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Assessing the possibility of gas leakage through drilling induced fractures in shallow formations

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Samenvatting

Kunnen putten lekken via door boren veroorzaakte beschadigingen?

Wat is de hypothese? In recente literatuur wordt voorgesteld dat boren altijd breuken rondom het boorgat veroorzaakt die als migratiepaden dienen voor gas in ondiepe (< 1000 m diepte) sedimenten. Deze hypothese is in recente publicaties voorgesteld voor de sedimenten van de Nordland Groep onder de Noordzee in Noorwegen, maar wordt ook voorgesteld voor het equivalent in het Britse deel van de Noordzee. TNO heeft deze hypothese onderzocht door middel van een literatuuronderzoek dat zich richt op de mechanische eigenschappen van ondiepe sedimenten, de vervormingskarakteristieken en op de boorcondities die voorkomen in Noordzeeputten op de betreffende diepten.

Het ondiepe gedeelte van de aardlagen onder de Noordzee bestaat uit ongeconsolideerd (los sediment, geen vast gesteente) tot zwak geconsolideerd zand en klei. Deze studie heeft zich specifiek gericht op de mogelijke beschadigingen[1] die veroorzaakt kunnen worden door het boren in kleilagen. Van de kleilagen wordt immers verwacht dat ze fungeren als afdichtende lagen die opwaartse migratie van gassen (zoals methaan) tegengaan. Dit in tegenstelling tot de ondiepe (zeer) permeabele zandlagen. Daarom zijn alleen klei-vervormingsmechanismen en de integriteit van afsluitende lagen van belang als het gaat om potentiële migratiepaden.

Er is geen bewijs dat breuken geïnduceerd door boren migratiepaden voor gas vormen.

Uit TNO's literatuurstudie blijkt dat de hypothese onjuist is en er is geen bewijs gevonden dat geïnduceerde breuken migratiepaden vormen voor (ondiep) methaan. De belangrijkste bevindingen van de literatuurstudie zijn:

1) Ondiepe sedimenten deformeren plastisch. Het is daarom zeer onwaarschijnlijk dat er breuken in ontstaan.

2) Zelfs wanneer gesteenten voldoende verhard (geconsolideerd) zijn, ontstaan breuken alleen wanneer er tijdens het boren een te zware boorvloeistof wordt gebruikt. Echter, deze booromstandigheden worden niet toegepast in het ondiepe interval.

3) Voor zover bekend zijn er geen gepubliceerde gevallen van migratie van gas door geïnduceerde breuken.

1) Ondiepe gesteenten zijn plastisch.

Wetenschappelijke publicaties tonen aan dat de ongeconsolideerde kleien van de Noordzee een ductiele (plastische) respons vertonen die niet gepaard gaat met het creëren van blijvende beschadigingen (zoals breuken). Mechanische tests op klei-

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[1] In de artikelen wordt gesproken van "drilling induced fractures", ofwel door boren veroorzaakte breuken. Wij gebruiken het algemenere woord "beschadiging". Een breuk is een langdurig blijvende beschadiging.

monsters van ondiepe sedimenten van de Noorse Noordzee (Nordland Groep) tonen aan dat de kleien zo ductiel kunnen zijn dat ze uit de testapparatuur vloeiden tijdens de test en dus niet braken. Bovendien is gevonden dat bepaalde klei/schalies formaties uit de Noordzee, die dieper liggen dan het bestudeerde interval (dus dieper dan 1000 meter), ook geassocieerd zijn met een ductiele respons en dus in staat zijn tot kruip (creep), waardoor holten tussen de verbuizing/het cement en de formatie worden afgedicht.

2) Boren gaat niet gepaard met drukken waarop ondiepe gesteenten breken.

Geïnduceerde breuken kunnen theoretisch wel ontstaan wanneer: 1) het sediment voldoende geconsolideerd (verhard/bros) is en 2) wanneer het boorvloeistofgewicht de drukgradient overschrijdt waarop gesteenten breken. Uit gegevens over boorvloeistofgewicht blijkt dat de booromstandigheden in de ondiepe delen van de Noordzee gewoonlijk dicht bij de hydrostatische drukgradient liggen, dus onder de druk waarop gesteenten breken. Omdat aan de twee voorwaarden niet wordt voldaan, is de vorming van breuken in ondiepe, ongeconsolideerde (ductiel) tot zwak geconsolideerde sedimentlagen zeer onwaarschijnlijk.

3) Geen gepubliceerd bewijs van lekkage door breuken geïnduceerd door boren.

In het onwaarschijnlijke geval dat er op bepaalde locaties wel aan de beide voorwaarden zou worden voldaan, kunnen er door breuken tijdens het boren ontstaan. Echter, voor zover de auteurs hebben kunnen nagaan, bestaat er in de literatuur helemaal geen gepubliceerd bewijs van gasmigratie door boren veroorzaakte breuken.

Waargenomen lekkage heeft een andere oorzaak.

De door boren veroorzaakte beschadigingen kunnen dus niet worden beschouwd als een algeheel voorkomend mechanisme voor methaanmigratie voor ondiep gas in de Noordzee. Dit gezegd hebbende, putten kunnen via andere mechanismen lekken en er is sprake van waargenomen methaan bubbels boven verlaten putten in de Noordzee. Deze methaanmigratie dient dus verder onderzocht te worden. Dit om het optreden van methaanemissies in de Noordzee beter te begrijpen en waar mogelijk te bestrijden.

Summary

Can wells leak through drilling induced fractures?

What is the hypothesis? In recent literature it is proposed that drilling always creates fractures around the wellbore (drilling induced fractures) that serve as migration pathway for gas in shallow (< 1000 m depth) sediments. This hypothesis has been proposed in recent publications for the Nordland Group sediments underneath the North Sea in Norway but is also proposed for the British equivalent of the North Sea. TNO has investigated this hypothesis by means of a literature study that focuses on the mechanical properties of shallow sediments, their deformation characteristics and the drilling conditions that occur in the North Sea wells at the depths of interest.

The shallow part of the North Sea consists of unconsolidated (loose sediment, not solid rock) to weakly consolidated sand and shales layers. This study has specifically focused on drilling induced damage[2] (including drilling induced fractures) of shale layers. After all, the shale layers are expected to act as seals that prevent upward migration of gasses (such as methane). This in contrast to the (highly) permeable sand intervals. Therefore, only shale deformation mechanisms and seal integrity are of interest when it comes to potential leakage mechanisms.

There is no evidence that drilling induced fractures are migration pathways for gas.

TNO's literature review shows that the hypothesis is incorrect and that there is no evidence that drilling induced fractures serve as migration paths for (shallow) methane. The main conclusions from this study are:

1) Shallow sediments deform in a ductile manner. Therefore, it is highly unlikely that fractures form.

2) Even when rocks are sufficiently consolidated (brittle), fractures only occur when the drilling fluid (mud weight) is too heavy during drilling. However, these drilling conditions are not typically applied at shallow intervals.

3) To our knowledge, there are no published cases of gas migration through drilling induced fractures.

1) Shallow rocks are ductile.

Scientific publications show that the weakly consolidated shales of the North Sea exhibit a ductile (plastic) response, not accompanied by the creation of permeable fracture-like planes. Mechanical tests on shale samples from shallow sediments from the Norwegian North Sea (Nordland Group) show that the shales can be so ductile that the tested material flowed out of the equipment during the test and thus did not fracture. In addition, it has been found, that certain North Sea shales located even deeper than the studied interval (deeper than 1000 m) are also associated

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[2] The articles refer to "drilling induced fractures". We use the more general word "damage". A fracture is a long-term permanent damage.

with ductile response and are capable of creep, sealing the void between casing/cement and the formation.

2) Drilling does not involve pressures at which rocks fracture.

