Statistical evidence of production driven seismicity at Groningen Field

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1. Abstract

Depletion of Groningen gas fields has induced earthquakes, although the north of the Netherlands is a tectonically inactive region. Increased seismic activity raised public concern and as a consequence a number of studies were initiated, with the aim of understanding the cause(s) of the earthquakes. If the relationship between production and seismicity were understood then the production could be optimized in such a way that the risk of induced seismicity would be minimal. The Minister of Economic Affairs of the Netherlands decided to reduce production starting from 17th January of 2014, specifically in the center of the gas field as it has the highest rates of seismicity, the largest magnitude events as well as the highest compaction values of the field. A reduction in production could possibly lead to a reduced rate of compaction. Additionally a reduction of production rate could lead to a reduced stress rate increase on the existing faults and consequently less seismic events per year. We have developed a method to assess seismic event rate, its changes and tendencies using Bayesian model comparison and Bayesian change point model herby answering the question of interest: whether the production reduction since January 2014 has had an effect on the seismicity occurring in the Groningen field.

2. Groningen gas field

- discovered in 1959
- production started in 1963
- > 75% of the gas has been produced
- Pressure decline from ~300 to ~100 bar
- first detected seismic event: December 1991 (M_L=2.4)
- Observed: constant rate first decade after 1991, followed by a tendency of increasing seismicity, both in frequency and magnitude, since the beginning of this century.

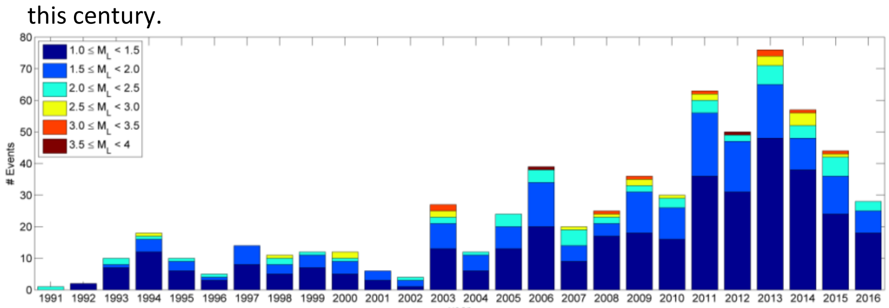

Fig. 2. Number of events occurring within the contour of the Groningen gas field as a function of time and magnitude (M_L) up to 15.11.2016

3. Methods

Bayesian Model comparison
The probability of occurrence of seismic events:

$$P(N(t)=k)=\frac{m(t)^k}{k!}\,e^{-m(t)}\;;\;m(t)=\int_0^t\lambda(\tau)d\tau$$

Bayesian model comparison method compares *constant-rate* Poisson models and *exponential-rate* Poisson models

Models: *Constant:* $\lambda=a$; *Increase*: $\lambda=ae^{\left(\frac{t}{\tau}\right)}$; *Decline*: $\lambda=ae^{-\left(\frac{t}{\tau}\right)}$

Bayesian change point model (Gupta and Baker 2015)
We compare two models: one model *M1* with a single constant event rate and another model *M2* which has one constant rate before the change point and another, different, rate after the change point.

Bayes factor determines the odds of two models:

$$\frac{P(M1|D,I)}{P(M2|D,I)}=\frac{L(D|M1,I)}{L(D|M2,I)}\frac{p(M1|I)}{p(M2|I)}$$

=Bayes factor x prior odds

5. Results of Bayesian model comparison

The comparison of the *increase* model vs. *constant* –rate model for the period 1st January 2003 to 17th January 2014.

Name Area	Bayes factor	# events, $M_L \geq 1$
Central	$5.4 * 10^4$	236
SW	25.4	43
Other	$1.4 * 10^5$	129

The comparison of the *decline* model vs. *constant –rate* model for the period 17th January 2014 to 15th November 2016.

Name Area	Bayes factor	# events, $M_L \geq 1$
Central	1.8	24
SW	69.7	25
Other	4.2	74

References and Acknowledgements
We are grateful to prof. Baker for the use of change point analysis.
Gupta A., Baker J.W., *A Bayesian Change Point Model to detect changes in event occurrence rates, with application to induced seismicity*. 12th Int. Conf. in applications of Stat. and prob. in Civil Eng., ICASP12, 2015

Relationship between gas production and seismic events?

