Introduction

The Groningen field is the largest onshore gas accumulation in Europe with 2900 × 10^9 Nm³ gas initially in place. The reservoir comprises aeolian and fluvial Rotliegend sandstones and fluvial Carboniferous sandstones (Grötsch et al., 2011). Continuous gas production since 1963 has led to induced seismicity in the field. The first earthquake was recorded in 1991 (Ml 2.4). From 2003 onwards the number of earthquakes and their magnitudes increased. The largest earthquake until present was recorded in 2012 near Huizinge (Ml 3.6) causing damage to buildings and public unrest. Since 2014, gas production has been adapted to reduce seismicity. After the Ml 3.4 earthquake near Westerwijnwier in 2019, the Dutch government decided to close in the Groningen field as soon as possible.

The seismicity results from stress release on pre-existing faults at reservoir level. The stress is caused by gas pressure depletion in the reservoir and appears to be sufficient to cause seismic slip along parts of these faults (Dost et al., 2012). Reflection seismic data shows many natural faults within the Rotliegend and Carboniferous strata. Recently, fault imaging in the Rotliegend reservoir and below has been significantly improved using seismic attributes (Kortekaas and Jaarsma, 2017). Manual interpretation of the deep-seated faults shows that many of the faults extend into the Lower Carboniferous strata.

Before 2015, the seismological network in the Groningen area was sparse, leading to a considerable uncertainty in the hypocentre locations of the earthquakes and herewith obscured the relationship between the earthquakes and nearby faults. Since late 2015, the density of the network significantly increased and the hypocentres can be determined with high accuracy (Spetzler and Dost, 2017; Willacy et al., 2019). In our study, the hypocentres of 482 seismic events between 2014-01-01 to 2019-06-14 have been updated using the Equal Differential Time (EDT) method (Spetzler and Dost, 2017). The method uses the travel time shift of the recorded waves between different stations.

Combining the detailed fault model with the updated high-resolution earthquake dataset, it is possible to study with confidence relations between faults and hypocentres. So far, we observe that most hypocentres are located on deep-seated fault systems. For 16 Ml ≥ 2.0 earthquakes, the associated faults have been characterised.

Fault interpretation and fault identification

Reprocessed and depth-imaged 3D PreSDM and RTM seismic datasets from 2015 cover the entire Groningen field (NAM, 2016). The datasets were input to fault interpretation and seismic attribute extractions including “ant tracking”, using Petrel software (@Schlumberger). The updated EDT hypocentre locations have been plotted on the ant tracking attribute extraction at top Rotliegend depth (Kortekaas and Jaarsma, 2017), see Figure 1. As the signal-to-noise ratio of the seismic data decreases with depth, ant tracking appears less suitable to map the deep-seated faults below the Rotliegend reservoir. The deep-seated faults have been interpreted on vertical seismic sections by visual inspection and manual picking. The fault interpretation, defined by fault sticks, were converted to fault plane interpretations. For 16 Ml ≥ 2.0 earthquakes well-defined hypocentre locations were available (either from EDT analyses by KNMI or from Moment Tensor Inversion (MTI) analyses by KNMI or Shell). The associated faults were identified using the ant tracking attribute extraction map and interpreted. Subsequently, the fault plane characteristics mean dip, azimuth and vertical offset were determined.

Deep-seated fault systems

Manual interpretation of the deep faults indicate the presence of several large-scale deep-seated fault systems in the Groningen field (Figure 2). In general, the faults trend NW-SE and NNW-SSE and display en-echelon fault patterns in map view. In vertical seismic sections the development of large flower structures are interpreted; both negative (downthrown) and positive (pop-up structures) are present. The faults are discontinuous; they die out and/or step over. These fault patterns observed are
typical for strike slip systems. They seem to relate to the deeper geology of the Groningen High and related Dinantian carbonate platform at about 5 – 7 km depth. Furthermore, the deep-seated NW-SE fault systems are transversed by several E-W trending deep-seated faults.

