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Estimating the Maximum Magnitude of Induced Earthquakes in the Groningen Gas Field, the Netherlands

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Key Points

- Most estimates of maximum magnitude are conservative, potentially exaggerating the perceived seismic risk.
- Approaches to estimating the maximum magnitude of induced earthquakes warrants re-evaluation.
- Future energy-related projects will be jeopardized by estimates that are not physically realizable.

Abstract

Gas production in the Groningen field in the northern Netherlands began in 1963. Since 1991, many production-induced earthquakes have occurred, the largest reaching magnitude **M** 3.5 in 2012. In October 2023, the Dutch government closed the field, a decision which was justified by the potential threat of larger earthquakes occurring with continued gas extraction. This outcome highlights how the estimation of maximum magnitude for induced earthquakes can have important implications for risk perception by regulators and the public. Thus, estimation of maximum magnitude for induced earthquakes that are not physically realizable can lead to unwarranted conservatism. Over almost three decades, considerable effort has been invested by a number of researchers to estimate the maximum magnitude of induced earthquakes in Groningen. These efforts culminated in international workshops focusing exclusively on this question in 2016 and 2022. The purpose of these workshops was to inform the decision-making of an expert panel charged with formulating a logic tree for the maximum magnitude of Groningen earthquakes. We argue that the evaluation of the final distribution of maximum magnitudes is overly conservative in terms of the largest events induced in the reservoir and, most importantly, the likelihood of triggering even larger tectonic earthquakes outside the gas producing reservoir. In view of the serious and far-reaching consequences of maximum magnitude estimates, we reconsider the approach of these assessments to draw lessons that may be critical for future energy-related projects associated with induced seismicity.

Introduction

Natural gas production began production in the Groningen gas field in the north of the Netherlands in 1963. Almost 30 years later, a sequence of production-induced earthquakes began in 1991. The largest earthquake of the sequence, with a moment magnitude (**M**) 3.5, occurred in August 2012. In October 2023, in response to the induced earthquakes, the Dutch government closed production from the field on the advice of the regulatory body, the State Supervision of Mines (*Staatstoezicht op de Mijnen*, SodM). This decision, with far-reaching economic, environmental, and even geopolitical consequences, may seem surprising in view of the relatively small magnitude of the induced events and the weak levels of ground shaking that these have caused.

The justification for the closure of the field has been framed not so much in terms of the impact of the earthquakes that have occurred but rather the possibility of larger earthquakes: the Inspector General of SodM stated that "*As long as people in Groningen run a higher risk of dying – due to the collapse of houses as a result of a major earthquake….. – phasing out gas production and quickly realising the reinforcements will remain necessary for the safety*" (HazardEx, 2022).

The notion of a 'major earthquake' in the Groningen field is inextricably linked with estimates of the largest magnitude event that could occur. These estimates have, in recent years, been made to be incorporated into probabilistic seismic hazard analyses (PSHA) and probabilistic risk assessments. The experience in Groningen highlights a pitfall that does not exist when such estimates are made for natural (tectonic) earthquakes, namely that the estimates are viewed by many as predictions – along with probabilities of occurrence. Maximum magnitude (M_{max}) estimates for induced earthquakes influence risk perception in a manner that never occurs with such estimates for natural earthquakes (Bommer and Verdon, 2024). Several energy-related projects, including the Basel deep heat mining project in Switzerland, the Castor offshore gas storage project in Spain, and the use of hydraulic fracturing for shale gas in the UK, have been shut down by risk concerns over induced earthquakes. In each case the cited reason being the assumed potential for much larger earthquakes to occur if the activities were to continue (Bommer, 2022).

In the case of Groningen, Sintubin (2018) makes the following observations regarding the impact of M_{max} estimates: "*Although the scientists coped with the uncertainties of their M_{max} estimates, public and policy makers got stuck on the worst case scenario, an **M** 5.0 'Big One.' ….. Remarkably, in the public perception, the fact that the **M** 5.0 earthquake is part of the PSHA is no longer interpreted as a probability that may never occur, but as a certainty, as the 'Big One' that one day will happen. Whether or not such an earthquake is physically possible, has, in their perspective, become irrelevant*." This is the context in which the M_{max} estimates for Groningen need to be assessed since regardless of efforts to communicate the meaning of this parameter, it seems almost inevitable that the maximum magnitude of induced earthquakes will be viewed by many, including members of the public and also the media, not as a remotely possible upper limit but rather as a forecast of the outcome of continuing the industrial operations causing the seismicity.

In the sections below, we begin with a brief description of the Groningen gas field in terms of the geology and the history of gas production, followed by an overview of the induced seismicity and the responses to the societal concerns generated by the earthquakes. We then provide a chronological summary of the proposals for M_{max} for the Groningen field, from the earliest estimates postulated

shortly after seismicity began in the field up to the international workshop convened in 2022 to address this specific issue. The M_{max} logic tree that was the outcome from that endeavor is then evaluated, initially in terms of the process that was followed and the impact of the updated M_{max} distribution on the hazard and risk estimates for the Groningen field. The distribution of proposed M_{max} values, and their associated probabilities, are then assessed considering both the physical constraints on induced (literally meaning that the strain energy being released in the earthquakes is industrially driven) earthquakes and the likelihood of triggered events (meaning that an anthropogenic activity is triggering the release of strain energy resulting from natural tectonic processes). We conclude with a discussion of the lessons learned both for Groningen and for the management of seismicity associated with energy-related projects, in general.

Induced Earthquakes in the Groningen Gas Field

To provide context for the discussion of M_{max} estimates for the Groningen gas field, this section provides an overview of the field in terms of the geology, the history of gas production, and the nature of the induced earthquakes, as well as the responses by different stakeholders to the seismicity.

Gas production in the Groningen field

The Groningen gas field was discovered in 1959 by a well drilled near the village of Slochteren in the province of Groningen. Initially, the size of the Groningen gas field was significantly underestimated, but after an appraisal campaign, it became clear the Groningen gas field, with approximately 2.9 x 10^{12} m^3 gas initially in place, was the largest gas field in Europe.

The gas is primarily contained in an aeolian and fluvial Rotliegend sandstones of Permian age at ~3,000 m depth. The reservoir is overlain by an impermeable Zechstein salt layer that serves as the cap rock (Figure 1). The faults in the Groningen gas field have been formed and reactivated during three compressional and extensional tectonic events (De Jager and Visser, 2017). Some of the faults in the Rotliegend reservoir extend to greater depth into the underlying Upper and Lower Carboniferous strata. Some 625 faults were identified and mapped in the seismic data (Visser and Solani Viota, 2017), but techniques such as ant-tracking (to bring out planar discontinuities in the data) showed the presence of many more faults (De Jager and Visser, 2017; Kortekaas and Jaarsma, 2017). The faults in the Rotliegend reservoir do not extend into the overlying Zechstein Formation. Fault structures in the supra-Zechstein overburden are related to halokinesis of the Zechstein evaporites (Jager and Visser, 2017; van Elk and Doornhof, 2017). The exact dating of the original fault offsets is unknown with certainty, but it is generally accepted that the faulting mostly occurred during the Late Jurassic or Early Cretaceous rifting period, the main Mesozoic tectonic event affecting the Dutch subsurface. Prior to the occurrence of induced seismicity at Groningen, there was no evidence for geologically recent movement on these faults.

Groningen natural gas production has provided the oil companies operating the field and the Dutch state with considerable revenue and northwestern Europe with energy price stability, security of supply (Correljé et al., 2003) and increased independence from external energy providers (e.g., Russia) (Hellema et al., 2004; Boersema, 2021). The natural gas produced from the Groningen gas field has a relatively high nitrogen content, making it a low-calorific gas, requiring a dedicated

pipeline network and gas market. The gas was consumed by households and small businesses in The Netherlands, Germany, Belgium, France and as far as Italy (Correljé, 1998). Approximately 20% of original gas in the remains in the field (~500 x 10^9 m^3), representing almost 15 years of natural gas consumption in The Netherlands.

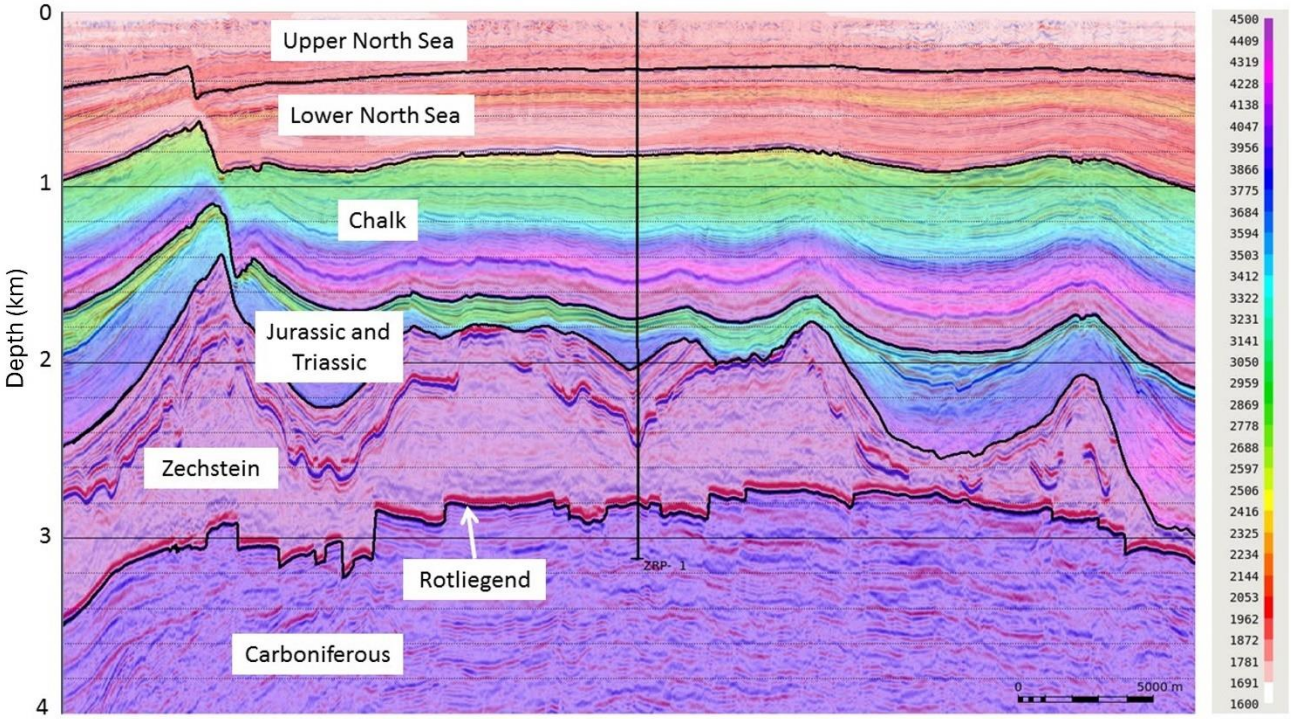

Figure 1. Cross-section through northern part of the Groningen field, intersecting the deep ZRP1 well, indicating the main stratigraphic intervals marked by black lines. Colors indicate P-wave velocities in m/s, shown in the legend (van Elk et al., 2019).

Induced seismicity in Groningen

Figure 2 shows the history of gas production and seismicity since 1991, when the first recorded earthquake occurred in the field. These histograms show both how activity increased over time and also how the seismicity rates began to drop after 2013 as a result of production limits imposed by the Dutch Ministry for Economic Affairs, which issues the licenses for gas extraction. There are less than 200 earthquakes represented in Figure 2, just 13 of which have had a local magnitude (M_L) of 3.0 or larger. Only four earthquakes have been as large as M_L 3.4 or greater. The largest earthquake that has occurred was the Huizinge event that took place in August 2012 and was M_L 3.6 or **M** 3.5; on average, the two magnitude scales have been shown to be nearly equivalent in Groningen for events of magnitude $\geq$ 2.5 (Dost et al., 2018; Dost et al., 2019). The second largest event was the Westerendem earthquake of 2006, which was assigned a M_L 3.5.

There is no record of natural seismicity in the region in either the instrumental or historical earthquake catalogues (van Elk et al., 2019), but induced earthquakes have been associated with several other gas fields in the region, the first induced event occurring in 1986 (van Eijs et al., 2006). The first event in

Groningen was the M_L 2.4 Middelstum earthquake of 5 December 1991, some 28 years after gas production first began.

