

The overall field wide (aggregated over all regions) changes in event occurrence rates are less pronounced compared to the regional contrasts. For events $M \geqslant 1.0$ there is evidence that the field-wide event occurrence rate has decreased in the post-epoch compared to the most recent pre-epochs (Appendix B). For events $M \geqslant 1.5$ there is no statistically significant difference.

Appendix A.

Rate change in the post-epoch

In the main body of the report, results are presented of statistical analyses of regional changes in event occurrence rates in the post-epoch compared to all pre-epochs. The post-epoch currently spans more than 2.5 years, and it is of interest to study potential changes in event occurrence rates within this post-epoch. This is possible only if the numbers of event occurrences are large enough to provide enough statistical power to detect potential trend changes. A more detailed analysis of changes in event occurrence rates in the period following January 2014 in the Loppersum region for events $M \geqslant 1.0$ is presented in this secton, as the numbers of event occurrences in this region were deemed to be sufficient for reliable statistical analysis.

The post-epoch is partitioned into two sub-epochs. The first sub-epoch, referred to as 'Post 1' contains half the number of events in the post-epoch closest in time to the shut-in date (01/01/2014) while the second sub-epoch ('Post 2') contains the remaining events. The standard methodology for estimating differences in average inter-event time as described in Paleja and Bierman [2016a] and Paleja et al. [2015] will be used to estimate evidence of rate changes within the post-epoch using the following test statistics:

- $\Delta\nu(post2 - post1)$.
- $\Delta\nu(post1 - pre)$ and $\Delta\nu(post2 - pre)$.

The analysis is restricted to the Loppersum region for events $M \geqslant 1.0$. This is because historically the majority of the events have been observed in this region. The reason for restricting the analysis to $M \geqslant 1.0$ and including potential aftershocks in the analysis is because the error in posterior ν and $\Delta\nu$ is inversely proportional to the sample size. However, this means that our conclusions are likely to be too optimistic regarding evidence of potential rate changes. Dividing the post-epoch into two sub epochs will result in a limited number of observations for all other cases and the conclusions can be misleading.

The Loppersum region has 43 events in the post epocs (see table 5.3. 'Post 1' epoch contains 21 events. The start and end dates for 'Post 1' epoch are 03/02/2014 and 30/09/2014 respectively. 'Post 2' epoch contains 22 events with 28/12/2014 and 28/08/2016 as the start and end date respectively. The inter-events times for the two post-epochs are shown in Figure A.1. We note that the green bar shows T^{cens}, the censored time or the time between the last event in 'Post 2' epoch (28/08/2016) and the date of generating the catalogue (29/09/2016).

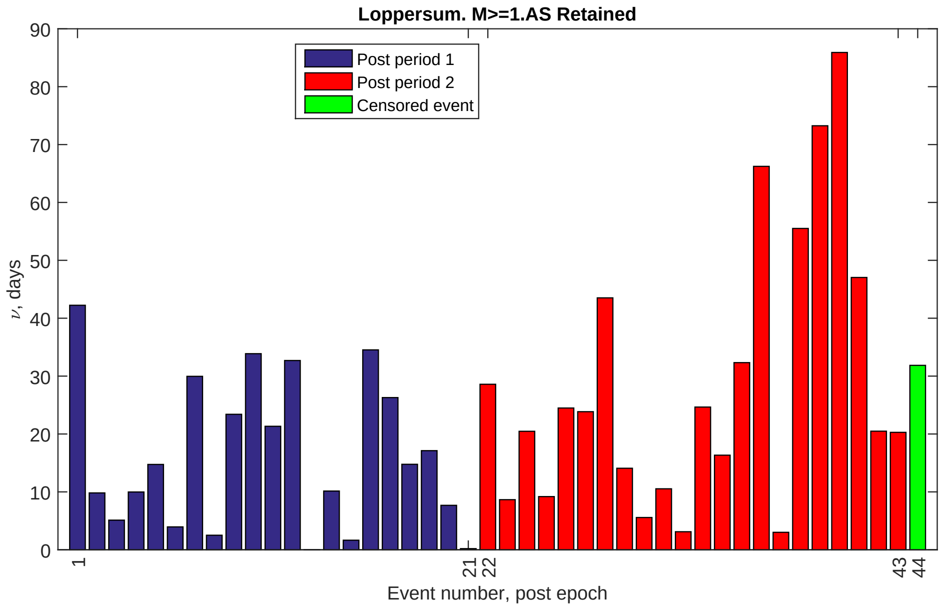

Figure A.1: Inter event times for 'Post 1' events (blue) and 'Post 2' events (red) for Loppersum, $M \geqslant 1.0$. The green bar shows the censor time, T^{cents}

The density plot of test statistic $\Delta\nu(post2 - post1)$ is shown in Figure A.2. The expected value is 14.0 days (95% CI = (0.4, 32.8) days) suggesting that the EQ occurrence rate in Loppersum for $M \geqslant 1.0$ has reduced with time post shut-in and events are less frequent now than at the beginning of the post shut-in period.

