

Original Article

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Corresponding author:

Jesper Spetzler
Email: jspetzler@yahoo.co.uk

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Inversion of source parameters for induced earthquakes in Groningen and surrounding small gas fields

Jesper Spetzler^{1,2} and Elmer Ruigrok^{1,3}

¹Royal Netherlands Meteorological Institute, De Bilt, the Netherlands; ²On Leave from the KNMI from January 2026; ³Department of Earth Sciences, Utrecht University, Utrecht, the Netherlands

Abstract

Source parameters of earthquakes provide valuable information in order to understand where the event occurred and what happened on the acting fault. This information can help to better understand why an area is prone to seismicity. We present a research earthquake catalogue between January 2016 and February 2025 for the induced seismicity in the Groningen gas field and a string of surrounding gas fields that are used for either production or storage. The earthquake catalogue is a list of relocated hypocentres, stress drops, seismic moments, moment magnitudes and moment tensor solutions with uncertainties. The updated list of hypocentres indicates that induced earthquakes in the Groningen field and surrounding gas fields have occurred in the reservoir. The general fault type is normal faulting with some strike-slip movement. The strike directions align well with known faults at the reservoir level. The stress drops generally increase with local magnitude. Some events with a local magnitude above 1.8 have stress drops up to 50–70 bar.

Introduction

The Groningen field is a well-known example of a largely depleted gas reservoir where induced seismicity has been recorded for more than 30 years. The largest earthquake had a local magnitude of 3.6 and occurred in Huizinge in 2012. The exploitation of the Groningen gas field ended in 2024. Besides the Groningen gas field, there are in the north-east of the Netherlands several smaller fields for gas production or storage, which are responsible for additional, however fewer and smaller, induced earthquakes. The seismological station network over the Groningen field has been extensively modernised starting in the end of 2014 with the installation of borehole stations (i.e. the G-network). The smaller gas fields on the flanks of the Groningen gas field were instrumented between 2017 and 2019. The database of seismological data in Groningen has been used to develop a ground motion prediction model for the Groningen gas field (Bommer et al., 2016, 2024; Ntinalexis et al., 2023).

The Royal Netherlands Meteorological Institute (KNMI) reports the local magnitude and epicentre of detected induced earthquakes swiftly after occurrence, resulting in an operational catalogue (KNMI, 2015). However, the waveform data contain extra information about source parameters of the earthquake. Important source parameters are the stress release at a nucleated fault, the strength of the earthquake in terms of the seismic moment or the moment magnitude and the type of fault movement and direction during the event. The stress drop and seismic moment can be estimated from a spectral fitting of displacement density spectra of waveform data using the Brune – and Boatwright source model, which accounts for the strength of an earthquake, corner frequency, near surface effects and attenuation of a propagating wavefield. Edwards et al. (2010) and Dost et al. (2018, 2019) applied the spectral fitting approach on waveform data of tectonic and induced earthquakes in Switzerland and the Groningen province in the Netherlands. Ameri et al. (2020) estimated stress drops and moment magnitudes of induced earthquakes in the Groningen gas field using waveform data from the deepest borehole sensors with the spectral fitting method. Dost et al. (2018, 2019) and Ameri et al. (2020) find comparable values for the stress drop and moment magnitude measurements of induced earthquakes with local magnitudes above M2 in Groningen. On the other hand, it is not an easy task to estimate stress drops with the spectral fitting method for low magnitude earthquakes because of a trade-off between source parameters if the attenuation function is unconstrained (Alloncle et al., 2025). The Southern California Earthquake Center (SCEC)/US Geological Survey (USGS) Community Stress Drop Validation Study (Baltay & Abercrombie, 2025) was initiated to investigate the variability of stress drop measurements. The study showed that indeed even with the same data, the stress drop results varied much because of the application of different methods and assumptions. One way to reduce the variability of stress drop measurements is to apply an attenuation model in the spectral fitting method, which uses kappa values of the near-

surface at station locations and a regional Q attenuation value for the deeper wavefield path (Alloncle et al., 2025; Bommer et al., 2015).

Information about the fault type and direction during earthquakes can be obtained with seismic moment tensor (MT) inversions of recorded waveform data. Kühn et al. (2020) extensively tested the Pyrocko MT software on waveform data from the Groningen gas field. One important finding in Kühn et al. (2020) was to use more station levels of the G-network in the MT inversion to obtain stable MT solutions. Dost et al. (2020) applied the Pyrocko tool to estimate the MT solutions of induced earthquakes in the period between 2016 and 2019 for local magnitudes ≥ 2 .