Drilling induced fractures can theoretically occur when: 1) the sediment is sufficiently consolidated (brittle) and 2) when the mud weight exceeds the pressure gradient at which rocks fracture. Mud-weight data shows that drilling conditions in the shallow parts of the North Sea are usually close to the hydrostatic pressure, i.e. below the local fracture gradient. Because the two conditions are not met, the formation of fractures in shallow, unconsolidated (ductile) to weakly consolidated sediment layers is very unlikely.

3) No published evidence of leakage from drilling induced fractures.

In the unlikely event that both conditions are met, drilling induced fractures can occur. However, to the authors' knowledge, there is no published evidence of gas migration from drilling-induced fractures in the literature at all.

Observed leakage has a different cause.

Drilling induced fractures cannot be considered as a common mechanism for methane migration for shallow gas in the North Sea. Nevertheless, well leakage can occur through other mechanisms and the observed bubble plumes above abandoned wells must be further investigated to better understand and mitigate methane emissions in the North Sea.

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1 Introduction

The subsurface of the North Sea can contain methane at various depths. We focus here on ‘Shallow Gas’, which is present in the upper most sediments (~1 km). As long as that methane remains underground, it does not contribute to climate change. However, some of the methane can migrate upwards and seep from the subsurface. This can take place as dissolved methane or as methane bubbles in the water-column, so called bubble plumes or ebullition. Although much of this released methane is absorbed in the water column, some of it will end up in the atmosphere and contribute to climate change as a greenhouse gas.

Methane seeps can occur naturally, but can also be caused by human activities. Methane emissions from abandoned boreholes in the North Sea have received the attention from Dutch governments since 2017, following the publication of reports stating that all wells drilled through shallow gas leak. This resulted in a scientific discussion whether drilling induced fractures could create a path for gas leakage along wells in shallow (< 1000 m) weakly consolidated sediments of the North Sea. One side of the argument (Vielstädte et al, 2015; Vielstädte et al, 2017; Böttner et al., 2020; Böttner, 2022) states that the gas migrates through these fractures and results in methane ebullition, leading to methane emissions. The other side (Wilpshaar et al., 2021) argues that fracturing of unconsolidated sediments is not likely or even impossible and consequently the leakage mechanism of drilling-induced fracturing is not realistic for the geographical settings at hand. The Dutch State Supervision of Mines (SodM) has asked TNO-AGE to conduct a study to assess the plausibility of drilling induced damage in shallow formations (<1000 m depth) acting as a leakage pathway for gas, under typical North Sea drilling conditions.

While well integrity issues that may favour the creation of leakage pathways concern mostly the casing, the cement and the interfaces between casing/cement and cement/formation, the publications mentioned above emphasise drilling-induced formation fractures as the dominant leakage mechanism along wells. In this study, the possibility of leakage through drilling induced fractures is examined by considering the formation characteristics of the upper shallow part of the North Sea and the drilling conditions of wells in the area of interest.

A literature review has been conducted to investigate the conditions that could lead to drilling induced damage, the types of drilling induced damage encountered, the failure mechanisms for different formation characteristics (brittle or ductile conditions) and the potential relation with permeability enhancement and leakage. It is then possible to estimate the drilling induced damage expected for shallow, weakly consolidated sediments in the shallow section (< 1000 m depth) of the North Sea and whether the formation of permeable and connected drilling induced fractures is a plausible scenario for the given in-situ and drilling conditions.

The shallow section of the North Sea consists of both weakly consolidated sands and shales. This study has focused only on drilling induced damage of shale units, as the shale intervals are expected to act as main seals to the migration of subsurface fluids and not the permeable sand intervals.

The report is organised in five sections:

- Drilling induced damage – literature study on the types and conditions of drilling induced damage
- Failure mechanisms of soft/ductile formations – literature study and examples of failure mechanisms of soft/ductile formations
- Nordland shale – literature study on the properties and deformation characteristics of the Nordland shale hosting the wells that show enhanced methane ebullition in the Norwegian North Sea
- Examples of other North Sea shales – literature study on two different shales/clays present in the North Sea comparing properties and deformation characteristics
- Discussion and conclusions

2 Drilling induced damage

Subsurface excavations are relevant in a number of applications such as hydrocarbon exploration and production, nuclear waste disposal, CO_2 storage, geothermal energy, tunnelling, et cetera. Drilling in the subsurface leads to material removal and redistribution of stresses around the open hole created. Stress redistribution around the open hole is usually accompanied by material deformation and in many cases damage.

While the type and location of damage around boreholes may inform on the direction and in some cases the magnitude of the in-situ stresses, wellbore instabilities may also pose risk affecting drilling efficiency, timing and success of a project. The type of wellbore instabilities strongly depends on the type of the formation, the in-situ conditions (stress, pore pressure) and operational parameters with the most important one being the drilling mud-weight, i.e., the pressure applied on the borehole walls. The most common wellbore instabilities consist of hole collapse, formation of breakouts (or cavings) and the formation of tensile fractures.

Depending on the formation characteristics, the instability mechanism observed may be controlled by the mud-weight applied (e.g. Lang et al., 2011) as illustrated in Figure 2-1. It is shown that there exists a safe mud-weight window for which efficient and successful drilling is achieved. However, for mud-weight values lower than the in-situ fluid pressure (pore pressure gradient), hole collapse is likely to occur while for slightly higher mud-weight violating the compressive strength criterion of the formation (breakout pressure gradient), borehole breakouts are expected. As the mud-weight increases above the minimum stress gradient, it is possible that fluid might leak into the formation leading to mud losses and lastly for high mud-weight values above the breakdown pressure gradient, tensile fractures are observed.

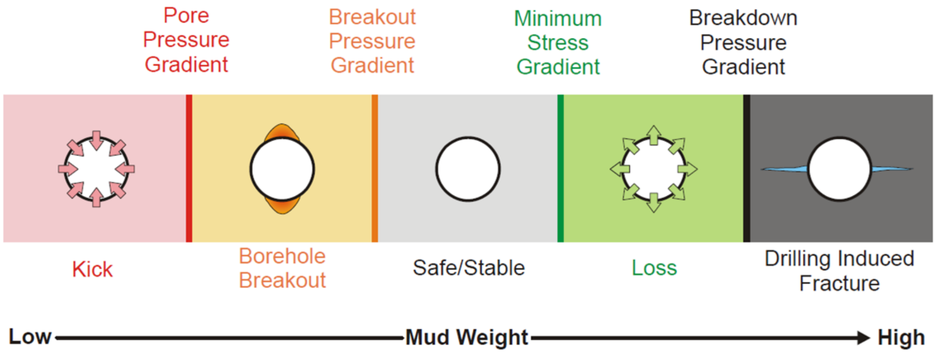


Figure 2-1 The concept of safe Mud Weight windows for drilling (from Rasouli and Evans, 2010).

Borehole breakouts are described as stress-induced enlargements of the wellbore-section (Bell and Gough, 1979) through the development of intersecting conjugate shear planes causing pieces of wellbore wall to spall off. The drilling-induced fractures develop as narrow sharply defined features due to tensile failure when the stress concentrated around the borehole exceeds the tensile strength of the material (Aadnoy, 1990).

Based on the in-situ stress field prior to drilling, the formation pressure and the pressure applied on the borehole walls (mud weight), it is possible to calculate the redistributed stresses around the wellbore based on the Kirsch theory (e,g, Zoback, 2010). Figure 2-2 (left) shows the in-situ principal stresses prior to excavation (σ_{Hmax}, σ_{hmin}) and the near-wellbore stresses after excavation at a given location. The distribution of the stresses around the well is illustrated in Figure 2-2 (right) for half of the well section. The maximum stress develops at angles -90/90° (location of σ_{hmin} prior to excavation) and the minimum stress at angles 0/180° (location of σ_{Hmax} prior to excavation). Therefore, the location of damage depends on the stress concentration and whether the thresholds for compressive or tensile failure of the formation are violated (e.g. Zoback 2010).