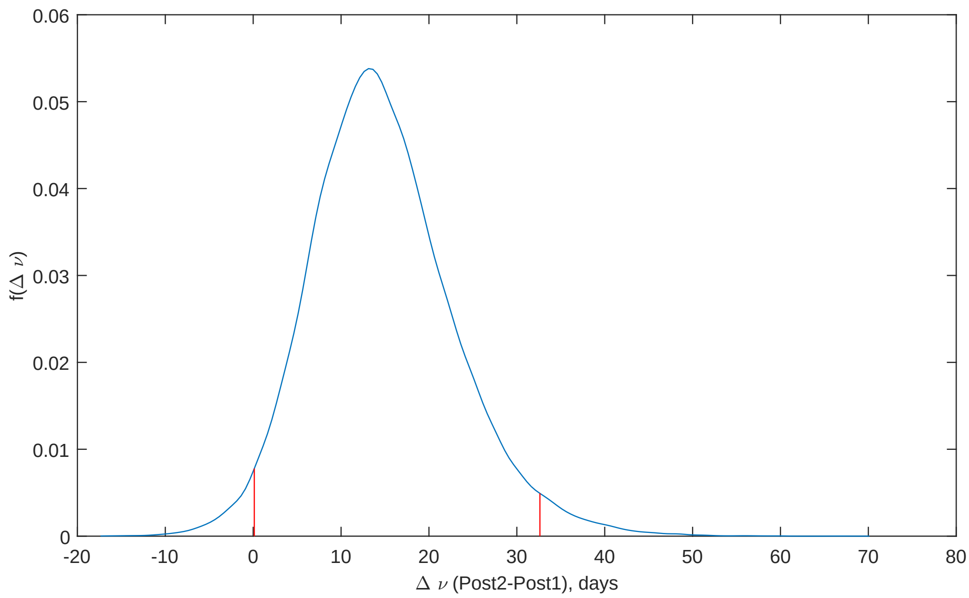

Figure A.2: Density of $\Delta\nu(post2 - post1), days$ test statistics in days. The two red lines show the 95% CI.

Figure A.3 shows the test statistic $\Delta\nu(post2 - pre)$ (bottom panel) and $\Delta\nu(post1 - pre)$ (top panel). The evidence for $\Delta\nu(post2 - pre)$ to be statistically significant is much stronger than for

$\Delta\nu(post1 - pre)$ suggesting that the EQ occurrence $M \geqslant$1.0 has decreased with time in the post-epoch.

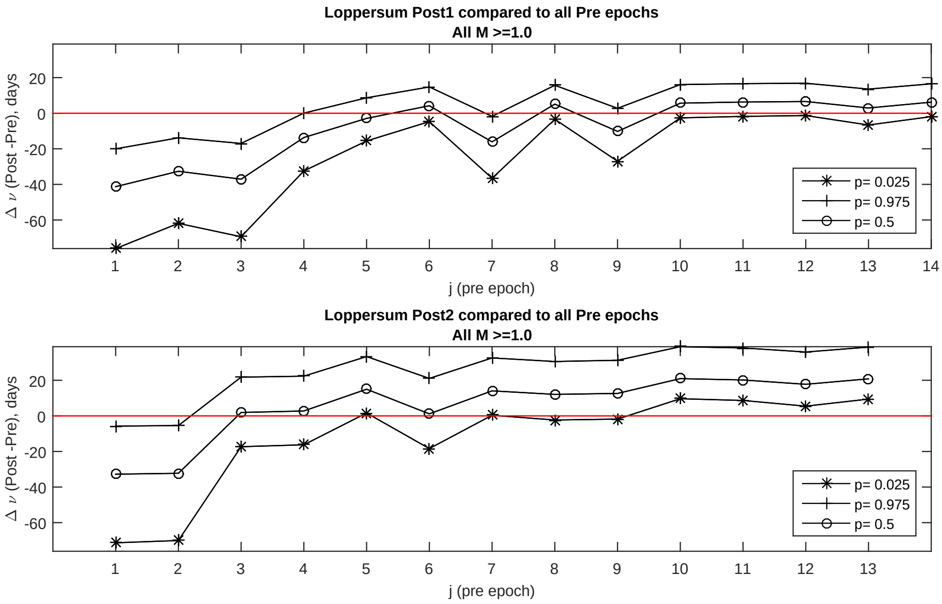

Figure A.3: Test statistics $\Delta\nu(post2 - pre)$ (bottom panel) and $\Delta\nu(post1 - pre)$ top panel for Loppersum, $M \geqslant 1.0$ with aftershocks retained

Appendix B.