The waveform data of induced earthquakes in the Groningen field have been analysed by several authors. Spetzler and Dost (2017) relocated a subset of induced earthquakes from the Groningen field with the Primary wave Equal Differential Time (P-EDT) method by Lomax (2005). Willacy et al. (2018, 2019) carried out a full-waveform earthquake relocation and MT inversion of induced events between 2016 and 2020. Smith et al. (2020) used the NonLinLoc hypocentre method (Lomax, 2005) to relocate induced earthquakes in the Groningen field between 2015 and 2017. In Siorattanakul et al. (2024), the Gaussian Mixture Model As-sociator (GaMMA) is used to associate the P- and S-wave arrival time picks to different earthquakes rather than for relocation itself. The earthquakes are subsequently located using HypoSVI developed by Smith et al. (2021).

In this study, the database of waveform data since 2016 from the G-network for induced seismicity in the north-east of the Netherlands has been reanalysed. The minor induced seismicity for the smaller gas fields is analysed for events from 2019 when two additional local networks had been installed. The induced earthquakes are relocated with a hypocentre method including P- and S-wave phase picks and accounting for the 3D structural model for the north-east of the Netherlands. The source parameters that are the stress drop, the seismic moment, the moment magnitude and the MT including their uncertainties are estimated. The presented list of reanalysed events is different from the operational KNMI catalogue for induced earthquakes (KNMI, 2015). The latter provides information about epicentres and depths (fixed to 3 km) and the local magnitudes, which are estimated with an average velocity model for the north of the Netherlands (Spetzler et al., 2024) and a hypocentre method by Lienert et al. (1986).

The characterisation of an earthquake in terms of the hypocentre and source parameters is discussed. An outline of the hypocentre method and the approach to measure the stress drops, moment magnitudes and MT solution of induced earthquakes in the Groningen field and smaller fields is summarised. Finally, the results of the analysis of waveform data for induced seismicity are presented.

Characterisation of an earthquake

Earthquakes occur primarily on existing faults in the subsurface. It is important to know the part of the fault that ruptures, how much energy is released in the rupture process and how the fault is moving. The hypocentre specifies the epicentre and the depth of the event. The seismic moment, moment magnitude and the local magnitude are quantities related to the amount of seismic energy released during the earthquake. The operational KNMI

earthquake catalogue reports the local magnitude (KNMI, 2015). However, for earthquakes worldwide, the moment magnitude is often used. In this analysis of induced earthquakes in the north-east of the Netherlands, we will add the moment magnitude. Besides in geomechanical studies of earthquakes, it is of importance to know how much the stress is changing (i.e. the stress drop) during the rupture process on the fault. The fault orientation and slip direction during an earthquake can be determined from a MT inversion of recorded waveform data.

Hypocentre estimation

The hypocentre location methodology is based on a combination of P-S and P-EDT phase delays (Spetzler et al., 2024). The P-S traveltime difference is good at estimating the depth of an earthquake, while the epicentre is estimated most accurately with P-EDT delays. Combining both types of phase delays in a hypocentre analysis provides a hypocentre with the least uncertainty. The P- and S-traveltime picks are estimated from waveform data from borehole level 4 (at 200 m depth) by kurtosis (Baillard et al., 2014).

The geology of the Groningen field is sedimentary layers with weak lateral variations over most of the area. Local 1D velocity profiles extracted from the 3D velocity model from Nederlandse Aardolie Maatschappij (NAM) for the north-east of the Netherlands (Romijn, 2017) were used to compute P and S traveltime tables for the source relocation analysis. The traveltimes were computed with a finite-difference (FD) solution of the wave equation (Robertsson et al., 1994). This approach will capture accurately the difference in P-S traveltime differences, which are essential in the estimation of the depth of induced earthquakes. Spetzler et al. (2024) explain in more detail the FD approach with an example from the Groningen field.

Observed traveltime picks of P- and S-phases in the recorded waveform data are compared with arrival times for hypothetical positions in the relocation procedure. The result of the hypocentre location of an earthquake is the epicentre, source depth and associated uncertainties in source position.

Stress drops, moment magnitude estimation and uncertainties

The analysis of the source parameters (i.e. stress drops and seismic moment) is performed with the spectral fitting method of the source displacement spectrum (Alloncle et al., 2025; Dost et al., 2018; Edwards et al., 2010). The amplitude spectrum for the source displacement is given by:

$$A(f) = \Omega_0 \frac{site(f)}{\left(1 + \left(\frac{f}{f_c}\right)^{2\gamma}\right)^{\frac{1}{\gamma}}} e^{-\pi f t^*}. \quad (1)$$