For a vertical well, borehole breakouts appear in the direction of the minimum horizontal in-situ stress where compressive stresses are expected to be maximum, while drilling-induced fractures appear in the direction of the maximum horizontal in-situ stress where the stresses are expected to be minimum/tensile (Figure 2-2, right).

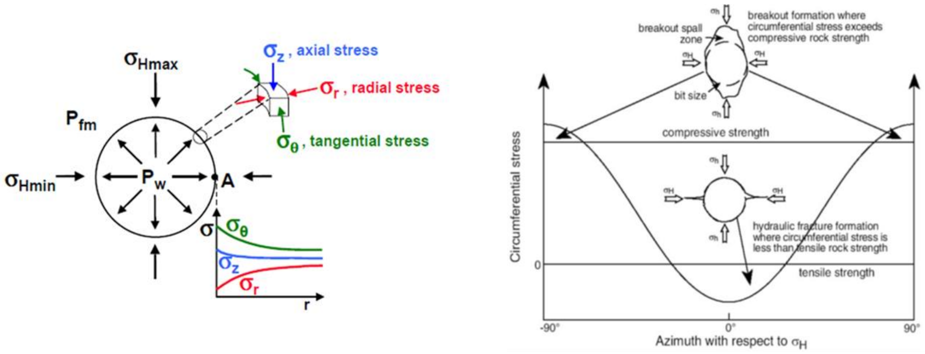


Figure 2-2 Left: Near-wellbore stress concentration induced by drilling a wellbore (from Hawkes et al., 2000); Right: Schematic cross-sections of borehole breakout and drilling-induced fracture (from Tingay et al., 2008 adapted from Hillis and Reynolds, 2000)

It is understood that, both the breakouts and drilling induced fractures may lead to the creation of distinct failure planes in the formation. Whether this type of failure is possible and whether such planes can act as leakage pathways depends on the material brittleness (e.g. Evans et al., 1990; De Paola et al., 2009).

When drilling in shales, both brittle and ductile conditions may be encountered. Brittle shales usually characterised by high compaction and low porosity, are expected to form breakouts in underbalanced conditions resulting in hole enlargement Figure 2-3 top, right). On the other hand, ductile (or Gumbo) shales usually found at shallower depths and characterised by high clay contents and high porosity may potentially experience swelling and exhibit plastic failure resulting in hole closure (Alfred and McCaleb, 1973) (Figure 2-3 top, left). The different possible instabilities encountered when drilling in shales are shown schematically in Figure 2-3 (bottom). The brittleness of the formation is controlled by multiple factors investigated in the following section.

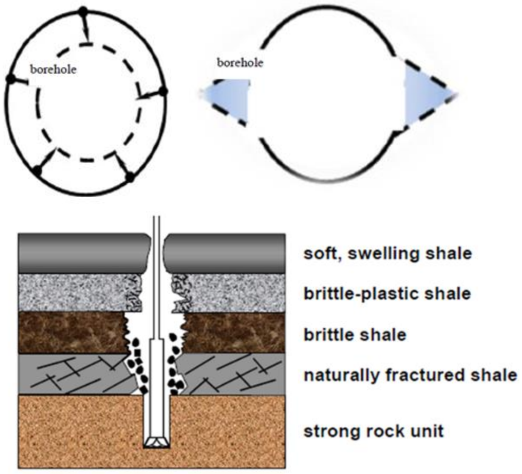


Figure 2-3 Top: homogeneously reduced hole (left) and produced cavings/break-outs (right). Ductile shale exhibits plasticity (left) while brittle shale causes hole enlargement (right) (from Islam et al., 2009). Bottom: Typical occurrences of wellbore instability in shales (from Hawkes et al., 2000)

3 Failure mechanisms of soft/ductile formations

3.1 Brittle vs ductile deformation

Shale behaviour and whether it is brittle or ductile under failure, depends on a number of factors that include consolidation history, confining pressure, drained or undrained conditions, mineral composition, temperature and fluid exposure (e.g. Holt et al., 2015). Estimation of the shale brittleness is relevant in many applications such as wellbore stability, hydraulic fracturing or abandonment operations of old wells. An important aspect of brittle vs. ductile deformation is the overconsolidation ratio (OCR = σ'_p/σ'_z) of the formation (e.g. Nygård and Gutierrez, 2002). In soil mechanics context, the consolidation history is expressed through the overconsolidation ratio which is defined as the maximum vertical stress experienced by the formation (preconsolidation stress, σ'_p) over the present vertical stress (σ'_z) and it indicates whether the present stress state is close to or lower than the maximum stress that the formation has ever supported. The OCR can take values of 1 or higher. For values equal to 1 the formation is characterised as normally consolidated and for values higher than 1 the formation is characterised as overconsolidated. A normally consolidated material has undergone loading such that the effective stress has reached equilibrium with the overburden effective stress through mechanical compaction and dissipation of excess pore pressure. Overconsolidation can result from unloading phenomena leading to lower effective vertical stress.

OCR of the material can be estimated through lab tests (Mayne, 1988) where the sample is loaded hydrostatically (equal stresses at all sides of the sample). The brittleness of the material can then be estimated through the pre- and post- failure response as the axial stress increases (triaxial conditions) resulting in the sample yielding and eventually failing. The short-term response under mechanical loading is dictated by several factors including the consolidation history (OCR), the confining stress, whether the material is loaded under drained or undrained conditions (pore fluid can escape or not), the loading direction with respect to the direction of anisotropy, the temperature and the fluid exposure (Holt et al., 2015). Focusing on the consolidation history and the confining pressure, Figure 3-1 (left) shows the Mohr diagram and the possible modes of failure and fracturing (Nygård et al., 2006) depending on the stress conditions. It is observed that at negative or low compressive stresses, mixed-mode extensional-shear fractures are expected to form, at intermediate confining stresses, brittle behaviour is observed with the formation of shear fractures and with increasing confinement, the behaviour becomes ductile with a more diffused deformation. The effect of OCR and confining pressure is also illustrated in Figure 3-1 (right) showing a brittle and dilative response with a significant strength decrease after failure for OCR larger than 1 and a ductile and contractive response without stress drop for OCR equal to 1. In terms of confining pressure, at high confining pressures (P’ high), the material behaves in a ductile manner and at lower confining pressures (P’ low), it behaves in a brittle manner. A brittle-ductile transition at intermediate confining stress (P’) may also be observed in many cases.

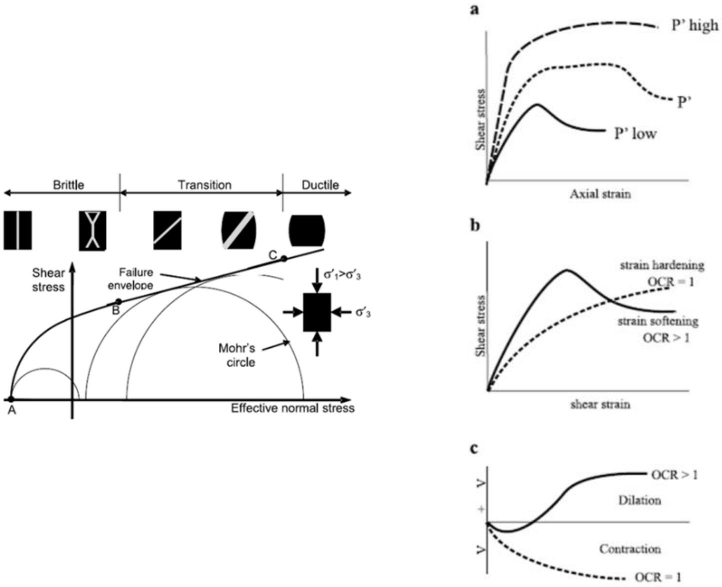


Figure 3-1 Left: Mohr diagram showing possible modes of failure and fracturing as a function of the confining stress (after Nygård et al., 2006); Right: (a) Brittle, transitional and ductile behaviour of mudstone with increasing confining pressure, in shear stress (τ) – axial strain (ε) – space. (b) Influences of the OCR on the brittle-ductile behaviour of mudstone deformation. (c) Variable volume changes in function of OCR (from Nygård and Gutierrez, 2002).