EQ occurrence rate: All regions

In this section changes over time in EQ occurrence rates are investigated for the entire Groningen field. The analysis is done for both $M \geqslant 1.5$ and $M \geqslant 1.0$ with and without aftershocks. Given that there is a contrast in EQ occurrence rate at a regional level, with lower EQ rate in Loppersum and higher rate in Zuidwest in the post-epoch, the aim of this analysis is to see if there is evidence that the overall (field-wide) rate of event occurrences has decreased. Since, at a field-wide level, the catalogue is sufficiently rich, we divide the post shut-in data into sub-epochs such that 20-30 earthquakes are in each post sub-epoch. Such a division allows us to do our analysis at a higher temporal resolution (smaller epochs) whilst ensuring that there are sufficient numbers of events for a reliable statistical analysis.

B.1. EQ occurrence rate of $M \geqslant 1.5$

There are 39 events of $M \geqslant 1.5$ that have occurred in the entire Groningen field in the post shut-in period with aftershocks retained. These are divided into 2 post-epochs ('Post 1 and 'Post 2'). The epoch 'Post 1' contains 19 events while 'Post 2' contains 20 events. The start and the end dates of the two post-epochs are given in Table B.1. The pre shut-in period is partitioned into pre-epochs with identical number of events and $\Delta\nu$ for each post-epoch is compared to the pre-epochs. The results are shown in Figure B.1

Table B.1: All Groningen field and $M \geqslant 1.5$. Partitioning EQ counts in post shut-in period into two epochs

post-epoch	Start date	End Date	n_q, #
Post 1	13/02/2014	25/02/2015	19
Post 2	24/03/2015	02/09/2016	20

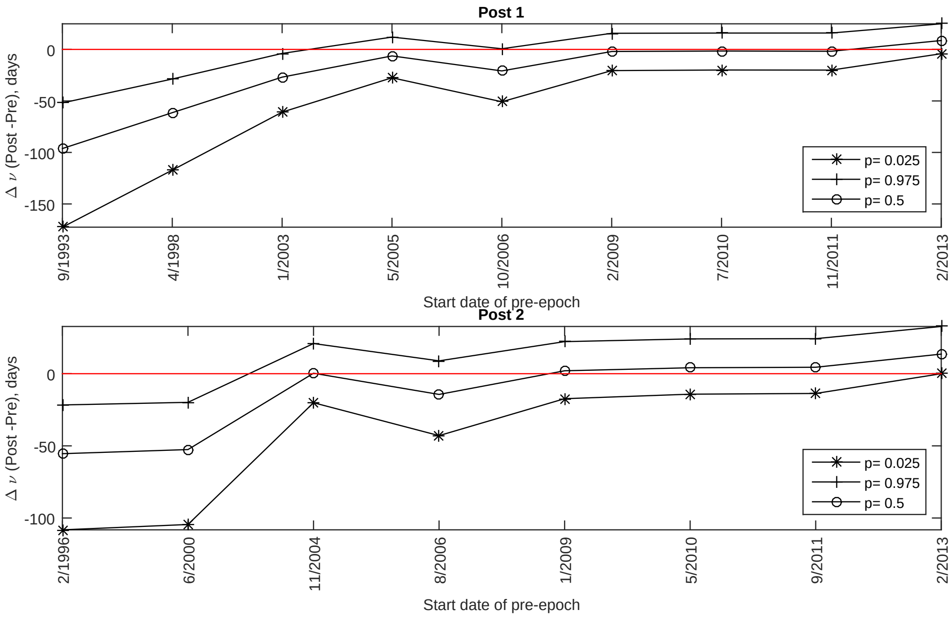

Figure B.1: Test statistics $\Delta\nu(post - pre)$ for events $M \geqslant 1.5$ with aftershocks retained for the entire Groningen field. Top left panel: 'Post 1' epoch, Bottom panel, 'Post 2' epoch.