The parameters Ω_0 is the low-frequency moment of the source displacement spectrum, f_c is the corner frequency and t^* is a frequency independent term depending on the attenuation of the wavefield. Alloncle et al. (2025) suggest to replace the parameter t^* with attenuation measurements at near-surface station sites (i.e. the kappa value, κ_s) and the regional frequency dependent Q-attenuation. The attenuation model is given by:

$$t^* = \frac{d_{hypo}}{v_s Q(f)} + \kappa_0. \quad (2)$$

with the hypocentre distance between the source and station defined by d_{hypo} and v_s is the shear wave velocity at source depth. A seismological source model (i.e. the Brune model (Brune, 1970) and the Boatwright model (Boatwright, 1980)) relates the dimensions of an earthquake to its strength in terms of the stress drop and the seismic moment. Both the Brune- and Boatwright model assume that the rupture area is a circular crack. Where the Brune model simplifies the rupture dynamics to an instantaneous and uniform stress release over the fault surface, the Boatwright model extends to a description of a more accurate dynamic rock physics model. For the Brune model in Eq. (1), $\gamma = 1$, while for the Boatwright model $\gamma = 2$. The site term due to near-surface amplification is assumed to be unity because geophones at 100, 150 and 200 m depth are used and the correction for the near-surface term is applied in the seismic moment and stress drop calculation. Attenuation measurements from G-stations are reported in a study by Ruigrok et al. (2022).

To calculate the seismic moment, the low-frequency moment of the spectral displacement spectrum Ω_0 and station-source specific elastic parameters of the seismic model are required (Ameri et al., 2020). The expression for seismic moment M_0 is given by

$$M_0 = \Omega_0 \frac{4\pi\sqrt{\rho_s}\sqrt{\rho_0}\sqrt{v_0}v_s^{2.5}}{\Re Fg(r)}, \quad (3)$$

where $\Re$ denotes the average radiation pattern for S-waves, which is assumed to be 0.63 for Groningen (Dost et al., 2018), F is the free surface amplification (set to 1 for the deeper geophone recordings), ρ_0 and ρ_s denote the density at the station and at source, respectively, while v_0 and v_s are the shear wave velocity at the station and source depth. The elastic parameters at the geophone level and source depth are extracted from the 3D NAM model for Groningen (Romijn, 2017). According to Dost et al. (2018), the geometrical spreading function $g(r)$ for the Groningen field can be described by the functional form:

$$g(r) = \frac{1}{R_0} \left[\frac{R_0}{R} \right]^\lambda, \quad (4)$$

with the reference distance R_0 set to 1000 m, R is the hypocentre distance and the parameter $\lambda = 1.9$ where the latter is estimated from the distance dependent low-frequency moment of the displacement Ω_0 . With a value of the seismic moment M_0 for an induced earthquake, the moment magnitude M_w is calculated from the Hanks and Kanamori relationship (Hanks & Kanamori, 1979):

$$M_w = \frac{2}{3} \log_{10} \left(M_0 \left[N \cdot m \right] \right) - 6.07. \quad (5)$$

The moment magnitude is based on physical properties of the earthquake and is more related to the energy release of an earthquake than other magnitude scales. It is considered the authoritative magnitude scale for ranking earthquakes by size. However, it is difficult to estimate the moment magnitude for small earthquakes. Instead, a local magnitude scale is often applied, which is calculated from the peak amplitude and a regional distance-attenuation correction Dost et al. (2004).

To calculate the stress drop, the corner frequency f_c , the seismic moment in Eq. (3) and the S-wave velocity at the source are required. The expression for stress drop (Brune, 1970; Eshelby, 1957) is:

$$\Delta\sigma = \frac{7}{16} \frac{M_0 f_c^3}{(0.37 v_s)^3}. \quad (6)$$

By combining waveform data from more borehole levels, the amplitude spectra will be reinforced and reduce the effect of notches at different levels. For the seismic moment, moment magnitude and stress drop estimations, waveform data from levels 2, 3 and 4 (at 100, 150, 200 m) are used.