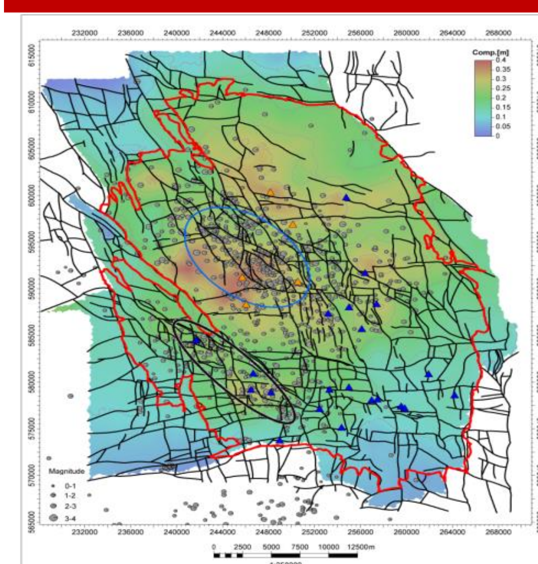

Fig. 1. Groningen gas field. Red=contour field, Blue ellipse = Central area, Black ellipse = SW area, black lines = faults, dots = seismicity. Background color is cumulative compaction [m] (TNO, 2016), orange and blue triangles are producing well clusters. The orange triangles are 5 clusters in the Central area where production has been cut off since January 2014.

TNO (2016): Groningen field 2013 to present; Gas production and induced seismicity . TNO report 2016R10425, May 2016. http://nlog.nl/groningen-gasveld-0

4. Results of Bayesian change point model

Due to the probably increasing event rate the Bayesian change point analysis is performed for 13 different time intervals.

Time interval	Pre rate (events/year)	Change point (CP)	Post rate (events/year)	Bayes factor
T_0: 1996 - 1.1.2004	~ 9	Dec 2002	~ 23	79
T_1: 1996 - 1.1.2011	~ 9	Dec 2002	~ 28	$6*10^{11}$
T_2: 1996 - 1.1.2012	~11	Oct 2004	~ 32	$1*10^{18}$
T_3: 1996 - 1.1.2014	~12	Jan 2005	~44	$1*10^{31}$
T_4: 1996 - 5.9.2015	~16	Oct 2008	~51	$2*10^{38}$
T_5: 1996 – 1.3.2016	~16	Oct 2008	~49	$4*10^{37}$
T_6: 1991 - 1.1.2012	~9	Dec 2002	~ 32	$3*10^{26}$
T_7: 1991 - 1.1.2014	~11	Jan 2005	~40	$6.*10^{44}$
T_8: 1991 - 1.3.2016	~11	Jan 2005	~42	$7*10^{54}$
T_9: 15.11.2012 - 05.09.2015	~73	May 2014	~47	15
T_{10}: 15.11.2012 - 01.03.2016	~73	May 2014	~44	200
T_{11}: 15.11.2012 - 20.09.2016	~73	May 2014	~40	$1.6*10^3$
T_{12}: 15.11.2012 - 15.11.2016	~73	May 2014	~39	$7*10^3$

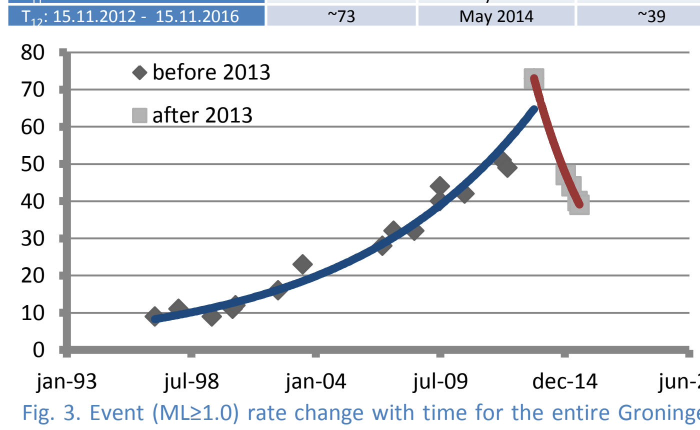

Fig. 3. Event ($M_L \geq 1.0$) rate change with time for the entire Groningen field. The solid lines are the exponential fits trough the data before and after 2013.

Conclusions

- **First change point of event rates is found in December 2002. Before that time event rate can be considered constant.**
- **Around the time of the first change point, the system has entered the phase where reduction/increase of production is connected with reduction/increase of seismicity.**
- **After production reduction in January 2014, we find a situation in which the event rates either decline or remain constant but it is clear that the upward exponential trend which was clearly visible before 2013 is not continued.**