Removing the aftershocks results in 38 events of $M \geqslant 1.5$. These are divided into 'Post 1' and 'Post 2' epochs with 19 events in each. The start and end dates for the two post-epochs do not change and remain as shown in Table B.1. The test statistic $\Delta\nu$ for each post-epoch is compared to the pre-epochs. The results are shown in Figure B.2

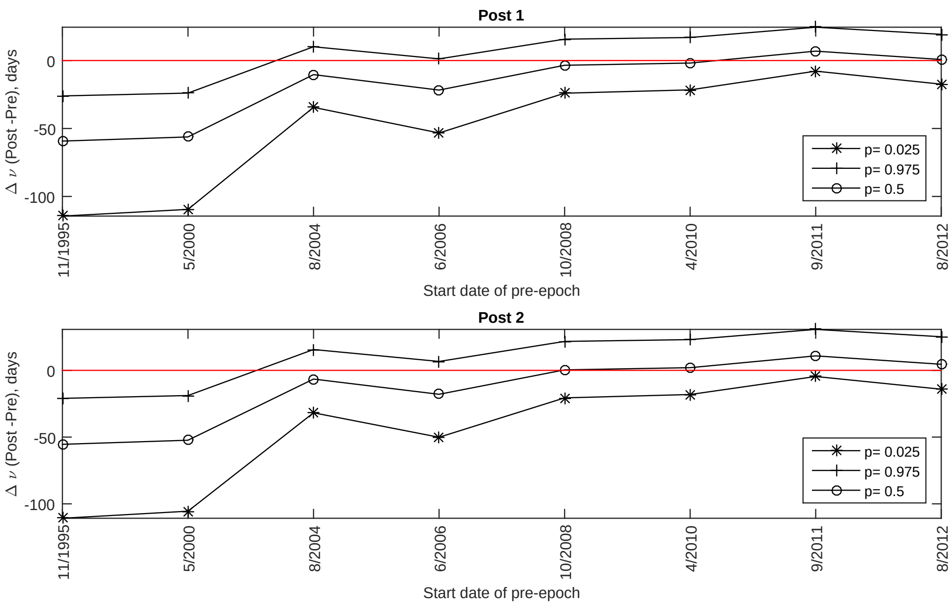

Figure B.2: Test statistics $\Delta\nu(post - pre)$m $M \geqslant 1.5$ with aftershocks removed for the entire Groningen field. Top left panel: 'Post 1' epoch, Bottom pannel, 'Post 2' epoch

The analysis shows that there is some evidence of a decrease in EQ occurrence rate for $M \geqslant 1.5$ across the entire Groningen field as all the quantiles of $\Delta\nu(post - pre)$ are slightly higher for 'Post 2' compared to 'Post 1'. However, the differences are not statistically significant and we believe the overall EQ occurrence rate for $M \geqslant 1.5$ now is not very different to the rate in the most recent pre-epoch (starting date 02/2013).

B.2. EQ occurrence rate of $M \geqslant 1.0$

There are 113 events of $M \geqslant 1.0$ that have occurred in the entire Groningen field in the post shut-in period with aftershocks retained. These are divided into 4 post-epoch ('Post 1', 'Post 2', 'Post 3' and 'Post 4'). The first three post-epochs contain 28 events each which the last post-epoch contains 29 events. The start and the end date of each post-epoch are in Table B.2. The pre shut-in period is partitioned into pre-epochs with identical number of events and $\Delta\nu$ for each post-epoch is compared to the pre-epochs. The results are shown in figure B.3

Table B.2: All Groningen field and $M \geqslant 1.0$. Partitioning EQ counts in post shut-in period into four epochs

post-epoch	Start date	End Date	n_q
Post 1	02/01/2014	17/05/2014	28
Post 2	12/06/2014	31/01/2015	28
Post 3	04/02/2015	29/10/2015	28
Post 4	30/10/2015	21/09/2016	29

