Induced seismicity of the Groningen gas field: History and recent developments

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Abstract

Induced seismicity of the Groningen gas field is caused by the production of gas. Because of the large areal extent of the reservoir, the long history of depletion, and the available data sets (which exist as a result of consequences and public unrest caused by induced seismicity), the field presents a valuable case for studying the relationships among geologic, flow-dynamic, geomechanical, and seismological models. Gas production from the Groningen field started in 1963. Induced seismicity of the field first was recorded in 1991 (M_L 2.4). During the subsequent 10 years, induced seismicity stayed at a rate of about five events ($M_L \geq 1.5$) per year. Starting in 2003, the number of events and magnitudes started to increase. In 2012, the largest event (M_L 3.6) occurred, which caused the most damage to date. As a consequence, studies carried out in 2013 have fundamentally changed the way to look at the relationship between induced seismicity and gas depletion. There appears to be a close link between induced seismicity and reservoir compaction resulting from extraction of gas. Because compaction manifests itself as surface subsidence, accuracy of the subsidence measurements is deemed much more important than previously thought. The same holds true for quality and specific details of the static and dynamic models of the reservoir and its surroundings. In January 2014, it was decided to limit gas production in the central and highest-subsidence part of Groningen field and allow more production from the less compacted field periphery. Seismicity observed in 2014 was markedly different from that in earlier years. Although not yet statistically significant, this observation suggests a close link among production, compaction, and seismicity.

Introduction

The Groningen gas field, in the northeastern part of the Netherlands, is the largest gas field in Western Europe, with gas initially in place (GIIP) of close to 3000 billion m^3 (bcm). The field was discovered in 1959 with the drilling of the Slochteren-1 well. From the start of production in 1963 through January 2015, 2115 bcm (75% of the GIIP) had been produced. The field is still a major supplier of natural gas to the northwestern European gas market.

Since 1986, seismic events have been recorded in the northern part of the Netherlands, which is thought to be a tectonically inactive region. The existing national seismic network was expanded in the north of the Netherlands in 1992, with the first borehole seismometer (five geophones at depths of 0 m, 75 m, 150 m, 225 m, and 300 m). A further extension to 19 permanent seismometers, which include 11 borehole seismometers in the north, was implemented in 1995. Since 1986, seismicity in the north of the Netherlands, ranging in magnitude from M_L −0.8 to M_L 3.6, has occurred over various small gas fields and is considered to have been induced by gas production.

For the large Groningen field, the first seismic event was recorded in 1991. The largest magnitude was an M_L 3.6 event on 16 August 2012. Even though the magnitude of the event was, seismologically speaking, not high, intensities as high as VI were observed because of the shallow depth of the event (3 km, i.e., reservoir depth) and the soft surface soils in the area (TNO, 2013a), causing damage to houses in the area.

Until 2012, a maximum magnitude of 3.9, with a probability of exceedance of 16% (van Eck et al., 2006), was seen as the upper size limit for induced seismicity in the north of the Netherlands. However, since 2003, seismicity in the field has increased in number and magnitude. It has become increasingly clear that induced seismicity of the Groningen field is nonstationary and increases with time (Muntendam-Bos and de Waal, 2013).

Because of the nonstationarity of the induced seismicity, maximum magnitude cannot be defined from statistical data analysis only. Therefore, the need arose for fundamentally different models that take the subsurface explicitly into account. This has led to some studies in 2013 (for example, NAM, 2013; TNO, 2013b) in which the links among the geology of the field, reservoir dynamics, and geomechanics have been investigated.

These studies have revised the assessment of induced seismicity of the Netherlands, especially the Groningen field. The empirical relation proposed by Bourne et al. (2014) directly links the cumulative compaction, which is highest in the center of the field, to seismicity. In TNO (2013b), compaction was shown to react partly instantaneously on pressure changes, which provides a possible handle on the induced seismicity.

In January 2014, it was decided to reduce overall production of the Groningen field to 42.5 bcm in 2014 and 2015 and 40 bcm in 2016. More important, the production for five clusters of wells in the center of the field, corresponding to high compaction values, was limited to 3 bcm per year for 2014 through 2017, an 80% reduction from 2013 rates.

We present an overview of the Groningen gas reservoir and its induced seismicity, using the relations among geologic modeling, reservoir-dynamic models, and geomechanical models. The observations of 2014 are presented to assess the relation between production and seismicity.

