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A phenomenological relationship between gas production variations and tremor rates in Groningen

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The views expressed in this paper are those of the author and do not necessarily reflect the policies of Statistics Netherlands.

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Nederlands

Deze rapportage is een verslag van het onderzoek dat is uitgevoerd in het kader van fase 1 van een onderzoeksproject door het CBS in opdracht van Staatstoezicht op de Mijnen (SodM). Dit onderzoek is ten behoeve van een statistische onderbouwing van het meet- en regelprotocol voor optimale gasexploitatie in de provincie Groningen, met in fase 1 in het bijzonder de aandacht gericht op de relatie tussen productie variaties van de diverse relevante productieclusters in het gasveld en de aardbevingen in Groningen.

Uit de analyse blijkt dat er een duidelijke correlatie is in de zin dat voorafgaand aan aardbevingen er teruggeprojecteerd naar de locatie van die aardbeving een hoger dan gemiddeld gasextractiesignaal is. De jaarlijkse modulatie van gasextractie is duidelijk zichtbaar, hetgeen niet het geval is wanneer dezelfde analyse op een verzameling van willekeurige tijdstippen en locaties wordt uitgevoerd. Nauwkeurige analyse van de modulatie maakt aannemelijk dat de waarschijnlijkheid voor het optreden van aardbevingen op een bepaalde locatie binnen enkele maanden reageert op veranderingen in gasproductie die hebben kunnen propageren naar die locatie. Er zijn echter ook aanwijzingen voor een invloed die op een veel langere tijdschaal van 8 tot 10 jaar werkzaam is.

English

This is a report on the research that has been carried out within phase 1 of a research project being carried out by Statistics Netherlands and commissioned by State Supervision of Mines (SodM). This research is part of the underpinning of the statistical methods employed to support the protocol for measurement and control of the production of natural gas in the province of Groningen. In phase 1 the particular focus is on the relationship between gas production variations at the various relevant well clusters and the earth tremors in Groningen.

From the analysis it is clear that there is a correlation, in the sense that prior to earthquakes there is an enhanced signal of gas extraction projected back to the location of the earthquake. The annual modulation of gas extraction is clearly visible, which is not the case if the same analysis is applied to a collection of random locations and times. A closer analysis of that modulation shows that it is plausible that the probability for a tremor to occur at any given location reacts within months to changes in gas extraction that have propagated to that location. However there are also indications that some influence from the gas extraction is acting over much longer timescales of 8 to 10 years.

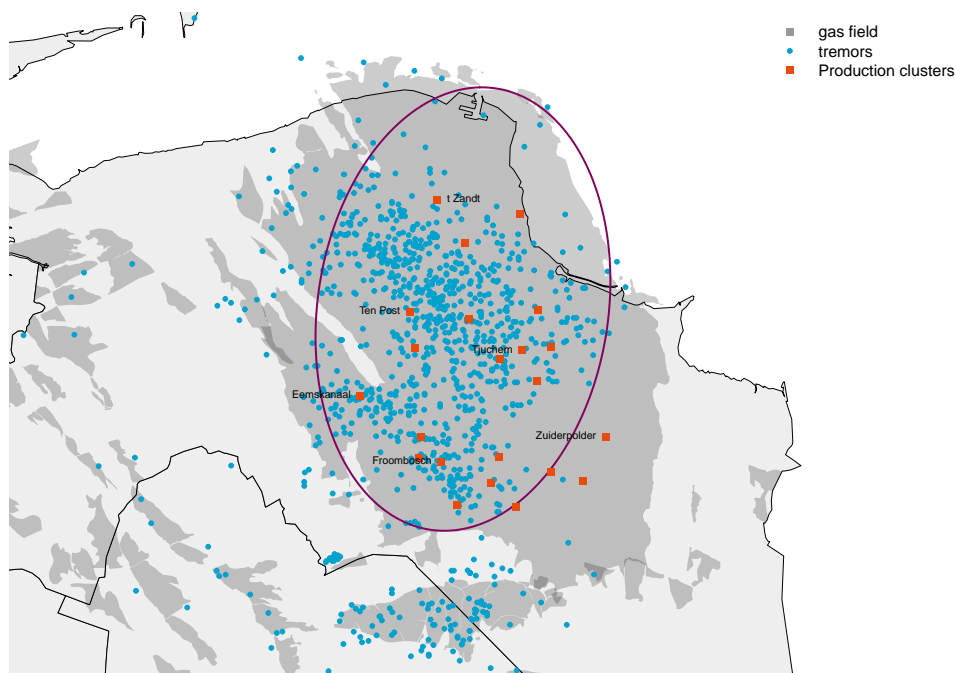
1 Introduction

For some decades earthquakes of modest magnitudes have occurred in and around the Groningen gas field. It is recognized that tremors can be induced by the production of gas from a field eg. (Wetmiller, 1986); (Grasso, J. and Wittlinger, G., 1990); (Bourne, S.J., Oates, J., van Elk, J., Doornhof, D., 2014). An extensive study program is in place to improve the understanding of the risk and hazard due to gas production-induced earthquakes in the Groningen field (Nederlandse Aardolie Maatschappij BV, 2013). A protocol is being established with the aim of mitigating these risks and hazards by adjusting the production strategy in time and space. Also the NAM is active

in improving safety of housing through structural strengthening of buildings. In order for this to be effective it is necessary first to understand whether tremor frequency and ground subsidence can be influenced at all by adjusting production. If so, it needs to be established how quickly the system reacts to production adjustments. Even if causality can be demonstrated, and the reaction time scale shown to be sufficiently short, implementation of the regulation protocol with adaptive control of production will require regular measurement of the effects on subsidence and earthquakes to provide the necessary feedback for production control.

The causality relationship between gas production and earthquakes is difficult to establish unequivocally, purely on the basis of time series analyses. For instance, a constant rate of gas extraction might lead to a likelihood of tremors that increases with time through the compaction of the reservoir layer, cf. (Bourne, S.J., Oates, J., van Elk, J., Doornhof, D., 2014), but a correlation analysis would not necessarily provide any evidence of this. Because in practice the rate of production does vary periodically throughout the year, as well as incidentally for operational reasons, it becomes possible to pursue a correlation analysis between variations in tremor incidence and production variations. Preliminary results on a correlation analysis between ground subsidence and production variations (Pijpers, F.P. and D.J. van der Laan, 2015b) provide some support for the feasibility of this approach. There is no doubt that the extraction of natural gas strongly influences the balance of forces in the reservoir layers, eg. (Mulders, 2003). However, every tremor is the realisation of a stochastic process, for which the balance of forces in part determines the probability distribution function of that process. Because of this stochasticity there is an intrinsic decorrelation between variations in gas production and variations in tremor incidence frequency. Conversely, even if a correlation can be established between gas production and tremor incidence, it will depend on the exact nature of that correlation whether causality can be considered proven or likely.

Figure 1.1 The locations of all tremors within the zone in Groningen relevant to this analysis, recorded after 1 January 1995. The red squares are locations of the production clusters, some of which are identified by name. The production field is also shown in dark gray, overplotted on a map of the region.



As with the CBS reports from the previous phases of this project, starting point for the analysis of

the statistics of tremors is the catalog of tremors as reported by the Royal Netherlands Meteorological Institute (KNMI) based on their processing of the network of seismometers that they manage. Further selections from that catalog are made as necessary, for instance in order to filter out tremors that have occurred outside of the zone of interest, or tremors from an epoch when the seismometer network was less sensitive and may suffer from more serious completeness issues. The selection/filtering criteria are chosen to be consistent with those of the previous Statistics Netherlands reports, (Pijpers, 2014b), (Pijpers, 2015), (Pijpers, F.P., 2015): tremors before 1995 are excluded and the spatial region of interest is the same as in those reports (see fig. 1.1).

The production data have been made available to SodM and Statistics Netherlands by the NAM. At this stage the data used are monthly production data per cluster of wells of which there are 22. The data span a time range from January 1971 to December 2014. These monthly rates are converted to weekly rates using straightforward linear interpolation. This improves the temporal resolution, but also introduces some noise. There will also be a contribution to noise due to the uncertainty of localisation of tremors and the spread in the localisation of the clusters in the reservoir. Given that even the interpolated production data are still one week averages, spatial uncertainties of less than about 500 m are irrelevant for this analysis. For convenience the production data are range scaled, which means that the maximum value of monthly production in the entire dataset is used as a normalisation factor, so that after normalisation all monthly production values fall in the interval [0, 1].

