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ABSTRACT: Over 190 gas fields have been exploited in The Netherlands and only 15-20% have been associated with induced seismicity. We assess the geomechanical characteristics of stress changes on faults due to gas depletion for 180 producing gas fields in the Netherlands. We confirm findings from earlier generic studies that inter-reservoir offset faults require less reservoir depletion to reach failure compared to bounding and small offset faults. However, the stress changes on the offset faults alone are not sufficient to explain the observed seismicity. We find that the presence of the visco-elastic Zechstein formation probably has a crucial influence on the in-situ stress field in the Dutch subsurface and significantly impacts the fault stability of the gas reservoirs in the Netherlands. By accounting for this influence, our results show remarkable consistency with the observed (non)occurrence of induced seismicity in the Dutch gas fields. A more detailed study taking into account the detailed geological information of reservoir and fault geometry available at the operators and the slip weakening behavior of the frictional strength is required to further refine the predictive power of our analysis.

1. INTRODUCTION

The production of hydrocarbons causes stress changes which can reactivate faults inducing earthquakes. Worldwide many cases have been observed (e.g. Yerkes & Castle, 1976; Segall, 1989; Grasso, 1992; Segall et al, 1994). In the Netherlands about 15-20% of the producing gas fields, including the large Groningen gas field, have been associated with induced earthquakes (e.g. Van Eijs et al., 2006; Van Thienen-Visser et al., 2012; Van Wees et al., 2014; Muntendam-Bos et al., 2015; De Waal et al., 2015; Qcon, 2018). Geomechanical aspects of extraction induced seismicity has been studied both numerically and analytically (Grasso, 1992; Roest & Kuilman, 1994; Nagelhout & Roest, 1997; Scholtz, 2002; Mulders, 2003; Muntendam-Bos et al., 2008; Buijze et al., 2017; Van Wees et al., 2017; Van den Bogert, 2015; 2016; 2018; Qcon, 2018; Jansen et al. 2019; Hettema, 2020). However, these studies have been either generic, highlighting only the key-aspects, or have been focused specifically on a very limited number of gas fields: Eleveld (Roest & Kuilman, 1994), Norg (Nagelhout & Roest, 1997; Van de Bogert, 2016), Bergermeer (Mulders, 2003; Muntendam-Bos et al., 2008), Roswinkel (Van Wees et al, 2003) and Groningen (Buijze et al., 2017; Van Wees et al., 2017; Van den Bogert, 2015; 2018).

In this paper, we focus on the geomechanical characteristics of induced seismicity due to gas depletion in the Netherlands. By using closed-form analytical expressions for production-induced stresses on displaced faults (Jansen et al., 2019) we will, for the first time, assess the stress changes associated with production for each of the onshore Dutch gas fields. We compute the shear and normal stresses due to poro-elastic stressing and differential compaction on faults of varying offset ("displaced faults") present in each of the gas fields and determine whether slip could have occurred on these faults. The results of our analysis are related to the observed (non)occurrence of induced seismic events.

2. GEOLOGICAL SETTING AND IN- SITU STRESS CONDITIONS

2.1. Characteristics of the Dutch gas field formations

The source of the gas contained in the Dutch gas fields (Fig.1) are the coal layers of the Carboniferous formation. This gas migrated upward and was successively trapped in the sandstones of the Carboniferous Limburg (DC) formation, the Rotliegend (ROT) sandstones, the Z2 and Z3 Zechstein Carbonate (ZEC) layers, the Lower and Upper Triassic (TR) sandstone layers, and the Lower Cretaceous (LC) sandstones (For reference, a stratigraphic column is provided in appendix A).

Most gas fields in the Netherlands are found in the zone where the Rotliegend Slochteren Sandstone is overlain by thick Zechstein salt deposits. This zone forms a fairway from England through The Netherlands and Germany all the way into Poland. The thickness of these impermeable evaporites (halite and anhydrites) varies from a couple of hundred to 2000 m thickness at the location of salt domes. Towards the south, the thickness of the Zechstein group becomes thinner and vanishes roughly at the line Amsterdam-Arnhem (dark dotted line fig. 1).

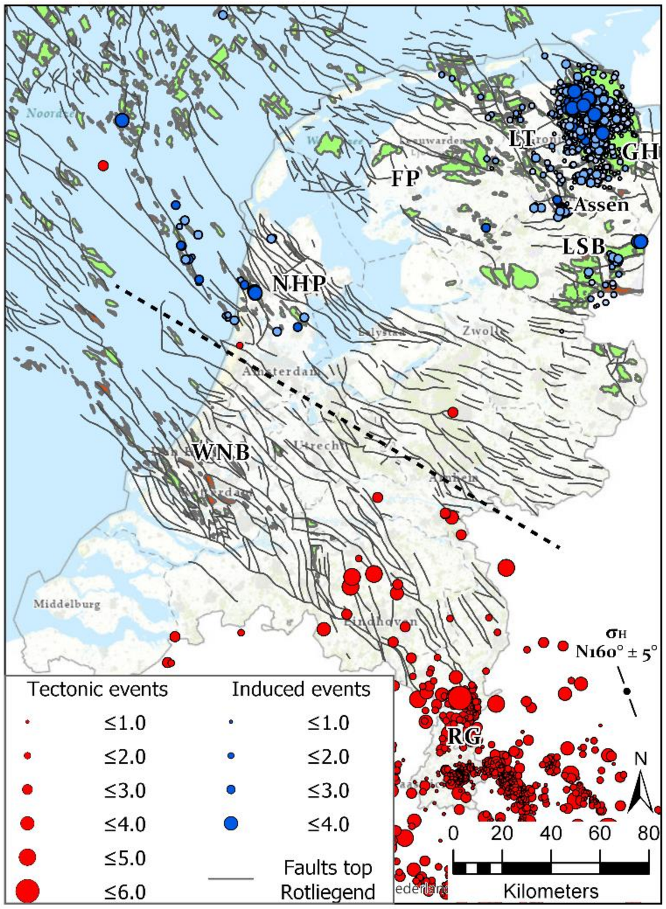

Fig. 1. Overview of the tectonic regions, seismicity and hydrocarbon reservoirs in The Netherlands. The induced seismic events are indicated with blue circles; natural, tectonic events with red circles. Hydrocarbon reservoirs are indicated in green (gas) and red (oil). WNB: West Netherlands Basin; NHP: Noord-Holland Platform; FP: Friesland Platform; LT: Lauwerssea Trough; GH: Groningen High; LSB: Lower Saxony Basin; RG: Rhine Graben. Source: seismic catalogue – www.knmi.nl; faults, hydrocarbon reservoirs – www.nlog.nl..

The DC, ROT and ZEC reservoirs contain many steeply dipping internal faults (75°-85°). Fault offsets vary from almost absent to very large (well exceeding the thickness of the reservoir layer).

The TR fields consist of sandstone layers intermittent with shales. Structurally the fields contain a fault-dip closure, which means they are part fault bounded and in part by the reservoir dipping below the Gas-Water-contact (GWC).