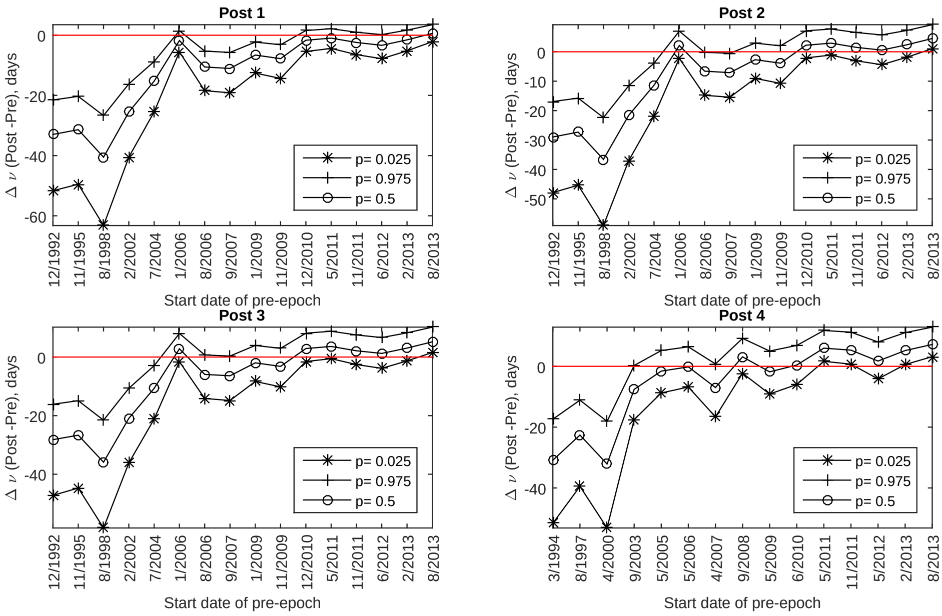

Figure B.3: Test statistics $\Delta\nu(post - pre)M \geqslant 1.0$ with aftershocks retained for the entire Groningen field. Top left panel: 'Post 1' epoch, Top right panel: 'Post 2' epoch, Bottom left panel 'Post 3' epoch, Bottom right panel 'Post 4' epoch

A similar analysis after removing the potential aftershocks can be done. In this case, we have 112 events after in the post shut-in period and dividing them into to four epochs results in 28 events in each post-epoch. Each post-epoch is similarly compared with all the pre-epochs. The results are shown in Figure B.4.

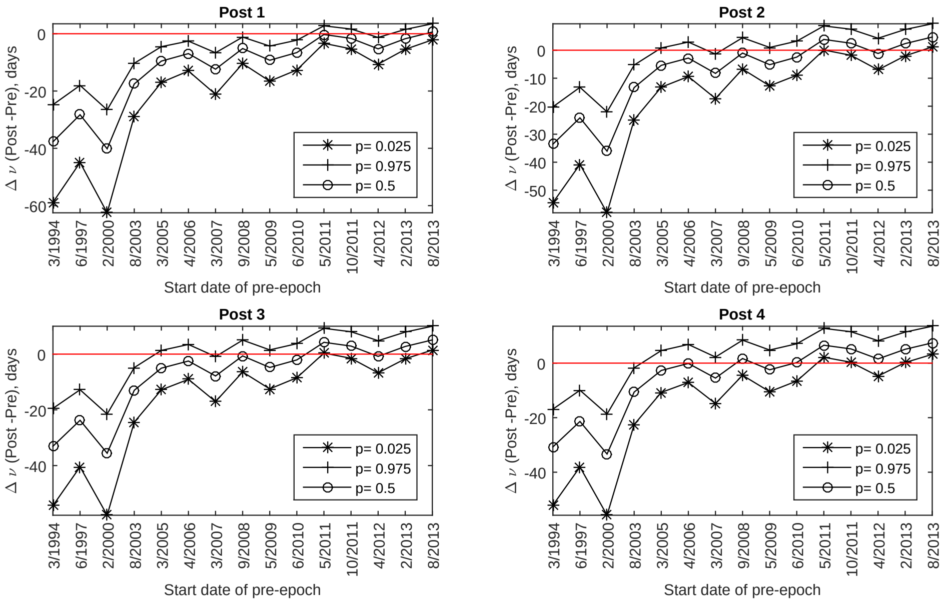

Figure B.4: Test statistics $\Delta\nu(post - pre)M \geqslant 1.0$ with aftershocks removed for the entire Groningen field. Top left panel: 'Post 1' epoch, Top right panel: 'Post 2' epoch, Bottom left panel 'Post 3' epoch, Bottom right panel 'Post 4' epoch

Figures B.3 and B.4 show a gradual increase in the $\Delta\nu(post - pre)$ for all the pre-epochs as we move from 'Post 1' to 'Post 4'. This suggest a gradual slow down in EQ occurrence rate in the post shut-in period. The slow down can also be quantitatively assessed by comparing $\Delta\nu(post - pre_{08/2013})$ i.e.all the four post-epoch with the most recent pre-epoch with start date 08/2013. The expected $\Delta\nu(post - pre_{08/2013})$ and their 95% CI with and without aftershocks are in Table B.3. The table shows the expected value is trending upwards from 'Post 1' to 'Post 4' and the change is statistically significant from 'Post 2' onwards.

Table B.3: $\Delta\nu(post - pre_{08/2013})$, $M \geqslant 1.0$ with after shocks retained (outside brackets) and removed (inside brackets)

	p = 0.025	p = 0.5	p = 0.975
Post 1	-2.1(-2.1)	0.6 (0.6)	3.5 (3.5)
Post 2	1.0(1.2)	4.5 (4.7)	9.2 (9.4)
Post 3	1.6 (1.4)	5.2 (5.0)	10.2 (10.0)
Post 4	3.1(3.2)	7.2(7.4)	12.9 (13.5)

B.3. Summary

The analysis shows that there is evidence that the field-wide event rate of events $M \geqslant 1.0$ is lower in the post shut-in period compared to the pre-epochs. When only events $M \geqslant 1.5$ are used, there is no strong evidence to suggest that the rate in the post-epoch is different from the rate in the pre-epochs. We recommend that this analysis should be conducted regularly to understand the overall hazard across the entire Groningen field.