2 Background

2.1 Propagation of the signal of gas extraction

It is clear that the locations of tremors do not coincide with the locations of the wells. If the gas extraction at the wells is to have an influence at other locations, a signal has to pass from the well to those other locations. There are two ways that can be envisaged in which the signal of gas extracted from the reservoir layer can propagate outwards from that location.

A fast signal can propagate whenever the rate at which gas is extracted changes. Depending on whether the rate increases or decreases a rarefaction wave or compression wave will pass through the medium at the local speed of sound in the solid (porous) matrix with the gas contained within it. As such a pressure pulse propagates away from a well the amplitude will decrease as 1 over distance squared, but there may be additional attenuating effects: thermalisation/damping of the wave, as well as dispersion and mode conversion. While the propagation of such a signal is therefore quite fast, the magnitude of that signal could well be rather modest. In the rest of this paper these signals are not considered.

A slower signal occurs as gas diffuses through the reservoir layer, to replace the gas extracted at the well, or cluster of wells. A diffusive model for the signal of gas extraction has been used for instance by Baranova et al. (1999; their eq. 5) to model induced seismicity by hydrocarbon production in western Canada. A more general description can be found in Russell & Wheeler (1983). A diffusive process is described with a differential equation:

$$\frac{\partial \psi}{\partial t} = \nabla \cdot (D \nabla \psi) \quad (1)$$

where ψ describes the density of the quantity that is diffusing, and D is the diffusivity with SI units [$m^2 s^{-1}$]. The diffusivity D is a factor that is determined by material properties of the medium and the diffusing material:

$$D = \frac{\kappa}{\eta \phi_p \beta} \quad (2)$$

in which κ is the permeability of the medium and ϕ_p its porosity, η is the viscosity of the diffusing gas and β its compressibility. None of these properties are necessarily constant throughout the region, and they may even change with time as the reservoir layer compacts. To simplify the analysis, typical values appropriate to the Groningen field are used (TNO, personal communication, see also NAM (2013) chapter 2) to obtain a reasonable average value for D .

$$\begin{aligned} \kappa &= 9.9 \cdot 10^{-14} \text{ m}^2 \approx 100 \text{ millidarcy} \\ \eta &= 1.5 \cdot 10^{-5} \text{ kg m}^{-1} \text{ s}^{-1} \\ \phi_p &= 0.2 \\ \beta &= 8.74 \cdot 10^{-8} \text{ m s}^2 \text{ kg}^{-1} \end{aligned} \quad (3)$$

This leads to a value of $D = 0.38 \text{ m}^2 \text{ s}^{-1}$. In the analysis that follows, values higher or lower than this by a factor of 10 will also be used to assess whether the particular value that is arrived at strongly influences the results. The true value is highly unlikely to lie outside of this range. Spatial or temporal variation in D may also modify the analysis, but requires much more detailed modelling of the flow and pressure in reservoir layers (eg. using MoReS (Por et al., 1989)) which is beyond the scope of this paper.

The geometry of the reservoir layer from which gas is extracted also plays a role in solving equation (1). For simplicity it is assumed here that this layer has a very small vertical extent, compared to the horizontal extent, so that it can be modelled as a flat, two-dimensional system. With these conditions the solution to equation (1) has the form:

$$\psi(r, t) = \frac{1}{4\pi Dt} e^{-r^2/4Dt} \quad \forall \quad 0 < t < T \quad (4)$$

in which r is the horizontal distance from the well cluster, and the normalisation is such that the integral of ψ over the 2-D plane is 1 at all times $t > 0$. The total length of time over which gas has been extracted sets an upper limit to the use of ψ , hence the maximum of T . ψ has units of per surface area.

With the solution (4) in hand, it is possible for any given location and time to calculate the reduction in gas density in the reservoir at that location and time, due to the diffusive flow of reservoir gas to a particular cluster. Since the equation (1) is linear, the total effect of all clusters of wells combined is a sum of the individual contributions. Each individual contribution $\phi_k(x, y, t)$ from cluster with index k at location (x, y) can be determined out of the convolution integral of the amount of extracted gas at the cluster and the appropriate $\psi(r, t)$.

$$\phi_k(x, y, t) = \int_0^T \psi(r_k, t - t') P_k(t') dt' \quad (5)$$

$$\phi \equiv \sum_k \phi_k \quad (6)$$

Here the gas production P_k is usually expressed as a normal volume (gas volume under standardised conditions) per unit of time. For convenience of the numerical coding, a normalisation is applied by dividing by a maximum volume $V_{ext \max}$, so that after normalisation all values of P_k lie in the interval $[0, 1]$ and have as units $time^{-1}$. After the convolution integral

the quantities ϕ_k and ϕ then have the same units as ψ : per surface area. In this paper wherever ϕ is plotted, the units chosen are [km^{-2}].

From the behaviour of the solution (4) it is clear that close to any given cluster in active use, the depletion of gas is higher than further away, whereas the tremors do not appear to show a strong spatial clustering close to clusters. The gas depletion is therefore clearly not the only factor determining where tremors occur. Another important factor are structural weaknesses such as pre-existing faults. Another effect could be that apart from the vertical compaction, caused by the reduction in gas pressure, the horizontal forces generated by pressure gradients in the sum over all clusters of the ϕ also play a role, ie.: $\frac{\partial \phi}{\partial x}$ and $\frac{\partial \phi}{\partial y}$ or a combination of these:

$$|\nabla_h \phi| \equiv \sqrt{\left(\sum_k \frac{\partial \phi_k}{\partial x}\right)^2 + \left(\sum_k \frac{\partial \phi_k}{\partial y}\right)^2} \quad (7)$$

For this reason this quantity is also determined. The relationship between ϕ and the reservoir gas pressure is clarified in section 2.2. Note that this horizontal gradient for a single cluster will be 0 right at the location of that cluster because of the behaviour of ψ in (4). A correlation of such a signal with likelihood of tremor incidence would therefore not be expected to produce a higher incidence closer to clusters.

2.2 the relationship between ϕ and the gas pressure

The amount of gas extracted is usually expressed as volumes of gas under normal/standardised conditions for pressure and temperature. Using a molar volume under those same conditions, the amount can be expressed in terms of moles.

$$n_{ext} = V_{ext}/V_m \text{ (units[mol])} \quad (8)$$

Within the reservoir the extraction of this amount of gas is equivalent to a local reduction in gas pressure:

$$\Delta P = n_{ext}RT_{res}/V_{res} = V_{ext}(RT_{res}/V_m)/V_{res} \quad (9)$$

Where R is the gas constant, and T_{res} and V_{res} are the temperature and volume (hydrocarbon bearing pore volume) of the gas inside the reservoir. Applying this equation presumes that the gas behaves as an ideal gas. While this is only approximately true, for the analysis at hand it is sufficiently accurate. The volume taken up by the gas in the reservoir can be expressed as $V_{res} = Ad\zeta$. Here A is a surface area which will drop out of the analyses, d is the thickness of the reservoir layer, and ζ is the fraction of this volume available for the gas. The latter is slightly smaller than the porosity ϕ_p given in Eq. (4) of the gas bearing rock, since some of this volume is taken up by water. The volume of extracted gas is related to the quantity ϕ by:

$$V_{ext} = A\phi V_{ext \max} \quad (10)$$

which can be used with equation (9) to give:

$$\frac{\Delta P}{P_{res}} = A\phi V_{ext \max} \frac{RT_{res}}{P_{res}V_m} \frac{1}{Ad\zeta} = \phi \frac{T_{res}}{T_{std:0^\circ C}} \frac{P_{std:1 \text{ bar}}}{P_{res}} \frac{V_{ext \max}}{d\zeta} \quad (11)$$

The normalisation value $V_{ext \max} = 7.18 \cdot 10^8 \text{ m}^3$, and an appropriate (mean) value for $\zeta = 0.15$. The reservoir temperature is taken to be $T_{res} \approx 373 \text{ K}$, the pressure $P_{res} \approx 100 \text{ bar}$, and the

thickness $d \approx 100 \text{ m}$. With these values the conversion between ϕ and relative pressure change is:

$$\frac{\Delta P}{P_{res}} = 0.654 \times \phi \quad (12)$$

where the constant $0.654 \text{ [km}^2\text{]}$ is again merely an approximation for an appropriate mean value.