The LC gas reservoirs, located in the Vlieland sandstone, are four-way-dip-drape structures without any major faults. The LC Vlieland claystone acts as a seal for these gas fields.

2.2. Initial stress conditions

Apart for the ongoing extension of the Rhine-graben in the southeast of The Netherlands, no tectonic activity has occurred in the subsurface since the Cenozoic. This agrees with the absence of recorded historical natural seismicity in the north and west of the country (Fig.1). The absence of natural seismicity strongly suggests that the stress field away from the southeast is non-critical.

The Dutch subsurface stress field shows a normal faulting stress regime. The general direction of the maximum horizontal stress is N160° ± 5° (Heidbach et al, 2016). The level of anisotropy between the horizontal stresses is found to be very low (2-3%) (Van Eijs, 2015).

Verweij et al. (2016) made an assessment of the variations in the vertical stress field in The Netherlands based on density log data and basin modelling. It was found that the very low densities of the Zechstein halites had a reducing effect on the vertical stress, both in the layer itself as well as in the underlying Rotliegend and Carboniferous formations. In fact, the thicker the halite layer, the lower the vertical stress. For the DC, ROT and ZEC gas fields a vertical stress gradient of 21 MPa/km is derived.

Above the Zechstein, the vertical stress in the Triassic sediments was found to be close to lithostatic. The vertical stress in the West Netherlands Basin (WNB) was found to be lithostatic as off 2500 m. Hence, a lithostatic vertical stress gradient of 23 MPa/km is adopted for the Triassic gas fields. Generally, the vertical stress in the Vlieland Lower Cretaceous sandstones was found to be below lithostatic due to the very low densities in the Cenozoic sediments. For these reservoirs a vertical stress gradient of 20 MPa/km is adopted.

To estimate the minimum horizontal stress σ_h leak-off test data is publicly available online (www.nlog.nl; Van Wees et al, 2014). The data was grouped per gas-bearing structural region and for each region a minimum horizontal stress gradient was derived (Table 1). For three regions separate gradients were derived for the more shallow and the deeper formations, respectively.

Using the depth and initial pressure of the gas field, the effective minimum horizontal and effective vertical stress of each of the Dutch gas fields can be calculated following Terzagi's concept (Terzaghi, 1943; Fig.2). In a normal faulting regime, the effective stress ratio $K' = \sigma_h'/\sigma_v'$ provides a measure for how critically stressed the faults are. Given a typical coefficient of friction of $\mu = 0.6$ the frictional limit to generate slip on favourably orientated faults is (Byerlee, 1978):

$$K'_{\mu=0.6} = \frac{1}{\left(\sqrt{(\mu^2+1)}+\mu\right)^2} = 0.32 \qquad (1)$$

Table 1. Overview of the horizontal stress gradients for the six gas-bearing structural regions derived from LOT-data. FP: Friesland Platform; LSB: Lower Saxony Basin; GH: Groningen High; LT: Lauwerssea Trough; NHP: North Holland Platform; WNB: West Netherlands Basin (Fig.1).

Region	σ_h-gradient (Mpa/km)
FP (d < 1.5 km)	13.4
FP (d > 1.5 km)	17.8
LSB	19.6
GH & LT (d < 1.5 km)	14.8
GH & LT (d > 1.5 km)	19.9
NHP	17.0
WNB (d < 2.5 km)	15.8
WNB (d > 2.5 km)	18.1

From Fig.2 it can be seen that indeed a relatively stable stress regime existed in the Dutch gas fields prior to gas production. This is consistent with findings in other tectonically quiescent areas (Fjaer et al., 1993). The shallower TR fields in the WNB have the lowest K_0' of ~0.43 for the shallower gas fields. The largest K_0' of 0.87, close to a lithostatic $K_0' = 1$, is found for the ROT gas fields in the Groningen High (GH) and Lauwerssea Trough (LT) region and the ZEC and DC fields in the Lower Saxony Basin (LSB). These fields are all overlain by, or within the very thick Zechstein evaporate formation (> 500m on average). The ROT and ZEC gas fields of the North Holland Platform (NHP) and Friesland Platform (FP) where the Zechstein formation is much less thick (100-500 m) show a lower K_0' of ~0.6. Clearly the thickness of the isotropic, viscous Zechstein formation affects the stress state of the ROT, ZEC and DC gas fields.

3. CORRELATION BETWEEN RESERVOIR PROPERTIES AND INDUCED SEISMICITY

The first induced seismic event in The Netherlands was observed on December 26 1986 near the town of Assen and had a magnitude of ML=2.8. The event was recorded by the KNMI network far away in the southeast of the Netherlands and was located very near the Eleveld gas field. Initially, any relation to the gas production was denied. However, as more events near more gas fields in the area were recorded by a quickly installed local network, a causal relationship was acknowledged in the early 1990's (BOA, 1993; Roest & Kuilman, 1994). A seismic network with a magnitude of completeness of ML=1.5 and a 1-σ location uncertainty of approximately 1 km was installed by the Royal Dutch Meteorological Institute (KNMI) in 1995. An extension of the network in the north of The Netherlands in 2010 has allowed for the detection of more smaller magnitude events since.

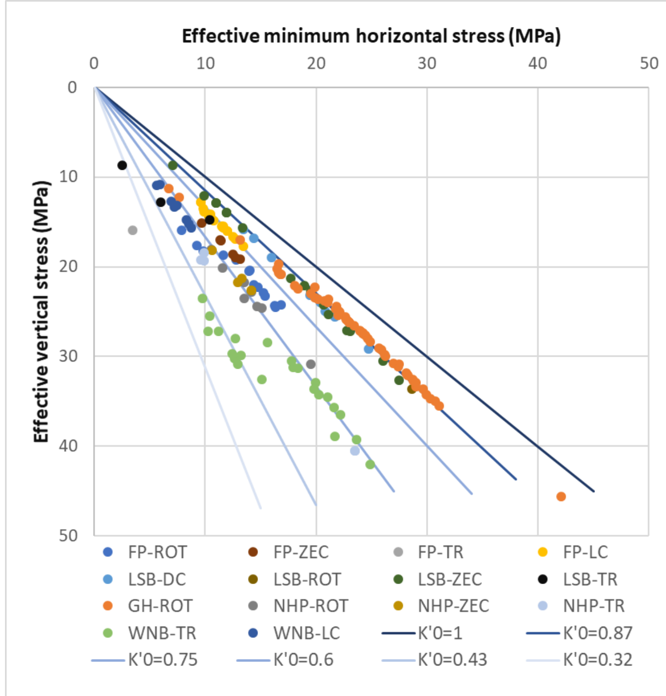

Fig. 2. Effective minimum horizontal stress ($\sigma_h' = \sigma_h - p$) versus effective vertical stress ($\sigma_v' = \sigma_v - p$) for the Dutch gas fields. Both σ_h and σ_v have been determined using the gradients for the structural regions and plays, respectively, and the depths of the gas fields. For p the actual initial gas pressure of the gas reservoirs is used. LC: Lower cretaceous reservoirs; TR: Triassic reservoirs; ZEC: Zechstein carbonate reservoirs; ROT: Rotliegend reservoirs; DC: Carboniferous (Limburg) reservoirs. A stratigraphic column is provided in appendix A.