The Groningen area experienced a succession of tectonic phases. The deep-seated NW-SE basement fault trend is seen throughout the Netherlands and the North Sea and is associated with the Silurian to Early Devonian Caledonian Orogeny (Ziegler, 1990). The subsequent N-S compressional phase during the Carboniferous Variscan Orogeny caused oblique-slip along these faults while E-W trending faults were formed during this time as well. Fault reactivation occurred during the Mesozoic NE-SW extensional phase and the Late Cretaceous-Early Tertiary Alpine inversion with N-S compression (e.g. Ligtenberg et al., 2011).

*Figure 1* Ant tracking attribute extracted from NAM’s 2015 PreSDM seismic volume. Extraction along top Rotliegend in depth domain, high ant tracking values indicate faults (Kortekaas and Jaarsma, 2017). Top Rotliegend depth (NAM, 2016) is shown as background map. The Groningen gas field is outlined in blue. Circles indicate revised hypocentre locations of earthquakes between 01-01-2014 and 14-06-2019 (Spetzler and Dost, 2017).
Figure 2 SW-NE seismic section, displaying the deep-seated fault systems. The location is indicated in Figure 1. 3x Vertical exaggeration is applied for visualisation purposes. Faults interpreted in this study are visualized by bold black lines, thin short black lines indicate the NAM fault model (NAM, 2016). Green circles indicate the revised EDT hypocentre locations (Spetzler and Dost, 2017).

Fault characteristics at updated hypocentre locations

The detailed fault map has been compared with the EDT earthquake hypocentre dataset (Spetzler and Dost, 2017), which is mostly in agreement with MTI solutions of Willacy et al. (2019). Almost all events can be linked to a fault within 200 m. Horizontal uncertainty of the EDT hypocentre locations varies between 100 - 200 m, the vertical uncertainty is within ±300 m. We observe that most hypocentres are located in the reservoir and align along the deep-seated NW-SE fault systems. For 16 $M_L \geq 2.0$ events, the associated fault properties have been determined with means and standard deviations. The mean dip angle and mean normal fault strike of these (NW-SE) faults is $68 \pm 5^\circ$ and $152^\circ \pm 18^\circ$, respectively. The vertical offsets of the faults at the hypocentres are in a wide range $6 - 163$ m (Figure 3).

Fault dip, offset or throw and fault azimuth are required for a geomechanical analysis, including dynamic rupture modelling. In most models, slip occurs when the stress on the fault exceeds a Coulomb failure criterion. Hettema (submitted) has worked out the Coulomb stress function and applied it to determine the criticality of faults in depleting reservoirs which depends on fault mechanical properties, fault dip, throw and azimuth in the stress field.

Figure 3 (left) Stereonet showing the strike and dip data of the faults associated with the 16 earthquakes ($M_L \geq 2.0$). (right) Vertical offset of the faults at hypocentre locations (bin width=40 m).
Conclusions

The combined detailed fault model (Kortekaas and Jaarsma, 2017) and high-resolution earthquake location dataset (Spetzler and Dost, 2017) makes it possible to study with more confidence relations between the hypocentres and focal mechanisms of earthquakes and detailed fault properties.

Seismic reflection data and attribute extractions show that most faults in the Groningen field extend from the Rotliegend reservoir into the underlying Upper Carboniferous strata. Many faults extend even deeper into the Zeeland Formation of the Lower Carboniferous Limestone Group. The interpretation of these faults in seismic reflection data indicate the presence of large deep-seated NW-SE (former) strike-slip fault systems.

Almost all EDT hypocentres are within 200 m horizontal distance of identified faults. Most hypocentres are located on the deep-seated NW-SE fault systems. Faults associated with 16 $M_t \geq 2.0$ events have a dominant NW-SE strike direction and a mean fault dip of 68°. Combining this detailed fault characterisation with geomechanical analyses will increase our understanding of earthquake mechanisms in relation to the complex fault structure present in and around the Groningen reservoir.

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References