MT inversions

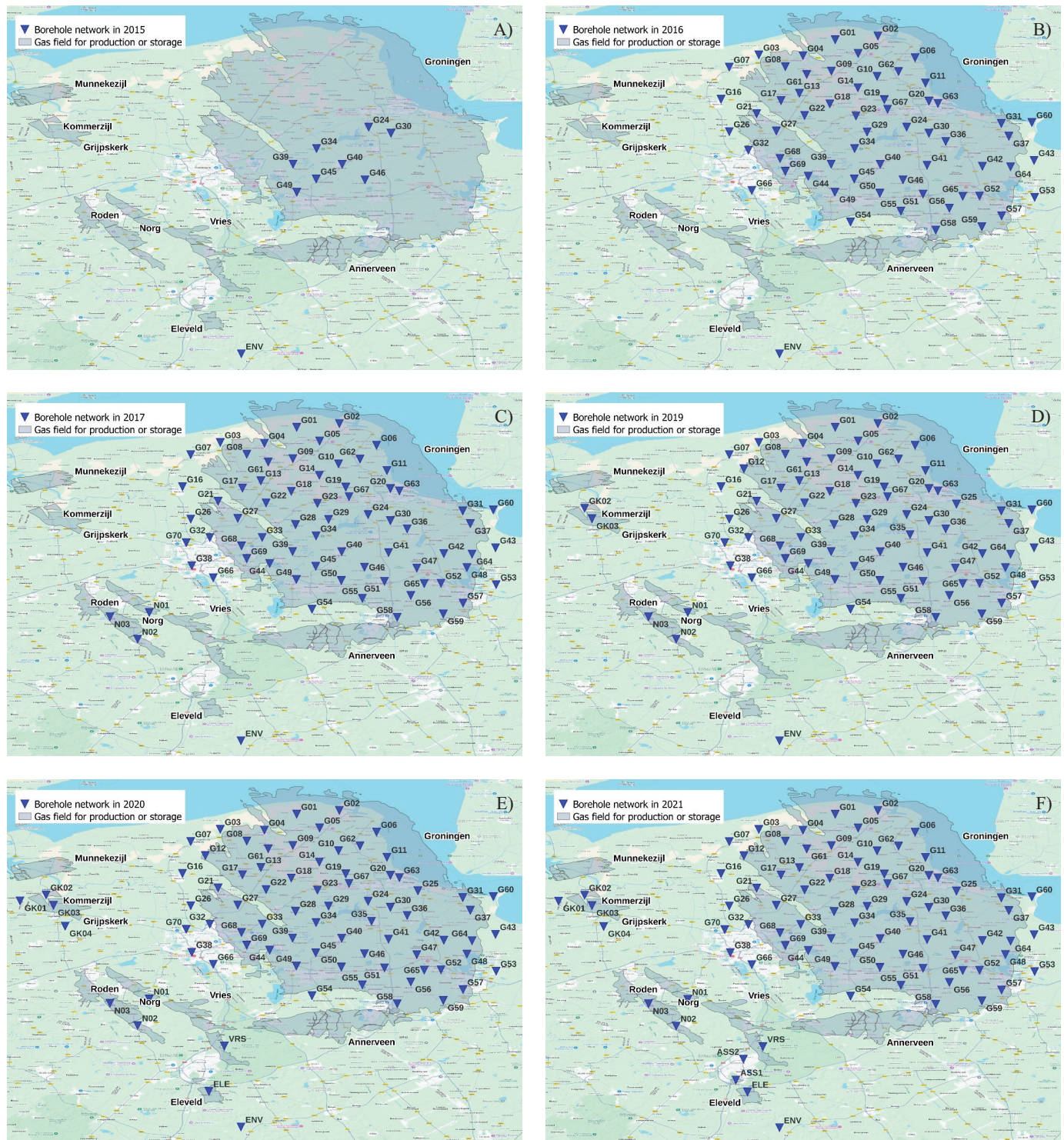
To calculate MT solutions for the induced earthquakes in Groningen, the open-source software Pyrocko (model Grond) is used (Heimann et al., 2017). This is a probabilistic MT inversion approach, which yields for each inverted parameter the most probable solution and its uncertainty. The current version of Pyrocko only allows to use 1D elastic profiles to calculate Green's functions. To take into account the 3D structure of the Groningen field (Romijn, 2017), local 1D profiles distributed over the area of induced earthquakes with local magnitudes greater than M1.5 were extracted.

Kühn et al. (2020) did a thorough examination of the parameter setup in Pyrocko to obtain stable MT solutions for one induced earthquake in Groningen. The feasibility analysis indicated that it was not enough to apply waveform data from only the level 4 (200 m) of the G-station network to get robust results. Instead, waveform data were required from multiple levels to overcome notches in the amplitude spectra due to interference of up- and downgoing waves. Dost et al. (2020) restricted the waveform data to the levels 3 and 4 (150 and 200 m) of the G-stations due to computational limitations. In this article, waveform data from levels 2, 3 and 4 (100, 150 and 200 m) of the G-stations are used in the MT inversion.

The MT inversion results in one MT which can be decomposed into the dip of the fault patch on which the rupture happened, the rake direction (slip), the percentage of volume change and the percentage of compensated linear dipole vector motion (Kühn et al., 2020). The interpretation of the physical motion of a fault is ambiguous since two focal mechanisms exist with the same MT. The focal mechanism of the two solutions is chosen to be consistent with the strike and dip of known faults. The rake indicates whether the fault motion was strike-slip, normal, reverse, or a combination of these modes.