Nowadays, over 1650 induced seismic events have been recorded being attributed to 37 gas fields (Fig.1). A complete list of all seismic events recorded in The Netherlands can be found on the website of the KNMI (www.knmi.nl).

Based on the KNMI catalogue of January 2020, the induced seismic events were assigned to individual reservoirs. This assignment is based on temporal consistency with reservoir production and spatial proximity of the event epicentre and the reservoir. From the 180 gas reservoirs included in this study, 37 are associated with seismic activity.

The associations are critically dependent on the accuracy of earthquake epicentres. In case of neighbouring or stacked gas fields, a unique association of an earthquake to a specific gas field is often not possible. In order to avoid bias, we use the classification scheme of Qcon (2018) to further distinguish between reservoirs which have most likely produced seismicity (A-fields), reservoirs associated with seismicity in the main database (B-fields), reservoirs for which a possible association with seismicity, given the location uncertainties of the seismic events, cannot be excluded (C-fields), and reservoirs for which an association with induced seismicity is very unlikely (D-fields).

In Fig.3 the seismic moment released by the events in the A- and B-fields has been plotted as a function of the level of depletion at the moment of the first seismic event induced. For non-seismically active fields (C- and D-fields) the seismic moment released is off course zero, but has been artificially fixed at 10^9 and plotted at the current level of depletion of the gas field. As expected given the non-critical in-situ stress field, all gas fields show a clear delay of at least 8.7 MPa prior to the occurrence of the first seismic events. There is a significant spread in the level of depletion required for a field to become active.

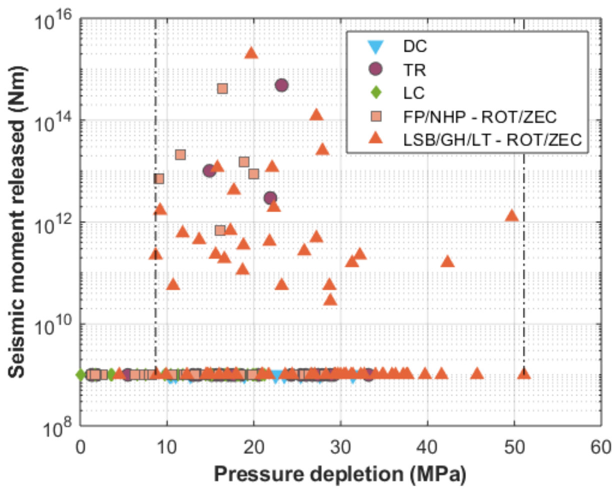

Fig. 3. Total seismic moment released in the gas fields as a function of the reservoir pressure depletion. Note: the seismic moment released by the non-seismically active fields has been artificially fixed at 10^9 for displaying purposes only.

The majority of the seismically active A- and B-fields are located within the ROT and ZEC. There are only three seismically active TR gas fields. None of the gas fields located in de Lower Cretaceous or the Carboniferous have been associated with seismic activity. Here we should note that the KNMI by default allocates all induced events at a depth of 3 km. This influences the epicenter location in case the event in reality occurred significantly deeper or shallower than this a priori depth. In addition, in the case of vertically stacked reservoirs, it significantly hinders the identification of the seismically active reservoirs. Hence, it is impossible to indisputably attribute an event to a particular reservoir layer based on empirical evidence alone. Still, the fast majority of gas fields (D-fields) do not show any seismicity despite comparable levels of depletion.

4. THE INFLUENCE OF FAULT OFFSET

It is well known that the stress changes induced by the production of gas can induce seismic slip on reservoir faults in the Rotliegend formation (e.g. Roest & Kuilman, 1994; Segall & Fitzgerald, 1998; Mulders, 2003; Van den Bogert, 2015; 2018). Inter-reservoir faults with a relative offset of about half to one reservoir thickness are found to be particularly susceptible. Little is known about the seismic potential of faults within the other gas-bearing formations in The Netherlands.

Here we will evaluate the onset of slip on faults in various configurations in all gas-bearing formations. We use the fast analytical solution of Jansen et al. (2019) to compute the development of stresses on a finite, inclined (offset) fault of variable offset in all 180 gas reservoirs. It is well-known that the analytical solutions observe shear stress singularities at either the internal or external corners (Jansen et al., 2019). In reality, the stresses remain finite by small amounts of slip and non-elastic deformation of the reservoir rock. Introducing a 1 m wide fault zone in the model, allows (1) full control over the pressure change within the fault, and (2) to obtain a finite resolution comparable to numerical solutions.

Table 2. Overview of the parameters used in the geomechanical analysis.

Formation	E (GPa)	ν (-)	μ (-)	Dip (°)	References
LC	19	0.25	0.7	70	Muntendam-Bos et al, 2008; Hangx et al, 2015
TR	12	0.25	0.7	70	Muntendam-Bos et al., 2008; Erickson et al., 2015; Egert et al., 2018
ZEC	30	0.25	0.7	70	Muntendam-Bos et al., 2008; Buijze et al., 2017
ROT	19	0.2	0.6	70	Muntendam-Bos et al., 2008; Hunfeld et al, 2017
DC	19	0.25	0.5	70	Muntendam-Bos et al., 2008; Hunfeld et al, 2017

The onset of slip is a function of the Coulomb Failure Function (ΔCFF) and the in-situ stress conditions in the reservoir:

$$\Delta CFF = \Delta\tau - \mu\Delta\sigma_n' \quad (2)$$

where $\Delta\tau$ is the shear stress change on the fault, $\Delta\sigma_n'$ is the change in the effective normal stress on the fault, and μ is the coefficient of friction. Table 2 provides an overview of the parameters used in our analyses. The reservoir specific parameters such as reservoir thickness, initial pressure, and reservoir formation have been collected from the public production plans available on www.nlog.nl.

For each gas reservoir we evaluate the ΔCFF on four distinct fault configuration (Fig.4): 1) reservoir bounding fault with depletion in the hanging wall reservoir block; 2) reservoir bounding fault with depletion in the footwall reservoir block; 3) inter-reservoir fault with depletion in both the foot- and hanging wall reservoir blocks with a) small to no fault offset and b) fault offset of half the reservoir thickness or more. An inter-reservoir fault completely offsetting the reservoir layer can be represented by either configuration 1) for the hanging wall reservoir section or configuration 2) for the footwall reservoir section.