Geology

The Groningen gas field is on the Groningen High in northeastern Netherlands, between the Ems Graben to the east and the Lauwerszee Trough to the west. The structure formed during the late Kimmerian extensional phase. Reservoir depth is 2600 to 3200 m. The seal is formed by Zechstein salt covering the whole of the field and varying in thickness from a few tens of meters to more than 1 km. The reservoir consists mostly of Permian sandstones of the Upper Rotliegend Group. From south to north over

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the field, sediments change from mainly sandstone to more claystone. The thickness of the Rotliegend varies from ~ 100 m in the south-southeast to ~ 300 m in the north-northwest of the field. From east to west, thickness is relatively uniform (Mijnlieff and Geluk, 2011; van Ojik et al., 2011; TNO, 2013b).

During the Kimmerian extensional phase, northwest-southeast-oriented faults formed in the region (Figure 1). East-west-oriented faults formed before the Saalien unconformity. More than 1800 faults (NAM, 2013) have been identified by using "ant tracking" of the 3D seismic cube. Only the 707 largest faults have been modeled. Density of the faults and orientations vary across the field. The largest fault density is in the center of the field, predominantly oriented northwest-southeast. This area corresponds to the largest reservoir compaction and the area of the most induced seismicity.

Subsidence

Regulations require estimates of the amount of subsidence for each gas field in the Netherlands before production starts, with regular updates as production continues. The mining law of the Netherlands has a long history, having been implemented by Napoleon Bonaparte in 1810. The most recent revisions in mining law occurred in 2003. In the Groningen field area, surface subsidence is an important issue because the field is close to or below sea level. Groundwater levels and salinity, which are affected by subsidence, are important for the agricultural industry in the area. Furthermore, height and stability of nearby dykes are important to reduce the risk of flooding.

The Groningen surface subsidence has shallow and deep causes. Shallow subsidence is caused by the compaction of clay, oxidation of shallow peat, and artificially modified groundwater levels. Deep subsidence results from reservoir compaction related to gas production. Because of gas depletion, the reduction of gas pressures causes compaction in the reservoir (Figure 2). The elastic properties of the overburden transfer the compaction almost instantaneously to the surface, and this is measurable as subsidence.

The Groningen field covers a wide area (about 900 km^2), and the subsidence bowl related to the production is quite extensive (about 40 × 50 km). Subsidence caused by compaction of the Groningen field has been measured since 1964 by using optical leveling. After the first campaign, which was limited to the central and southern parts of the field, the benchmark network was extended to the entire field, and density was increased for the second campaign of 1972. In 1987, the density of the optical-leveling network was improved further.

Until 2008, repeat surveys were performed every few years. Interferometric synthetic aperture radar (InSAR) data have been available for the region since 1996, which has improved the frequency and spatial coverage of the subsidence measurements. InSAR uses persistent scatters, typically buildings, to measure subsidence rates. Currently, optical-leveling campaigns and InSAR are performed to check for consistency. In 2013 and 2014, 12 GPS stations were installed over the field to monitor subsidence in real time.

Compaction

Subsidence of the Groningen field was slow to initiate from 1964 to 1975 but accelerated after that date (Hettema et al., 2002) (Figure 3). This delay in the onset of subsidence is not yet understood physically, although multiple hypotheses are being investigated (for example, Mossop, 2012; TNO, 2013b), with reservoir compaction being a likely candidate.

Three types of compaction models — time decay (Mossop, 2012), isotach, and rate-type compaction (RTiCM) in isotach formulation (TNO, 2013b) — have been fitted to the measured subsidence (TNO, 2013b). Figure 3 shows the fit to the measured subsidence for an optical-leveling point in the center of the field.

The estimates resulting from the compaction models for total subsidence differ by 5 to 10 cm. These compaction models all capture the delay at the start of production. The isotach model derived from shallow geotechnical models (Den Haan, 1994) fits the observed subsidence data quite well. The time-decay model has been used previously in other gas fields in the Netherlands