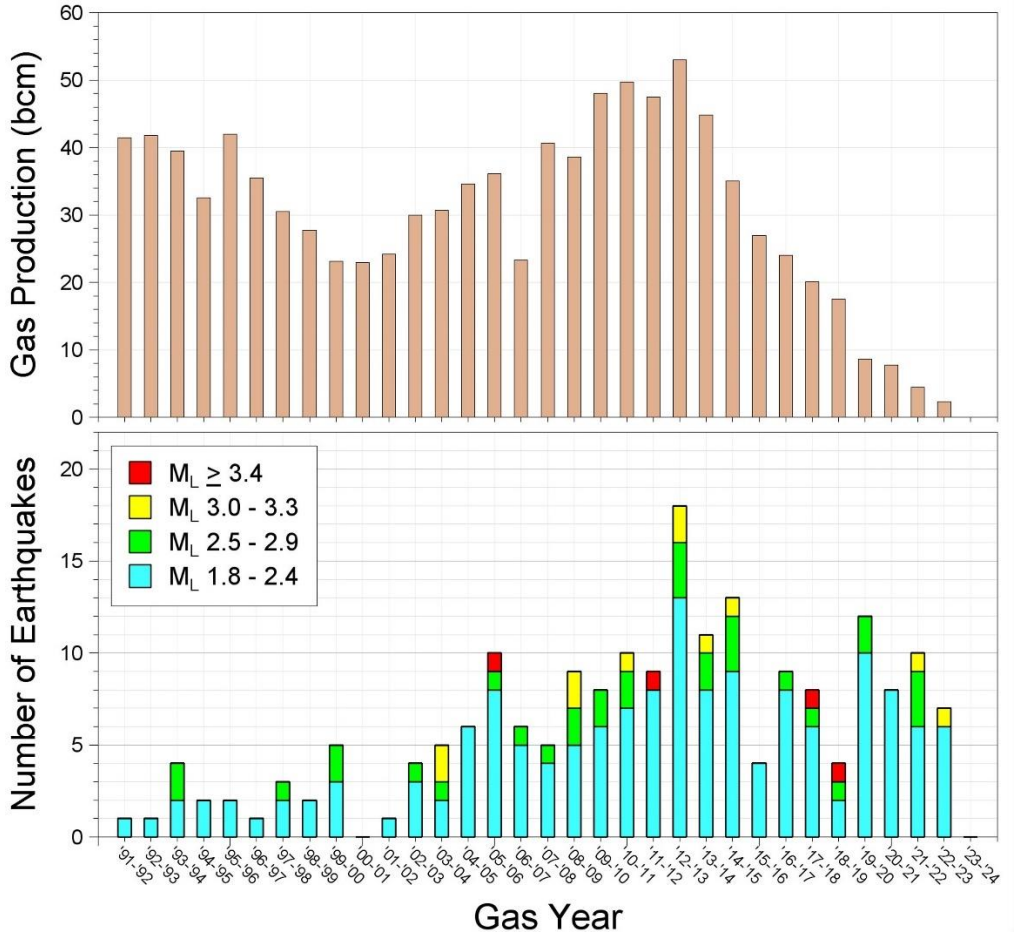

Figure 2. Upper: Annual gas production by gas year (October 1 to September 30) in billion cubic meters since 1992; lower: number of earthquakes of $M_L \geq 1.8$ in each gas year.

As noted earlier, there are numerous faults, mostly trending NNE-SSW throughout the field (Buijze et al., 2017), which offset different portions of the gas reservoir. The extraction of the gas leads, logically, to a reduction in the reservoir pressure (van Oeveren et al., 2017), which in turn results in compaction of the reservoir (Bourne and Oates, 2017) and surface subsidence. One hypothesis that explains the occurrence of production-induced seismicity is related to differential compaction of the reservoir on either side of the pre-existing faults. This compaction creates a shearing stress that eventually leads to re-activation of some of the faults and the small-magnitude earthquakes that have been occurring (e.g., Buijze et al., 2017; Bourne et al., 2018; Kaveh, 2023; Candela et al., 2018). The delay between initiating production and the onset of induced seismicity is likely related to a threshold of compaction required to develop sufficient stress to cause reactivation of the faults (Bourne et al., 2014; Kaveh et al., 2023). The induced earthquakes have occurred throughout most of the gas field but there is a clear spatial correlation between the earthquake epicenters and the reservoir compaction (Bourne and Oates, 2017). For this reason, there has been very little seismicity close to the outer limits of the field as shown in Figure 3.

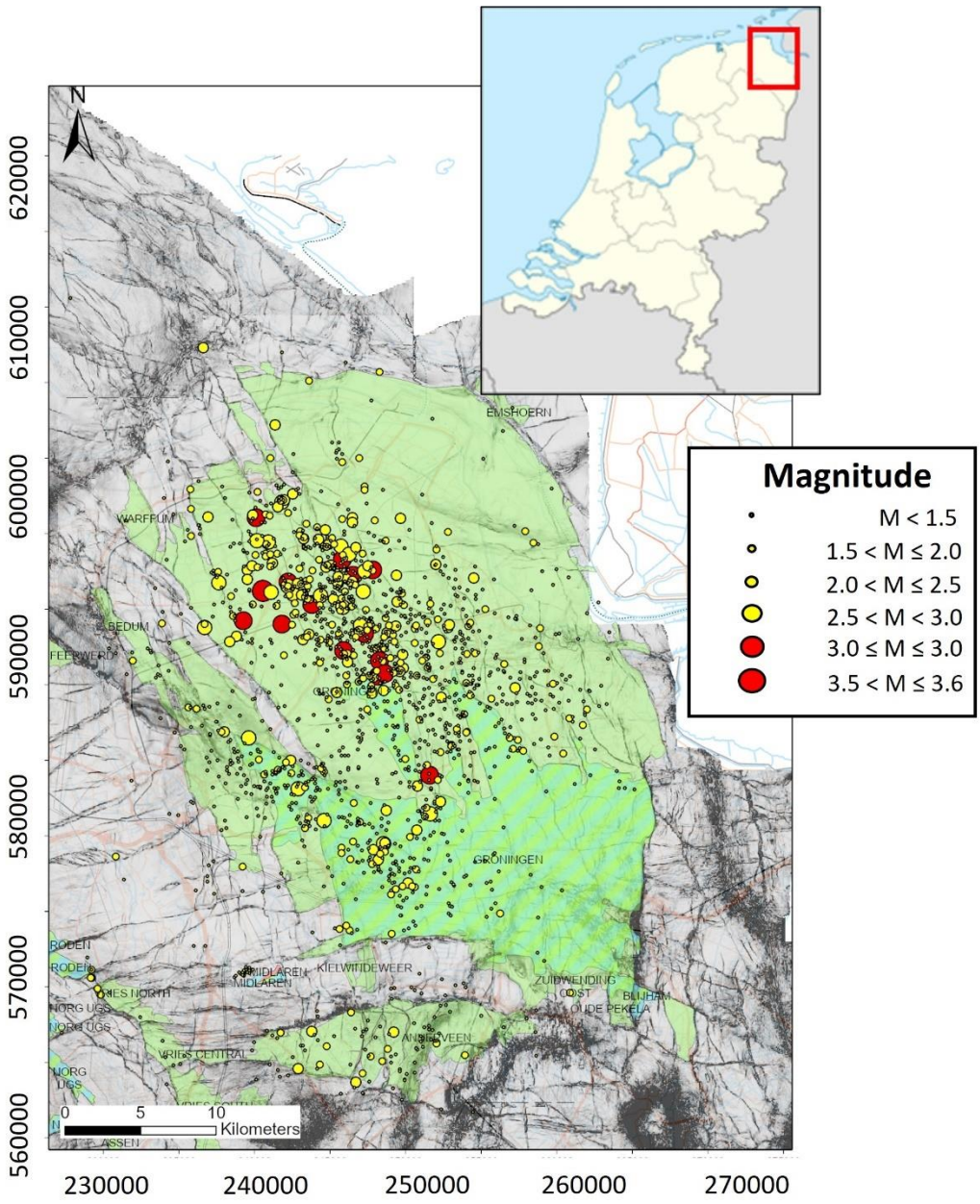

Figure 3. Induced earthquakes in the Groningen gas field and adjacent fields (shaded green), with the symbol reflecting the local magnitude of the event.

Several studies have confirmed that the earthquake hypocenters are always located within the gas reservoir (e.g., Spetzler and Dost, 2017; Willacy et al., 2019), with some small events inside the overlying Zechstein anhydrite caprock (Smith et al., 2020). Importantly, no hypocenters have been located within the underlying Carboniferous formation. Since seismometers were deployed within the reservoir in specially drilled wells in late 2013, hypocentral depth uncertainty was significantly reduced. The studies cited above suggest that induced seismicity within the reservoir is not triggering fault slip either below or outside the zone of production.

In the case of the Groningen field, the seismicity observed to date can be classified as a genuine case of induced rather than triggered seismicity; definitions of the two types of events are reviewed by Bommer and Verdon (2024). The occurrence of earthquakes is correlative in time and space with

production. Importantly, seismicity has been observed only in the reservoir and there is no evidence of earthquakes being triggered below the reservoir, nor outside the reservoir. In common practice, the term "induced seismicity" is often used as a collective term for both industrially driven and triggered earthquakes (Bommer and Verdon, 2024). In fact, most cases of "induced" seismicity are actually cases of triggered seismicity, meaning that the earthquakes are due to the release of tectonic stresses, usually by injection-related pore pressure increases reducing the effective normal stress on pre-existing, already-stressed faults (e.g., Raleigh et al., 1972). The first earthquake was recorded in the Groningen field after 1.35 x 10^{12} m^3 (almost half the gas reserves initially contained in the field) had been produced. Thus, the Groningen seismicity can be referred to as true case of induced (or anthropogenically driven) seismicity.

As shown in Figure 4, the earthquakes are essentially normal faulting events (some with a small strike-slip component), on faults that predominantly trend NNW-SSE with dips of 50°-70° (Dost et al., 2020). The direction of maximum horizontal stress in this area is NNW-SSE (Heidbach et al., 2018), sub-parallel to the pre-existing fault trend shown in Figures 3 and 4. It clear, therefore, that production-induced stress perturbations are activating slip on well-oriented normal faults (*i.e.*, steeply-dipping and striking sub-parallel to the direction of maximum horizontal stress) that formed during Late Cretaceous/Early Jurassic rifting

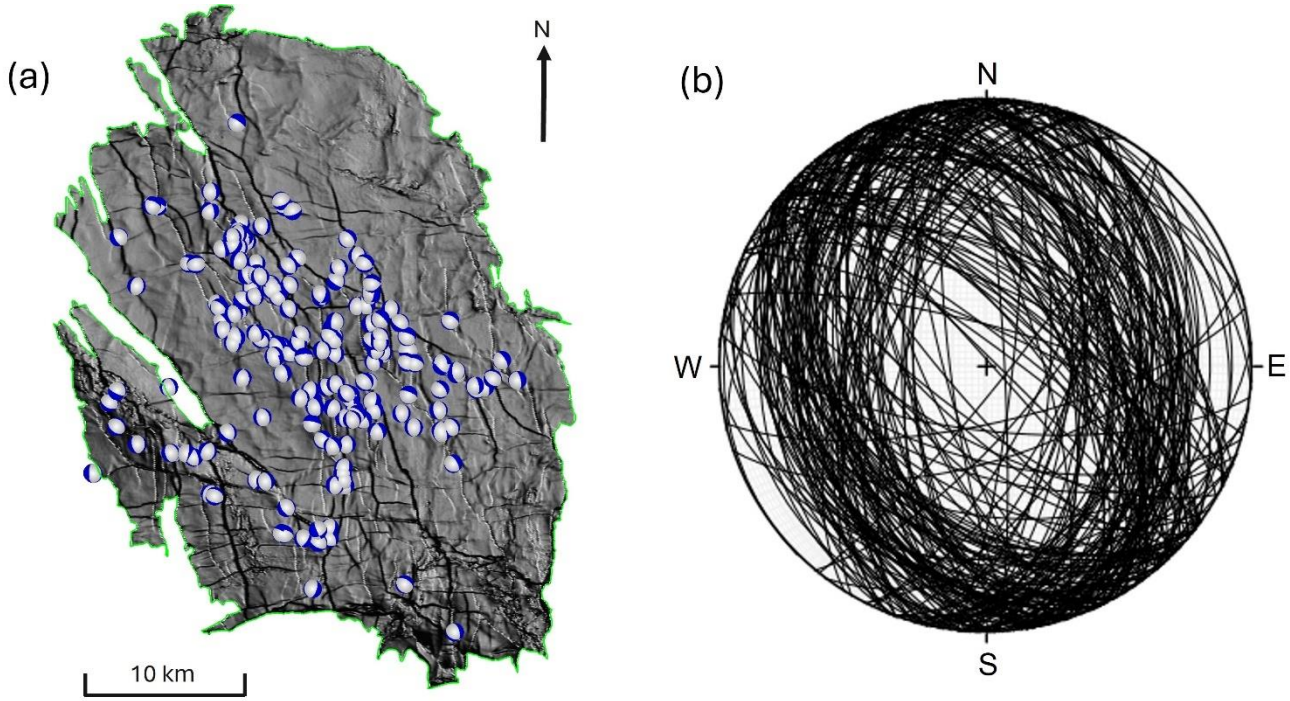

Figure 4. (a) Focal plane solutions superimposed on a fault map of the field, updated from Willacy et al. (2019); (b) composite plot of fault planes for events of $M_L \geq 1.0$.

Regulatory responses to the earthquakes

The first induced earthquake associated with gas production in the northern Netherlands occurred in 1986 in the Eleveld field with many events occurring subsequently in other gas fields in the region,

including Groningen (van Eijs et al., 2006). The seismicity was monitored by the seismological service of the Royal Dutch Meteorological Agency (*Koninklijk Nederlands Meteorologisch Instituut*, KNMI), which also performed simple deterministic risk assessments on the basis of M_{max} and intensity dependence on magnitude (Haak and de Crook, 1994). KNMI also conducted the first PSHA for the region (van Eck et al., 2006). Claims for damage were submitted following some induced earthquakes, including the 2006 M_L 3.5 Westeremden event in Groningen, the majority of which were settled by the field operator NAM (*Nederlandse Aardolie Maatschappij B.V.*). As stated in a paper written by staff members from the regulator SodM, "*structural damage to buildings and personal risks would not occur…. Based on these outcomes induced seismicity was considered a nuisance, causing damage without posing a safety risk*" (De Waal et al., 2017).