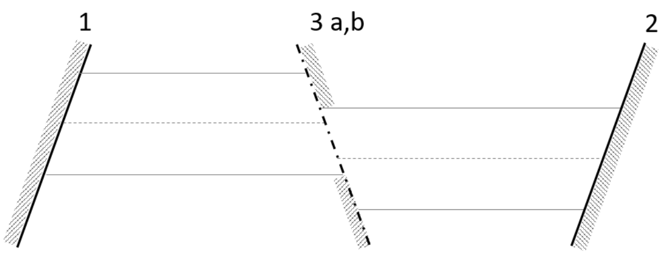

Fig. 4. Schematic representation of the four fault configurations assessed: 1) reservoir bounding fault with depletion in the hanging wall reservoir block; 2) reservoir bounding fault with depletion in the footwall reservoir block; 3) inter-reservoir fault with depletion in both the foot- and hanging wall reservoir blocks with a) small to no fault offset and b) fault offset of more than half the reservoir thickness.

As we only have access to structural maps to determine whether offset faults are present, we model all faults with a derived normalized offset (offset divided by reservoir thickness) clearly less than 0.5 by a representative fault with a normalized offset of 0.25, and all faults with normalized offsets of 0.5 or larger by a representative fault with a normalized offset of 0.75. The depleting reservoir pressure is adopted within the 1 m wide, offset inter-reservoir fault. For the boundary faults a large normalized offset of the reservoir layers of 0.95 is adopted and depletion is only incorporated on either the foot- (1) or hanging wall side (2) of the fault. As the boundary fault is a sealing fault, the initial reservoir pressure is maintained within the 1 m wide fault.

We acknowledge that these simplifications introduce a level of bias which is over-predicting in some and under-predicting in other cases. However, considering the level of uncertainty in all parameters, we consider this a reasonable first-order approximation. Finally, in our 2-dimensional model the strike of the faults within the reservoirs has been ignored, which is justified by the very low ambient horizontal stress ratio observed in The Netherlands.

Based on the ΔCFF and the in-situ stress condition (τ_0, σ'_{n_0}; Fig.2), the shear capacity utilization (SCU) for each of the fault configurations is computed for the 180 Dutch gas fields:

$$SCU = \frac{\tau}{\tau_{max}} = \frac{\tau}{C+\sigma'_n\mu} = \frac{\tau_0+\Delta\tau}{C+(\sigma'_{n_0}+\Delta\sigma'_n)\mu} \quad (3)$$

In our analysis we assume no cohesion, C, is present on the reservoir faults. We utilize the level of depletion in 2016 as derived from P/z-plots by Qcon (2018) and, where applicable, the level of depletion at the time of the first seismic event. When $SCU > 1$ the fault has reached failure conditions and slip on the fault may occur. However, this does not necessarily mean seismic slip is induced. This will be discussed in more detail in the Discussion section.

We note that though the location at which onset of failure occurs differs, the SCU values derived for fault configurations 1) and 2) are identical. As we focus in this paper only on the feasibility of failure and not on the location and characteristics of the onset of slip, we further report bounding faults of both configurations as configuration 1 (indicated by '…_1' in Fig. 5-9).

4.1. Lower Cretaceous gas fields

The results of our analysis for the gas fields in the LC are shown in Fig.5. For two fields the structural maps show no identified faults. These fields have been included in Fig.5, but no SCU values were calculated. The SCU values for all other LC gas fields remain (well) below 0.7. This is consistent with the fact that no seismic activity has been observed for any of these fields and the fact that the fields are characterized by four-way-dip-drape structures without any major faults. Where both are present, the SCU values on the offset faults are found to be slightly larger than the SCU values on the boundary faults in the same reservoir.

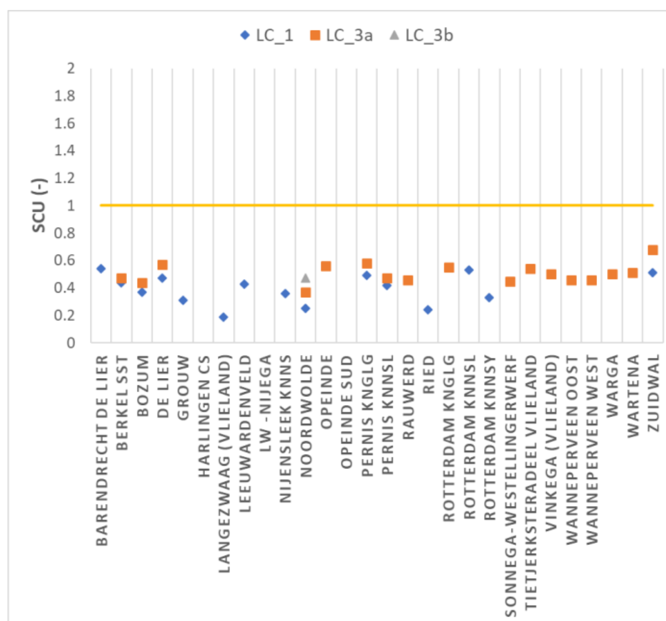

Fig. 5. Analytically derived SCU values for all the gas fields in the Lower Cretaceous sandstones. Dashed line indicates the critical value at which failure conditions are reached and (aseismic) slip may be induced.

4.2. The Triassic gas fields

The SCU values for the TR gas fields (Fig.6) reach higher values than those obtained for the LC gas fields. The faults in most fields do not reach failure conditions except for the offset faults in the Sleen gas field. This gas field is located in the LSB (Fig.1) and was initially significantly overpressured (~15 MPa). This overpressure leads to very low initial stresses on the sub-vertical faults and near failure conditions. However, the Sleen gas field has not been associated with any recorded seismicity. Production from the field was terminated in 1998 due to production related problems. With the installation of the seismic network in 1995, seismic events with magnitudes $M_L \geq 1.5$ could be detected. Smaller magnitude events and larger events prior to 1995 may have remained undetected.

The Roswinkel, Q04-A and Q04-B gas fields have shown significant seismic activity at a level of depletion significantly below a SCU of 1.0 (0.85, 0.71 and 0.53, respectively; crosses in Fig.6). Considering a location uncertainty (1σ) of ~1 km in the epicenter locations and the time of occurrence, it is unlikely the seismic events recorded at these gas fields can be attributed to neighboring or nearby gas fields. However, clearly the combination of the in-situ stress field derived from LOT's and the stress accumulation on the offset faults due to the depletion cannot fully explain the occurrence of these events.