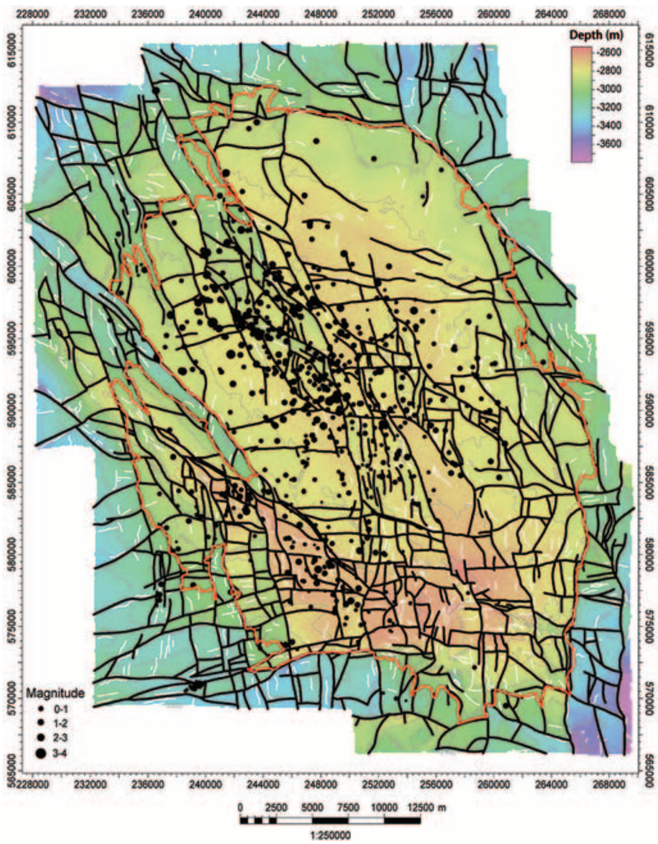

Figure 1. Top of Rotliegend (top of reservoir) with contour of the Groningen gas field in red. Black lines indicate modeled faults. White lines show faults identified by using the ant-tracker algorithm of Petrel (NAM, 2013). Circles indicate seismic events from December 1991 through November 2013. After TNO (2013b), Figure 2.5. Used by permission of TNO.

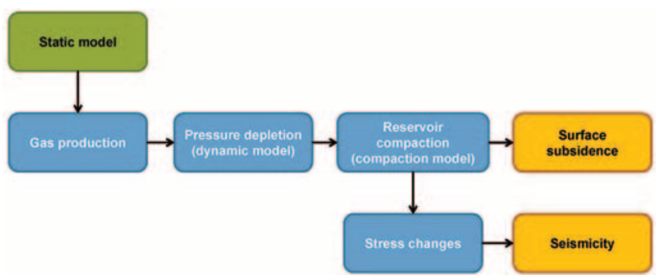

Figure 2. Schematic description of the relation between gas production and the resulting subsidence and seismicity.

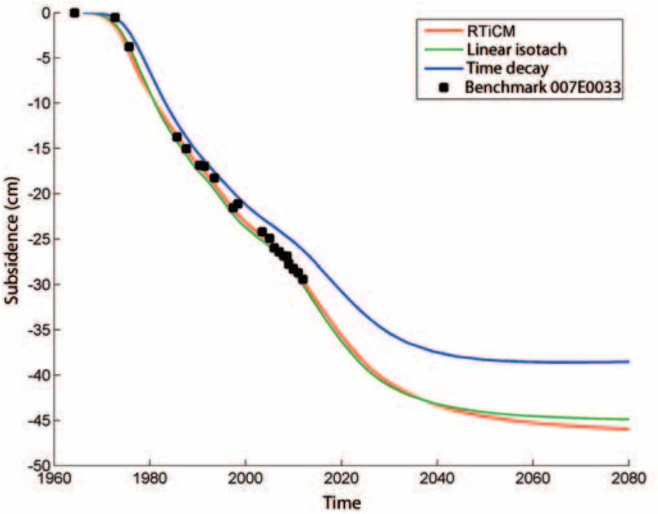

Figure 3. Different compaction models (RTiCM, linear isotach, and time decay) and their fit to a leveling benchmark in the center of the field.

(Mossop, 2012; NAM, 2013). The rate-type compaction model was proposed in the past for Groningen (de Waal, 1986) and was reformulated in 2013 (TNO, 2013b). This model output contains direct (elastic) and secular (creep) strain at different production rates, more closely following the observed subsidence.

The compaction models mentioned above differ in the ways they predict the final compaction and in their responses to a sudden local change in gas pore pressure. The rate-type behavior model reacts partly instantaneously (direct strain) and partly with a delay (secular strain), whereas the time-decay model reacts only with a certain delay on the order of years.