The situation changed radically following the August 2012 Huizinge earthquake, even though its magnitude (M_L 3.6) was only fractionally larger than that of the 2006 Westeremden event. Following the 2012 earthquake, NAM initiated a major data acquisition program which included a major expansion of the seismic monitoring networks, development of a model for site amplification effects across the region, and the characterization of the exposed building stock. These were integrated into a seismic risk model that enabled sensitivity analyses to be performed to explore the potential benefits of different mitigation strategies, including reduced gas production rates and building strengthening (van Elk et al., 2019). One interesting feature of the Groningen earthquakes revealed through the data collection and analyses is that the amplitudes of the recorded ground motions are rather low when compared with recordings of earthquakes of comparable size in other areas. This can be illustrated by comparing the recorded amplitudes of motion with predictions from published ground-motion models (GMM), for which we use the model of Atkinson (2015). This model was derived from Californian earthquake recordings but intended specifically for application to induced earthquakes. The comparison is made by calculating ground-motion residuals, which are the logarithm of the recorded amplitude minus the logarithm of the predicted amplitude for the same magnitude, distance and site condition. These residuals are therefore equivalent to the logarithm of the ratio of observed to predicted ground motions. Positive residuals indicate that the motions are underpredicted by the model, negative residuals that the motions are lower than the expectations from the model. Figure 5 shows residuals of recorded values of horizontal peak ground acceleration (PGA) and peak ground velocity (PGV) values from earthquakes of $M_L \geq 3$ relative to the model of Atkinson (2015). As can be clearly seen, the average Groningen ground-motion amplitudes (as represented by the straight-line fits through the residuals) are consistently about a factor of ~2 less than predicted by the GMM. The Groningen motions have also been found to be systematically lower than those recorded during induced earthquakes in the adjacent Roswinkel gas field (Bommer et al., 2022).

Responding to societal concerns, protests by the local population, and advice from SodM, the Dutch government imposed a series of reductions on the production levels over the years following the 2012 Huizinge earthquake as shown in Figure 2. Correspondingly, the annual number of earthquakes of $M > 1.8$ and larger earthquakes dropped to less than half the number associated with peak production. By order of the Minister of Economic Affairs, at 6 am local time on October 1, 2023, production from the field was completely stopped – although during a cold spell in January 2024, NAM was ordered to briefly resume production of small volumes of gas. The decision to close the field has had many repercussions, including a considerable loss of income for the Dutch government, and the need to develop a plant to mix nitrogen with imported high-calorific gas for compatibility with installations

designed for burning Groningen gas. In light of these consequences, the decision to close the field in response to earthquakes of modest magnitudes and low levels of ground motion has clearly been strongly influenced by the perceived potential for larger earthquakes. As stated by De Waal et al. (2017): "*The magnitude 3.6 Huizinge event in August (2012) …. was followed by an independent investigation by the regulator which showed that significantly stronger earthquakes, potentially with magnitudes up to 5.0, could not be excluded and that seismic risk levels in Groningen could be considerable*." The statement that magnitudes up to 5.0 "*could not be excluded*" (when the largest earthquake after 54 years of production was **M** 3.5) clearly deserves scrutiny.

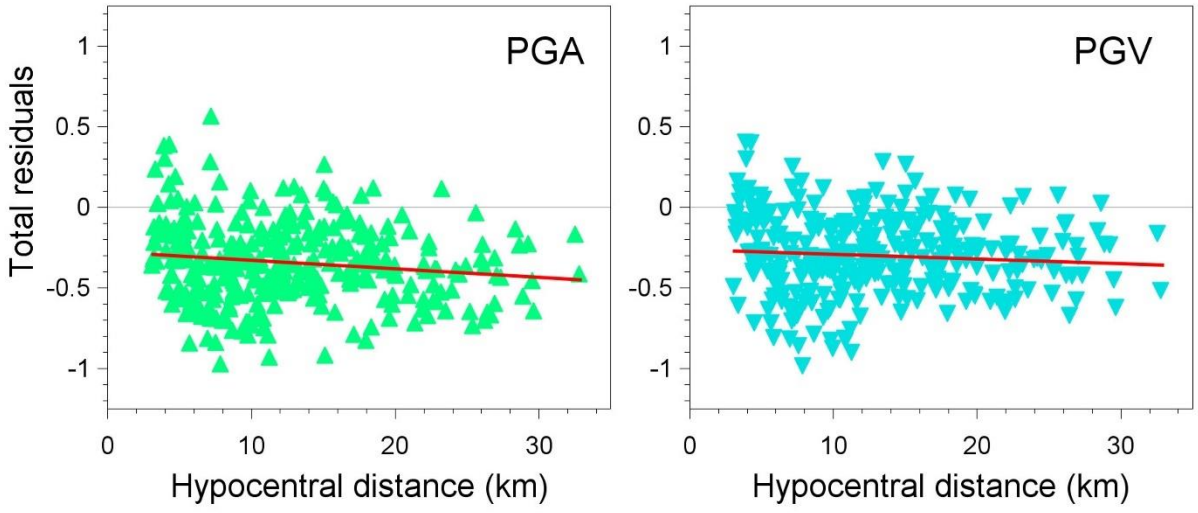

Figure 5. Total residuals of PGA (left) and PGV (right) of Groningen ground-motion recordings from events of $M_L \geq 3$ with respect to the predictive model of Atkinson (2015) plotted against hypocentral distance. The plot is generated using the alternative near-source saturation model of Atkinson (2015), which predicts lower amplitudes than the original model.

Estimates of Maximum Magnitude for Groningen Through Time

Over the years, a number of estimates of the maximum magnitude of Groningen earthquakes have been developed, utilizing a variety of methodologies. The history of the earliest estimates, most of which were not published in accessible journals (and were often in Dutch), is summarized in the Electronic Supplement. We focus herein on the efforts to estimate M_{max} following the 2012 Huizenge earthquake.

Post-Huizinge estimates of M_{max}

The earthquake on the 16 August 2012 near the village of Huizinge with a magnitude M_L 3.6 (**M** 3.5) prompted new efforts to re-evaluate M_{max} for the Groningen field, even though the earthquake was only 0.1 units greater than the previous largest earthquake in 2006 and was below the KNMI M_{max} estimate of M_L 3.9 in place at the time (see Electronic Supplement). The renewed and heightened interest in M_{max} can be viewed as direct response to the earthquake, but it may have owed as much to

actions by the public and by the regulator as to the impact of the ground shaking (Bommer, 2022). The largest horizontal PGA recorded during the earthquake, close to the epicenter, was just 0.08*g*.

In the weeks following the Huizinge earthquake, SodM, KNMI and NAM all reconsidered the maximum magnitude for the Groningen gas field and arrived at new conclusions. SodM concluded that M_{max} may be larger than the value of M_L 3.9 that had been estimated prior to the earthquake by KNMI as noted above, and its report discussed values of M_L 5 and greater (Muntendam-Bos and De Waal, 2013). KNMI increased their estimate of the maximum probable magnitude to 5.0 (Dost and Kraaijpoel, 2013), based on a study of induced earthquakes (Klose, 2013), that at that time was under review. This study relates the largest magnitude of induced earthquake sequences to the total mass removed by extraction or added through injection or impoundment.

NAM initially refrained from making an estimate of M_{max}, conscious of the impact that this parameter could have and the lack of relevant internal expertise. NAM was also reluctant to simply adopt the KNMI proposal. However, as NAM embarked on the development of probabilistic seismic hazard and risk models it became clear that it was important to include estimates of M_{max}. After internal discussions, it settled on a very high estimate of **M** 6.5 (Bourne et al., 2015) implemented as a single value without any epistemic uncertainty. The rationale for this estimate was the release of all the strain associated with complete production of the field in a single earthquake, which is highly conservative given the wide distribution of earthquakes throughout the Groningen field (Figs. 3 and 4a) and that only a small fraction of the strain has been released seismically. Moreover, the rationale is premised on the mechanism of driven (induced) seismicity, whereas an earthquake with the resulting M_{max} estimate would need to be a triggered tectonic event for reasons highlighted below (see Appraisal of Current Maximum Magnitude Distribution).

The 2016 Mmax Workshop

NAM convened an international panel of independent experts to undertake the assessment of the maximum magnitude to be used in the hazard and risk analyses (Bommer and van Elk, 2017). The panel was comprised of eight widely recognized experts in the fields of seismic source modeling and induced seismicity (see Acknowledgments). A week-long workshop was convened in Amsterdam in March 2016, during which many presentations were made to inform the Panel's deliberations (NAM, 2016). These included presentations on the geology, production history and seismicity of the Groningen field, as well as overviews of the global databases of human-induced earthquakes (*e.g.*, Davies et al., 2013). A key feature of the workshop were several proponent models for M_{max} in Groningen. Many of these evaluations have been documented in reports and papers published both before and after the workshop (e.g., TNO, 2014; van Thienen-Visser et al., 2013; DeDontney et al., 2016; Dempsey and Suckale, 2017; Zöller and Holschneider, 2016). Most of the proponent experts estimated the maximum magnitude of induced earthquakes in Groningen to fall in the range between **M** 4 and **M** 5. The estimate prepared by DeDontney et al. (2016) also included the possibility of triggered earthquakes.

Following the workshop, the panel produced a report proposing a logic-tree for M_{max} that extended from a lower value of **M** 4.0, peaking at **M** 4.5, and with an extended upper tail reaching **M** 7.0 (Coppersmith et al., 2016; Bommer and van Elk, 2017). In the assessment of the Expert Panel,

earthquakes of magnitude greater than **M** 5 would require ruptures extending outside of reservoir, which would therefore be triggered tectonic events rupturing the Carboniferous (upwards ruptures into Zechstein salt would not be seismogenic). The upper end of the distribution was influenced by estimates of M_{max} adopted in regional seismic hazard studies for tectonic earthquakes (Woessner et al., 2015) and analogies drawn with other cases of induced seismicity associated with gas production, including the Gazli, Uzbekistan, earthquakes (Simpson and Leith, 1985).

The Expert Panel report from the Workshop (Coppersmith et al., 2016) noted the relatively short time that was made available to the evaluators to digest the information provided and to formulate their proposed M_{max} distribution, a consequence of regulatory pressures to issue periodic updates of the seismic hazard and risk estimates (Bommer and van Elk, 2017). The report therefore recommended additional work that could be undertaken to constrain the range of possible values for the maximum earthquake that could be caused by continued gas production from the Groningen field.

The 2022 M_{max} Workshop

Six years later, with considerable expansion of the Groningen databases and extensive new modeling exercises having been undertaken, it was decided to reconvene the same Expert Panel and to organize a second workshop to explore whether there was a basis to update the M_{max} distribution for Groningen. As for the first workshop, a comprehensive collection of geological, geomechanical, geodetic, production, pressure, and seismological data were made available to all the participants (see Data and Resources section), in preparation for a week-long workshop held in Amsterdam in June 2022 (NAM, 2022).

As in 2016, the workshop included extensive presentations on the geology, seismicity, and production history of the Groningen field, as well as many proponent models for the maximum earthquake magnitude. New insights had been obtained on induced seismicity, including greater emphasis on discriminating induced and natural earthquakes (e.g., Wilson et al., 2017; Foulger et al, 2018; Verdon et al., 2019; Foulger et al, 2022; Foulger et al., 2023). Several new proponent models for M_{max} in Groningen were presented, many of which have since been published in the open literature (e.g., Boitz et al., 2024; Dempsey and Suckale, 2023; Eisner et al., 2023; Muntendam-Bos and Grobbe, 2022; Vlek, 2023; Weng et al., 2022; Wentinck and Kortekaas, 2023; Zöller and Hainzl, 2023). The objective was to provide the broadest possible range of views for consideration by the Expert Panel, even including proposals by an Emeritus Professor of Environmental Psychology and Decision Research at the University of Groningen, based on public statements made regarding the largest earthquakes that could occur in Groningen (Vlek, 2016). The proponent models presented in 2022 were generally centered on lower values than the models presented in 2016, as discussed below in the section Appraisal of Current Maximum Magnitude Distribution.

The logic tree proposed by the Expert Panel (Coppersmith et al., 2022) is shown in Figure 6. With regards to the 2016 logic tree, an important change is the clearer distinction between induced (driven) events and triggered tectonic earthquakes, with an explicit probability (10%) assigned to such triggering being a physical possibility. We note that the Expert Panel assigned a weight of 0.1 in the logic tree, but in probabilistic seismic hazard and risk analyses such weights are treated as probabilities (*e.g.*, Bommer, 2012). Another important change is the absence of any estimates based on analogues, reflecting the fact that there are very few cases of induced seismicity associated with conventional gas

extraction, and there are many reasons why these are unlikely to be analogous to the Groningen gas field. While it has been argued that seismicity in the Gazli field resulted from production, it is also likely that water injections may have been the primary cause of induced seismicity (*e.g.*, Grasso et al., 2021) and Gazli is located in a very different tectonic setting. Very small volumes of water were injected at the flank of the Groningen gas field below the gas-water contact, but very few earthquakes occurred in this area and there was never an elevated level of seismicity above that forecasted based on extraction. The uppermost magnitudes of triggered events were informed by the M_{max} distribution used for the most recent European seismic hazard model (Danciu et al., 2021).