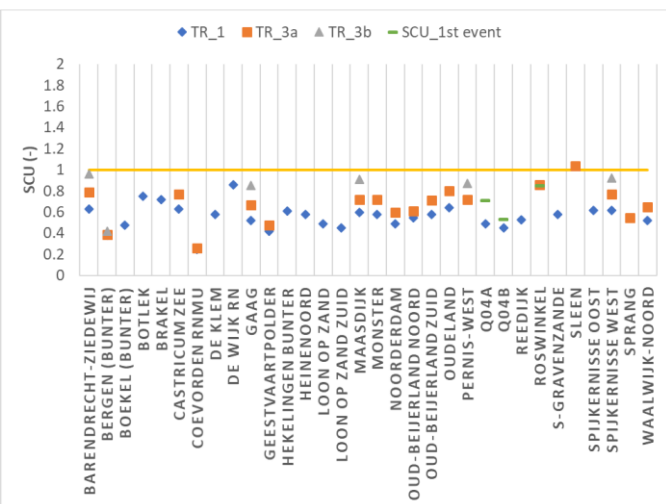

Fig. 6. Analytically derived SCU values for all the gas fields in the Triassic sandstones. Yellow line indicates the critical value at which failure conditions are reached and (aseismic) slip may be induced.

4.3. The Zechstein and Carboniferous gas fields

The SCU values derived for the Zechstein carbonate gas fields (Fig.7) are comparable to the values derived for the Triassic gas fields. Based on the in-situ stress field in combination with depletion induced stresses none of these fields should be associated with seismic activity. However, in several gas fields particularly in the LSB (eg. Dalen, Emmen, Emmen-Nieuw Amsterdam and Coevorden) seismic events have been recorded. The SCU at the time of the first seismic events in these fields is indicated by the green bars in fig. 7.

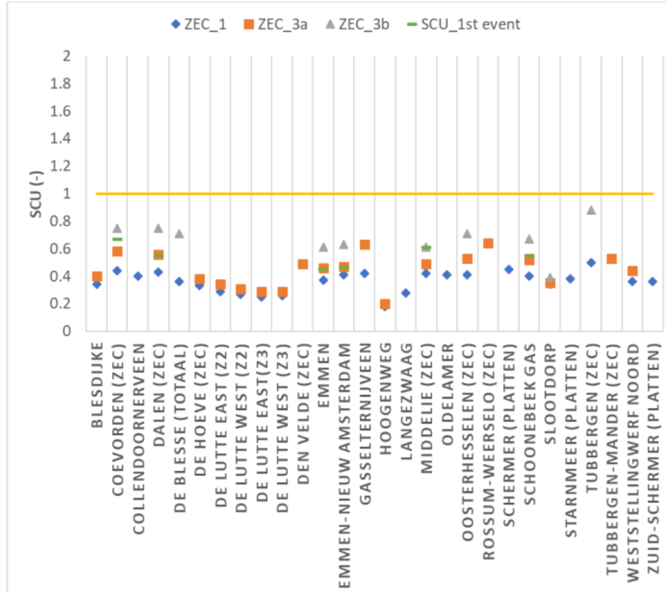

Fig. 7. Analytically derived SCU values for all the gas fields in the Zechstein Carbonates. Yellow line indicates the critical value at which failure conditions are reached and (aseismic) slip may be induced.

Here we reiterate that the KNMI a priori fixes the depth of all induced seismicity to 3km. For some fields, such as Dalen and Coevorden, it is therefore possible that the seismicity actually occurs not in de Zechstein reservoir, but in the deeper DC reservoirs. Fig. 8 shows the SCU-values calculated for the DC gas fields. Generally, the trend is comparable to the ZEC gas fields, except for Coevorden, where the analysis for large offset faults shows SCU-values reaching close to failure conditions at the level of depletion in 2016. However, the first seismic event was recorded already on August 16, 1996.

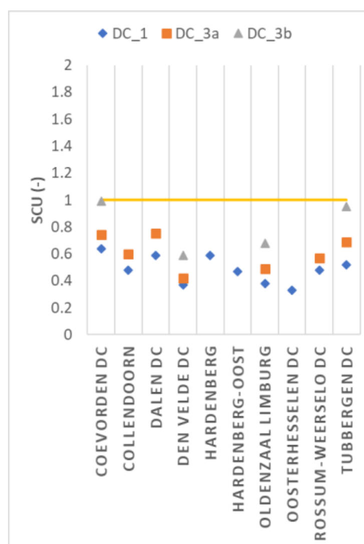

Fig. 8. Analytically derived SCU values for all the gas fields in the Carboniferous sandstones. Yelllow line indicates the critical value at which failure conditions are reached and (aseismic) slip may be induced.

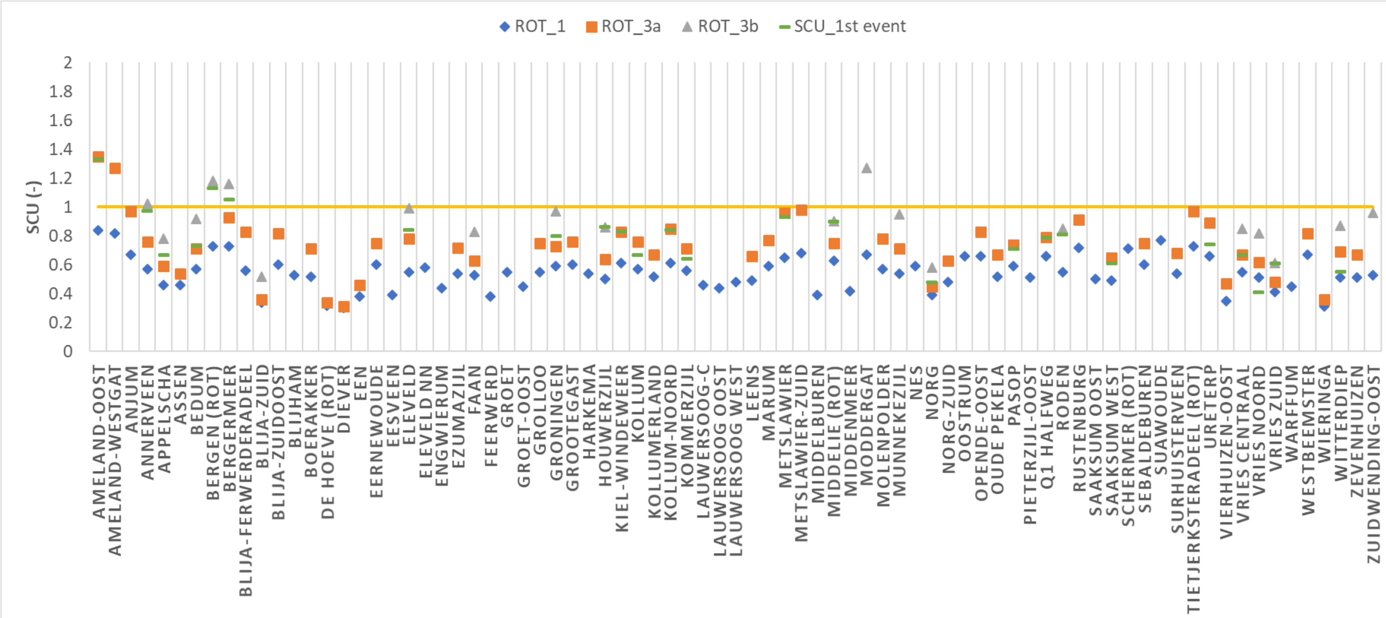

Fig. 9. Analytically derived SCU values for all the gas fields in the Rotliegend sandstones. Yellow line indicates the critical value at which failure conditions are reached and (aseismic) slip may be induced.