Application of compaction models to the Groningen field

Figure 4 shows cumulative compaction in the reservoir for January 2012, calculated with the rate-type compaction model in isotach formulation (TNO, 2013b). Compaction (TNO, 2013b) was derived using a dynamic reservoir model (NAM, 2013) in which pressures are distributed over the field in such a way that the historic pressure and gas-flow measurements are matched. The static geologic reservoir model was used for detailed information on reservoir thickness, depth, and porosity values. Porosity was determined from petrophysical analysis of well logs. The compaction coefficient (the amount of compaction per 1 bar pore-pressure depletion) was determined from laboratory compaction experiments. For low porosities, low compaction coefficients ensue, and the coefficients increase exponentially for increasing porosity (TNO, 2013b). One of the major uncertainties in compaction modeling is porosity distribution over the field, especially in areas with limited or no well control.

Another large uncertainty is the amount of aquifer activity. The Groningen gas reservoir is connected to aquifers which might or might not respond as the reservoir depletes. Additional depletion in the aquifers will give additional compaction and subsequently will cause subsidence away from the reservoir. As shown in Figure 4, compaction is largest in the center of the Groningen field.

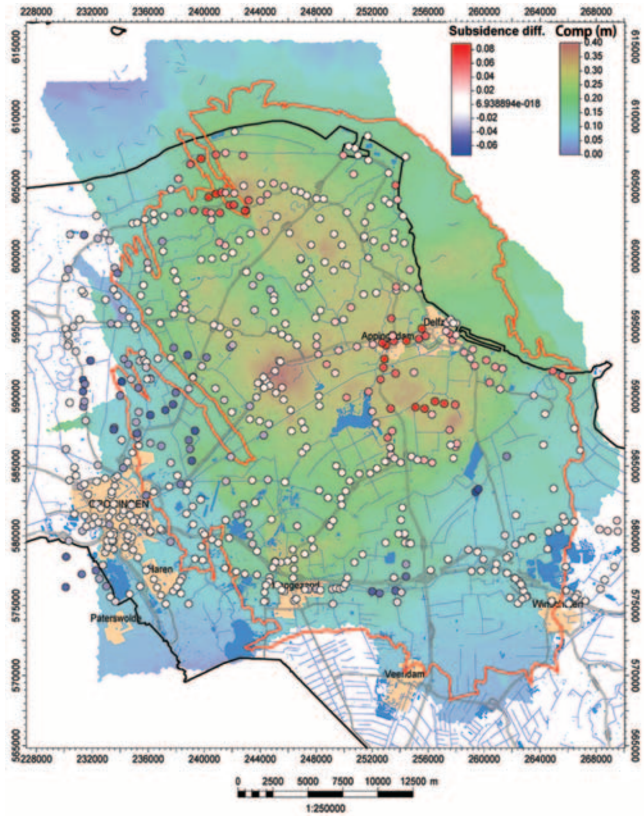

Figure 4. Compaction in the Groningen reservoir in January 2012, calculated with the RTCM model. The difference between calculated and measured subsidence is indicated in colors at the benchmark locations (labeled "Subsidence diff."). Red indicates that the calculated subsidence is larger than the measured subsidence. After TNO (2013b), Figure 5.13. Used by permission of TNO.

Several areas had poor fit between the measured and modeled subsidences (Figure 4) (TNO, 2013b). In the area east of the Groningen field, a reduction of 15% in porosity resulted in a much better subsidence fit. Misfits in the northern field might be caused partly by a depleting aquifer. Both examples illustrate that compaction modeling is influenced strongly by the quality of the static and dynamic reservoir models.

Seismicity

Northern Netherlands contains no records of instrumental or historical naturally occurring seismicity. One event might have occurred in 1262, but there are indications that it might have been meteorologic rather than seismic. This region is considered to be tectonically stable. The first recorded induced event in the Groningen field was on 5 December 1991 (M_L 2.4).