It is understood that under brittle conditions, distinct fracture-like features are expected that could potentially enhance the permeability of the formation, while under ductile conditions, plastic response results in more diffuse deformation not usually accompanied by permeability increase (Nygård et al., 2006; Petrini et al., 2021). Based on the above, the same material may exhibit brittle or ductile response or a combination depending on consolidation history and confining pressure. Therefore, the determination of formation brittleness is not straightforward, and a single index does not exist that classifies formation as brittle or ductile under given conditions.

The sediments where shallow gas accumulations are encountered, consist of unconsolidated or weakly consolidated formations (TNO report TNO2019 R11562) with a high content of clay minerals, mainly illite and smectite. Experimental data that would determine whether the formation exhibits a ductile or brittle response under in-situ conditions are rare.

Experimental studies to determine shale brittleness for hydraulic fracturing, wellbore stability or shale barriers after well abandonment (Nygård et al., 2006; Holt et al., 2011; Nygård and Gutierrez, 2013; Fjçr and Nes, 2013; Holt et al., 2015; Holt et al., 2019), have shown that shales with higher porosity, and higher clay content (and lower cementation within the rock matrix) behave as normally consolidated and deform in a ductile manner with a less localised shear band and distributed failure outside the shear band. According to the references stated above, such conditions may be encountered in the overburden shales in the North Sea that are also fully brine saturated under in-situ conditions. Shales with lower porosity and clay content (and high cementation) were characterised as overconsolidated and failed with the formation of open shear fracture under triaxial conditions. Shales that exhibit highly brittle response usually represent unconventional shale gas formations. Figure 3-2 shows examples of different failure modes under brittle and ductile conditions.

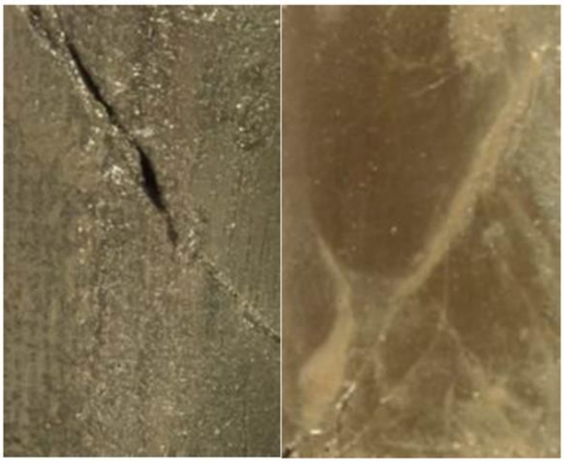


Figure 3-2 Left: Image of overconsolidated shale (Pierre I shale, North America) showing the formation of an open shear fracture post-failure. Right: Image of normally consolidated shale (B shale, North Sea) showing a less localised shear band as well as distributed deformation outside the band after the test (after Holt et al., 2019)

For the investigation of barrier forming shales, hollow cylinder experiments showed that creep is more profound in weak unconsolidated formations. More specifically, the formations observed to repeatedly form barriers are high porosity weak rocks with high amounts of clay minerals and in particular smectite, and low amounts of carbonates and quartz (Brendsdal, 2017 and references therein). It has therefore been proposed that shale barriers are associated with ductile behaviour involving mechanisms such as creep and plastic deformation (Holt et al., 2019).

4 Nordland shale

The debate about drilling induced fractures started with the publications of Vielstädte et al., 2015 and 2017 in which they describe bubble plumes of biogenic methane observed at three abandoned wells in Norway (Figure 4-1). Vielstädte et al., 2015 describe the seal as following: “The interval from 300 m below sea floor down to the Utsira Formation thus consist of clay-rich sediments known as Nordland Shales (Horvig,1982) largely acting as a seal for upward migrating fluids, except for sections with pre-existing or pressure-induced fractures.”

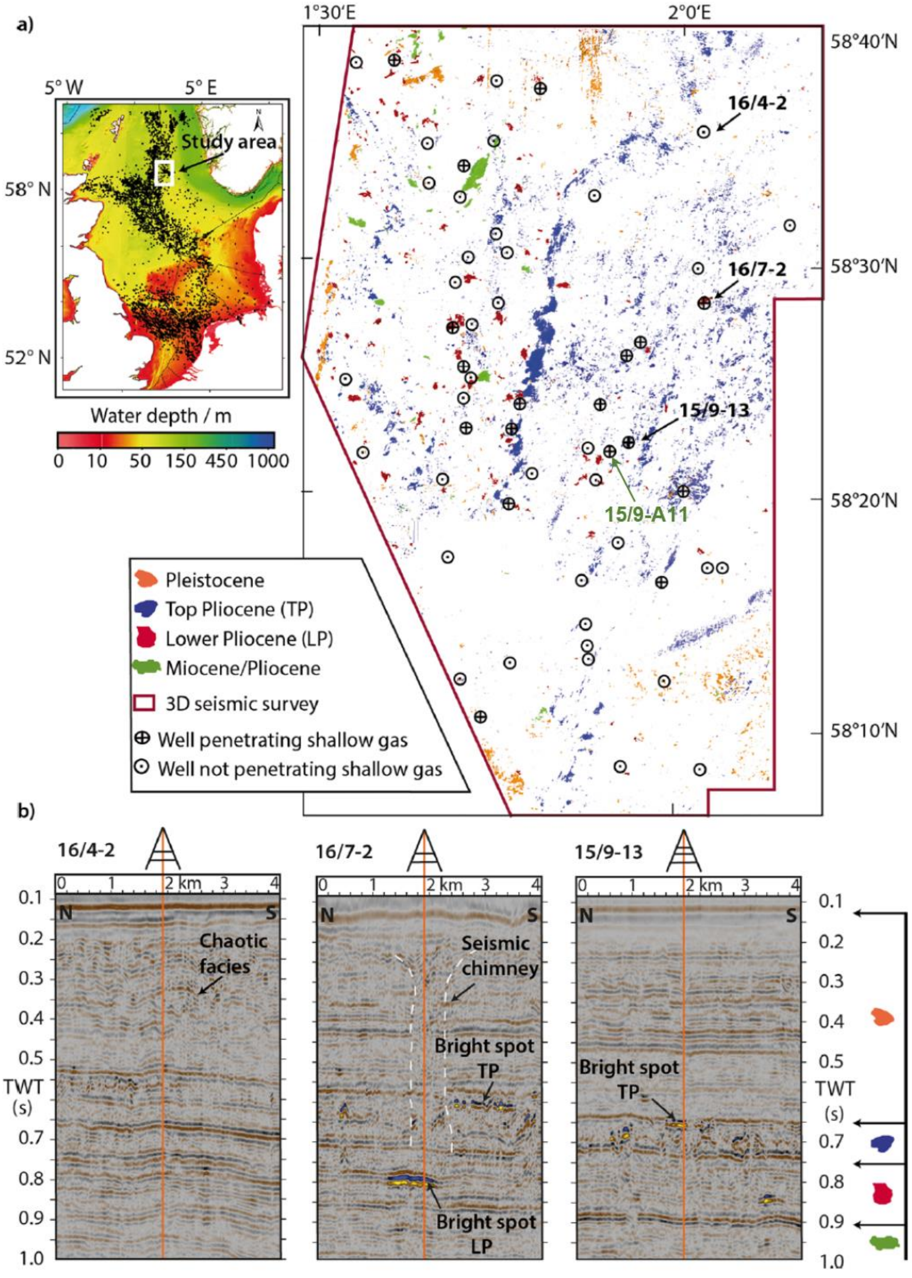


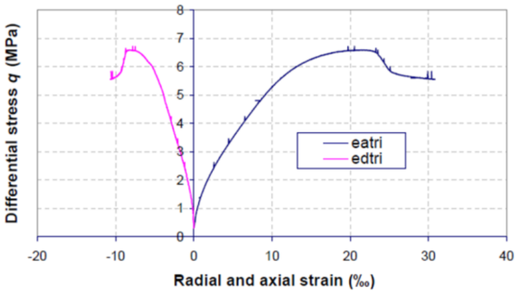
Figure 4-1: Modified from Vielstädte et al., 2015. Above three abandoned wells a bubble plume was observed. The bubbles consisted of methane of a biogenic origin.