In the case of Emmen and Emmen-Nieuw Amsterdam no other reservoir layers are present and seismicity should be associated with these fields. This implies that either the in-situ stress field in the ZEC gas fields should be significantly different from the log- and LOT-derived stress field or an additional process influences the local stress field at the faults enabling failure.

4.4. The Rotliegend gas fields

Of all the gas bearing layers, the ROT contains the most gas fields with associated seismic activity (23). However, the ROT gas fields show a similar pattern as the Zechstein Carbonate gas fields. The SCU values of most fields (Fig.9) remain well below the failure threshold. Only a few fields in the NHP and the significantly overpressured gas fields in the northern extent of the LT exceed a SCU of 1.0, which could explain the observed seismic events in the Ameland, Bergen and Bergermeer gas fields. The observed seismic activity at the other twenty gas fields, including the large Groningen gas field, seem to occur well before failure on the faults should occur.

4.5. Summary

Our analytical analysis shows that given the log- and LOT-derived in-situ stresses, the occurrence of induced seismicity in the Dutch gas fields cannot be explained by the Coulomb stress changes on the faults due to reservoir depletion. For the majority of the fields which have been indisputably associated with induced seismicity, our analysis shows SCU values well below 1.0. Only a few gas fields with very high initial pressures and ROT gas fields with large offset faults in the more critically stressed NHP (K_0' ~0.6) reach failure conditions.

5. THE INFLUENCE OF THE VISCOUS ZECHSTEIN SALT

The presence of visco-elastic salt can influence the occurrence of seismic slip on faults in multiple ways. Firstly, the isotropic stress state (σ_h/σ_v ~1) within the salt influences the stress state of the ZEC, ROT and DC formations leading to the observed high σ_h'/σ_v'-ratios of 0.87 at the GH, LT, and LSB gas fields (Fig.2) in contrast to the much lower σ_h'/σ_v'-ratios of 0.65 observed in comparable ZEC and ROT reservoirs underneath the much thinner salt layer at the NHP and FP.

But the presence of salt in the immediate vicinity of the gas fields can also strongly affect the stress system near a fault. The high horizontal stresses within the salt can dilate the top of a (sub-)vertical fault under extension. Subsequently, salt may locally intrude downward along the fault zone (Roest & Kuilman, 1994, Ketterman et al. 2017). After a fracture has been intruded by the salt, the high horizontal stress in the salt amplifies the dilation of the fault and can significantly reduce the horizontal stresses on the fault to as low as σ_h/σ_v ~ 0.7 (Roest & Kuilman, 1994; Jackson & Hudec, 2016; Orlic & Wassing, 2013). At the same time, salt penetrating the fault zone forming a continuous salt layer spanning the whole length of the fault zone leads to low frictional strength and aseismic creep rather than seismic slip (Ketterman et al, 2017).

Finally, the viscous nature of the salt will unable stress to accumulate on a fault juxtaposed to it. Creep within the salt layer will dissipate the stresses due to reservoir depletion and inhibit seismic slip (Orlic & Wassing, 2013). Hence, (bounding) faults in the ROT, ZEC and DC with larger offsets (offset > reservoir thickness) and juxtaposition to ZE halite are unlikely to induce seismicity.

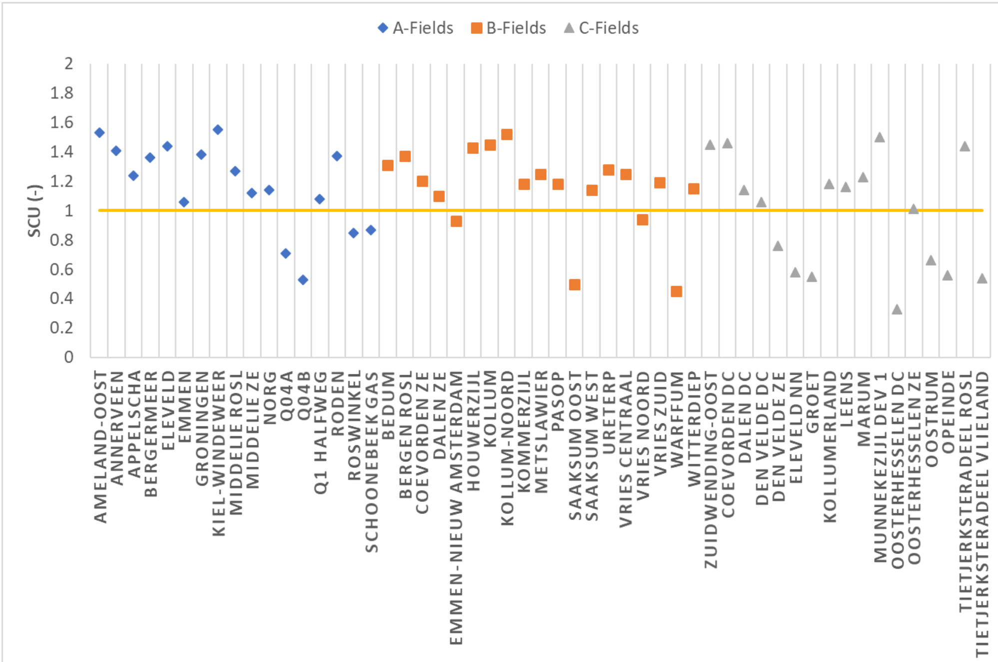

Fig. 10. Analytically derived SCU values at the time of occurrence of the first seismic event for all the A- and B-fields and at the level of depletion in 2016 for the C-fields. Yellow line indicates the critical value at which failure conditions are reached and (aseismic) slip may be induced.

As seen in the previous section, the influence of the salt on the in-situ stresses reduces the seismic potential of faults in the Dutch gas fields. In contrast, the local reduction of the horizontal stresses on offset reservoir faults due to partial salt intrusion can increase the seismic potential of the Dutch gas fields (Ketterman et al., 2017). Unfortunately, the exact local effect has yet to be fully investigated and quantified. In a first attempt to mimic the possible influence of the local effect of the salt on the seismic potential of the Dutch gas fields, we apply a correction to the LOT-derived σ_h/σ_v-ratio and compute the subsequent adjusted minimum horizontal stress for each reservoir. With this correction we effectively reduce the LOT-derived σ_h/σ_v-ratio to ~0.7 for all offset faults in the Carboniferous, Rotliegend and Zechstein Carbonate gas reservoirs (Roest & Kuilman, 1994; Orlic & Wassing, 2013).

5.1. *Results for the A-, B- and C-fields*

Fig. 10 shows the derived SCU values for the A-, B- and C-fields after implementation of the stress-ratio correction. For the A- and B-fields the values at the time of occurrence of the first seismic event is given. For the C-fields the SCU-value at the level of depletion in 2016.