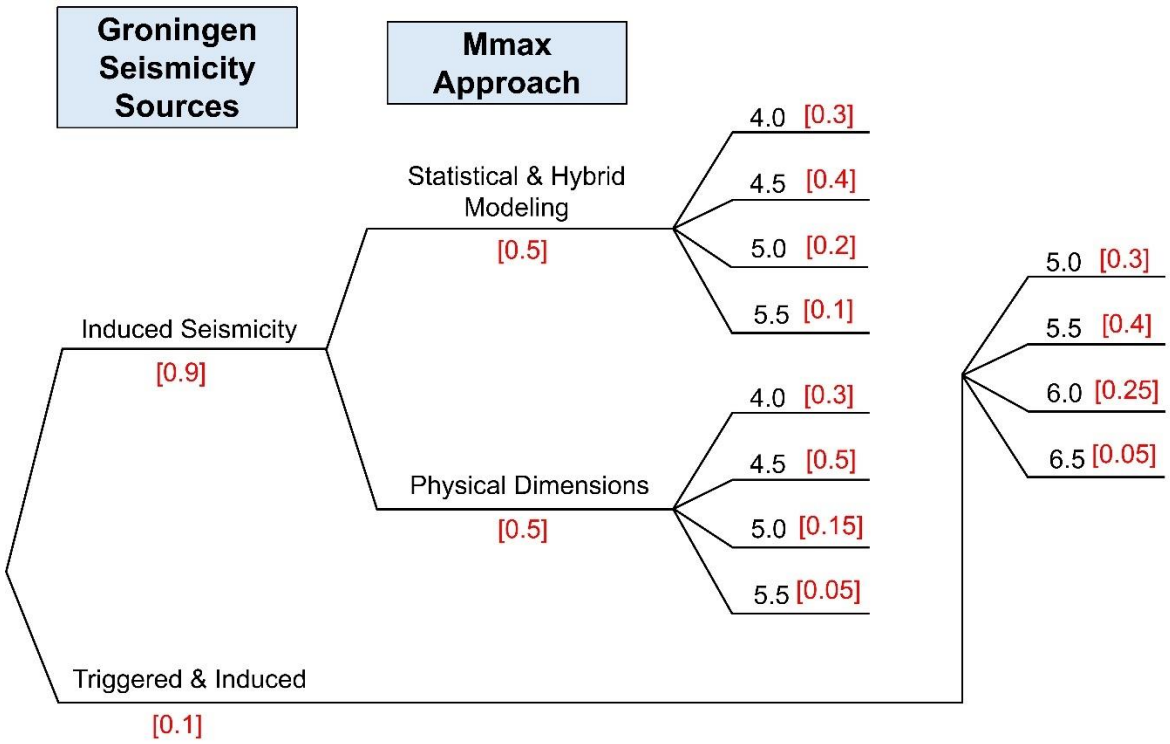

Figure 6. Logic tree for M_{max} in the Groningen gas field proposed by the Expert Panel. Redrawn from Coppersmith et al. (2022).

Another notable change is that whereas the 2016 report loosely defined events of magnitude larger than **M** 5 as being triggered earthquakes, the 2022 logic tree proposes an upper limit of **M** 5.5 for induced (driven) earthquakes. Figure 7a shows the resulting distribution as a histogram, distinguishing between induced and triggered events, from which it can be appreciated that the triggered events, by virtue of the 10% probability assigned to such earthquakes being feasible, contribute a relatively small portion of the total distribution. However, for reasons discussed above, the presence of values of magnitude $\geq$ **M** 6 is very noteworthy in terms of the potential impact in terms of seismic risk perception.

Figure 7b displays the histogram as a continuous distribution and also compares this distribution with that proposed in 2016. The comparison clearly highlights how the distribution has shifted to lower values and truncated the uppermost end of the distribution. At the same time, it can be appreciated that for intermediate M_{max} estimates, the change in the distribution is fairly modest: the weighted mean

value of M_{max} dropped from **M** 5.0 in 2016 to 4.61 in 2022, with the median value only decreasing from **M** 4.77 to 4.53. However, the cumulative probability of events ≥ **M** 5 is about 25%, again very noteworthy with respect to seismic risk perception.

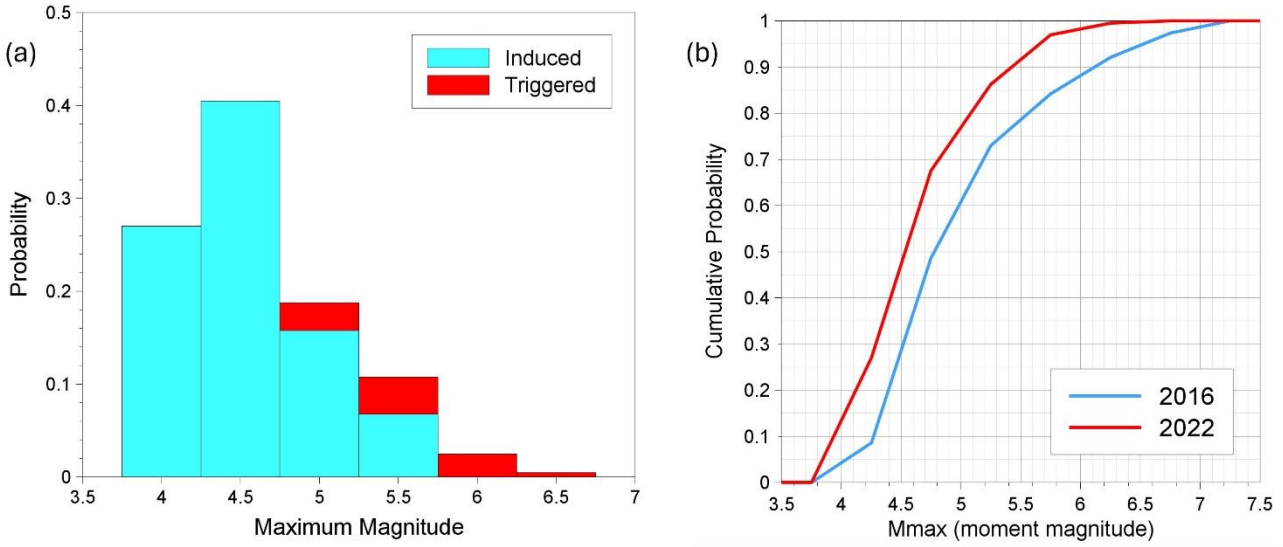

Figure 7. (a) Histogram for 2022 logic tree; (b) comparison of continuous distributions for the 2016 and 2022 M_{max} logic trees.

The impact of the updated distribution on hazard and risk estimates is rather modest, however, due the fact that the damage estimates are driven by earthquakes of around **M** 4.0-5.5 rather than the upper tail (van Elk et al., 2017). This is confirmed by Figure 8, which shows estimates of seismic risk – in terms of the number of locations where injury could occur and the annual probability of such injury occurring – for the Groningen region, calculated using both the 2016 and 2022 M_{max} distributions. The shift of the M_{max} distribution from 2016 to 2022 does result in a reduction of the estimated risk but this reduction is modest because the risk estimates are not highly sensitive to the upper end of the distribution, where the largest changes were made (Fig. 7b).

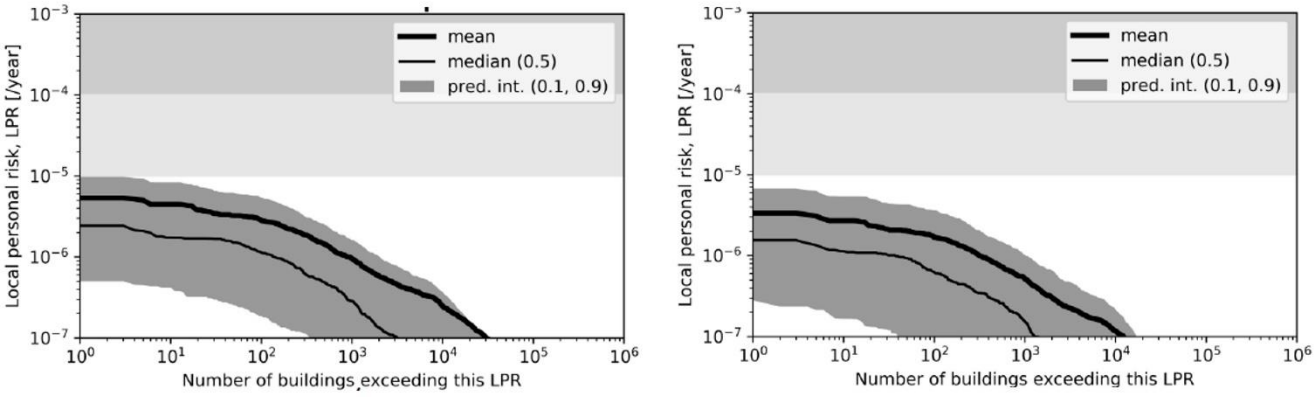

Figure 8. Comparison of risk estimates in terms of loss-frequency curves for hypothetical production scenarios over 2024-25 using the 2016 (left) and 2022 (right) M_{max} distributions.

Appraisal of Current Maximum Magnitude Distribution

There is probably no other case of induced seismicity for which so much effort has been invested to estimate the maximum possible magnitude as for the Groningen gas field. This reflects both the importance of the field and the societal impact of the induced earthquakes, but also perhaps the fact that new approaches to M_{max} estimation have had to be developed. As noted above, there are no close analogues that can be used to guide these estimates, and the majority of methods developed for estimating M_{max} for induced seismicity have been focused on injection of liquids rather than production of oil and gas (e.g., Eaton and Igonin, 2018; Bommer and Verdon, 2024).

Before entering into our appraisal of the current M_{max} distribution, it is interesting to bring together the seismic history of the field and the evolution of M_{max} estimates, as shown in Figure 9. The first and most obvious observation is that as no earthquake in Groningen has exceeded **M** 3.5, every M_{max} estimate since 1996 has been quite conservative. From this perspective, it is not entirely clear why the 2012 Huizinge earthquake, which was only 0.1 magnitude units larger than the 2006 event, prompted a major reassessment of the maximum magnitude in Groningen, starting with the report by SodM (Muntendam-Bos and De Waal, 2013). Moreover, while the magnitudes of earthquakes have not increased in time since the 2012 event, the estimates of M_{max} have increased markedly. A critical question, therefore, is whether this increase in M_{max} results from a change in the how the seismotectonics of the earthquake generation is being interpreted or by the procedural issues employed to make the estimates.

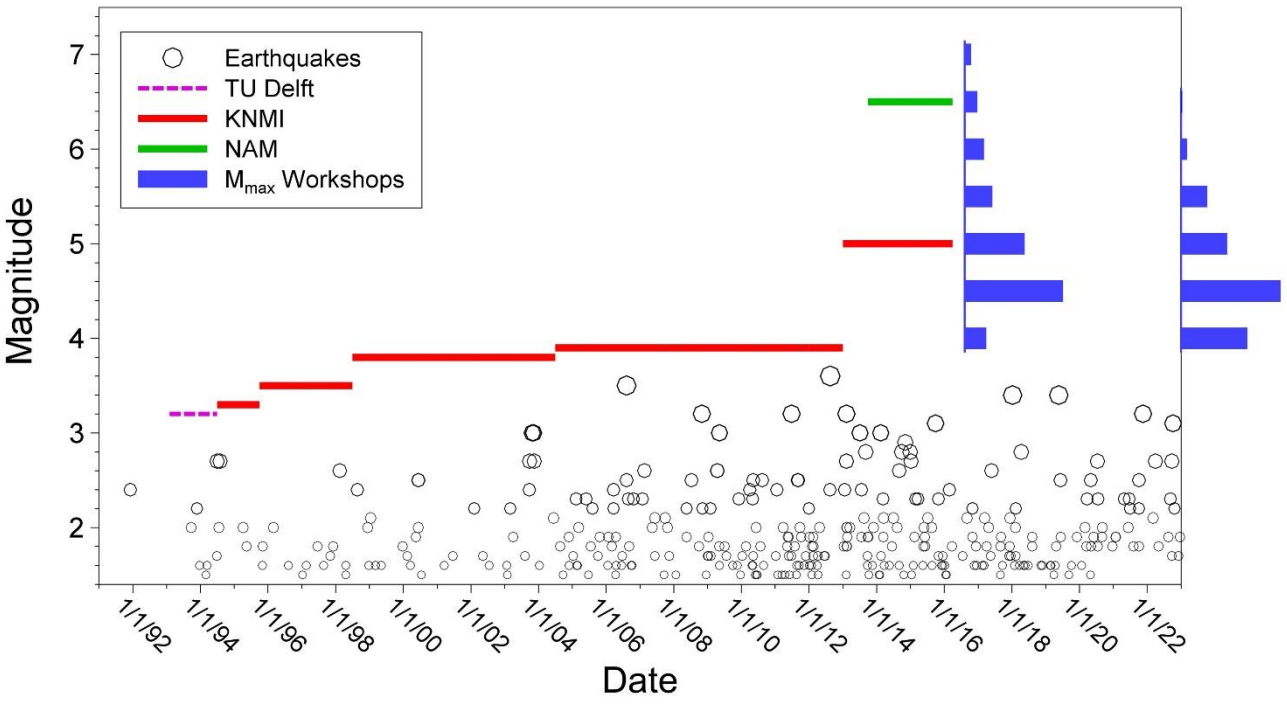

Figure 9. Evolution of M_{max} estimates for Groningen over time compared with the seismicity. The first estimate of M_{max}, by TU Delft, was actually for another, smaller gas field (Eleveld) but has often been interpreted as applying to the Groningen field, for which reason it is included here (see Electronic Supplement). The histograms represent the distribution of M_{max} estimates of the 2016 and 2022 panels

Before beginning our own appraisal of the Expert Panel's proposed M_{max} logic tree, it is fair to quote their own statements regarding the approach they adopted: "*As stated in the Expert Panel report, we view our charge as not requiring statistical proof that our M_{max} distribution is correct; rather, we are providing a technically-defensible distribution whose shape and limits reflect the Panel's knowledge and assessment of the uncertainties after due consideration of the available pertinent information. Note that the assessment, like all assessments for purposes of seismic hazard analysis, it is intended to be a description of the future hazards. This assessment takes into consideration the features, events, and processes that have happened in the past (e.g., the locations, rates, and sizes of past earthquakes), but it is also takes account of the processes or events that have not (yet) been observed at Groningen but have some chance of occurrence based on comparisons to analogous case histories. This is especially true for rare phenomena like M_{max} that may not have been witnessed in the relatively short observational record.*" (Coppersmith et al., 2022).