Regarding the leakage mechanism they conclude: “Thus, leakage problems often are compounded by geotechnical fracturing of sediment around the well bore and by insufficient filling of these fractures with cement, resulting in a fracture system along the well (Gurevich et al.,1993).” In addition, they state: “Nordland Group sediments from ~300 m below sea floor down to the Utsira Formation primarily consist of clay as indicated by high gamma ray values in the well logs. Therefore, they provide an efficient barrier for capillary gas invasion holding gas at a higher pressure than sand. Hence, strata-crossing upward migration of gas should only be possible along secondary, either natural or well-induced pathways.” Lastly, in Vielstädte et al. (2017), the authors state that: “Drilling disturbs and fractures the sediment around the wellbore mechanically, thereby creating highly permeable pathways for the buoyancy-driven migration of the gas” attributing the presence of well-induced pathways to drilling induced fractures in the sediments.

In the following, we investigate the possibility of the formation of drilling induced fractures in the Nordland group sediments considering the mechanical response of the formation with the data available regarding the Nordland shale. It is shown that the Nordland shale is a very good representation of the shale layers in the Dutch North Sea. In addition, the drilling conditions usually applied during drilling at shallower depths in the North Sea are examined, to investigate whether overbalanced drilling has been applied at this depth.

4.1 Nordland shale mechanical characterisation

To investigate the possibility of the formation of drilling induced fractures in the Nordland shale, mechanical characterisation data are necessary. For the evaluation of the long-term seal integrity during CO_2 geological storage at the Sleipner field in the North Sea, rock mechanical triaxial tests have been performed on Nordland Shale in a study by Pilliteri et al. (2003). The Nordland shale samples were characterised by a porosity of 35%, clay content of 55% and they were taken from well 15/9-A11 (see Figure 4-1(a) for the well location). This well is only 1650 m away from one of the wells (15/9-13) where Vielstädte et al., (2015, 2017) reported leakage due to drilling induced fractures. The tests were performed at different confining pressures and they revealed an almost elastic-perfectly plastic behaviour with no fracturing observed (Figure 4-2). It should be mentioned that at the lower confining pressure tested (5 MPa), the test failed because the sample “flowed” through and plugged the serrated plate. This elastic-perfectly plastic response with a low Young’s modulus indicates that fracturing is very unlikely in the shales of the Nordland group (Skurtveit et al., 2018).



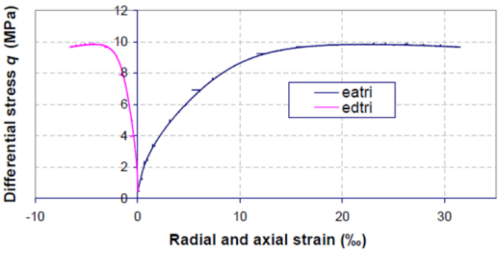


Figure 4-2 Differential stress q versus axial and radial strain at confining pressure of 9 MPa (top) and 13 MPa (bottom) (from Pilliteri et al. 2003).

4.2 Nordland Group, lateral equivalent of the Dutch Upper North Sea Group

Nordland shales are characterised as weakly consolidated and are considered to be a time-equivalent formation to the Upper North Sea Group of the Dutch sector (see Figure 4-3, Figure 4-4 and Figure 4-5) and thus the two materials' history and properties are not expected to differ significantly. As shown in Figure 4-3 the porosity of sampled mudstones up to 1000 m TVDss is in the range of the initial porosity value of the Nordland shale core samples. In addition, for the specific porosity range, the clay content values range from 40-to-60%.

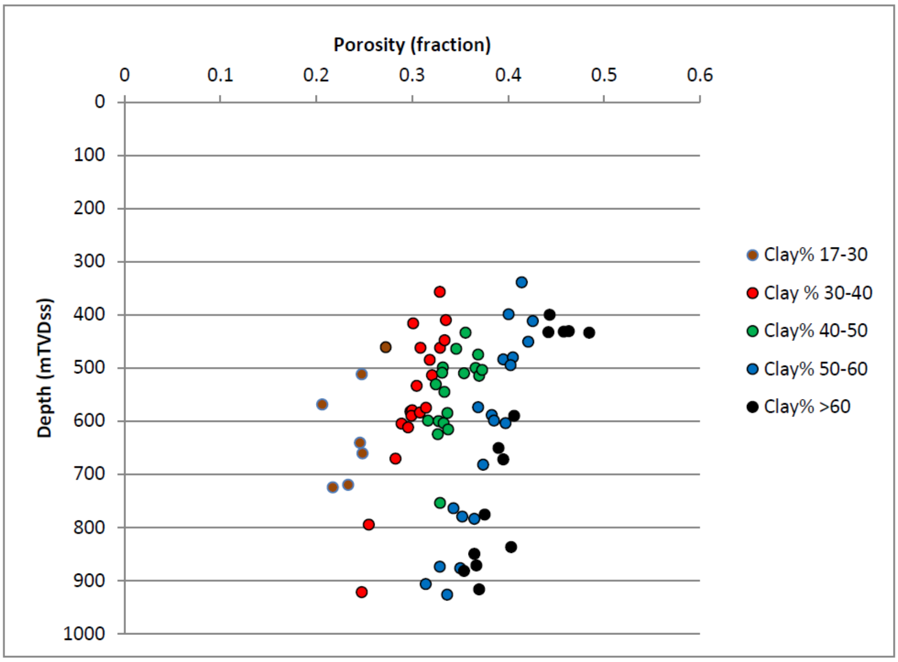


Figure 4-3: Cross-plot of calculated porosities of sampled mudstones from the Dutch Northern Offshore versus depth for different clay contents (from TNO 2013 R10060).

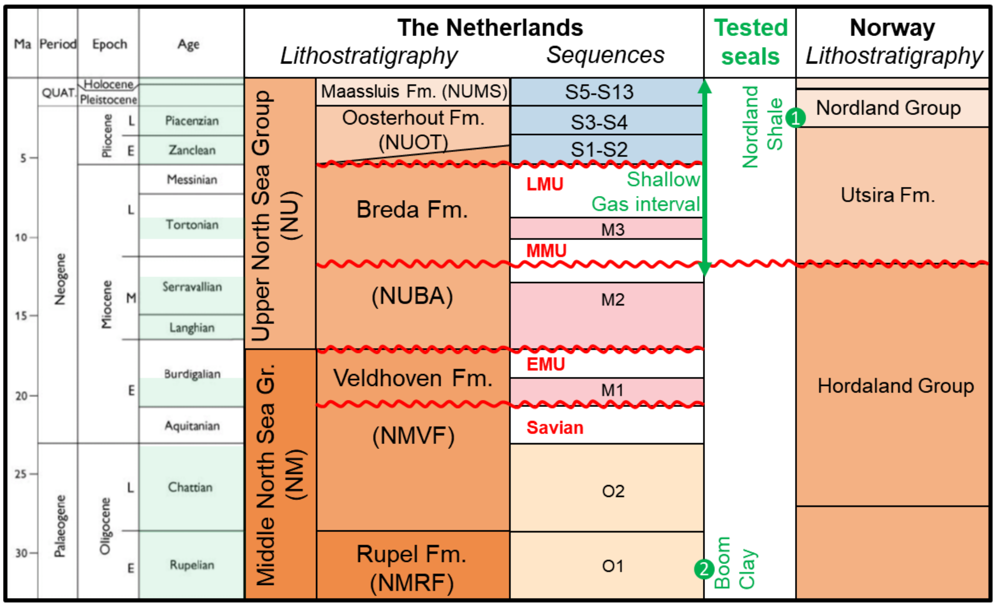


Figure 4-4: Stratigraphic columns of the Dutch and Norwegian North Sea. Note that the Shallow gas interval is found above the Mid Miocene Unconformity (MMU) in both the Netherlands and Norway. The Nordland shale is a lateral equivalent of the Dutch Shales. They are both part of the same sedimentary system. Therefore, the Nordland shale is a very good representation of the shale layers in the Dutch North Sea. The Boom Clay is found below the interval that contains the shallow gas. EMU: Early Miocene Unconformity, LMU: Late Miocene Unconformity. After: TNO R10425.