Research earthquake catalogue for the Groningen gas field, the Grijpskerk field, the Norg field and the Eleveld field

It became easier from 2016 to detect and locate induced earthquakes with the installation of the G-stations over the Groningen gas field. The majority of the G-network was completed by the beginning of 2016. The small fields west of the Groningen field were instrumented from 2017. See Figure 1 for an illustration of the development of the station network in Groningen over time. The research earthquake catalogue



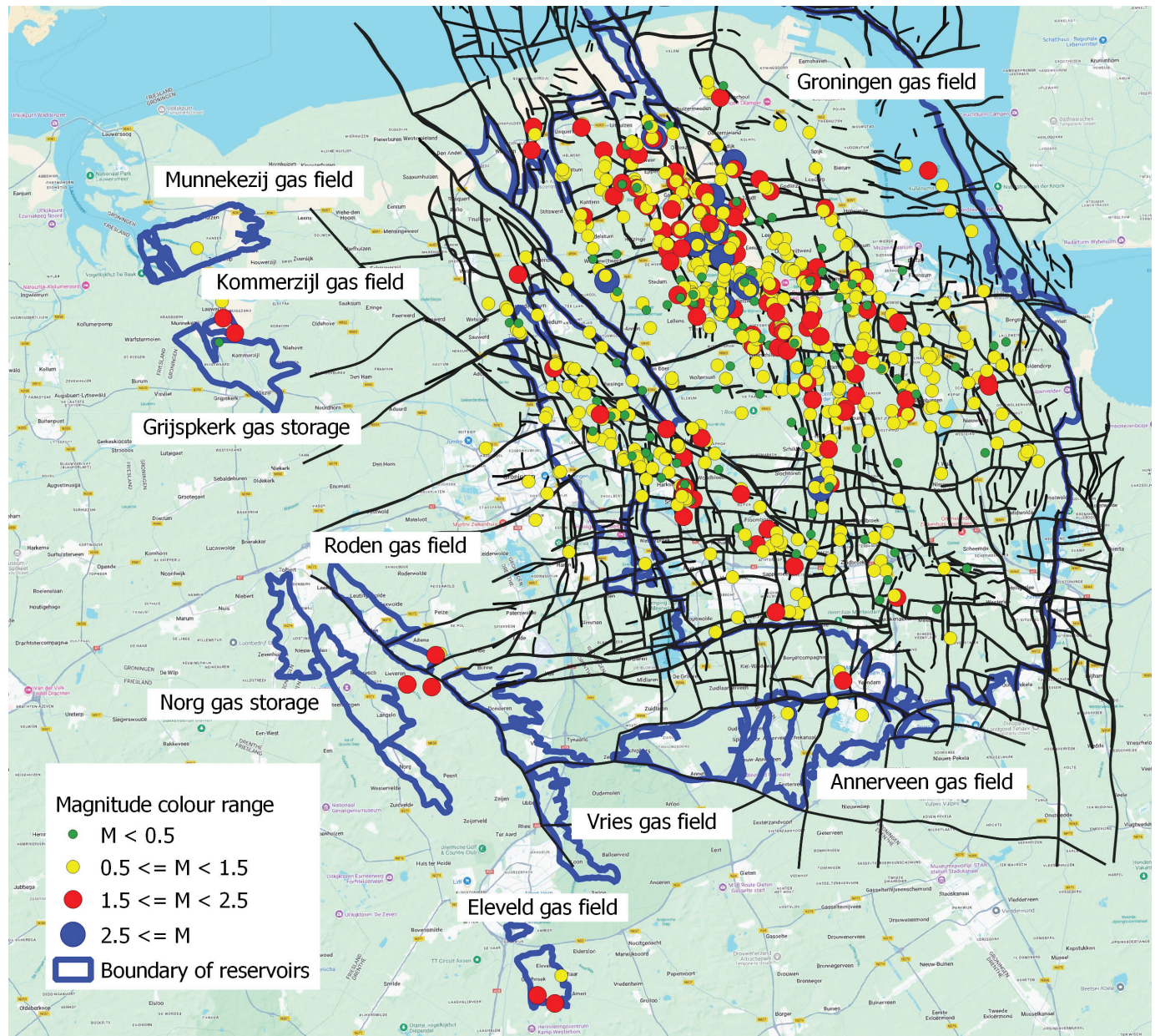


Figure 2. The epicentre distribution of induced earthquakes in the Groningen and surrounding small fields.

with the fault system. For the induced events located outside the Groningen gas field, there are four events near the Grijpskerk, the Kommerzijl and the Munnekezijl gas fields. The fault system model does not extend as far to the west to the area with these gas fields. Near the Norg, the Roden and the Vries gas field, there are three induced events present. Three induced events in the Eleveld gas field and three earthquakes related to the Annerveen gas field have been relocated.