Appendix C.

Magnitude of completeness, Mc

The Magnitude of completeness M_c is defined as the lowest magnitude at which all of the earthquakes in the Groningen gas reservoir are detected and recorded in the earthquake catalogue. Historically, the probability that an earthquake with associated magnitude M<1.5, when it occurs within the Groningen field, is detected by the geophone network and included in the EC cannot be assumed to be unity or to be spatio-temporally invariant. The Royal Dutch Meteorological Society (KNMI) has indicated that inclusion probabilities for events with magnitudes $M \geqslant 1.5$ can be assumed to be unity or close to unity throughout the Groningen field and throughout the time-series under consideration (Dost et al. [2012]). In Bierman et al. [2016] it has been reported that there is evidence of both seasonal (within-year) and diurnal (within-day) fluctuations in occurrence rates of events with $M < 1.0$, which may be due to fluctuations in the detectability of these events. In particular the diurnal fluctuations of events with $M < 1.0$ are consistent with the hypothesis of cultural noise causing fewer of these events to be detected. M_c depends largely on the capability of the network of geophones. In the Groningen field, the geophone network has been improved over time and more recently a major upgrade of the network was implemented. The expectation is that this has led to an improved detectability of events with magnitudes $M < 1.5$. Here we present a statistical assessment of the temporal evolution of M_c. This is important in the context of detecting changes in EQ occurrence rate. We cite various techniques that are reported in the literature. Subsequently, we apply the Maximum Curvature (MAXC) technique to the entire Groningen field.

C.1. Methods from the literature

Migan and Woessner [2012] provides a good overview of various methods suggested to evaluate M_c. The methods can be broadly divided into two approaches (a) Catalogue-based approach and (b) Network-based approach. The former encompasses statistical methods that use historical catalogue to determine M_c while the latter approach is purely based on the properties of seismic network. Focusing on catalogue-based approach, the suggested methods in literature are

- Maximum Curvature (MAXC) method proposed by S.Wiemer and Wyss [2000]
- The Goodness-of-Fit Test (GFT) by S.Wiemer and Wyss [2000]
- M_c by b value stability (MBS) approach by Cao and Gao [2002]
- M_c from the Entire Magnitude Range (EMR) by Woessner and Wiemer [2005] Ogata and Katsura [1993]
- The Median-based analysis of the segment slope (MBASS) by Amorese [2007]
- The day-to-night noise modulation (day/night method) by Rydelek and Sacks [1989]

All techniques, except for the Rydelek and Sacks (1989) method, are based on the validity of the Gutenberg Richter (G-R) law. The main distinction is whether they are parametric (GFT, MBS, EMR) or non-parametric (MAXC, MBASS). Parametric techniques are based on fitting the frequency-magnitude distribution (FMD) while non-parametric techniques are based on the evaluation of changes in the FMD particularly a change in slope.

There is no consensus in the literature on the most appropriate method and different techniques can provide different results. We use the MAXC method over the entire Groningen field and determine the temporal changes in M_c. The method involves simply counting the number of events in different magnitude bins. Starting at the highest magnitude in the catalogue, the count is low but as the magnitude decreases, the count increases non-linearly following the G-R law. A maximum is reached below which the count decreases again due to incomplete observations. The magnitude, at which maximum count is reached, is called M_c. To understand how M_c has changed with time, we divide the entire Groningen catalogue into 4 non overlapping epochs, each containing 200 events. We believe this is the maximum count we can afford and in which we can assume G-R law to be valid. A count above this reduce temporal granularity . The start and end dates for each epoch are in Table C.1. Figure C.1 shows the frequency-magnitude distribution four the four epochs. The vertical red line shows the magnitude at which the maximum is reached in each epoch. The M_c values from epoch 1 to epoch 4 are 1.2, 0.9, 0.9 and 0.6. We note that it is not possible to evaluate M_c before March 2003 due to a limited number of observations before this date. Nevertheless, we see that between 2003 and 2009, the catalogue may be incomplete below $M = 1.2$. Thus, $\Delta\nu(post - pre)$ for $M \geqslant 1.0$ and pre-epoch before May 2009 may be conservative.