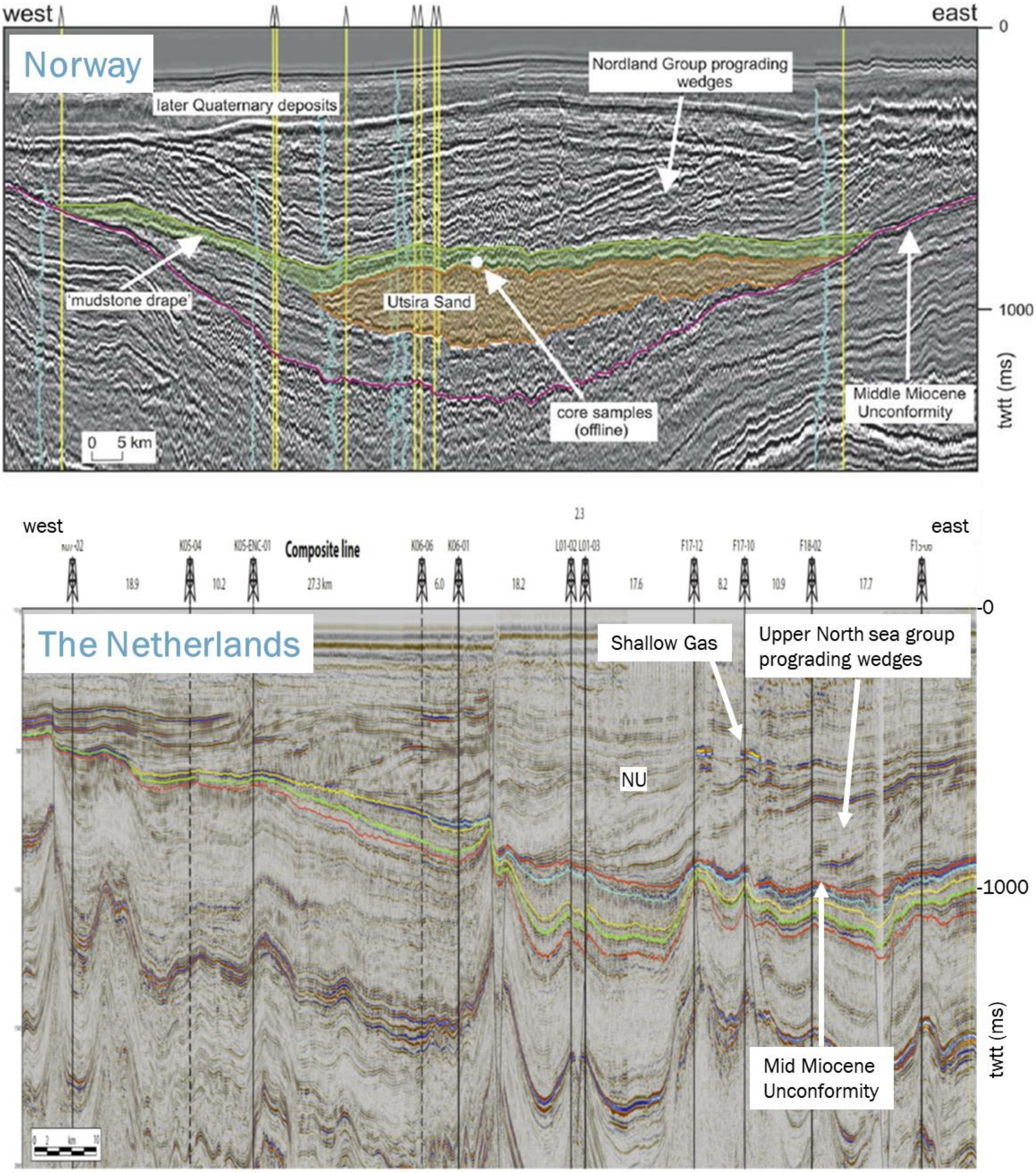


Figure 4-5: Seismic comparison between shallow sediments in Norway and the Netherlands (from https://doi.org/10.1016/j.marpetgeo.2003.12.002; TNO Report 2017 R10425). The image at the bottom was squeezed to match the scale of the image at the top. This was done to show that both intervals are of the same age and the same depth interval. Basically, The Nordland shale is a lateral equivalent of the Dutch Shales. They are both part of the same sedimentary system. Therefore, the Nordland shale is a very good representation of the shale layers in the Dutch North Sea.

4.3 Drilling conditions in the Dutch North Sea area

It has been discussed that weakly consolidated shales such as the Nordland shale encountered in the shallow gas sections of the North Sea tend to behave in a ductile manner where fracturing is very unlikely and therefore leakage through drilling-induced fractures is not a realistic scenario. Nevertheless, assuming that fractures may form even at shallower depths, the formation of drilling induced fractures requires that the mud-weight exceeds the fracture pressure gradient, i.e. the pressure at which a fracture will be formed in the formation. The fracture pressure gradient is usually estimated through leak-off tests where fluid is injected in the formation until a pressure drop is observed denoting the creation of a permeable path (Addis et al., 1998). For Dutch North Sea, the used mud-weight pressure is plotted against the hydrostatic pressure line as shown in Figure 4-6 (left). For the depth of interest (up to 1000 m approximately), the mud-weight pressure applied is close to the hydrostatic line, implying that these wells were not drilled under overbalanced conditions. In addition, if the mud weight value at 1000 m is plotted in the leak-off pressures plot (Figure 4-6, right) for the North Sea Supergroup (N: orange points), it can be seen that the point lies comfortably below the fracture pressure gradient (TNO report TNO2015 R10056). Therefore, the formation of fractures due to overbalanced drilling does not occur at the depth of interest in the Dutch North Sea considering the drilling conditions.

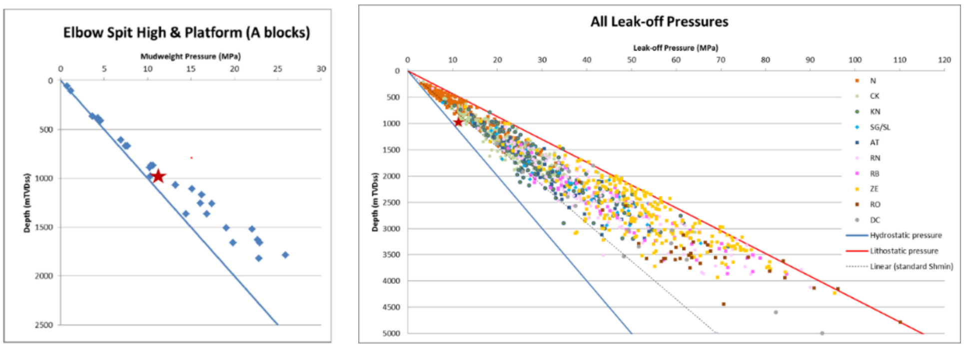


Figure 4-6 Left: Multi-well cross plot showing mud-weight pressure versus depth in the North Sea Supergroup in the Elbow Spit High & Platform. Right: Cross plot of all leak-off pressures versus depth for the main stratigraphic units (from TNO report TNO2015 R10056). The red star in both plots denoted the maximum depth of interest (1000 m). N is the entire North Sea Supergroup, which consist of the Lower-, Middle, and Upper North Sea Group. Almost all shallow gas is found in the Upper North Sea Group.