Figure 5 shows the number of seismic events on a yearly basis. Seismicity has increased over time with more frequent and larger events, which is also visible in the cumulative seismic moment. The number of events above magnitude M_L1.5 appears to have been quite stable until 2003, after which an increase in the number of events is observed. The year 2003 also marked the first event with a magnitude larger than 3.0. In 2006, a M_L 3.5 event occurred, and in 2012, the largest events to date occurred near the village of Huizinge on 16 August with a magnitude of M_L 3.6. Induced seismicity at Groningen

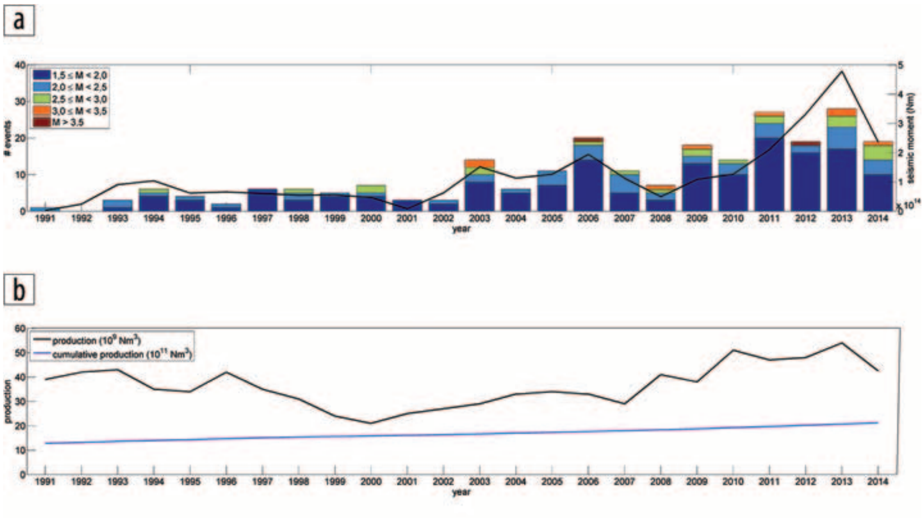

Figure 5. (a) Number of events, magnitude of events, and seismic moment per year (in newton meters [N m]). (b) Yearly gas production (in 10^9 Nm^3/yr = 1 bcm/yr) and cumulative production (in 10^{11} Nm^3) for 1991 through 2014. Gas production is expressed as normal cubic meters (Nm^3) to indicate that gas is at standard temperature and pressure.

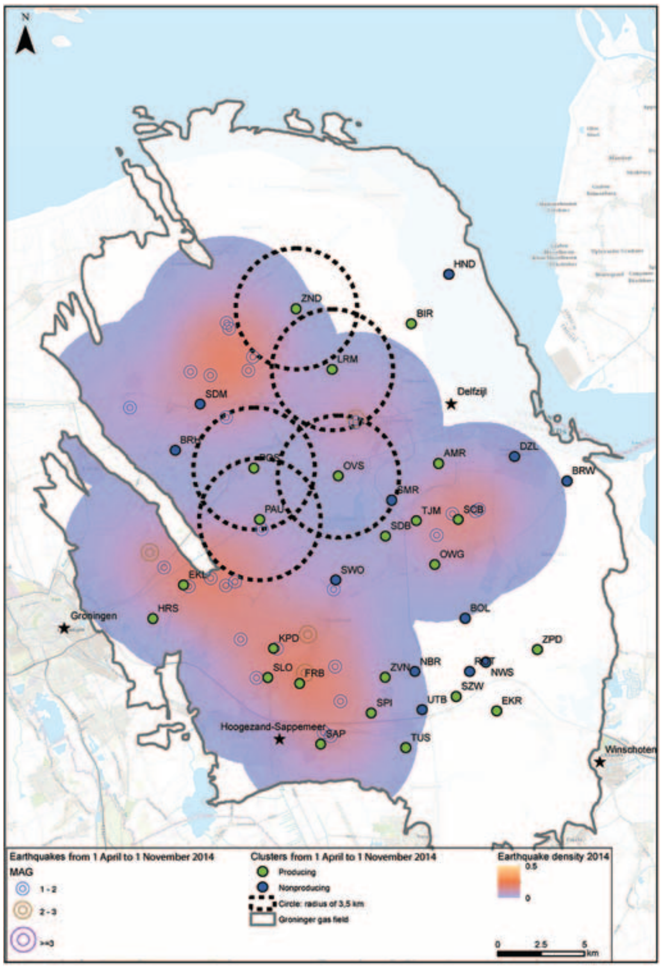

Figure 6. Event density (number of seismic events per square kilometer) from 1 April 2014 through 1 November 2014. Dashed circles indicate areas of 3.5 km in which the pressure wave has traveled in 10 months (with an average permeability of 150 mD). Small colored circles indicate observed events in the same period and their magnitudes.

appears to be nonstationary and is increasing with time (Muntendam-Bos and de Waal, 2013).