For four A-fields the derived SCU-values remain well below the threshold for the onset of slip: Q04-A, Q04-B, Roswinkel and Schoonebeek Gas. Q04-A, Q04-B and Roswinkel are TR fields. These TR gas fields are located on top of the Zechstein formation and are therefore not affected by our correction. Closer analysis of these three fields show them to be located on top of active salt structures. Beneath these fields salt domes are present. The upward force of the rising salt dome could be imposing extensional stress within the layers above it and induce normal faulting in the crest (Jackson & Galloway, 1984). This extensional stress is not incorporated in our general assessment of the horizontal stresses derived from the LOT's. Hence, the stresses computed from the horizontal stress gradients will significantly overestimate the actual horizontal stresses in these fields and reduce the SCU values obtained. A local assessment of the actual horizontal stresses in these fields is necessary to properly determine the in-situ stress field of these three fields.

At Schoonenbeek Gas a total of four events were observed. The first event occurred in 1996. The other three occurred relatively recent in 2014, 2016 and 2017. For Schoonebeek Gas we may have underestimated the effect of the salt on the faults.

For the B-fields we generally derive SCU values well in access of 1. Again, we find four fields for which the SCU-values remain (just) too low for seismicity to have been induced: Emmen-Nieuw Amsterdam, Saaksum Oost, Vries Noord and Warffum. Though seismic events were attributed to these gas fields, the fact that these are B-fields means the seismicity could also be associated with a neighbouring gas field. Based on our assessment the first events attributed to Emmen-Nieuw Amsterdam and Vries Noord could also associated with, at the time of occurrence already active, Emmen and Roden gas fields, respectively. However, given the uncertainties of our analysis seismic activity in these fields cannot definitely be excluded either. For the gas field Warffum the SCU value is well below 1. It is therefore unlikely the field could have been seismically active. In fact, the field is adjacent to the very active, large Groningen gas field. Hence, the event of April 23, 2006 is very likely associated with the gas production from this gas field.

Saaksum-Oost is immediately adjacent to the Leens gas field, separated only by a single partially offset (normalized offset of ~0.83) fault. At the time of the only seismic event observed on December 25, 2006, the Leens gas field had been depleted by approximately 17.4MPa, while Saaksum Oost was depleted by 18.7MPa. The SCU value for this intra-reservoir fault between the two gas fields at the time of the event is 1.28. We conclude the event most likely occurred on this intra-reservoir fault and is due to the joint depletion in both fields.

Of the C-fields, our analysis indicates that an association with induced seismicity is very unlikely for the Den Velde ZEC, Eleveld NN, Groet, Oosterhesselen DC, Oostrum, Opeinde and Tjietjerkstradeel Vlieland (LC) gas fields. For all other C-fields an association with induced seismicity cannot be ruled out on the basis of our analysis.

There are two vertically stacked gas fields which may both be associated with induced seismicity: the Coevorden ZEC/DC and Dalen ZEC/DC fields. All reservoirs show clear SCU-values in excess of 1 at the moment the first seismic event was observed. Based on our analysis it remains impossible to distinguish which reservoir layer is more likely to have experienced seismic slip. Given the level of exceedance it is plausible the DC reservoirs are in fact the seismically active ones.

5.2. Summary

The presence of the viscous halite layers within the Zechstein evaporite formation may have a significant influence on the in-situ stresses on the (offset) faults of reservoirs within and immediately below this formation. The high horizontal stress within the salt is capable of wedging of the top of offset faults and significantly reduce the horizontal stress on the fault at reservoir level (Roest & Kuilman, 1994; Orlic & Wassing, 2013). At the same time, the active salt domes within the salt reduce the horizontal stresses on faults in reservoirs on top of these structures. Taking these effects of the visco-elastic salt into account significantly increases the SCU values obtained for the gas reservoirs affected. By considering the combined effect of fault configuration and the influence of the salt, more realistic estimates for the SCU values are obtained. In fact, these estimates allow us to for the first time qualitatively explain the observations of (non)occurrence of seismicity in the Dutch gas fields.

6. DISCUSSION

We have presented induced seismicity observations and the results of an analytical, geomechanical stress assessment for 180 depleted gas fields in the Netherlands. With our study we seek to identify general characteristics for depletion induced seismicity in the Netherlands and to qualitatively explain the (non)occurrence of seismicity. However, we do not claim their general validity.

Geomechanically, the onset of slip strongly depends on the in-situ stress conditions in the subsurface. In this study we have used the best and most recent data and analysis available (Verweij et al., 2016; Van Wees et al., 2014). Though this provides reasonable regional stress gradients it ignores local effects on reservoir faults due to dome formation underneath gas reservoirs (Jackson & Galloway, 1984) and possible salt intrusion (Roest & Kuilman, 1994; Ketterman et al, 2017). Several studies have shown that these local effects can significantly influence the stress regime of the faults and its seismic behaviour (Roest & Kuilman, 1994; Ketterman et al, 2017) and stress ratio's significantly lower than the LOT-derived in-situ stresses are required (and generally assumed without motivation) to model the occurrence of seismic slip in the Dutch gas reservoirs overlain by thick Zechstein evaporites (e.g. Roest & Kuilman, 1994; Van den Bogert, 2015; 2016; 2018; Buijze et al., 2017). Our results confirm this observation in a more general sense: the fast majority of the Dutch gas fields would be inactive if some process lowering the measured in-situ stresses would not be present. The influence of the Zechstein salt formation is currently the only plausible physical process capable of providing such a reduction of the horizontal stresses.

At the location of the Bergen and Bergermeer gas fields, in the NHP, as well as on the FP, the Zechstein halite formation is thin and the derived in-situ effective stress ratios are already low (~0.6). The effect of the salt increasing the general minimum horizontal stress in the reservoir rocks is minor. The gas fields in the north-east of the Netherlands are overlain by a thick Zechstein halite formation. Here the in-situ stresses have been increased significantly to effective stress ratios of almost 0.9. In our analysis we adopted a crude correction of the stress ratios reducing the LOT-derived σ_h/σ_v-ratio to ~0.7 for all offset faults in the Carboniferous, Rotliegend and Zechstein Carbonate gas reservoirs as suggested by Roest & Kuilman (1994). Implementing this adjustment in our analysis results in SCU-values for the seismically active gas fields at which slip is induced and seismic activity could occur. However, the exact impact of the presence of the Halite salt on the in-situ stress conditions and on the horizontal stresses of offset reservoir faults of the Zechstein Carbonate, Rotliegendes and Carboniferous reservoirs requires more research.

Our approach has not taken into account any local effects of salt intrusion geometry (salt lenses versus continuous, partial intrusion) or the fact that through salt intrusion the seismic behavior of the fault may become loading rate dependent (Ketterman et al., 2017). This is beyond the scope of our current analysis and requires more advanced numerical modelling techniques.