Furthermore, when a well is constructed in the Dutch North Sea, a large diameter steel pipe (typically 26 to 42 inch) is pile driven into the ground. This pipe is called the stove pipe or conductor, and it is driven about 50 to 70 m into the ground. It runs all the way up to the drilling floor compressing the surrounding sediments. Drilling is then commenced inside this pipe. This means that the upper sediments (50 to 70 m below the sea floor) will never come into contact with the drilling fluids at any point during or after the drilling operation. Therefore, drilling induced fractures cannot form there.

4.4 Drilling induced fractures are highly unlikely in shallow North Sea Shales

In conclusion, the triaxial tests show that fracturing is highly unlikely in the shales of the Nordland group, and mud-weight pressure data from the Dutch North Sea demonstrate that overbalanced drilling (which could lead to the formation of fractures) does not occur at the shallow gas interval. Therefore, the hypothesis that all wells in this interval leak through drilling-induced fractures is not supported by any scientific evidence.

5 Examples of other North Sea shales

We have established that drilling induced fractures are highly unlikely for shallow shales of the North Sea (in which shallow gas is found). However, it is useful to investigate at which depth, age and shale characteristics drilling induced fractures could occur. Therefore, a literature review of deeper and older shales will be presented below. Both formations presented are encountered in the North Sea (Dutch or Norwegian) and lie below the weakly consolidated, upper sediments. The formations presented in the following are the Boom clay and the Draupne formation (Figure 5-1).

The formations reported are shale formations or argillites and the experimental studies have been performed in the context of CO_2 and nuclear waste storage. Both shales and argillites are characterised by a high content in clay minerals and a layered structure (Brendsdal, 2017 and references therein). Despite their shared characteristics, these formations may exhibit different response in terms of brittle or ductile conditions.

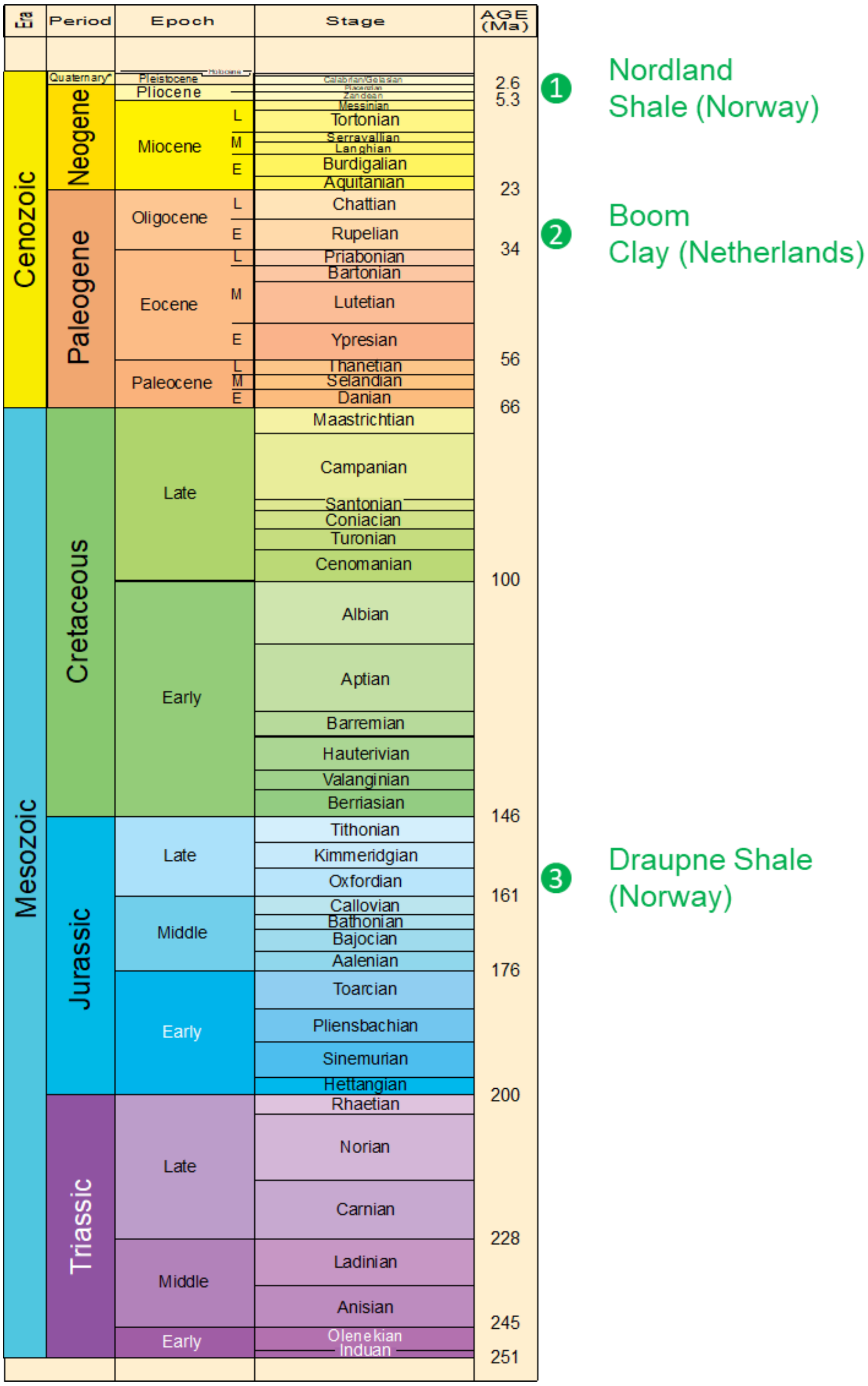


Figure 5-1: Geological time scale showing the ages and location of the different types of shales/clays that have been experimentally tested and presented in the following section.

5.1 Boom clay

The Boom clay (Early Oligocene) has been extensively studied as a host rock at the nuclear waste storage facilities in Mol, Belgium. It is considered a lightly overconsolidated material, also encountered in the Netherlands and is part of Middle North Sea Group. The Middle North Sea Group is stratigraphically below the interval that contains most of the shallow gas in the Dutch North Sea (see Figure 5-2). The clay content ranges from 25-60% approximately and the porosity is measured at 35-45% (Wiseall et al., 2015 and references therein). Due to the presence of smectite, it has been observed that the material may experience swelling under specific conditions. The response of the Boom clay during deviatoric loading appears to be strongly affected by the swelling experienced during the isotropic stage preceding triaxial compression through an apparent reduction in overconsolidation and therefore increased ductility (Sultan et al., 2010). More specifically, the longer the swelling before shear, the more the response under shear becomes ductile and the lower the initial stiffness.