The depth distribution of the induced events in the Groningen gas field is shown in Figure 3. The majority of events have a depth range between 2800 and 3000 m, which is the depth of the Rotliegendes reservoir in the centre of the Groningen gas field. There is a minor tail distribution of more shallow depths from 1000 to 2200 m. The tail distribution for deeper relocated events is rather short. This indicates that few of the relocated events have a possible source location in the

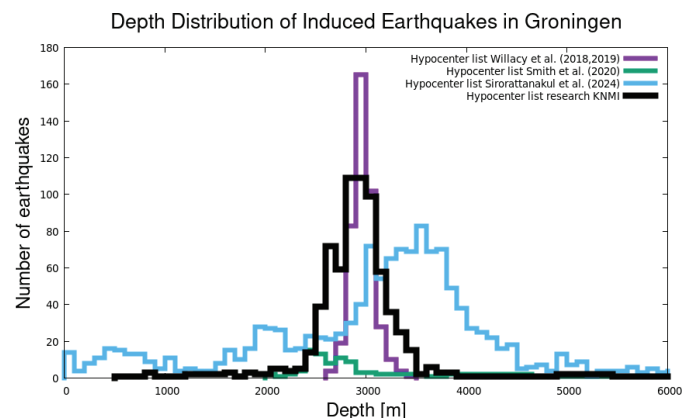


Figure 3. Distribution of depths of relocated events.

Carboniferous layer beneath the Rotliegend gas reservoir. The depth distribution of the relocated earthquake catalogues by Willacy et al. (2018, 2019); Smith et al. (2020); Sirorattanakul et al. (2024) are added to Figure 3. For Willacy et al. (2018, 2019), all the relocated events are found inside the Rotliegend gas reservoir. This is partly due to the two-step strategy for hypocentre relocation in Willacy et al. (2018, 2019). A secondary minimum of the objective function inside the reservoir is used to relocate the event if the first hypocentre is found outside the Rotliegend gas reservoir. The majority of relocated events in Smith et al. (2020) are found in the reservoir or within 500 m from the top of the reservoir. Sirorattanakul et al. (2024) find a depth distribution of seismicity in Groningen that is rather wide. The relocated induced earthquakes are not constrained to the gas bearing Rotliegend reservoir. The uncertainty in the relocated hypocentres in this study is on average 100–200 m for the epicentre and 200–400 for the depth estimate, which is shown with the hypocentre uncertainty plot in Figure 4.

Stress drops estimations

The measurement of stress drops includes an estimation of the uncertainty. The uncertainty of the stress drop is calculated from the uncertainty in the measured low-frequency moment

and corner frequency. Figure 5 shows the stress drop variation in the earthquake catalogue. The stress drop unit is in bar (i.e. 10^5 Pa). The results show a correlation between earthquake size

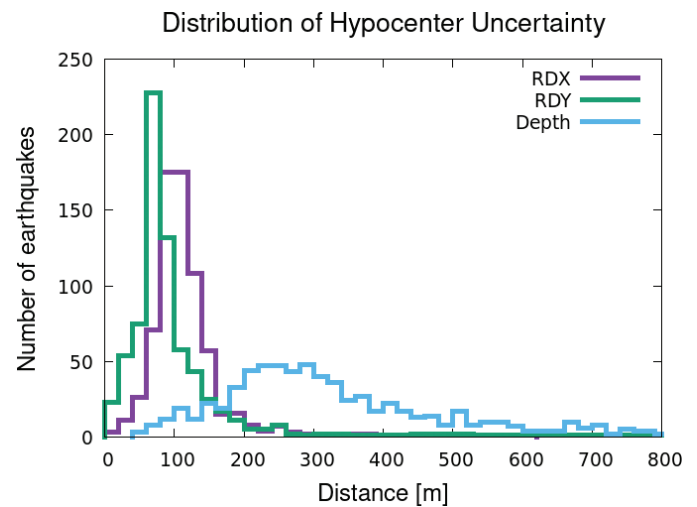


Figure 4. Uncertainty distribution (expressed as standard deviations in three orthogonal directions) of relocated hypocentres.