Table C.1: Start and end dates for the four epochs

Epoch	Start date	End date
1	06/04/2003	08/05/2009
2	26/05/2009	17/08/2012
3	23/08/2012	23/09/2014
4	24/09/2014	27/09/2016

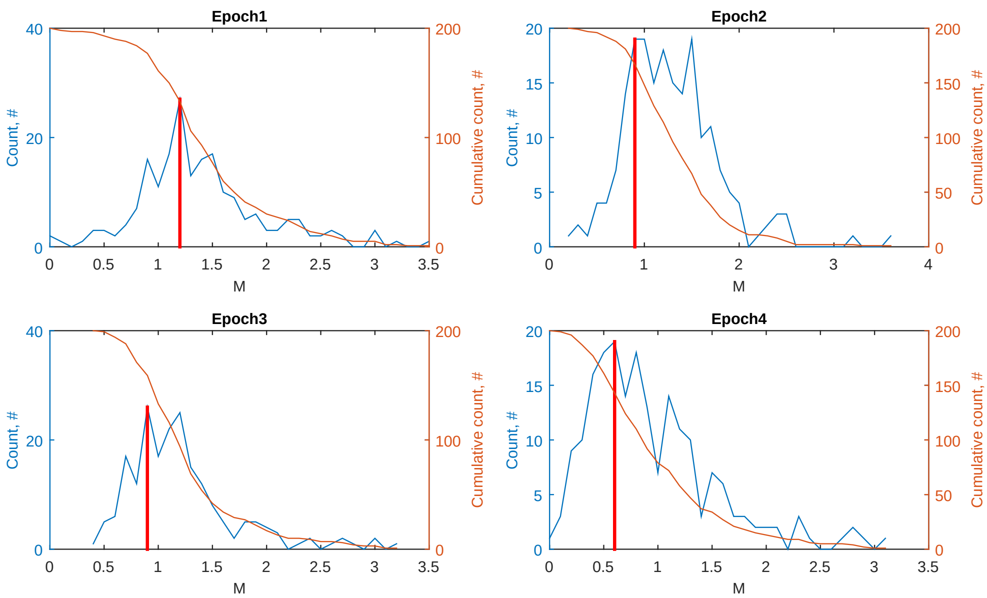

Figure C.1: Frequency-Magnitude distribution (FMD) for the four epochs. See Table C.1for start and end dates. Each epoch has 200 events. The red line shows the Magnitude at which the maximum number of events has been observed

We note that there is considerable uncertainty in M_c estimated as the FMD plots are not smooth. This is partly because our sample size (200) may be too small to obtain a smooth FMD curve. In order to estimate the uncertainty, we bootstrap the catalogue in each epoch with replacement and re-evaluate M_c for each bootstrapped sample. The results of M_c for each epoch obtained by boot-straping are presented in Figure C.2. The figure shows that for the first three epoch three epochs, the inter-quartile ranges are largely overlapping but in the fourth epoch, which contains most recent events following major network upgrade, the inter-quartile range of M_c is much lower.

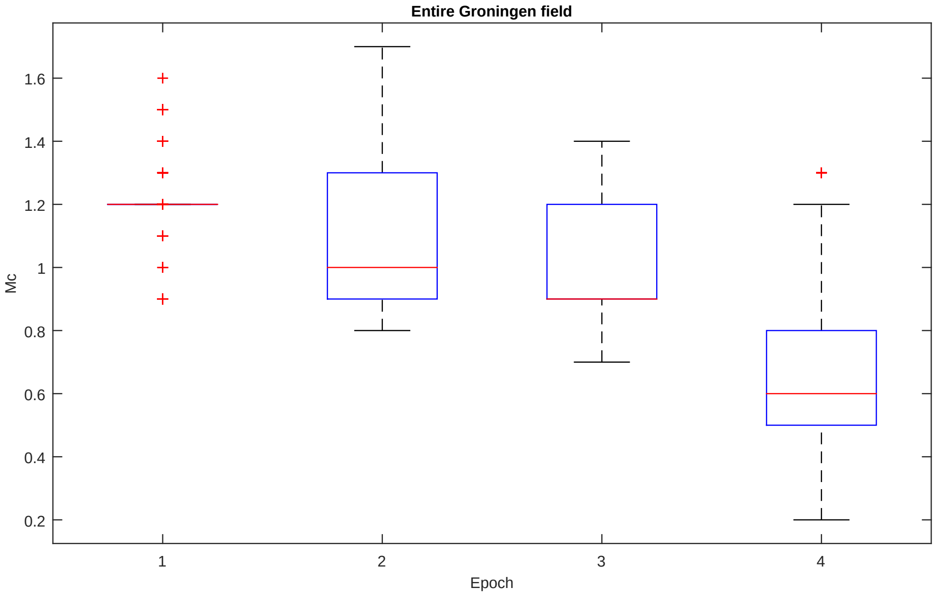

Figure C.2: M_c as estimated by the MAXC method, for four epochs (uncertainty estimated by bootstrapping the events in the respective epochs).