2.3 the local extraction history for tremors

In order to assess whether there is any kind of statistical correlation between the gas extraction throughout the Groningen field and the generation of tremors it is of interest to reconstruct the history of the gas extraction signal at the location of tremors in the period leading up to the time of the tremor. It is assumed that the occurrence of tremors is not a fully deterministic process, but rather that an identical set of circumstances gives an identical finite likelihood for a tremor to occur. A single event is then of limited value in terms of the information that it carries. Therefore one would wish to combine the history of every relevant tremor to find the typical local gas extraction history for tremor events. The time at which the tremor occurs is set to 0, and the signal of all wells is summed, as described above, for a range of time values counting back from that tremor time. This is done for all tremors after which straightforward averaging of the time histories for every (selected) tremor achieves the goal of obtaining the typical history of local gas extraction signal before tremors as a function of 'look-back' time.

Obtaining this averaged local extraction history for tremors is not yet sufficient for the purposes of the analysis. If instead of using locations and times of the selected tremors, one would pick an equal number of randomly chosen locations and times, a local extraction history could be obtained by applying the same technique of co-adding of gas extraction signal histories. Since by definition such a randomly chosen set of locations and times is not special, it is only the differences between the histories of true tremors and artificial 'events' that is of interest. If the co-added extraction signal history of true tremors is statistically indistinguishable from the co-added extraction signal history of random locations and times, no causality between gas extraction and tremors can be demonstrated.

The analysis thus requires that a set of locations and times be set up, which can be used to build a local history of gas extraction in the same way that it is done for the true set of selected tremors. It might not be appropriate however to generate such a set using a completely uniform distribution over space or time. It is clear from fig. 1.1 that the spatial distribution of tremors is not uniform, and it is known that the distribution over time also is not completely uniform. It is desirable to mimic at least some aspects of the real distribution over space and time in the distribution for the set of artificial events. To this end the number of tremors in $5 \text{ km} \times 5 \text{ km}$ grid squares is counted. For the artificial events the number of events in each of these squares is reproduced, but random (x, y) -coordinates uniformly distributed within each grid square are generated. Similarly, for the timing of these artificial events, the full time range since 1995 is sectioned into intervals of length 300 d and the number of true events in each of these sections counted. The number of artificial events must match this true number but the actual timing within each subinterval is generated from a uniform distribution. The comparison is performed a number of times with different realisations of the random numbers used to generate the artificial events. In the following sections the plots are shown for a typical single realisation of random events.

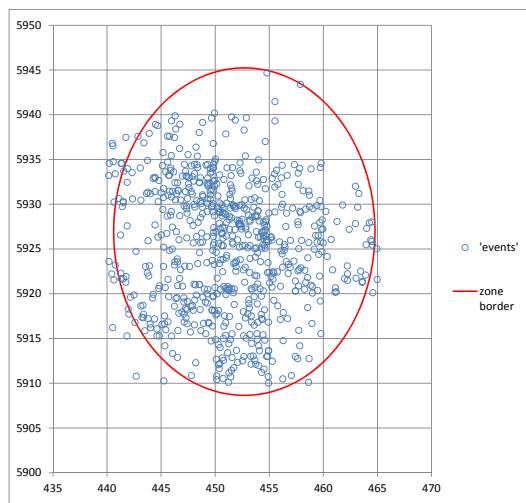
3 Comparison of histories

In the following sections, several different selection criteria are applied to the catalog of earthquakes in the Groningen field. In section 3.1 all earthquake data are used, in section 3.2 only those tremors are included with magnitudes $M > 1$ for which the catalog is likely to be complete in terms of detection, and in section 3.3 tremors with $M > 1.5$ which are most likely to be well-localised as well as complete in the catalog. The set with $M > 1$ is also used in section 3.4 to explore the effect of an overall change in diffusivity. In section 3.5 is shown how one can attempt to eliminate the influence of aftershocks in the flow back-projection, which involves a subset of tremors from the set with $M > 1.5$. Finally, in section 3.6, both the set with $M > 1$ and the subset from the tremors with $M > 1.5$ without aftershocks of section 3.5 are used, where the aim is to distinguish whether it is the timing or the location of the tremors that is most important in determining the characteristics of the back-projection. Both the gas extraction signal and its horizontal gradient are considered in all sections.

3.1 all tremors

In the manner as described in section 2 in the first instance all tremors are selected having occurred within the relevant region and also having occurred after Jan. 1 1995, as indicated in fig. 1.1. For comparison the set of random events is shown in fig. 3.1. A total of 696 tremors (cq. events) is involved. The local gas extraction history for each tremor, and also for each artificial

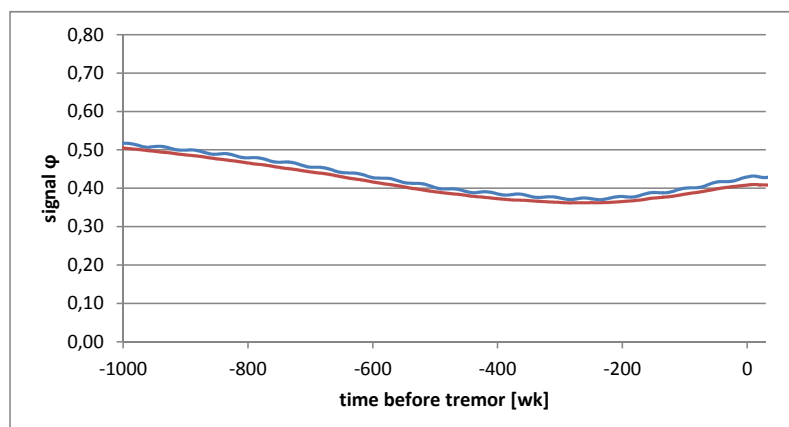
Figure 3.1 The locations of artificial events set up as described in section 2.2, for comparison when selecting all true tremors after 1995. The indicated scales are in km



event, is constructed, and then co-added to obtain the mean history as a function of look-back time.

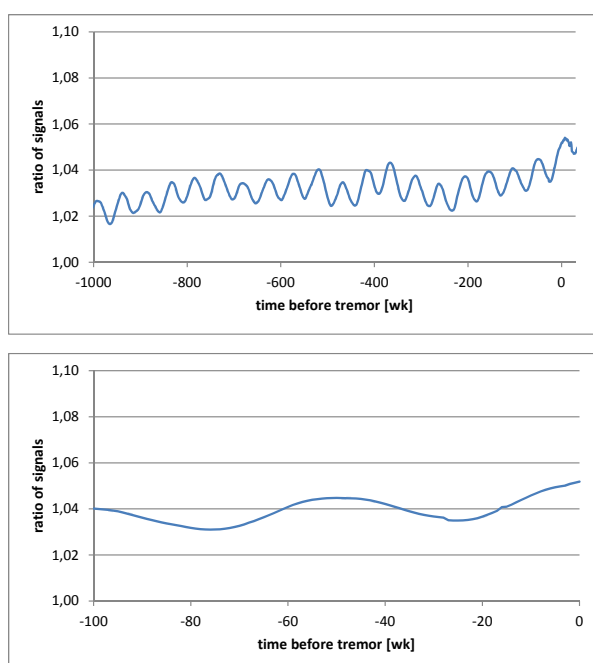
Fig. 3.2 shows the extraction signal history both for the true tremors and for the artificial events for a (typical) realisation. While the detection timing of the tremors is very precise, the production rate data used are the monthly cumulative values. The extraction history is therefore binned in time, with 1-week bins which is also the time unit shown.

Figure 3.2 The co-added histories of extraction variations propagated to locations of tremors (blue) and the set of artificial events (red), as a function of time (in weeks).