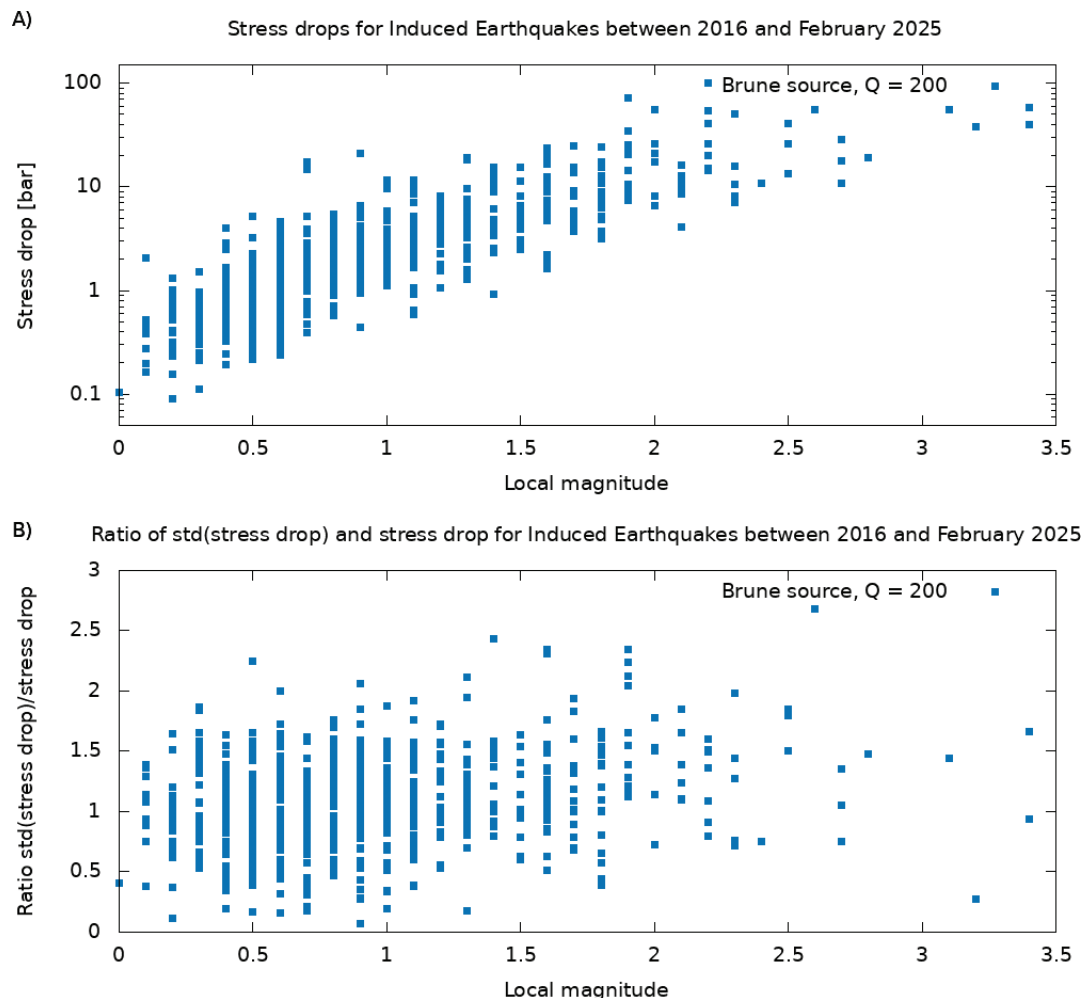


Figure 5. Stress drop estimates for the Brune source model and a regional Q -value equal to 200. (A) The measured value. (B) The ratio of the standard deviation of the stress drop and the stress drop measurement.

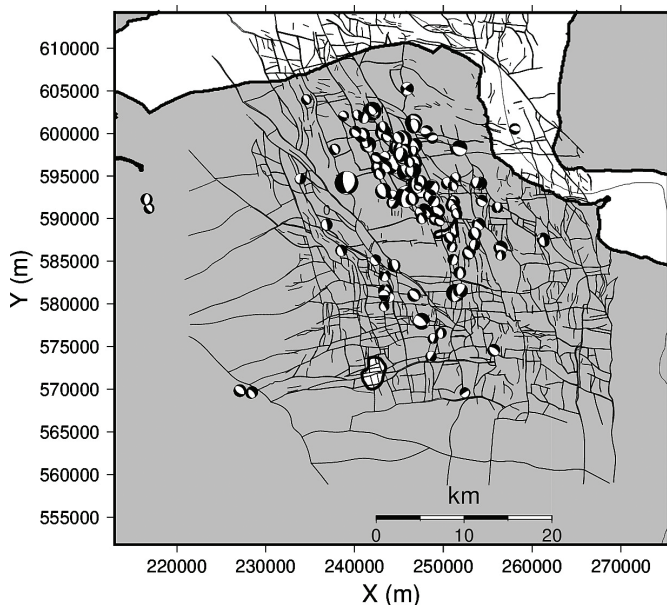


Figure 6. Moment tensor solutions for induced events with a magnitude greater or equal to M1.5 from 2016 until July 2025.

(local magnitude) and estimated stress drops. Most stress drops are between 0.5 bar and 10 bar, which corresponds to a local magnitude range from 0.5 to 2. Several events have stress drops from 10 to 70 bar. Only when using the Brune source with $Q = 200$, a stress drop to 100 bar is obtained. The ratio of the standard deviation of the stress drop and the stress drop measurement in Figure 5 shows no correlation with the event (local) magnitude. The Nyquist frequency of the stations in the G-network is 100 Hz with a cap for an unaliased bandwidth of 80 Hz. For smaller magnitudes, the corner frequency estimation is possibly affected by the bandwidth of data.

Seismic MT estimations

The MT solutions of induced events with a local magnitude of M1.5 or above have been calculated. The number of MT solutions in the research earthquake catalogue is 120. Figure 6 shows the MT solutions of induced earthquakes in the Groningen gas field and the surrounding small fields. Most of the MT solutions are illustrated by a beach ball, which corresponds to normal faulting with a small strike-slip component. By looking at the orientation of the beach ball, one can observe a good alignment between the strike direction of estimated focal mechanisms and fault lines on which the induced earthquakes occur. There is one particular MT solution standing out in the northern part of the Groningen field having a strike-slip motion with very little vertical movement on the fault. The MT solution for this event was recalculated with a wider range of borehole stations without a change of result. The MT solutions for the induced events near the Grijskerk and the Norg field show normal faulting and a strike direction parallel to the long north-west to south-east directed fault to the west of the Groningen field.