Our study focusses on the possibility of faults in the Dutch gas reservoir reaching failure conditions and onset of (aseismic) slip. This does not imply seismicity will occur immediately or even at all. An important aspect for the occurrence of an earthquake after the onset of slip on a fault is the subsequent loss of frictional strength (e.g. Scholtz, 1998). This implies that additional depletion is required after the onset of slip and prior to the nucleation of a seismic event. Hence, the predictive power of our analysis is very limited.

Assessing the geomechanical characteristics of depletion induced seismicity is complicated as relatively little seismic data is available and the attribution of events to specific gas reservoirs is often non-unique (Qcon, 2018). Our assessment is further hampered by the lack of subsurface information. Though oil- and gas operators in the Netherlands have detailed geological models of their gas fields, often based on 3D seismic data, public information is limited to production plans and structural maps. This necessitated a somewhat crude categorization of the fault offsets in just three categories: bounding faults, small offset faults (normalized offset of 0.25) and large offset faults (normalized offset of 0.75). Hence, our analysis is associated with large uncertainties and SCU values should be well below 1 (≤ 0.8) in order to conclude seismicity is unlikely for a particular field.

7. CONCLUSIONS

Geomechanical analytical computations were conducted to study the effect of fault configuration and in-situ stresses on the stability of bounding and internal, offset faults in 180 Dutch gas fields. Based on observation data from these gas fields, we investigate the prime causes for seismicity and the specific geomechanical characteristics differentiating seismic from non-seismic gas fields. Our assessment yielded the following conclusions:

- The log- and LOT-derived in-situ stress field in the Dutch subsurface in far from criticality. Especially for gas reservoirs in and below the Zechstein salt formations effective stress ratio's as high as $K' = 0.85 - 0.9$ have been derived.
- Given these in-situ stresses, failure cannot be achieved for the fast majority of the gas fields, except for a few highly over-pressured gas fields in the LT and the Bergen and Bergermeer gas fields in the NHP.
- The presence of the visco-elastic Zechstein salt formation probably plays a crucial dual role on the in-situ stress conditions. On the one hand, the high horizontal stresses in the salt increases the horizontal stresses in the reservoir rock, as observed in the LOTs, resulting in the very high effective stress ratio's. On the other hand, the high horizontal stresses may locally lead to intrusion and dilation of (sub-) vertical faults significantly reducing the local horizontal stresses on the fault at reservoir level.
- By implementing a crude in-situ stress correction this local effect of the salt is introduced in the analysis and failure conditions on offset faults in the gas fields definitely associated with induced seismicity are observed.
- Though the general influence of the salt domes on the overlying formations is well established, the exact impact of the local effect of the salt on the offset reservoir faults of the Zechstein Carbonate, Rotliegendes and Carboniferous reservoirs requires more research.
- A more detailed study taking into account the detailed geological information of reservoir and fault geometry available at the operators and the slip weakening behaviour of the frictional strength is required to obtain predictive power.

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APPENDIX A

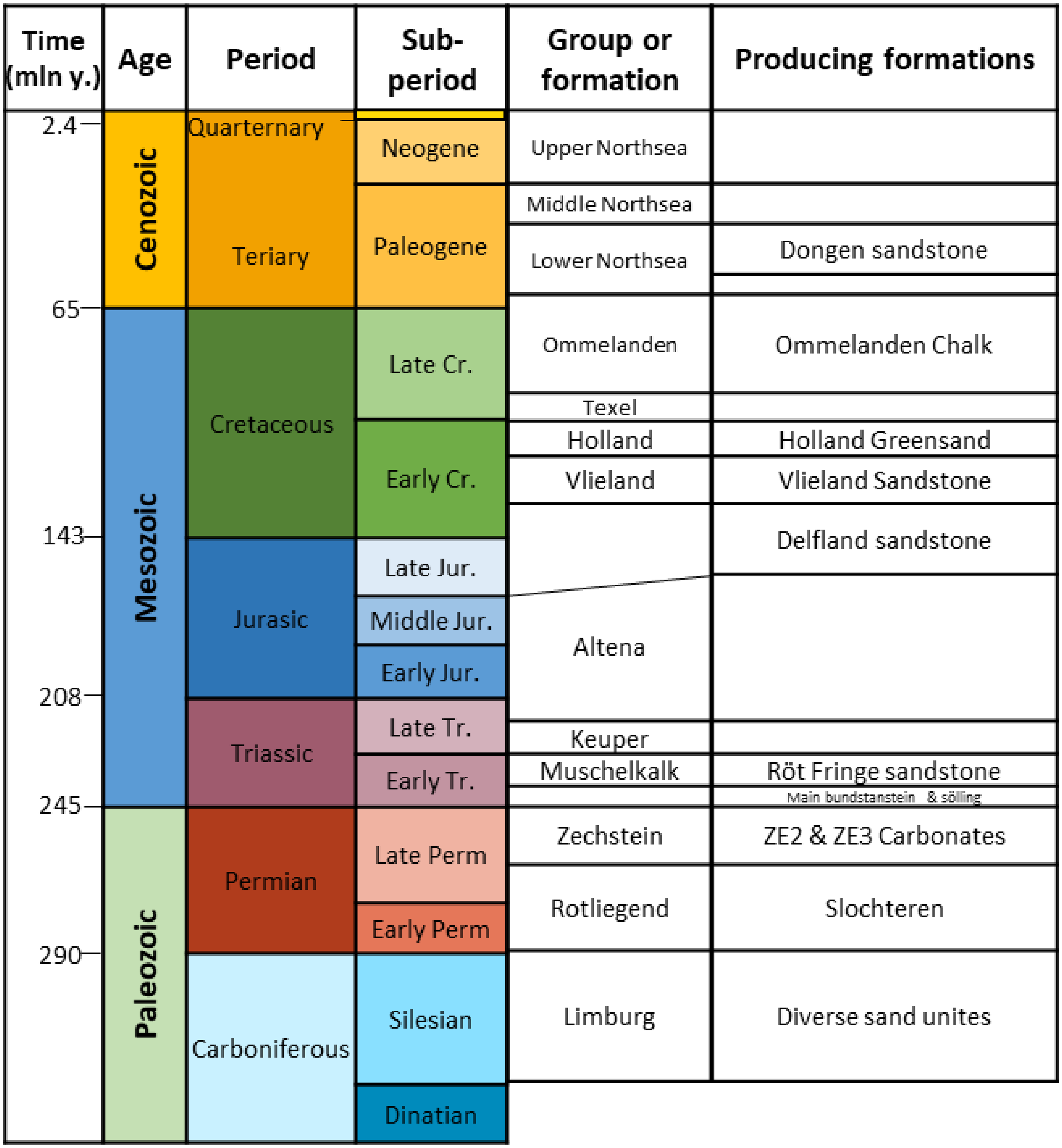

Fig. A-1. Stratigraphic column of the Dutch subsurface. More information can be obtained in the Stratigraphic Nomenclature available at https://www.dinoloket.nl/en/stratigraphic-nomenclature.