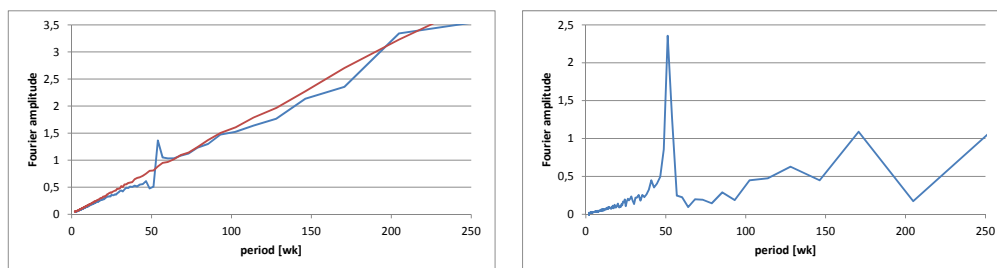
By comparing these histories it is clear that the co-added extraction signal history for tremors show a periodic signal, which is absent from the artificial events. By taking the ratio of the two co-added signal histories the common behaviour can be removed so that it is possible to focus on the differences between these histories. fig. 3.3 shows this ratio, where it is seen that the periodic signal persists.

Figure 3.3 The ratio of the co-added histories of extraction variations of true tremors and artificial events, as a function of time (in weeks). The lower panel shows at greater magnification the behaviour of this ratio close to $t = 0$



Although there is an annual modulation of gas production, the different time delays between an arbitrary location in the field and each cluster would be expected to 'wash out' such a signal, especially after co-adding the histories for a large number of events as indeed is seen in the history for the reference set. Also, it is clear that the ratio of the history of true tremors and the reference set has values well above 1 and only dips down at very large negative times, ie. very long before tremors occur. In the detail of the ratio (lower panel of fig. 3.3) it is seen that $t = 0$ lies on an increasing section of the gas extraction signal both because of the annual modulation

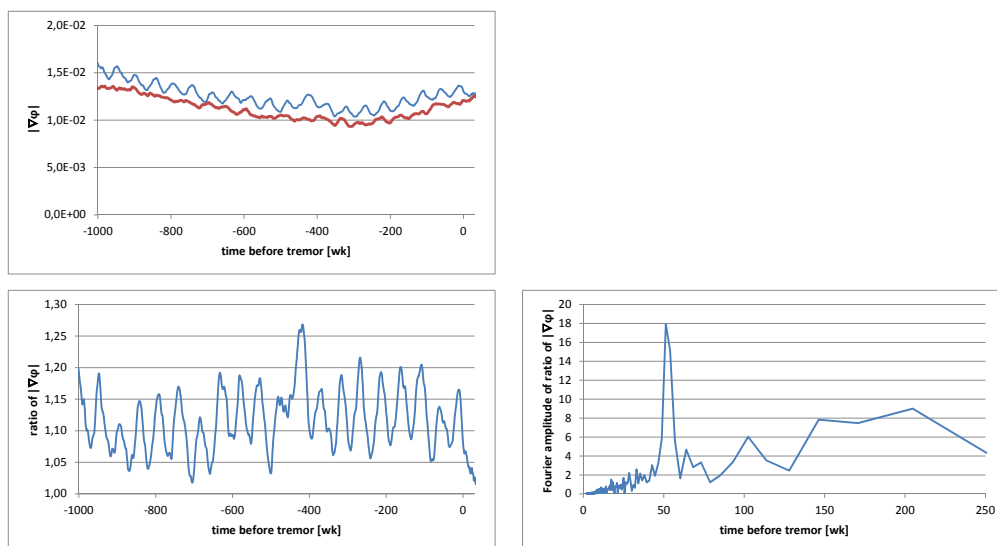
Figure 3.4 Left panel : the Fourier amplitude of the history for the tremors (blue) and for the reference set of artificial events (red). Right panel: the Fourier amplitude of the ratio of the two histories.



but also because of an underlying trend.

Given that there appears to be a modulation of the signal, it is useful to perform a Fourier transform of this ratio time series. The Fourier transform is generally complex valued, unless a time series is symmetric around 0 which is not the case here cf. (Bracewell, 1965). In fig. 3.4 the Fourier amplitude (complex modulus) for the two time histories are shown, as well as the Fourier amplitude of the ratio of the two. In the Fourier amplitude there is a peak, at a period of 1 year. This implies that the timing of tremors correlates with the minima and maxima in the signal of the gas extraction, which has an annual modulation. The peak in the Fourier domain is superposed on a slope, which arises from the structure in the time domain on long time scales: with the underlying trend in ϕ decreasing slowly to 1 at early times.

Figure 3.5 Top panel: the absolute value of the horizontal gradient of the gas pressure for the true tremors (blue) and for the artificial events (red). Bottom left Panel: The ratio of the local horizontal gradient of gas pressure for true tremors and for artificial events, as a function of time (in weeks). Bottom right panel : the Fourier amplitude of this gas pressure.



The local horizontal gradient of the gas pressure affects the local horizontal stress due to the spatial variations in gas pressure averaged for all tremors, and is shown in fig. 3.5. The top panel shows the signal for true tremors and the reference set, and their ratio is shown in the bottom left panel. Here an annual modulation is clearly seen, which is due to modulation in the true tremor history, since the signal for the reference set shows no such modulation. The Fourier amplitude shown in the right panel clearly shows a peak at a period of one year.

While not absolute proof, this gives a strong indication that the likelihood for a tremor to occur reacts causally to gas production in the sense that locations of true tremors have a significantly higher than random extraction signal history, in which the annual modulation is clearly visible. A purely periodic signal in the gas extraction history of true tremors could still have been a coincidence in the sense that a speculative natural effect might produce an annual variation in tremor likelihood. This speculative process unrelated to gas production would then introduce a spurious correlation simply because it has an annual variation as does the gas production rate. However, the fact that the ratio of time histories is well above unity for look back times up to about 13 years before dipping down toward unity, reduces the plausibility of such an alternative scenario.

3.2 tremors with magnitudes $M > 1$

Figure 3.6 Left: the locations of selected tremors after 1995 with magnitudes $M > 1$. Right: the locations of artificial events set up as described in section 2.2, for comparison when selecting true tremors after 1995 with magnitudes $M > 1$. The indicated scales are in km

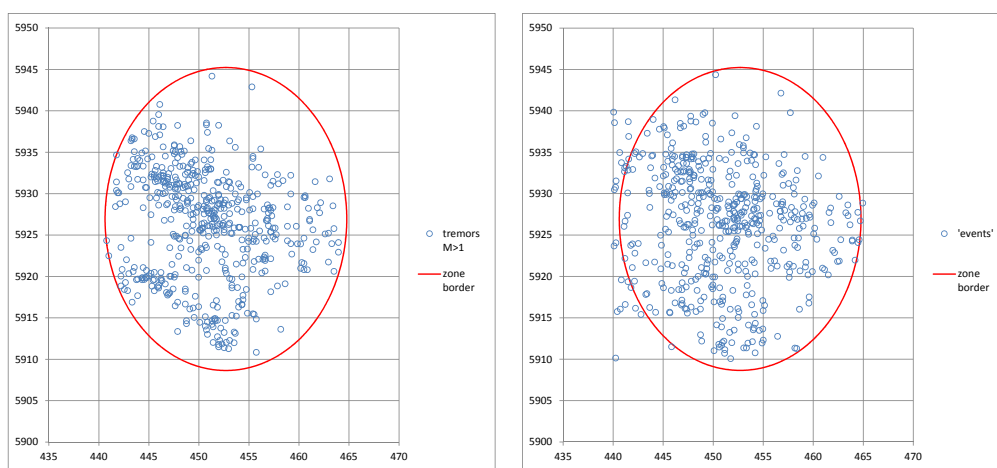
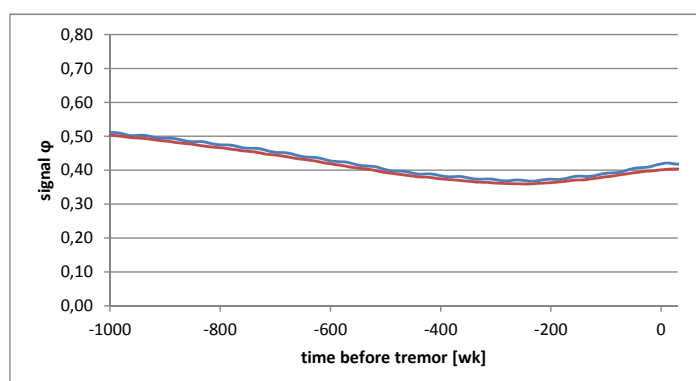


Figure 3.7 The co-added histories of extraction variations propagated to locations of tremors with $M > 1$ (blue) and the set of artificial events red), as a function of time (in weeks).