Histograms for the dip and rake distributions of the MT solutions are plotted in Figure 7. The distribution of the dip parameter has a mean value around 55–65 degrees. This is a lower range than the reference value of 70 degrees for the

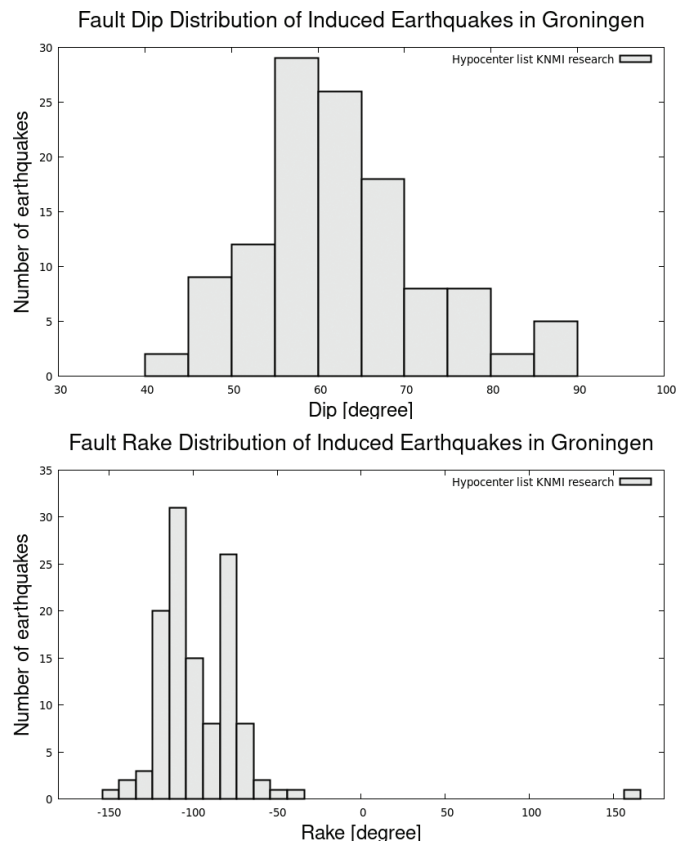


Figure 7. Distribution of estimated focal mechanism parameters. (A) The dip distribution. (B) The rake distribution.

inclination of faults in the Groningen gas field. The rake distribution shows two peaks, one at -70 degrees and another at -100 to -110 degrees. A pure normal fault movement would have had a rake at -90 degrees. Instead, the rake distribution plot suggests that the faulting type is mostly normal fault with some strike-slip movement. The MT solution in the northern part of the Groningen with a suggested strike-slip motion has the rake equal 160 degrees.

Conclusions

Information about hypocentres and source parameters is important in order to understand the seismicity, to image where active faults are present and to characterise the movement of these faults. A research earthquake catalogue with hypocentres and source parameters for induced seismicity in the north-east region of the Netherlands is presented. In this area, the Groningen gas field and several small fields for gas production and storage are present. Induced earthquakes in the KNMI operational earthquake catalogue from 2016 to February 2025 have been relocated using the 3D velocity model from NAM and a hypocentre method that uses an optimal combination of P-wave and S-wave arrival times. Additional calculated source parameters are the stress drop, the seismic moment (from which the moment magnitude is derived) and the MTs.

The list of relocated hypocentres shows that induced events in the Groningen gas field coincide with known faults in the reservoir. The induced events take place in the Rotliegend layer between 2800 and 3500 m depth. In the central part of the

Groningen field, the hypocentre depths tend to be about 2800 m. At the boundaries of the Groningen gas field, the hypocentre depths are often deeper than 3000 m. The hypocentre depths of the induced events in the small fields to the west of the Groningen field are in the range of 3200 m to 3600 m, which is in agreement with the depths of the Rotliegend layer. The stress drops show an increasing trend for increasing local magnitude. Generally, half of the stress drops values have smaller uncertainties than the stress drop estimates, while the remaining stress drop estimates show variations in the order of the stress drop estimate or higher. Event (local) magnitudes below 1.8 have stress drops up to 10 bar. From local magnitude 1.8, the largest stress drops are in the range 50–70 bar. The MT inversions of the induced earthquakes clearly show that the strike of the focal mechanisms follows the direction of the known faults in the Groningen gas field. The active fault patches have a dip of 55–65 degrees and the typical faulting mode is a normal fault with some strike-slip motion. The presented earthquake catalogue is enclosed in the supplementary material.

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