C.2. Day-Night modulations

In Bierman et al. [2016] it was reported that there is evidence of both seasonal (within-year) and diurnal (within-day) fluctuations in occurrence rates of events with M <1.0, which may be due to fluctuations in the detectability of these events. In particular the diurnal fluctuations of events with M <1.0 are consistent with the hypothesis of cultural noise causing fewer of these events to be detected. M_c depends largely on the capability of the network of geophones. Annual estimates are obtained as proportions of events during the hours of 07:00-11:00 in the morning out of all events that occurred between either 07:00-11:00 (morning) or 22:00 - 02:00 (night), for events $1.0 > M \geqslant 0.5$ and events $M \geqslant 1.0$. Under the hypothesis that each time-slot (07:00-11:00 or 22:00-02:00) has an equal event occurrence rate we would expect on average equal rates (a proportion of 0.5 in each time-slot). There is evidence that the morning-night modulation of events $1.0 > M \geqslant 0.5$ is less pronounced in recent years (figure C.3), with an estimate of exactly equal rates in each time-slot during in 2016 although this is based on a small number of events. On an annual basis, the numbers of events are small which results in wide confidence bounds (the confidence bounds on the proportions have been estimated using the Clopper-Pearson method: see e.g. Price and Bonett [2000]). When events are aggregated over the years 2014, 2015 and 2016 the estimated proportions in the 07:00-11:00 time-slot (out of all events that occurred between either 07:00-11:00 or 22:00-02:00) are: 0.33 (0.17-0.54) for events $1.0 > M \geqslant 0.5$ and 0.54 (0.39-0.67) for events $M \geqslant 1.0$. When all events are used which occurred in the years 2011, 2012 and 2013 the estimated proportions in the 07:00-11:00 time-slot are: 0.14 (0.05-0.29) for events $1.0 > M \geqslant 0.5$ and 0.42 (0.30-0.55) for events $M \geqslant 1.0$. Thus, for events $1.0 > M \geqslant 0.5$ there is evidence that the day-night modulation has reduced in recent years, although it is not possible to conclude yet with confidence that there is no longer a diurnal modulation. For events $M \geqslant 1.0$ there is an indication that the day-night modulation has reduced and in recent years there is no evidence of any remaining diurnality.

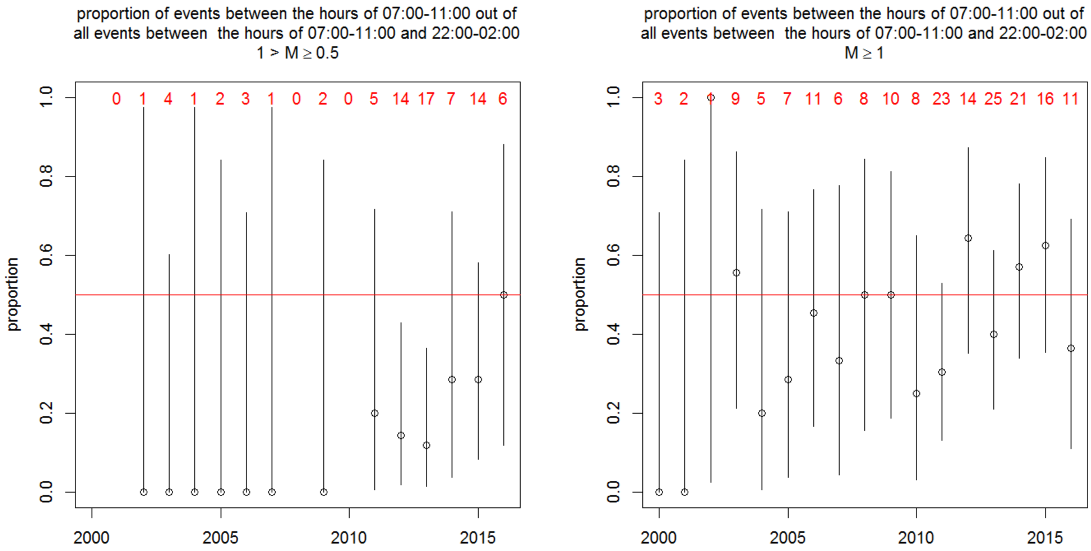

Figure C.3: Annual estimated proportions (open circles) with 95% confidence bounds (vertical lines) of events during the hours of 0700-11:00 in the morning out of all events between 0700-11:00 (morning) and 22:00 - 02:00 (night), for events $1.0 > M \geqslant 0.5$ (left pane) and events $M \geqslant 1.0$ (right pane). The red vertical line indicates the proportion as expected under the hypothesis that each period (day or night) has an equal event occurrence rate.

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