Relationship between compaction and seismicity

Stress changes induced in the reservoir by pressure depletion cause compaction, which is visible at the surface as subsidence. Close to existing faults, compaction induces shear stress changes on the fault because of the initial inability of faults to move. Depending on friction of the faults and magnitude of the stress change, faults can slip, resulting in seismic events. Compaction can be considered to be the driving force of seismicity, albeit details of the connecting mechanisms are not well defined.

Bourne et al. (2014) analyze the relation between seismicity and compaction in the Groningen field. They find empirically that seismic moment is an exponential function of cumulative compaction. Seismic moment in turn is a measure of the energy that can be released seismically. TNO (2013b) proposes a partially direct response of compaction in the reservoir to pressure changes which lead to a direct response in terms of seismicity. Compaction, therefore, has become a critical indicator for subsidence and induced seismicity in the field.

Developments in 2014

Because compaction is largest in the center of the field (Figure 4), following the theory of Bourne et al. (2014), the amount of energy that can be released seismically is largest also in the center of the field (NAM, 2013).

On the basis of this observation, combined with the observation of increasing seismicity over the field, dwindling societal acceptance, and the possible direct response of induced seismicity to pressure changes (TNO, 2013b), the Dutch minister of economic affairs decided to reduce (Figure 5) overall production of the Groningen field, as mentioned above.

Observations

From January 2014 through January 2015, 19 events with M_L larger than 1.5 have occurred in the Groningen gas field (Figure 5). Figure 6 shows the event density over the field from 1 April 2014 through 1 November 2014. Five production clusters (LRM, PAU, POS, OVS, and ZND) significantly reduced production rates starting in January 2014.

Because of hydraulic resistance, it takes time for a pressure wave to travel through the gas-bearing pore space of the reservoir. Assuming an average permeability of 150 mD, under the present reservoir conditions (pressure, gas density, and viscosity), the pressure wave will have traveled ~ 3.5 km from the clusters where production was lowered by 1 April 2014 (TNO,