Procedural issues

The current M_{max} distribution for Groningen was proposed by the Expert Panel following the 2022 workshop. It may seem unusual that the organizers of this workshop (the first two authors of this article) are presenting a critical assessment of the outcome. To provide the context for this situation, it is necessary to acknowledge the constraints within which the Expert Panel was required to work and how this may have affected the original aims of the workshop.

The intention in both the 2016 and 2022 workshops was to conduct an impartial assessment of the center, body, and range of possible M_{max} values following the methodology—but not the strict guidelines—of a SSHAC (Senior Seismic Hazard Analysis Committee; USNRC, 2012b; 2018) process. In 2016 there had been general satisfaction that the workshop resulted in a useful improvement over the previously used single-value estimates of M_{max}. Unfortunately, in the 2022 exercise it became apparent that the process was not providing the Expert Panel with conditions that would be consistent with a high-level SSHAC process. A key element of the SSHAC process, and the one that most clearly distinguishes it from classical expert elicitation, is that the evaluation and integration processes are conducted by impartial subject matter specialists who become experts in the specific question at hand through a prolonged period of examination of the available data, method and models. This includes interactions with both resource and proponent experts, and, where appropriate, informed by sensitivity analyses. In an appendix to their report (Coppersmith et al., 2022), the Expert Panel highlighted the important deviations from the SSHAC process in requiring them to return to the study of the Groningen field after a six-year absence and to absorb all of the available information in one week. Specifically, "*The model-building process for the Groningen M_{max} assessment was contracted to essentially a single one-day meeting of the Panel to consider the data and assessments made by project participants, followed by remote correspondence amongst the Panel members to consider the range of possible assessments and the technical defense of the uncertainties quantified*". The panel also noted that it would have been ideal to conduct the entire Groningen seismic hazard and risk assessment as a SSHAC process, a proposal that had been made several years earlier by NAM but did not receive the necessary support from the ministry and the regulator (Bommer, 2022). In light of their limited engagement and compressed schedule for their work—exacerbated in part by delays to the 2022 workshop because of Covid-19 and the need for input to a periodic update of the hazard and risk model for Groningen—it is recognized that the Expert Panel were not able to conduct their assessment with the depth that would be expected in a full SSHAC process: "*Although the Panel*

argues that the technical assessment of M_{max} documented in this report is defensible, the assessment would be much more robust if it was an integrated component of a full SSHAC study of seismic hazard and risk for Groningen" (Coppersmith et al., 2022).

Consequently, we conclude that although the Expert Panel applied its considerable expertise to the formulation of the final logic tree and the weights assigned to the branches (Figure 6), the outcome may have been different had this assessment been conducted as a full SSHAC process. In such a process, there is an extended process of evaluation and integration by a Technical Integration Team given the appropriate and substantial opportunity to review and evaluate proposed models, and to then construct their own model that captures the center, body, and range of technically defensible interpretations, including the possible exclusion of some of the proponent models. In the light of these considerations, we believe it is legitimate and helpful for us to re-evaluate the proposed logic tree and discuss potential changes that might have resulted from a more comprehensive assessment based on employing a formal SSHAC process.

Figure 10 summarizes the proponent models presented at the 2022 workshop together with the distribution that would be obtained by assigning all nine models the same overall weight and then calculating the weighted average for each magnitude bin. The proponent experts listed in the figure were invited to participate in the workshop on the basis of being engaged in work to estimate the maximum magnitude of induced earthquakes in Groningen and to present their research to the Expert Panel. The lowermost row compares these proposals with the distribution proposed by the Expert Panel. Note that Dempsey and Suckale (2023) did not assign relative weights to their estimates corresponding to bounded and unbounded (runaway) ruptures, but in correspondence Dr. Dempsey provided weights of 0.9 and 0.1, respectively. The latter number arose from Dr. Dempsey's judgement that the likelihood that future ruptures will be "unbounded" is very unlikely, which places his estimate of the unbounded branch between 1% and 10% according to the IPCC (Intergovernmental Panel of Climate Change) scale (https://desevun.org/ipcc-likelihood-terms/), from which he conservatively leant to the high end of 10%. While this coincides with the value proposed by the Expert Panel, Dr. Dempsey stressed that this should not be interpreted as agreement with their model since the approach to arrive at this weight was not described.

Two important observations can be made regarding the comparison in Figure 10, particularly if one focuses on the differences between the composite of the individual proponent models and the Expert Panel's model. First, although the total weight assigned by the Expert Panel to M_{max} values that would correspond to triggered tectonic events is relatively small (see also Figure 7a), it far exceeds the ponderance given to such runaway ruptures by most of the workshop participants. However, it should also be noted that the modeling approaches adopted by several of the participants only focused on what would be classified as driven (induced) earthquakes and in some cases the importance of also addressing the possibility of triggered events was also noted, such as the presentation of Dr. Andrzej Kijko. One could therefore conclude that the Expert Panel developed an M_{max} distribution that did account for this possibility, albeit that the consensus of the workshop was that it was likely to be rather improbable. We discuss this issue further in the Triggered Tectonic Earthquakes section below.

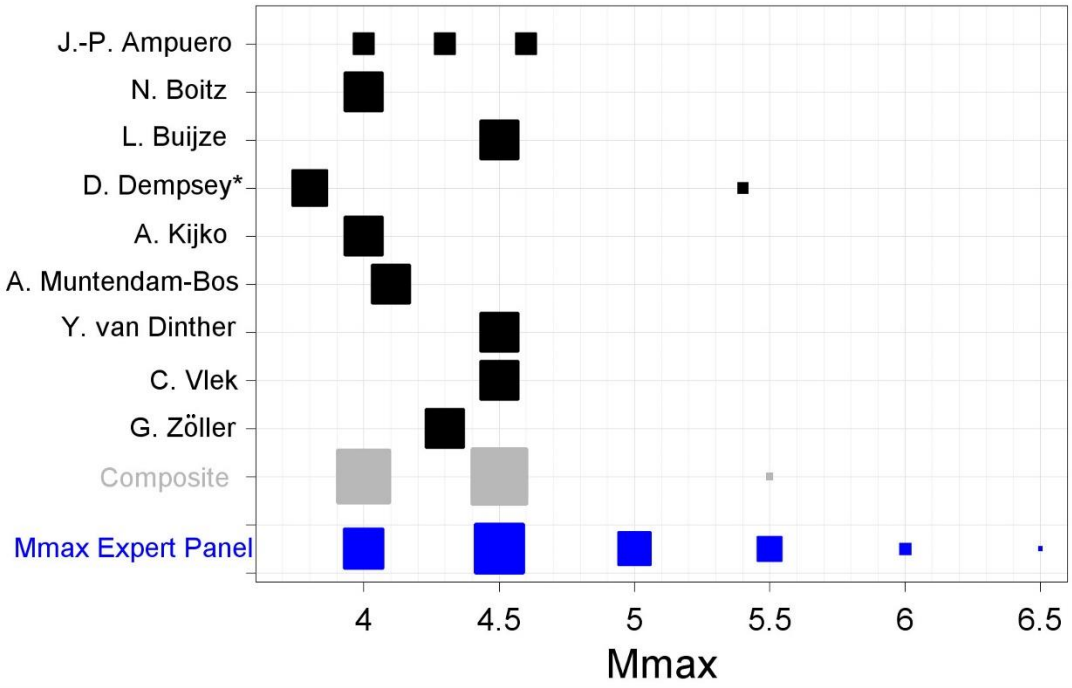

Figure 10. M_{max} distributions proposed at the 2022 workshop, with symbol sizes proportional to the weights (using a different scale for the lowest two rows in order to allow the smallest symbols to be visible). The models are identified by the name of the presenter. The row labeled 'Composite' shows the weighted mean distribution (in 0.5-magnitude unit bins) of the proponent models with equal weight applied to all the models. *see notes in text.

The second important observation from Figure 10 is that the Expert Panel's distribution for M_{max} values associated with induced (driven) earthquakes is far broader than the composite of the proponent models, which effectively assign the total weight to an interval between **M** 4.0 and **M** 4.5. This is very important in light of the results shown in Figure 8, since the composite distribution would move the cumulative probability distribution in Figure 7b considerably to the left. Here again, one could interpret the Expert Panel's distribution as having captured the full range of epistemic uncertainty associated with the largest possible induced event. There are also physical constraints on the largest bounded rupture that could occur, which would make the Panel's assessment exceedingly conservative as discussed in the next section.

Maximum magnitude of driven (induced) earthquakes

The current distribution of M_{max} estimates for anthropogenically driven earthquakes ranges from **M** 4.0 to **M** 5.5, with 25% of the total weight assigned to events of $M \geq 5$ (Figure 6). We believe that there is scope for challenging these ranges of estimates for the maximum size of an induced earthquake at Groningen.

Starting with the upper bound, it is noteworthy that among the proponent models presented at the 2022 workshop, the majority of the estimates were limited to $M_{max} \leq 4.5$, with a single proposal including M 4.6 (Figure 10); the only proponent estimate for larger events required the assumption of runaway ruptures that would correspond to triggered events. It is important to recall that to date all earthquakes have been located within the reservoir, a sandstone layer that does not exceed 300 m in thickness.

Even considering the offsets across the faults being reactivated by the production-induced compaction of the reservoir, the available width for ruptures on the faults is limited.

The 2012 M_L 3.6 Huizinge earthquake is consistent with the largest expected event for a fault slipping over the entire thickness of the reservoir. Figure 11a (after Zoback and Gorelick, 2012) represents well-established scaling relationships from earthquake seismology (e.g., Stein and Wysession, 2003) that relate the size of a fault segment that slips in an earthquake (the source dimension), to the size of the earthquake (expressed either as magnitude or moment) and the amount of slip, depending on the stress drop of the earthquake. The range 0.1 to 10 MPa captures the stress drops of moderate earthquakes in the upper crust (Figure 11b, after Abercrombie, 1995). The thickness of the Rotliegend reservoir, as noted previously, is approximately 300 m. Thus, a **M** 3.6 earthquake (yellow star) is consistent with a ~300 m source dimension (assuming an approximately square fault rupture patch) and with well-established scaling relations (for a stress drop slightly in excess of 10 MPa) for moderate size earthquakes around the world.

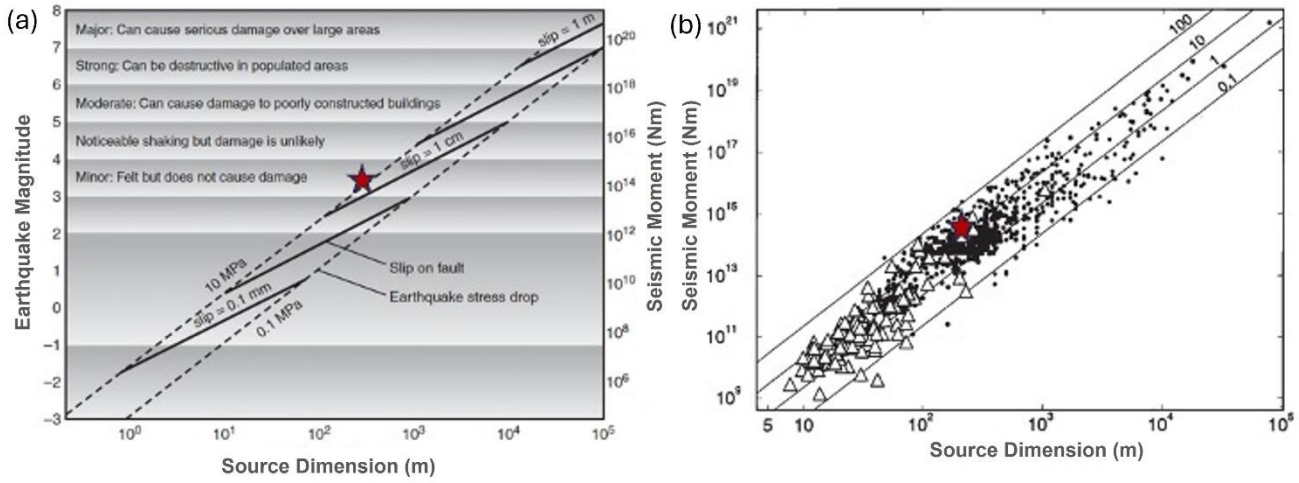

Figure 11. (a) Relationship among various scaling parameters for earthquakes (after Zoback and Kohli (2019). The larger the earthquake, the larger the the source dimension (the dimension of the fault that slips) and amount of slip, depending on the stress drop of the earthquake. Observational data indicate that earthquake stress drops typically range between 0.1 and 10 MPa. The M 3.6 Huizinge earthquake (represented by the red star) is consistent with a fault dimension comparable to the thickness of the Rotliegend reservoir. (b) Empirical scaling relationships between seismic moment, source dimension and stress drop determined from downhole seismic recordings (after Abercrombie, 1995). The red star represents the Huizinge earthquake assuming a source dimension equal to the reservoir thickness. The rupture dimension corresponds to the side length of an approximately square fault rupture. Note that the vertical scales on the two plots are not the same.