Although the catalog provided by the KNMI contains data for a large number of tremors with magnitudes $M < 1$ it is likely that many such tremors have not been picked up by the seismic network, so that the catalog is not complete. It is therefore necessary to assess whether the lack of completeness affects the results of the analysis. The same steps as described in section 3.1 are

therefore executed for a smaller set of tremors, with 514 tremors, for which the magnitude $M > 1$. New sets of artificial comparison events are also constructed, in order to ensure that the most appropriate comparison is made.

Figure 3.8 The time series of the ratio of the extraction histories (left panel) and its Fourier transform amplitude (right panel) for tremors with $M > 1$

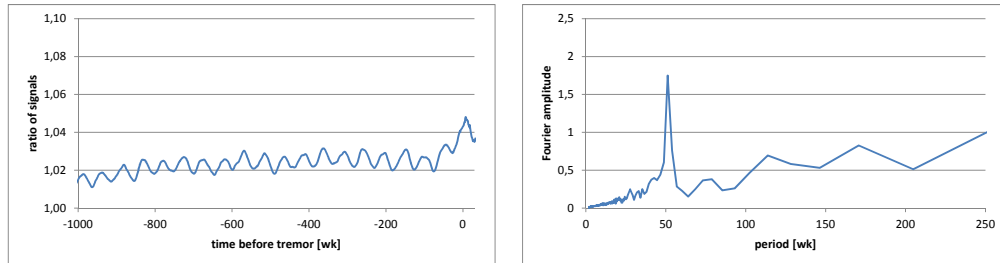
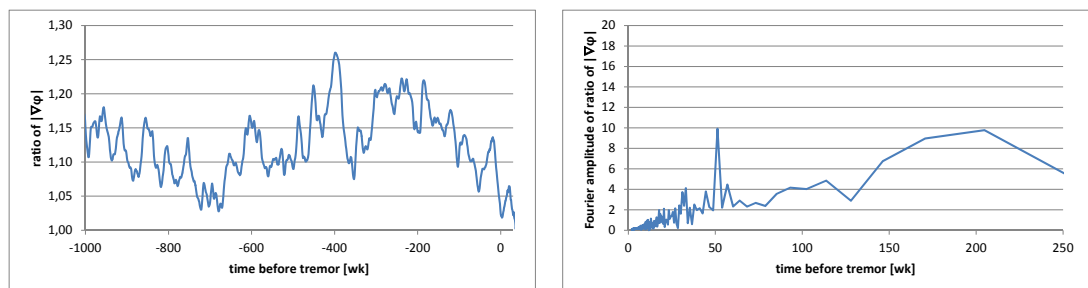


Figure 3.9 Left Panel: The ratio of the local horizontal gradient of gas pressure for true tremors and for artificial events, as a function of time (in weeks). Right panel : the Fourier amplitude of this gas pressure, for tremors with $M > 1$



In fig. 3.6, the left-hand panel shows the true tremors with magnitudes $M > 1$, and the panel on the right shows the locations of the artificial events generated to provide the comparison material. Fig. 3.7 shows the extraction signal history both for the true tremors and for the artificial events. A periodic signal is still visible in the extraction history. In the history for artificial events there is also some periodic signal present so that in the ratio the amplitude is reduced. In the left panel of fig. 3.8, the ratio of the two is shown. While there is clearly a substantial spread, the annual modulation can still be seen. The amplitude of the Fourier transform (right panel of fig. 3.8) shows that the amplitude of the periodic signal, with the 1 year period, is now smaller than it is if no selection on magnitude is applied.

The absolute value of the local horizontal gradient of the gas pressure, is shown in fig. 3.9 in the left panel, and the amplitude of its Fourier transform on the right. Here there is more irregular variation, but the annual modulation is still seen in the history for the gas extraction in fig. 3.9. Here this is due to modulation in the true tremor history, since the signal for the reference set shows no such modulation. As with the full set, it is clear that the ratio of the history of true tremors and the reference set has values well above 1 and only dips down at very large negative times, ie. very long before tremors occur. The time at which all the tremors are aligned $t = 0$ lies on an increasing section of the gas extraction history but after a maximum in the horizontal pressure gradient history, as is the case when using all tremors.

3.3 tremors with magnitudes $M > 1.5$

While it is likely that the completeness of the KNMI catalog for tremor magnitudes $M > 1$ is good, there are nevertheless some reservations concerning the accurate spatial localisation of

tremors with magnitudes between $M = 1$ and $M = 1.5$.

Figure 3.10 Left: the locations of selected tremors after 1995 with magnitudes $M > 1.5$. Right: the locations of artificial events set up as described in section 2.2, for comparison when selecting true tremors after 1995 with magnitudes $M > 1.5$. The indicated scales are in km

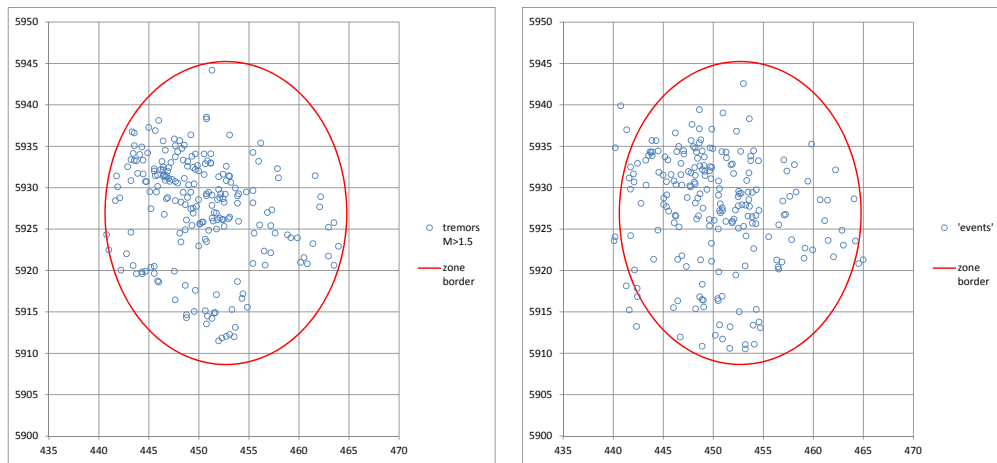


Figure 3.11 The co-added histories of extraction variations propagated to locations of tremors with $M > 1.5$ (blue) and the set of artificial events red), as a function of time (in weeks).

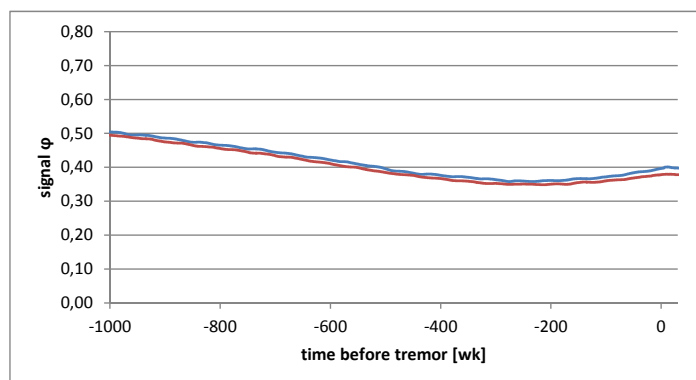
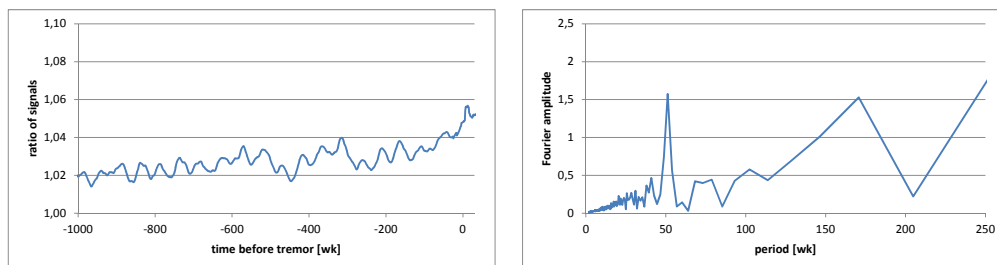
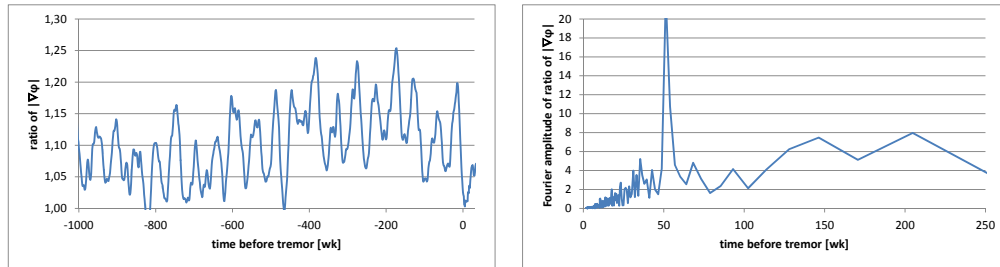