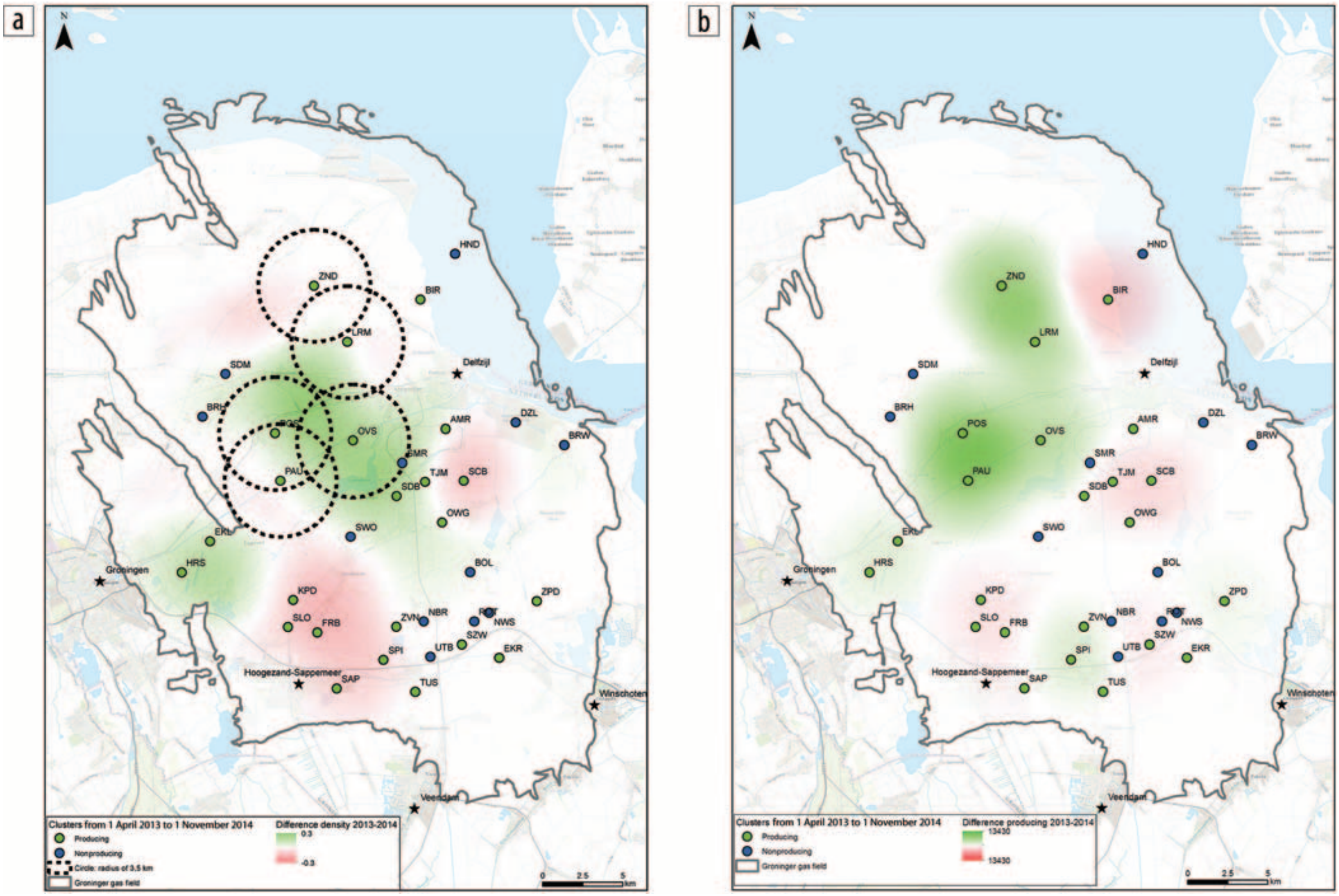

Figure 7. (a) Difference in event density (number of events per square kilometer) between 1 April and 1 November in 2013 and in 2014. A positive (green) difference indicates a lower event density in 2014 compared with 2013. Dashed circles indicate areas of 3.5 km in which the pressure wave has traveled in 10 months (with an average permeability of 150 mD). (b) Difference in production (in 10^5 Nm^3) from 1 April to 1 November in 2013 compared with the same months in 2014. A positive (green) difference indicates a smaller production in 2014 compared with 2013.

2014). Seismicity in this area is low and is reduced compared with that of previous years.

Note that in 1991 through 2012, most seismicity occurred in the center of the field (Figure 1). Figure 7 shows the difference in event density and production levels between 2013 and 2014. The region with reduced production appears to correspond to a reduction in seismicity.

If seismicity is linked directly to cumulative compaction, as described in NAM (2013), the decrease in production rate should not affect the rate of seismicity because cumulative compaction in the center of the field remains high. If the inducing mechanism for seismicity, i.e., compaction inducing stress changes on the existing faults, is caused by, for example, the rate of compaction, the rate of seismicity should be affected by the change in production rate.

A decrease in event densities is observed for 2014 (Figure 7). This finding, however, is not statistically significant yet, as determined by Bayesian statistical analysis (TNO, 2014). Because the number of events per year is about 20, we expect that several years will be needed to convincingly prove a decrease in the number of events as a reaction to the reduction in production. Although not yet statistically significant, the observations suggest a close link among production, compaction, and seismicity.

Conclusions

The relationship among geologic, flow-dynamics, geomechanical, and seismological models has been studied for the Groningen reservoir. In this near-coastal region, surface subsidence is monitored, and predictions are used for pumping and dyke heights. Surface subsidence is caused by compaction, which is caused by production of gas. Observed mismatches between modeled and measured subsidence were explained by porosity anomalies and aquifer activity, illustrating the need for high-quality static and dynamic models.

The induced seismicity of the Groningen reservoir is related to compaction, which results in stress changes on the many existing faults in the reservoir. The slip on those faults created the observed seismic events. Even though magnitudes are not as high as in tectonically active areas, intensities are quite high because of the relatively shallow depth and soft soils in the area, leading to damage of houses and infrastructure. The induced seismicity of the Groningen field increased in magnitude and number of events from 2003 to 2014, with the largest events occurring in areas where compaction is largest.

In 2014, production was reduced in the entire field, mainly focused on wells in the center of the field. Seismicity recorded in 2014 suggests that activity has decreased in the center of the field, correlating with the area where production was decreased.

This would indicate a direct relation among production, compaction, and seismicity. It is, however, too early to convincingly provide statistical evidence to this statement. TLE

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