In the context of these scaling relationships, if induced earthquakes are confined to the reservoir (seismogenic rupture upwards into the Zechstein salt is not possible and appreciable downward rupture into the Carboniferous shales is both physically unlikely and has never been observed), an event of $\mathbf{M} \geq 5$ would require an extended ribbon-like rupture. Consequently, earthquakes matching the upper ranges of the M_{max} distribution would require ruptures with very large aspect ratios, the rupture lengths exceeding the width by a very large factor. Very large earthquakes on crustal faults

can produce ruptures with large aspect ratios because the width is limited by the seismogenic thickness of the crust. Weng and Ampuero (2019) note that elongated ruptures can also be associated with smaller earthquakes but the examples that they provide all correspond to events of magnitude greater than **M** 6 and rupture widths of several kilometers. Examination of the 58 events with rupture widths no greater than 7 km in the database of Wells and Coppersmith (1994) reveals that the largest aspect ratio is 3.4 and 90% of the cases do not exceed 2.25. Thus, for a rupture occurring over the entire 300 m thickness of the reservoir, an aspect ratio of 3.4 would result in a rupture area of only about 1 km^2, implying a **M** 4 event (Wells and Coppersmith. 1994). Assuming that scaling relationships hold for such shallow earthquakes, a **M** 5 earthquake would require a rupture area about 7-8 times larger, which would mean an aspect ratio of more than 20 unless an appreciably larger rupture width was mobilized. From this perspective, the postulated maximum magnitudes of **M** 5 and larger is incompatible with the scale of available seismogenic structures. Moreover, Buijze et al. (2019) concluded from their geomechanical modeling of fault ruptures in Groningen that the faults with larger offsets, potentially offering greater rupture widths, are less likely to rupture over lateral distances much larger than the thickness of the reservoir.

At the lower end, a notable feature of the current M_{max} distribution is that it assigns zero probability to the M_{max} value being **M** 3.5, setting the lower limit to **M** 4.0. The distribution therefore dismisses the possibility that the 2012 Huizinge earthquake represents that largest value that could occur, despite the fact that after almost 60 years of production, as well the decade between the Huizinge earthquake and the second M_{max} workshop, its magnitude was neither equaled nor exceeded (Figure 9). If the Bayesian updating of global distributions for M_{max} using the local earthquake catalogue, which is widely used to obtain M_{max} distributions for PSHA studies in stable continental regions (e.g., USNRC, 2012a), were applied to Groningen—regardless of what would be considered an appropriate prior distribution—the resulting distribution would begin at **M** 3.5. Moreover, given that there have been a number of events with magnitudes within 0.5 units of this value, the likelihood function used for the Bayesian update would be reasonably peaked at **M** 3.5, leading to a non-trivial weight on this value as opposed to the weight of zero assigned by the Expert Panel.

The lower bound of the distribution can also be addressed from the perspective of the purpose of a logic tree, which is to capture the full range of uncertainty. This does not mean that the focus is exclusively on capturing the largest possible values, but rather encompassing the full range of possible outcomes. As Bommer and Verdon (2024) argue, once a formation has been fully produced (and the field restored to equilibrium), for example, the largest observed earthquake is *de facto* M_{max} – and should not, therefore, be outside the distribution of proposed M_{max} values. Were production in Groningen to have continued until the field were fully depleted, the largest observed event (allowing for a sufficient period of time for equilibrium to be restored) would be M_{max}. Therefore, if it is possible that the Huizinge earthquake was indeed the largest event that could occur, then the current distribution is an incorrect estimate of the epistemic uncertainty.

If it is accepted that the lower bound of the M_{max} distribution for induced earthquakes should be at **M** 3.5, then the next questions that arise are (a) what weight should be attached to this branch of the logic tree and (b) what would be the M_{max} values and associated weights occupying the remaining branches? While we do not propose to put forward definitive and detailed responses to these two questions herein, we do wish to make the case that (a) there is a significant probability that the Huizinge

earthquake represents that largest event that could occur and (b) that earthquakes as much as even half a magnitude unit larger might represent the absolute upper bound. In support of these assertions, we recall that all observed seismicity to date has occurred within the reservoir.

However, since there is variability in source scaling relationships, and uncertainty both in the choice of the most applicable relations for this situation and in the stress drop values for Groningen earthquakes, it would not be appropriate to propose this as a unique M_{max} value without any associated uncertainty, but branches for larger values that increase this estimate by more than half a unit would be difficult to justify. We note, for example, that using similar reasoning, Boitz et al. (2024) conclude that M_{max} estimates should be in the range of **M** 2.6 to 3.3 in the southeast of the Groningen field and **M** 3.5 to 4.1 in the northwest of the field. Adopting a single distribution for the entire field, a simple logic tree might contain three branches at **M** 3.6, 3.9 and 4.2, with the lowest weight assigned to the upper branch, the remaining weights being split with a slight preference for the central branch, which, it may be noted, is consistent with the pre-Huizinge estimate (Figure 9). To accommodate the views of the many proponent experts who participated in the 2022 M_{max} workshop (Figure 10), an additional branch might be added for **M** 4.5, but we would assign this a rather low weight. For an earthquake with magnitude greater than **M** 4.5 to occur in the Groningen field, we believe it would need to be a triggered tectonic event.

Triggered tectonic earthquakes

The current M_{max} model assigns a 10% probability that the largest earthquake in the field could be associated with triggering of tectonic earthquakes larger than **M** 5 and allows for the possibility of **M** 6.5 event, three magnitude units greater than the largest event to have occurred to date. In passing we note that the Expert Panel considered whether the weight on the branch for triggered seismicity should be 0.10 or 0.05. This part of the logic tree considers runaway ruptures descending well into the Carboniferous formation with fault slip occurring occurring at a scale of 10 km (Figure 11a) or a fault area on the order of 200 km^2 (Wells and Coppersmith, 1994). Rather than discuss the plausibility of such large magnitudes, we focus here on the probability assigned to this branch of the logic tree. We believe that there are several lines of reasoning against such a large probability being assigned to triggering of tectonic earthquakes in the Groningen field.

The first consideration is the lack of tectonic seismicity in the region. While it is not impossible that tectonic earthquakes with very long recurrence intervals could occur in this region, both the instrumental and historical records for the northernmost part of the Netherlands indicates a complete absence of any observed seismicity (van Elk et al., 2019).

Because of the extensive salt above the Rotliegend reservoir (Fig. 1), runaway ruptures in the Groningen field would need to initiate within the reservoir and propagate downwards and along strike. This would result in the hypocenter being very close to the upper end of the rupture, a situation that is almost never encountered (e.g., Mai et al., 2005). Large earthquakes have occurred with very shallow focal depths, but only in exceptional circumstances (e.g., Lomax, 2020). Similarly, there are no cases of induced earthquakes of **M** $\geq$ 4.5 with focal depths as shallow as 3 km (Bommer and Verdon, 2024). Das and Scholz (1983) explained the physical constraints, related to coefficients of friction and confining stresses both increasing with depth, that prevent fault ruptures of large earthquakes initiating at shallow depths and propagating downwards.

Segall (1989) modeled induced stress changes outside a depleting reservoir. The stress changes associated with depletion are compressional above and below the reservoir and would thus inhibit (not promote) normal fault slip. As the Groningen field is in a normal-faulting environment (as supported by the normal faulting focal plane mechanisms of the induced events shown in Figure 4), continued production would tend to inhibit possibly larger earthquakes occurring below the reservoir. Segall (1989) showed that the stress changes outside the reservoir that would promote normal fault slip are adjacent to the outer edges of the depleting reservoir.

Recent developments have shed further light on this topic. Over the past decade, the concept of viscoelastic stress relaxation (VSR), based on observed time-dependent rock deformation in laboratory studies of clay rich rocks, has been proposed to explain observations of lithology-dependent variations of the least principal stress (S_{hmin}) with depth (Zoback and Kohli, 2019). An easy way to think about VSR and stress magnitudes is that as a rock deforms as a function of time (viscous deformation), the lower the *differences* between the three principal stresses become. In normal faulting areas such as Groningen, this means that the least principal horizontal stress, S_{hmin}, would be expected to increase in relatively viscous (more ductile) rocks, thus lowering the difference between the vertical principal stress, S_V and S_{hmin} and thus inhibiting normal faulting. An example of this is illustrated in Figure 12 that shows S_{hmin} measurements from a group of wells in the Midland Basin of west Texas (modified from Kohli and Zoback, 2021). Note that there are differences of S_{hmin} with depth by as much as 10 MPa, which are correlative with clay plus organic content. In the low-clay, relatively brittle formations, S_{hmin} values are low and consistent with expected values based on normal faulting frictional equilibrium for known values of S_v, pore pressure and expected values of the coefficient of friction. This is illustrated with the Mohr circle representation at a depth of about 367.5 m (7780 ft.) (Fig. 12). In contrast, S_{hmin} values in relatively clay plus organic content intervals are much higher, and the state of stress is not in frictional equilibrium as indicated by the Mohr circle at approximately 361.5 m (7650 ft.) depth (Fig. 12). This means, of course that if a normal-faulting earthquake was to be triggered by fluid injection at a depth of about 368.5 m (7800 ft), propagation would be arrested by the stress barriers above and below that interval. The size of triggered strata-bound earthquakes in the Permian basin (**M**< 3.5) is evidence of this (Hennings et al., 2021). Zoback and Hennings (2024) point out that a general characteristic of **M** much larger than ~4 earthquakes triggered by injection of produced water throughout the North America over the past 15 years is that they are always associated with slip on pre-existing, critically stressed faults in crystalline basement. Simply said, earthquakes of relatively large magnitudes require slip on relatively large faults found in crystalline basement, but not in sedimentary sequences of limited thickness.

Stress measurements in the Coeverden gas field (also in the northern Netherlands, about 70 km south of the Groningen field) prior to production (Barton and Abou-Sayed, 1984), indicate the sands were in normal-faulting frictional equilibrium and the shales were not, exactly analogous to the situation illustrated in Figure 12. This would mean that vertical propagation of earthquake ruptures induced in the Rotliegend reservoir would be constrained above the reservoir by the Ten Boer shale and salt and by the Carboniferous shales below.

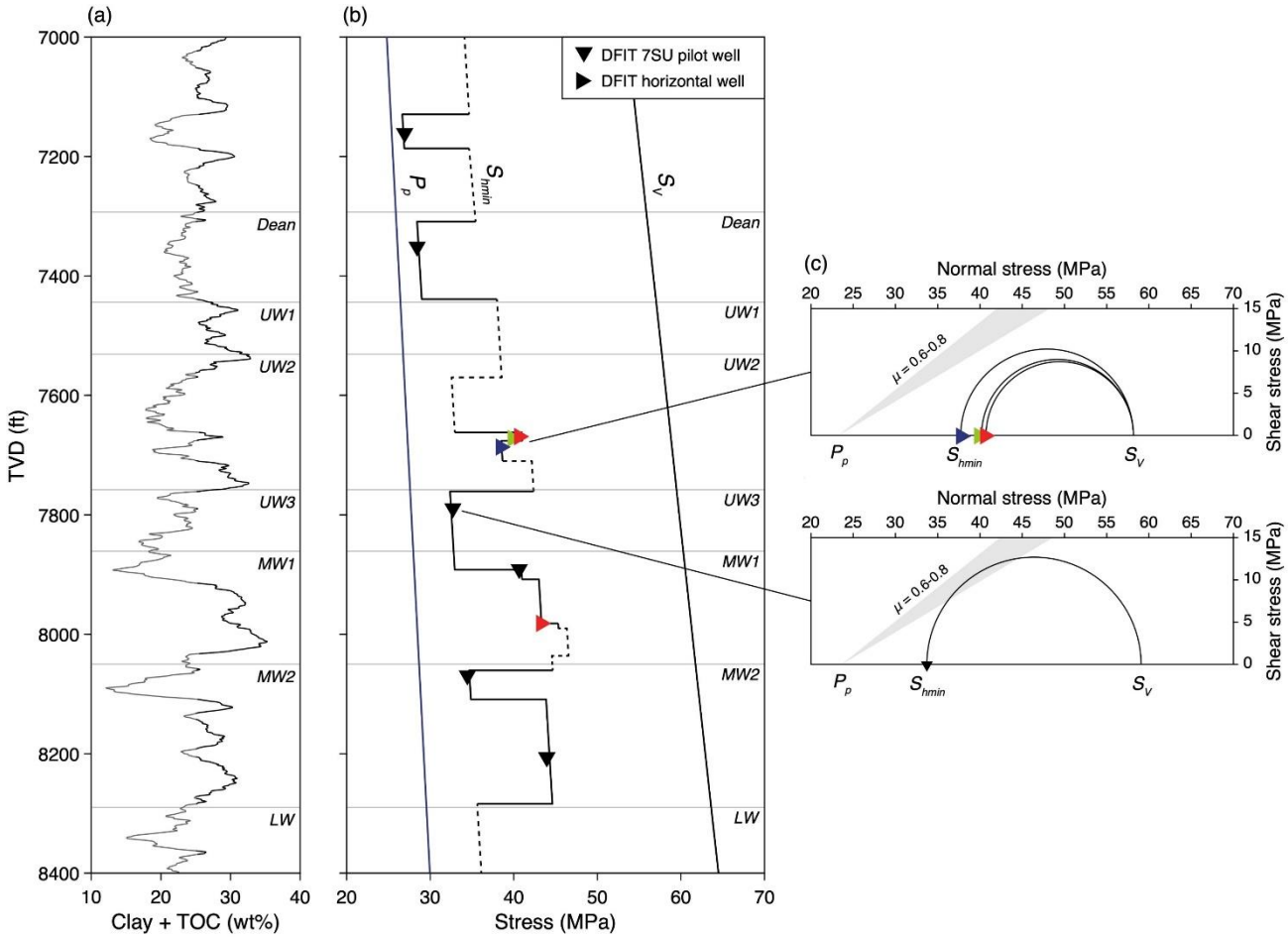

Figure 12. (a) Relationship between variations of clay plus organic content of the relevant lithologic units at the HFTS-1 test side in the Midland basin, (b) the magnitude of the least principal stress determined from DFIT tests (small scale hydraulic fracturing test and (c) corresponding Mohr circles at two depths (after Kohli and Zoback, 2019). TVD is true vertical depth (in feet). Note that in low clay plus total organic content (TOC) formations, one would expect well-oriented normal faults to be in frictional equilibrium (Mohr circle at 7790 ft depth) whereas in high clay plus TOC formations, visco-plastic creep results in higher values of the least principal stress, which results in a stress state that is not in frictional equilibrium (Mohr circles at about 7700 ft). The names of the formations associated with the abbreviations shown in (a) are as follows: UW1 (Upper Wolfcamp 1), UW2 (Upper Wolfcamp 2), UW3 (Upper Wolfcamp 3), MW1 (Middle Wolfcamp 1), MW2 (Middle Wolfcamp 2), LW (Lower Wolfcamp).