Figure 3.12 The time series of the ratio of the extraction histories (left panel) and its Fourier transform amplitude (right panel) for tremors with $M > 1.5$



For this reason it is useful also to consider the same analysis as described in the previous sections but selecting only tremors that have $M > 1.5$; numbering 219. For comparison, once again comparison sets of artificial events have been generated as well. It is evident that the number of events with magnitude $M > 1.5$ is rather smaller than could be used in the previous 2 sections. A periodic signal is not easily identified in the history itself (fig. 3.11) but can be seen in the ratio with the history for the artificial events (fig. 3.12), in particular at times between -800 and

Figure 3.13 Left Panel: The ratio of the local horizontal gradient of gas pressure for true tremors and for artificial events, as a function of time (in weeks). Right panel : the Fourier amplitude of this gas pressure, for tremors with $M > 1.5$



–200 weeks. The overall level of the ratio is still above 1.02 for 8 to 10 years before a tremor occurs. A qualitatively similar result is seen from the horizontal gradient of the gas pressure (fig. 3.13), although the overall level of the ratio is now closer to 1 for this quantity. A Fourier transform of the ratio of histories (see fig. 3.12) reveals that a periodic signal is still present. As in all the previous cases the ratio of the extraction histories is rising in the final weeks before a tremor, whereas in the pressure gradient signal the maximum has occurred some weeks before.

3.4 the influence of varying the diffusivity

The analysis of the data involves propagating the signal of gas extraction from the location of each of the clusters to the locations where tremors have occurred. In order to do this it is necessary to use a model for how the gas diffuses within the reservoir layer. The governing equation is equation (1), that contains the diffusivity D . As is discussed in section 2.1 a likely typical value can be determined, but the actual best value could be somewhat different. Also D might vary both spatially and in time. If sufficient information is available concerning the factors that together determine D , an improved modelling of the signal propagation would be possible, for instance by using finite element modelling. Such modelling is beyond the scope of this research. However, it is of interest to explore the extent to which different values of D affect the overall result.

In order to do this the analysis has been repeated for two different values of D . In both cases the set of 514 tremors with $M > 1$ is taken into account, but once with a value of D that is set a factor of 10 smaller than the typical value calculated in section 2.1, and once with a value of D that is set a factor of 10 larger. Fig. 3.14 shows the plot of the extraction histories and their ratio, for the true tremors and a set of comparison events generated using the same procedure as described above. The results for the smaller diffusivity (upper panels in fig. 3.14) show slightly larger amplitudes of the annual modulation, and also much larger overall values with a steep increase leading up to tremors (note the different scales in the different panels). For the larger diffusivity the annual modulation appears similar to what is obtained with the standard value of section 3.2 (figures 3.2 and 3.3). This is not unexpected, because for smaller diffusivities the signal of extraction variations will be less 'smoothed away' by the diffusion process than for larger diffusivities, so that variations survive for longer.

The signal in the horizontal gradient of the gas pressure is shown in fig. 3.15 for the two choices of D (again note that the two panels have a different vertical scale). Since the periodicity is seen for a considerable range in values for the diffusivity D it seems that the results are robust to such changes. Apart from the annual variations the inferred time scale of the underlying trend does

Figure 3.14 The histories of extraction variations (panels in left column) propagated to locations of tremors and to locations of artificial events, and also their ration (panels in right column) for a diffusivity 10× smaller (upper panels) and 10× larger (lower panels), than the value calculated in section 2.1.

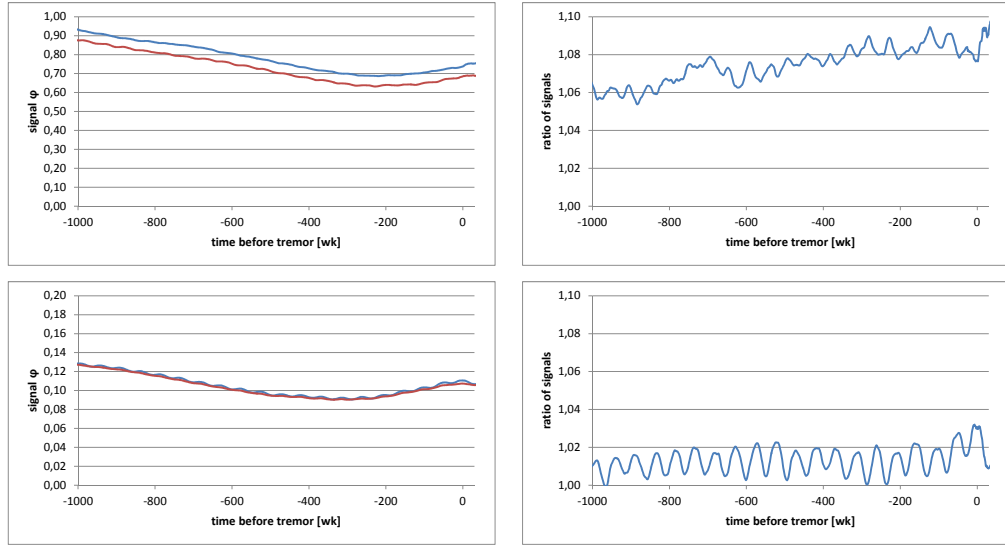
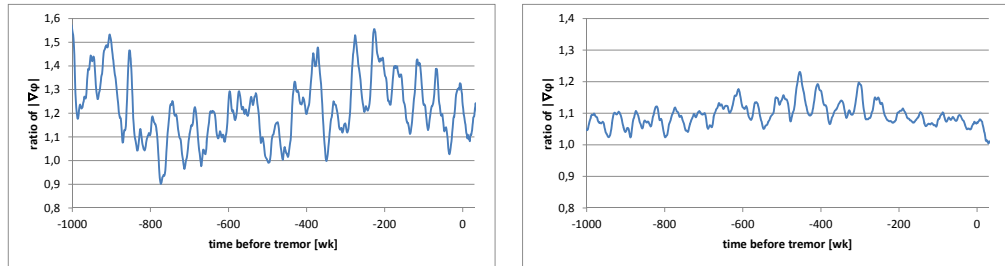


Figure 3.15 The ratio of the local horizontal gradient of gas pressure for true tremors and for artificial events, as a function of time (in weeks). Left Panel: for low D Right panel : for high D



appear to be more sensitive to the choice of diffusivity. If the true value of the diffusivity is closer to the smaller value shown here the rise time of the underlying trend appears to shorten to a few years, although there is still a 'plateau', lasting about a decade, of enhanced extraction signal.

A value of the diffusivity that changes over time is readily incorporated into the signal propagation described by equation (1). A change of variable from t to τ in which τ is defined by:

$$\tau \equiv \frac{1}{D_{ref}} \int_{t-T}^t D(t') dt' \quad (13)$$

will readily lead to a solution ψ very similar to (4) but with Dt replaced by $D_{ref}\tau$, in which D_{ref} can be any suitable reference value for D . If the behaviour of $D(t)$ is known a priori, this can be done explicitly. From the character of this dependence (13) it is clear that unless the material properties that go into determining D vary very strongly with time, the behaviour presented here will not be changed by very much. A systematic increase or decrease of D with time (eg. due to compaction of the reservoir layer) will have the effect of stretching or compressing the horizontal axis in the time history graphs in this paper.