In addition to these considerations, it is also possible that pressure depletion in the shales above and below the reservoir has made normal-faulting propagating down into the Carboniferous even more unlikely. In a study of compaction and subsidence in the vicinity of depleted gas reservoirs in coastal Louisiana (USA), Chang et al. (2014) calculated the change in pore pressure in shale formations immediately above and below the reservoir. Despite the relatively low permeability of the shales (a value for shale permeability of 10^{-19} m^2 [0.1 microdarcies] was used, following Kwon et al., 2001), 20-30 years after depletion, pore pressure changes in bounding shales are quite large, thus inhibiting the tendency for normal faulting. This suggests that there are two geomechanical factors tending to limit the vertical extent of fault rupture to the thickness of the Rotliegend reservoir – the likelihood of viscoplastic relaxation in the Ten Boer shale above the reservoir and the Carboniferous shales below and steadily decreasing pore pressure in these formations would increasingly inhibit fault propagation

with time. Collectively, these lines of evidence—the absence of natural seismicity in the region, the documented absence of any induced earthquakes occurring above or below the reservoir, the normal-faulting regime, the low probability of purely down-dip rupture propagation, and the geomechanical constraints specific to the reservoir and salt and shale overburden and Carboniferous shale underburden in Groningen—lead us to conclude that it is highly unlikely that gas production in the Groningen field could trigger stress release on faults of sufficient size to produce earthquakes as large as those included in the Expert Panel assessment. We note that Boitz et al. (2024) arrived at a similar conclusion, in their case based on the absence of such events despite the elevated levels of induced seismicity in the field.

Discussion and Conclusions

Since the onset of induced seismicity in the gas fields of the northern Netherlands, efforts have been made to estimate the M_{max} that these earthquakes could reach. By 1998, these estimates had stabilized at M_L 3.8, rising incrementally to M_L 3.9 in 2004. These values have never been exceeded. Nonetheless, following the M_L 3.6 (**M** 3.5) Huizinge earthquake in 2012, the question of the maximum possible earthquake magnitude in Groningen gained heightened prominence (despite an earthquake of M_L 3.5 having occurred in 2006), and new estimates were put forward that were significantly higher.

The uncertainty and controversy surrounding this issue prompted the field operator to engage an Expert Panel to assess M_{max} for Groningen, and two international workshops were convened to provide an opportunity for resource and proponent experts to present to the panel the available data and models relevant to their assessment. In retrospect, it has been recognized that although there was formidable expertise and experience within the panel, the timescale allowed for their assessment was inadequate, especially for the second workshop, which had been delayed by the coronavirus pandemic. Consequently, the current M_{max} distribution proposed by the Expert Panel could be viewed to some extent as an envelope of their individual judgments rather than a genuine consensus outcome from a more extended process of evaluation of the available data, methods, and models. This is not intended as a criticism of the Expert Panel, simply an acknowledgement of the somewhat unfair position that they were placed in to digest an enormous amount of information in a very short time and to translate this into a logic tree capturing the center, body, and range of technically defensible interpretations. Insufficient time was allowed for the iterative review process associated with the SSHAC procedure to work effectively.

We also believe that two additional factors need to be borne in mind when assessing proposed distributions for M_{max}, both for Groningen and other cases of induced seismicity. The first is that whereas the purpose of a logic tree node for any input to PSHA should aim to include the full range of possible parameter values, there is often a tendency to focus only on how large the maximum magnitude could be without asking the equally important question of how small could the limiting magnitude prove to be in practice – a question that sometimes can be answered retrospectively for induced seismicity in a way that is not possible for natural earthquakes. The second factor is that M_{max} estimates may be influenced, albeit unconsciously, by the understanding that this is a parameter that exerts relatively little influence on PSHA results, which possibly makes hazard analysts more relaxed about assigning high values. However, the influence of M_{max} is generally found to be low when the

logic-tree branches carry alternative large values, and this does not necessarily mean that hazard and risk results would not be impacted by broader distributions of M_{max}. For induced seismicity, where the lower bound of M_{max} may be fixed at the size of the largest observed earthquake to date, hazard and risk analysis results may be more sensitive to this parameter (see, for example, Fig. 10 in van Elk et al., 2017, and Fig. 15 in van Elk et al., 2019). And there is no doubt that M_{max} estimates can and do exert a very significant influence on the perception of the associated risk; indeed, the possibility of larger induced earthquakes has been cited as the main justification for suspending several energy-related projects, including gas production in Groningen.

The current M_{max} logic tree for Groningen begins with a node distinguishing between genuinely induced (*i.e.*, industrially driven) earthquakes and triggered tectonic events, assigning a weight of 10% to the latter. The seismological context and geological conditions of the Groningen field lead us to conclude that tectonic earthquakes being triggered in the underlying Carboniferous formation by gas production from the shallow Rotliegend formation is extremely unlikely. On the IPCC scale, this would translate into a probability $\leq$ 1%. A strict representation of the state of knowledge would therefore include a branch for triggered earthquakes with a weight not exceeding 0.01. However, such a branch would likely have very limited influence on any hazard results (the effective recurrence rates for earthquakes in the magnitude range covered by this node would be reduced by 100), yet it is likely to impact significantly on the perception of the risk. Consequently, we believe that a pragmatic logic tree would allow this branch weight to be zero, effectively stating that triggered tectonic earthquakes are a sufficiently remote possibility to be discounted in the assessment and management of induced seismic risk. We also acknowledge, however, that this have been difficult for the Expert Panel to propose since they were engaged to make a purely scientific assessment with no onus to take account of the resulting implications in terms of the perception of risk.

We argue here that the M_{max} logic tree for Groningen should include only genuinely induced (driven) earthquakes associated with bounded fault ruptures within the reservoir. The first branch should match the largest earthquake that has occurred to date (*i.e.*, **M** 3.6, invoking the equivalence of local and moment magnitudes in Groningen) since this may well prove to be upper bound for induced seismicity in Groningen. We would also propose that the weight on this branch should not be excessively small, since the Huizinge earthquake may well be the largest event that could occur. Preempting a possible objection to this position, should the distribution start with a non-trivial weight attached to **M** 3.6 and were a larger earthquake to subsequently occur, the M_{max} model would not in any sense be invalidated; that would only be the case, if an earthquake occurred that exceeded the upper limit of the distribution. Indeed, the weight of less than unity assigned to the **M** 3.6 branch would reflect both the possibility that this is the limiting value and accommodating the possibility that larger earthquakes could occur. What increments of magnitude above **M** 3.6 should be accommodated by the other branches is a subject for discussion but in our view the weights should be concentrated on values in the range from **M** 3.6 to 4.1. To reflect the broad consensus of proponent experts at the 2022 M_{max} workshop, an upper limit of **M** 4.5 might be included, but we would assign this a rather low weight.

Data and Resources

The databases of geological, geophysical, seismological, pressure and production information made available to all participants in the 2022 M_{max} workshop can be freely accessed from the EPOS site: https://public.yoda.uu.nl/geo/UU01/RHHRPY.html (DOI: 10.24416/UU01-RHHRPY;). The

earthquake catalogue for Groningen can also be obtained from the web site of KNMI at http://cdn.knmi.nl/knmi/map/page/seismologie/all_induced.csv. Gas extraction volumes (as in Fig. 2) can be obtained from NAM at https://www.nam.nl/gas-en-olie/gaswinning.html. The fault plane solutions used to plot Fig. 4b are available at https://nam-onderzoeksrapporten.data-app.nl/reports/download/groningen/en/d17fab6a-9ca1-4316-8ff6-0e0561e095ab. The ground-motion data used to generate Fig. 5 is freely available from the data repositories identified in the paper by Ntinalexis et al. (2023). The history of early M_{max} estimates made prior to the 2012 Huizinge earthquake is summarized for the interested reader in the Electronic Supplement. The references cited therein, which are mostly from the grey literature, are available on request from the corresponding author.

Declaration of Competing Interests

Bommer and Zoback have acted as an independent consultant for a variety of organizations including hydrocarbon operating companies, including Shell and NAM, and governmental organizations on issues pertaining to induced seismicity; van Elk is an employee of NAM. The views expressed herein reflect the independent professional judgements of all three authors and neither NAM nor Shell has exerted any influence on the authors' conclusions.

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Electronic Supplement to BSSA manuscript

Estimating the Maximum Magnitude of Induced Earthquakes in the Groningen Gas Field, the Netherlands

Julian J Bommer, Jan van Elk, and Mark D Zoback

This supplement contains a summary of the estimates of the maximum magnitude (M_{max}) of induced earthquakes in the Groningen gas field that were made prior to the M_L 3.6 Huizinge earthquake of August 2012. The cited references, all but one of which are from the grey literature (and several of which are in Dutch), can be made available in electronic format on request to the corresponding author.

Estimates of Maximum Magnitude for Groningen Gas Field prior to the Huizinge earthquake of August 2012

Over the years, a number of estimates of the maximum magnitude of Groningen earthquakes, utilizing a variety of methodologies have been prepared. Table S.1 summarizes the estimates of the maximum magnitude proposed prior to the 2012 Huizinge earthquake. The table also includes the total volume of gas produced at the time of publication of the M_{max} model, the number of earthquakes that has occurred ($M_L \geq 1.5$), and the largest observed magnitude at that time. We summarize the procedures used in these studies below.

Following the first earthquake induced by the production of natural gas in northern Netherlands near the city of Assen on December 26, 1986 and a second earthquake also near Assen almost one year later, on December 14, 1987, the regulator for the mining industry Staatstoezicht op de Mijnen (SodM), the Geological Service in the Netherlands (RGD), KNMI (the seismic authority in the Netherlands), and the company producing gas in the area (NAM) came together to study the cause of the earthquakes and estimate the maximum magnitude of earthquakes induced by gas production. After initial discussions, the Minister of Economic Affairs formally initiated a multi-disciplinary research program in 1991 which also included the University in Delft and Free University Amsterdam (VU). The studies were carried out under the supervision of a committee appointed by the Minister (BOA 1992, 1993). Later that same year on December 5, 1991, the first induced earthquake (M_L 2.4) in the Groningen gas field was recorded near Middelstum.

The TU Delft study concluded that the two earthquakes near Assen had been induced by gas production from the local Eleveld gas field. Based on geomechanical simulations (Roest and Kuilman, 1992;1993) the maximum magnitude of earthquakes in the Eleveld gas field was estimated at local magnitude (M_L) 3.22. Based on the magnitude-frequency relation of the earthquake catalogue for the North–Netherlands (Figure S.1), which consisted at that time of only 24 earthquakes, KNMI provided an estimate of the maximum magnitude as M_L 3.3 (Haak and de Crook, 1994). The approach they took argued that the maximum magnitude of an induced earthquake could be taken to be about ¾ magnitude units beyond the point where the magnitude-frequency deflects and is about ½ magnitude unit greater than the maximum observed magnitude. Using these two rules-of-thumb, the maximum magnitude was determined to be about M_L 3.3. The BOA study concluded with regards to the maximum magnitude of earthquakes: *"Statistically, the maximum expected magnitude of earthquakes in the Northern Netherlands has been calculated at M_L=3.3 on the Richter scale. The probability of such an earthquake occurring is negligible. Using the geomechanical modelling an estimate has also been made for the maximum earthquake magnitude to be expected. Despite the completely different approach, the value of 2.9 on the Richter scale is in good agreement with the result from seismology."* Although the TU Delft estimate was specifically for Eleveld gas field, the Mmax estimate was adopted by some stakeholders as also being applicable to the Groningen field.

With the increasing number of earthquakes added to the seismic catalogue of the North-Netherlands, the maximum magnitude of earthquakes in the North-Netherlands was re-evaluated in 1995,1998, 2006 and 2012. In 1998, based on a catalogue of 125 earthquakes in North-Netherlands, KNMI updated the estimate of the M_{max} of induced earthquakes (De Crook et. al., 1998). A Monte-Carlo procedure was used to prepare a distribution for the M_{max} (Figure S.2). The mean of this distribution

was at M_L 3.5. Adding one standard deviation to the mean, the report concluded: "*Based on the earthquakes in the period 1986 to 1997, the best estimate is for the maximum magnitude (M_{max}) has a value of 3.8 on the Richter scale*." The report also pointed out uncertainties in this estimate of the maximum magnitude and mentioned the possible triggering of tectonic stresses.