It is not very likely that D is spatially uniform due to spatially varying material properties, so that some areas could act as barriers (with much lower D) and others as low-resistance channels

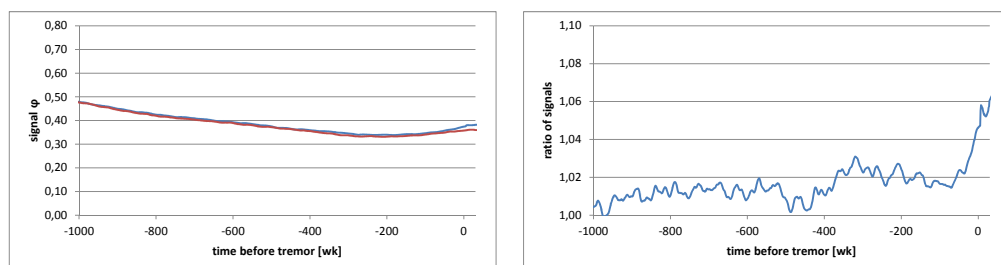
(with much higher D). Spatial variation in D is harder to incorporate analytically, because in equation (1) the divergence of D is taken. The behaviour of for instance the porosity (cf. (Nederlandse Aardolie Maatschappij BV, 2013), their fig. 2.6) indeed indicates a fair amount of lateral variation. On the other hand the connectivity of the reservoir as a whole appears to be good (Bourne, S.J., Oates, J., van Elk, J., Doornhof, D., 2014) as is indicated for instance by the low overall gradient in pressure depletion ((Nederlandse Aardolie Maatschappij BV, 2013), their fig. 2.11). The modelling carried out here would therefore appear to be a reasonable lowest order approximation. For improvements, one could take recourse to finite element modelling, cf. (Minkoff, S.E., Stone, C.M., Bryant, S., Peszynska, M., Wheeler, M.F., 2003) or (Jha, B. and Juanes, R., 2007), to obtain the signal propagation and carry through the analysis given a model for the lateral variation of D . Only such more detailed knowledge or modelling of the propagation of the gas extraction signal can address whether in the case of the Groningen field this has a major influence on the conclusions presented here. A collaborative effort to resolve this question, making use of a fluid flow code appropriate for the Groningen reservoir, is currently starting.

3.5 removal of potential aftershocks

The catalog provided by the KNMI contains all recorded tremors, which will also include tremors that should be seen as aftershocks, triggered by other tremors. For this reason such tremors are possibly less relevant to include in attempts to determine the influence of the external factor of gas extraction. Therefore it is of interest to attempt to exclude shocks that could be aftershocks, and repeat the analysis. In order to do this some operational choice needs to be made for (de-)selection criteria of tremors in the catalog. Here the choice is as follows. For this part of the analysis tremors are only selected if, in addition to occurring within the region demarkated in the previous section, they do not occur within 10 days and a distance of less than 5 km of a previously recorded tremor in the catalog. This is the same criterion as is used in the reports (Pijpers, 2014b), (Pijpers, 2015), and (Pijpers, F.P., 2015).

In order to ensure that only tremors are selected for which the localisation is of the highest accuracy, after de-selection of (potential) aftershocks, using the above rule, only tremors with a magnitude $M > 1.5$ are selected, and only those that occurred after January 1 2002. This leaves the smallest dataset of tremors used so far of 132 tremors.

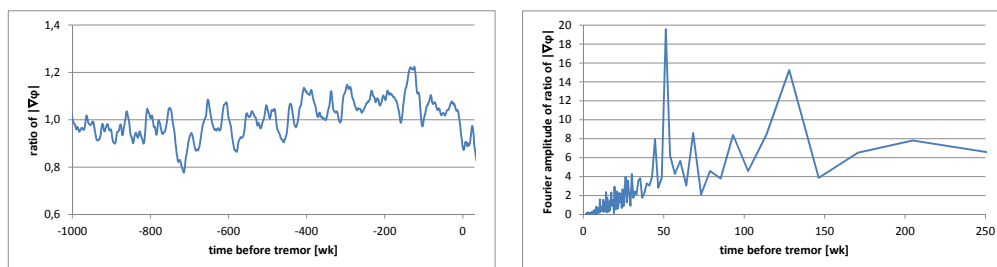
Figure 3.16 Left panel: the histories of extraction variations propagated to locations of tremors and to locations of artificial events applying the strict criteria to exclude aftershocks. Right panel: the ratio of the extraction history



For this small set, the extraction history of the reference time series now does show modulation as well as the extraction history for the tremors (left panel of fig. 3.16). In their ratio (right panel of fig. 3.16) there is some modulation but there is not a clear annual periodicity for this realisation of the reference set and no peak in the Fourier amplitude of the ratio time series. It is clear that the ratio lies well above unity with the values for the final two years before tremors

somewhat enhanced compared to earlier times, and a quick rise in the final 25 to 30 weeks. The

Figure 3.17 The ratio of the gas pressure gradient history for the true tremors and the reference set, applying the strict criteria to exclude aftershocks. Left panel: time domain, right panel : Fourier amplitude.



horizontal gradient of the gas pressure is shown in the left panel of fig. 3.16. Here a clear modulation is seen with a period of a year as is also evident from the Fourier amplitude (right panel in fig. 3.17).

3.6 spatial effects

In the analysis up to this point the reference sets used, against which the extraction signal history of gas extraction before true tremors is compared, are random both in space and in time. It is of interest to understand to what extent spatial correlation or temporal correlation of true events plays a role. This can be done by using as reference set events for which the time is chosen at random as described before, but to use the spatial locations for the actual events in the catalog. Conversely one can assign random locations, but keep the timing of the true events.

Figure 3.18 The ratio of the histories of extraction variations propagated to locations of tremors, for true events vs. events with identical locations but random times. Top: using the set of 514 events with $M > 1$. Bottom: using the same restricted set as in section 3.5. Left panels: the gas extraction signal, right panels: the local gas pressure gradient signal.

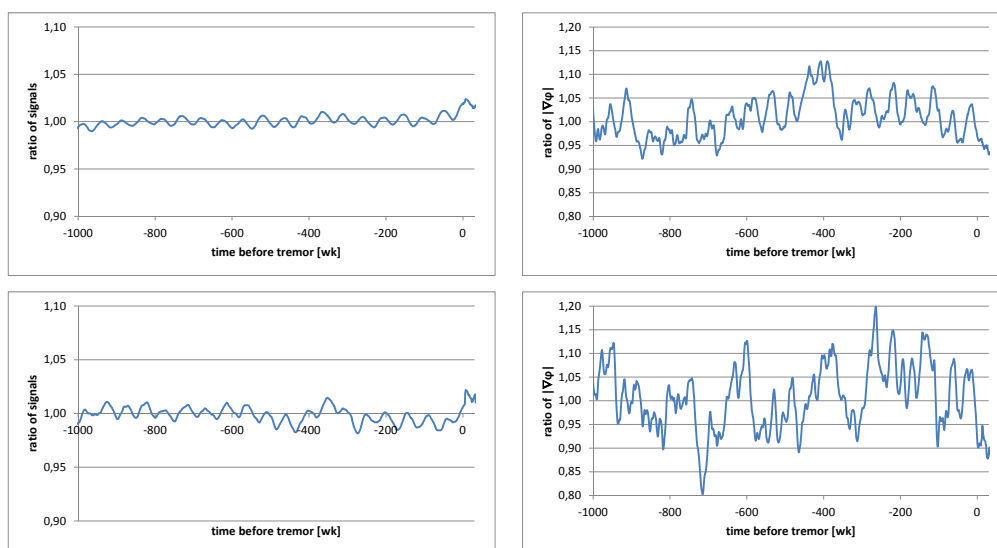


Fig. 3.18 shows the results for two different selections of events from the KNMI catalog. The top panels show the ratio of time histories, using the 514 events in the catalog with $M > 1$ as in section 3.2. The bottom panels show the result for the restricted set of 132 as used in sect. 3.5,

ie. excluding potential aftershocks and all events before Jan 2002, and with a threshold magnitude of 1.5. For the first set the two ratios shown have averages very close to 1 and show a modulation with a period of 1 year. For the more restricted set, there is still a modulation, but again no overall difference from 1. Since the histories for both the true set and the reference set show modulations it is not evident that the modulation in the ratio is evidence of an influence. The histories of the restricted set appear not to be distinguishable statistically from a set of events with the same locations as the true tremors but with random timing.

Figure 3.19 The ratio of the histories of extraction variations propagated to locations of tremors, for true events vs. events with identical timings but random locations. Top: using the set of 514 events with $M > 1$. Bottom: using the same restricted set as in section 3.5. Left panels: the gas extraction signal, right panels: the local gas pressure gradient signal.

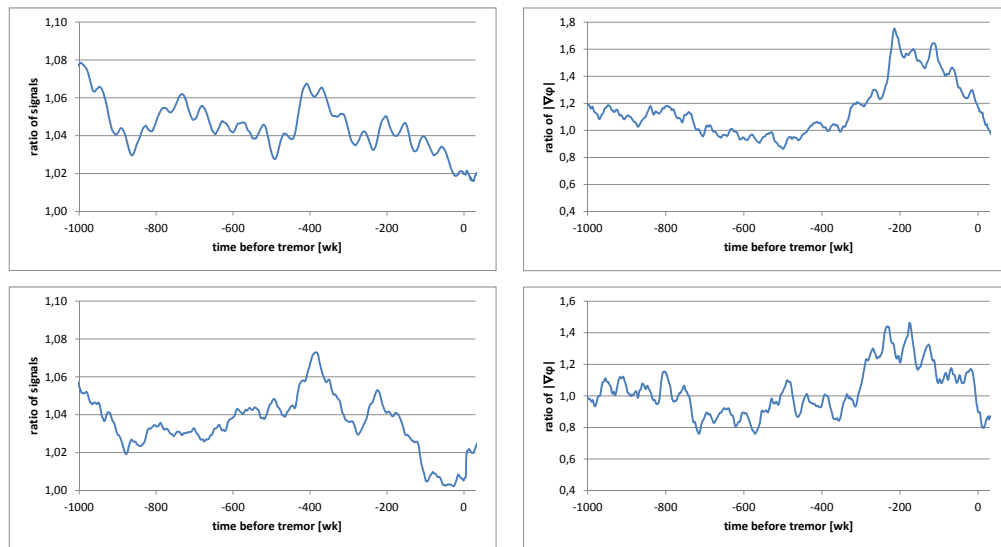


Fig. 3.19 shows the corresponding results, but now rather than keeping the locations of the true tremors for the reference sets as above, the locations are chosen at random, but instead the timing is kept to the timing of the true events. For this simulation all ratios show a clear excess above 1.

From the combination of these sets of simulations it appears that it is mostly the locations that are characteristic of tremors. A randomly timed set of events at the same locations as true events is difficult to distinguish statistically from those true events, whereas a randomly located set of events with the timing of the true events is clearly distinguishable.

4 Conclusions

There is a strong indication that the likelihood for tremors to occur reacts causally to gas production in the sense that increased production leads to an increased tremor likelihood within a time period of about a quarter of the annual cycle of an increase arriving at a tremor generating site such as a fault or fracture, best seen in a data set where only the best localized tremors are used, and a best effort is made to filter out aftershocks. This result is also present when less strict selection criteria are used for the earthquake catalog, but then the response time is less clearly established.

In the reports (Pijpers, 2014b), (Pijpers, 2015), and (Pijpers, F.P., 2015) it is demonstrated that a strong reduction in gas production at a number of clusters in the beginning of January 2014 was followed during that year by a reduction in frequency of tremors in the vicinity of those clusters, which is consistent with the time scale reported now. In work of (Pijpers, 2014a), (Pijpers, F.P. and D.J. van der Laan, 2015a), (Pijpers, F.P. and D.J. van der Laan, 2015b) a rapid response of the subsidence to production variations with a delay of about 9 weeks has been seen. Thus it would appear that production variations are followed first by subsidence variations and only later by variations in the generation rate of tremors.

Absolute proof of causality requires the ability to exclude or identify the influence of all other possible factors that could affect the likelihood of tremors. In the case at hand an, as yet unidentified, external process that might explain the timing of tremors instead of the gas extraction would need to introduce an annual modulation which in addition would have to be phased just right for the gas production variations propagated to tremor sites to coincidentally line up in the period leading up to tremors, as well as phasing these to increase just before tremors. Although such a process might exist, currently the data and this analysis do not give any reason to reject a hypothesis of causality through reservoir pressure variations induced by production. It is not unusual in such a case to apply Occam's razor and select, at least as working hypothesis, the most parsimonious attribution of causality ie. to the gas production itself.

The method of analysis requires a model for the propagation of the signal of production variations through the reservoir layer. In this model the diffusivity in the reservoir layer plays a role, which is uncertain. Tests show that the analysis results are robust to uniformly varying the diffusivity used in the propagation model, although the inferred time scales of response do depend somewhat on its value. A further limitation of the model is the assumption of a 2D geometry. Variations in the thickness of the reservoir layer could also play a role in the propagation of signals and hence in the inferred response time scales and magnitudes. Spatial variation in the diffusivity and reservoir thickness are the subject of further investigation.

The analysis of section 3.6 shows that the spatial distribution of tremor sites appears to play an important role in the correlation with the gas production, more than the timing does. When using tremor sites and random timings as reference set, at least for the most rigorously selected set of tremors, true and simulated events cannot then be distinguished. This behaviour is consistent with eg. the discussion in (Bourne, S.J., Oates, J., van Elk, J., Doornhof, D., 2014), where it is the interaction of reservoir compaction, because of pressure depletion, with pre-existing faults and fractures that generates tremors. The locations of those pre-existing faults or fractures is then the relevant spatial characteristic of the tremors that is found in the analysis presented here. It would be of interest to map out the full 'interference' pattern of the signal propagation of depletion or horizontal gradient from all combined clusters, and overlay this on maps of the pre-existing faults and fractures to assess whether higher incidence of tremors is spatially correlated or co-located with areas where these faults coincide with higher amplitudes of the signal. If so, this could provide a mapping tool that could be of assistance in assessing regionally differentiated hazard. Evidently this is limited by the spatial resolution and sensitivity with which faults can be mapped.

There are two time scales over which enhanced production appears to have an effect on tremor incidence. In general tremors show a history of enhanced signal for as much as a decade beforehand, on which the annual modulation is superposed. This longer time scale could correspond with the trend of increases in tremor counts and gas production over long time scales reported elsewhere, (Nederlandse Aardolie Maatschappij BV, 2013), (Bourne, S.J., Oates, J., van

Elk, J., Doornhof, D., 2014), (Pijpers, 2014b). In effect it is this longer time scale behaviour that is introduced as a heuristic within the models of (Bourne, S.J., Oates, J., van Elk, J., Doornhof, D., 2014) to tie down the behaviour of the strain partitioning function which in their models in part controls the generation of tremors. Within the context of critical systems, cf. (Main, 1995), one may hypothesize that the pressure depletion over long time scales has put the system of faults into a (nearly) critical state. The additional short term effect of production variations in this critical systems context might be that they act to push the system temporarily but repeatedly to a critical state and act as a trigger for tremor avalanches.

One could hypothesize that a reduction in the amplitude of the annual modulation of production levels would have the effect of reducing the tremor rate relatively quickly but possibly by only modest amounts. For the most restricted set of tremors discussed in section 3.5, with magnitudes $M > 1.5$, the short term effect appears to be twice the level of the longer term effect (Fig. 3.16), so that naively a reduction in tremor rates by roughly 2/3 might appear to be achievable. However, when smaller magnitude tremors are included, the effect reduces. This might be due to poorer localisation and hence decorrelation of the signal, or it might imply that reductions of no more than 20 – 30 % overall in tremors rates can be achieved in the short term. In this case obtaining a more sustained further reduction in tremor incidence could then require longer term reduction in production, the effect of which on tremor incidence might only be noticeable after some years.

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