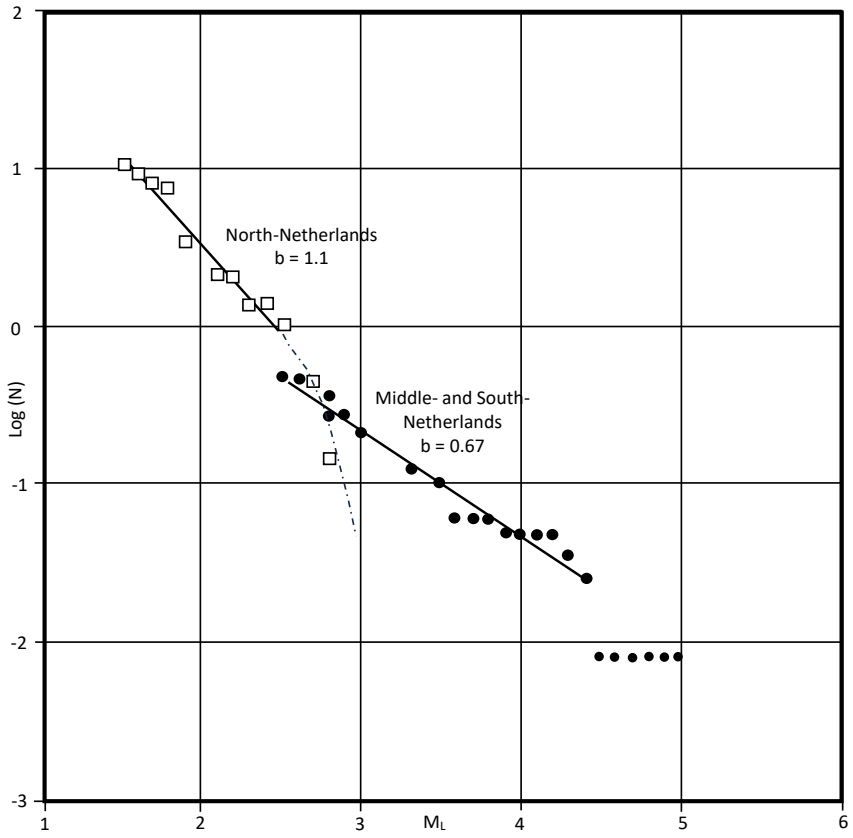

Figure S.1 Cumulative annual number of earthquakes as a function of the local magnitude for the tectonic earthquakes in the middle and south of the Netherlands (black dots) and the induced earthquakes in the North-Netherlands (white squares) (Haak and de Crook, 1994).

The increase in the estimate for the M_{max} was caused by a recent earthquake near the small Roswinkel gas field. KNMI reported that if this earthquake is omitted from the evaluation, the estimate for the M_{max} decreases to M_L 3.6, which is in line with previous estimates. The assessment of seismic risk for the induced earthquakes in the North–Netherlands heavily relied on the estimate of the M_{max} for these earthquakes. With the introduction of the new Mining Law in 2001, the gas producer was obliged to submit every five years a production plan (*Winningsplan*), which addressed both building damage and seismic risk. Aalbers (2003) reports that in the first production plan for the Groningen gas field submitted to the regulator (SodM) and the Minister of Economic Affairs in December 2003, NAM referred to the multidisciplinary research (BOA, 1993) and studies by KNMI (de Crook et al., 1998), "*which have demonstrated that earth-tremors will not be more severe than a magnitude 3.8 on the Richter scale.*"

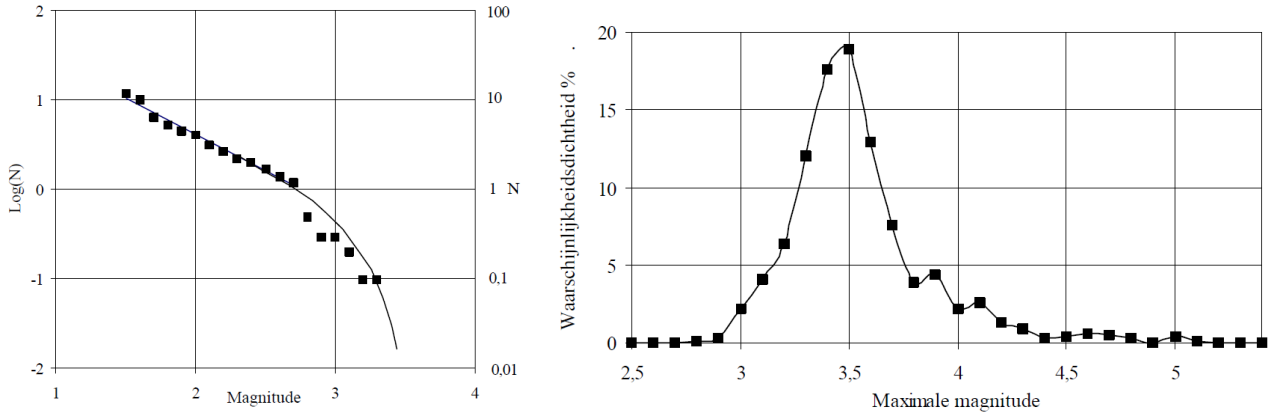

Figure S.2 *Left*: Frequency-magnitude relation for North-Netherland as a whole; *right*: distribution of M_{max} after 1000 experiments (De Crook et al., 1998)

In 2004 KNMI (van Eck et al., 2006) presented the basic methodology for a probabilistic seismic hazard analysis (PSHA) applied to small and shallow earthquakes in the North-Netherlands. For each updated analysis of the earthquake catalogue, the M_{max} distribution showed small changes (Figure S.3), with the largest change between the reports of 1998 and 2004.

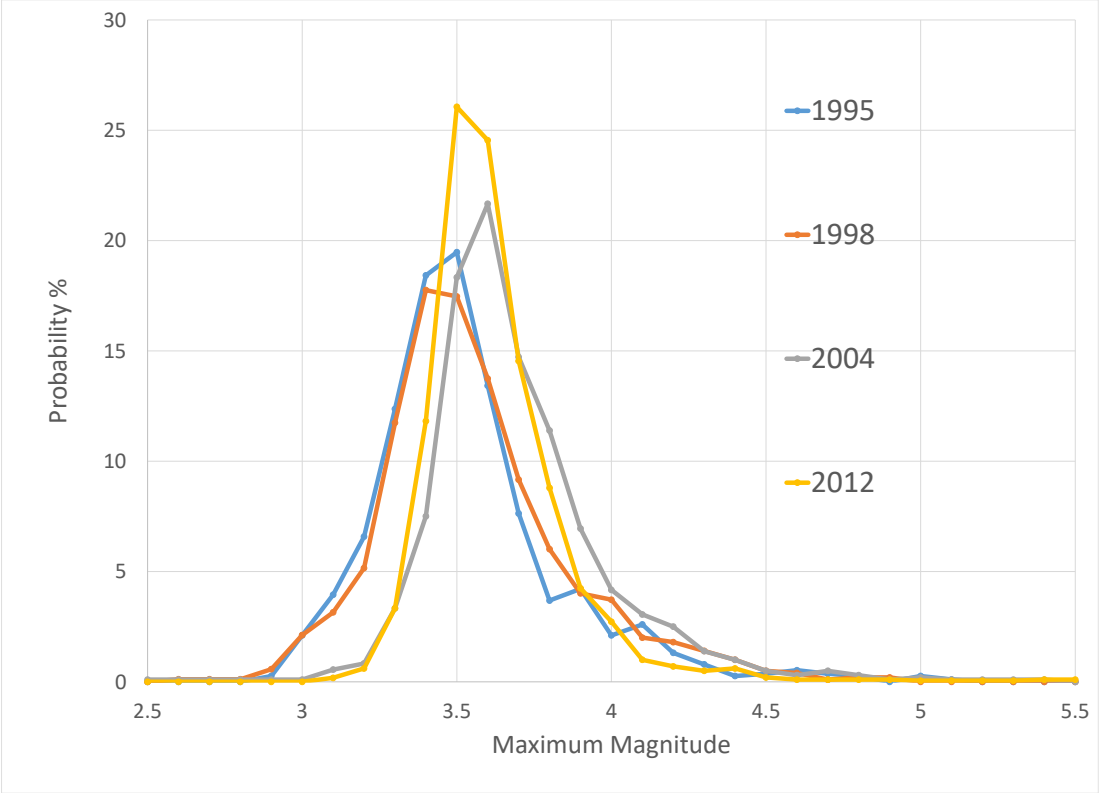

Figure S.3 Distributions for the M_{max} based on Monte-Carlo simulation as reported in the analysis of the earthquake catalogue for the North-Netherlands published by KNMI in 1995, 1998, 2004 and 2012 (De Crook et al. 1995; De Crook et al., 1998; van Eck et al., 2006l; Dost et al., 2012).

The probabilistic method gave a mean M_{max} of M_L 3.6 and a confidence limit of 84% at an M_{max} of M_L 3.9. The report concluded that the magnitude-frequency relationship and M_{max} in the northern Netherlands has remained fairly stable since 1998 and that the main conclusions of the evaluation in 1998 remained valid. Although the analysis in the report provided a distribution for the M_{max} of the earthquakes in the northern Netherlands, the conclusion of the report and the discussion of this in the press focus on "M_{max} is M_L 3.9". Comparing the effect of a M_{max} of M_L 3.5 and 3.9 the report concluded the effect of M_{max} on the hazard seemed consequently negligible compared with the uncertainties introduced by the ground motion prediction equations and other uncertainties in the hazard assessment.

In July 2012, Dost et al. (2012) provided a new update of the M_{max} of the earthquakes induced by gas production in the northern Netherlands was released by KNMI (Figure S.4), which stated: *"From Monte Carlo modelling the value for M_{max} is the same for both datasets: M_{max} = 3.7± 0.2. Since we add one standard deviation to the average value, M_{max} = 3.9, which is unchanged since the last update."* An important feature of the 2012 assessment of Mmax by KNMI was that for the first time, estimates were made separately for Groningen and for other smaller gas fields.

Another point that is noteworthy is that in all the KNMI reports, it was clearly stated that a probable M_{max} was estimated (with 85% probability). However, in the conclusion section of the reports and in communication with the Groningen community, only a single number was reported. This was then often interpreted in the press (and by many others) as an absolute upper bound, i.e., a magnitude that can never be exceeded.

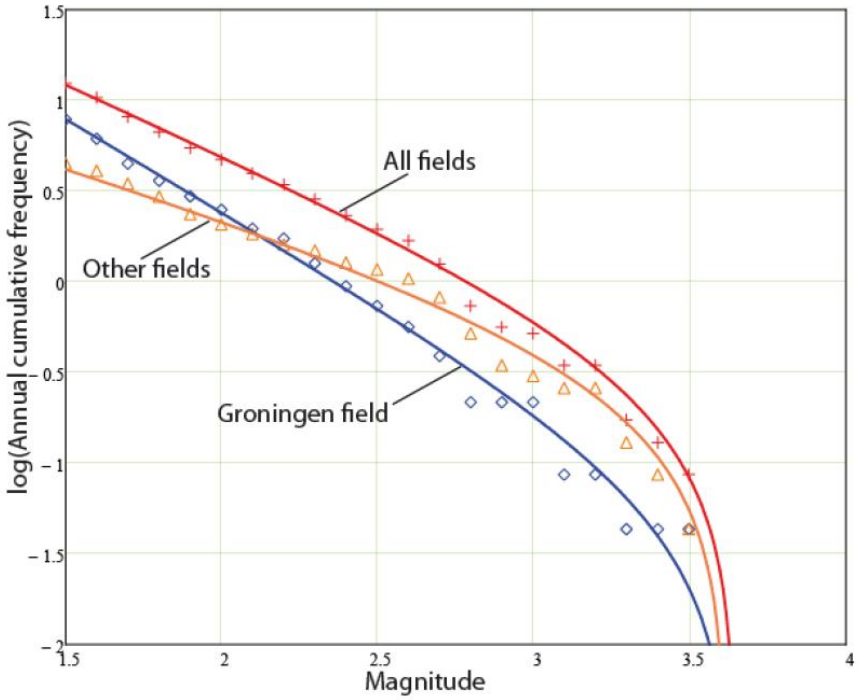

Figure S.4. Annual cumulative frequency as a function of magnitude for all fields together (red), only the Groningen field (blue) and the remaining other fields (orange) (Dost et al., 2012).

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Table S.1. Summary of M_{max} estimates published prior to the 2012 Huizinge earthquake.

Report with M_{max}-estimate	Year	Final month earthquake catalogue	Produced gas volume Groningen gas field [Bcm]	Number of earthquakes with magnitude equal or larger than M_L=1.5 in		Magnitude largest earthquake recorded (M_L)	M_{max} Estimate (M_L)	Basis for estimate of M_{max}
				North-Netherlands	Groningen gas field			
BOA-studie – Geomechanische analyse van de lichte aardschokken in het Eleveld reservoir, J.P.A. Roest and W. Kuilman, TU Delft.	1993	-	-	-	-	2.8	3.2	Geomechanical simulation of fault rupture in the Eleveld gas field.
BOA-studie – Seismische analyse van aardbevingen in Noord-Nederland, H.W. Haak and Th. de Crook, KNMI.	1994	08/1993	1,420	13	2	2.8	3.3	Based on largest observed earthquake and additional margin based on rule of experience.
Analyse van het seismische risico in Noord-Nederland, Th. de Crook, B. Dost and H.W. Haak, KNMI.	1995	09/1994	1.460	26	12	3.0	3.3	Based on largest observed earthquake, energy trend and Monte-Carlo simulation. For Northeast-Netherlands M_{max} is 3,4 and for area near Alkmaar M_{max} is 3,6.
Analyse van het seismische risico in Noord-Nederland, Th. de Crook, B. Dost en H.W. Haak, KNMI.	1995	-	-	-	-	3.0	3.5	Geomechanical reasoning based on fault dimensions.
Seismisch risico in Noord-Nederland, Th. de Crook, H.W. Haak and B. Dost, KNMI.	1998	02/1997	1,560	55	20	3.4	3.8	Based on largest observed earthquake, energy trend and Monte-Carlo simulation (16% exceedance).
Seismic hazard due to small shallow induced earthquakes, T. van Eck, F. Goutbeek, H.W. Haak and B. Dost, KNMI.	2004	12/2003	1,750	127	62	3.5	3.9	Based on largest observed earthquake, energy trend and Monte-Carlo simulation (16% exceedance).
Monitoring induced seismicity in the North of the Netherlands: Status Report 2010, B. Dost, F. Goutbeek, T. van Eck and D. Kraaijpoel, KNMI.	2012	01/2010	1,970	224	138	3.5	3.9	Bayesian Monte-Carlo (16% exceedance) for both the Groningen gas field and small fields.