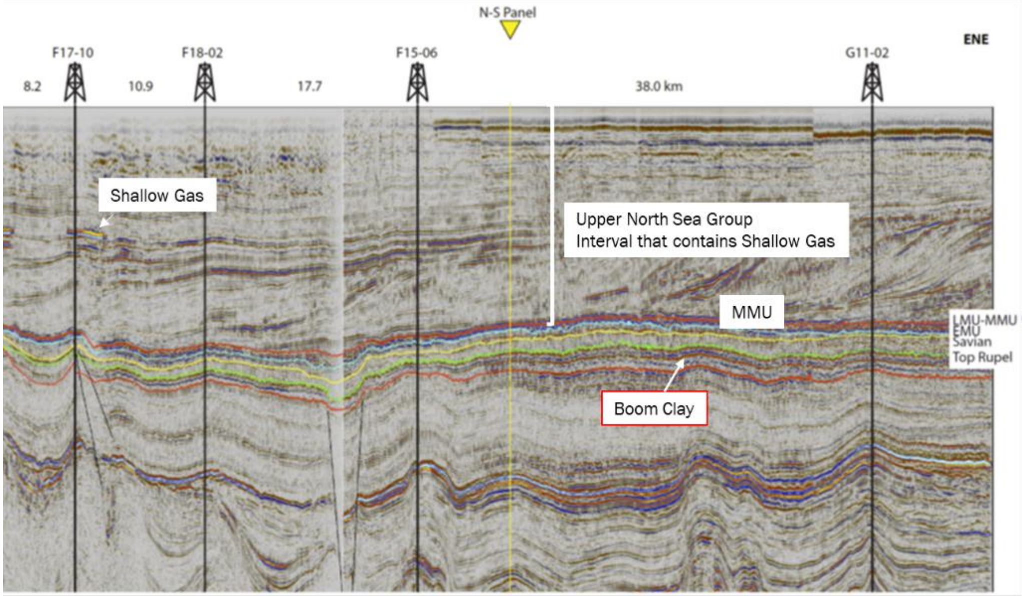


Figure 5-2 Boom clay in the Dutch North Sea (from TNO Report 2017 R10425). The Boom Clay is found below the interval that contains the shallow gas.

Hydromechanical tests on Boom clay samples have also been performed and it has been reported that fractures that may develop in the Boom clay tend to seal very fast. More specifically, it has been shown that artificially created fractures tend to close fast (after 4-5 hours) only due to saturation of the sample, in the absence of loading (Bastiaens et al., 2007; Bernier and Bastiaens, 2011). During the experiments, the sealing was confirmed through hydraulic conductivity measurements with the values measured after fracture closure being close to the undisturbed (intact) value. Figure 5-3 shows the sealing of the fracture after hydration.

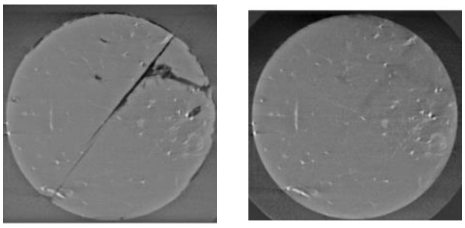


Figure 5-3 SELFRAC Self-sealing experiment. µCT images of artificially fractured clay sample: (a) taken after creation of artificial fracture; (b) taken after 4-5 h of hydraulic conductivity measurement (from Bastiaens et al., 2007).

5.2 Draupne formation

The Draupne formation is present in the Norwegian North Sea and is the main caprock in the Smeaheia site considered for CO_2 injection. The Draupne shale is a consolidated, organic-rich shale deposited during the Late Jurassic (Gabrielsen et al., 2020). A series of mechanical tests have been performed on the Draupne formation using cores sampled from a depth 2574.5–2583.5 m MD at well 16/8-3S (Figure 5-4) (Mondol, 2019; Soldal et al., 2021). The average initial porosity of the samples was 15.1% while the clay fraction constituted roughly 50% of the material with kaolinite, smectite and illite being the main minerals. The location of the well from which the samples were cored is in the vicinity of the area studied by Vielstädte et al. (2015), approximately 39 km from well 15/9-13 (Figure 5-5). The Draupne formation is present at much greater depths (> 2 km) than the depth of interest for shallow gas accumulations.

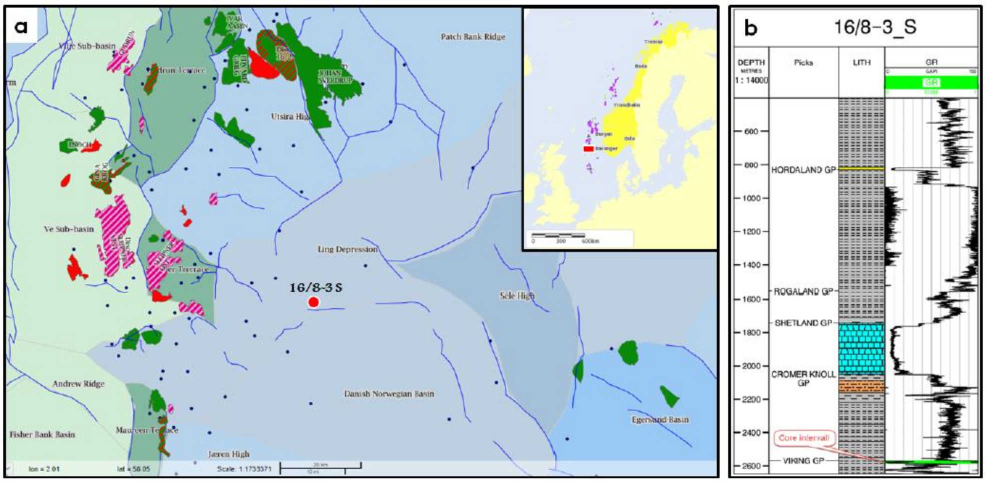


Figure 5-4: a) Index map overlaid with major structural elements of the Central North Sea). Location of the studied Lupin well (16/8-3 S, red circle) in the Ling Depression is shown on the map. Map modified from the Norwegian Petroleum Directorate (NPD FactMaps, 2019) and b) Gamma Ray Log of Lupin well showing a generalized lithostratigraphy and location of the core interval (Skurtveit et al., 2015), from Mondol (2019).

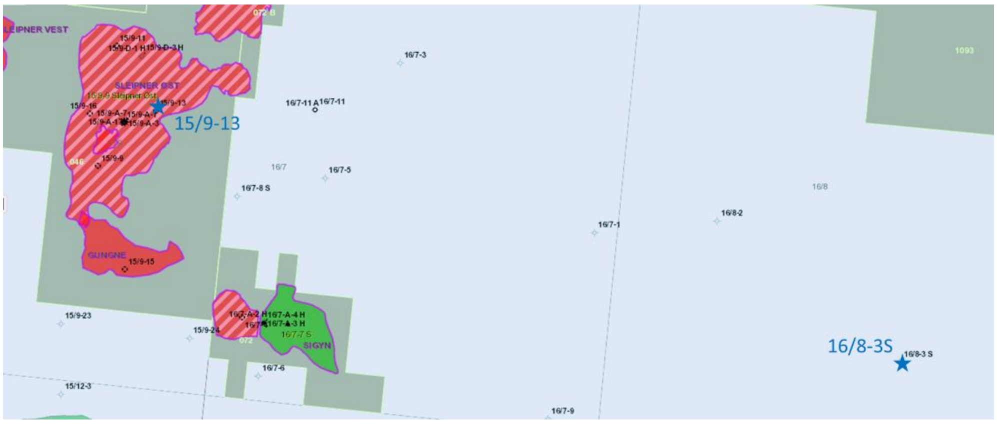


Figure 5-5: Location of well 16/8-3S from which the Draupne shale samples were cored from a depth of 2574.5–2583.5 m MD. The location of well 15/9-13 is also shown that has been studied by Vielstädte et al. (2015) (NPD FactMaps, 2022). The well of the Draupne formation cores is in the vicinity of the studied area by Vielstädte et al. (2015) and approximately 39 km from well 15/9-13.

In a study by Soldal et al. (2021), mechanical tests were performed that consisted of oedometer and undrained triaxial tests. The OCR of the Draupne formation was found to be slightly higher than one implying a normally consolidated to lightly overconsolidated shale owing also to diagenetic processes. Triaxial testing of the material was performed at different loading directions (perpendicular and parallel to the bedding planes) and resulted in the formation of shear fractures whose orientation was dependent on the bedding plane orientation. The shear stress – vertical strain curves from the triaxial tests are shown in Figure 5-6.

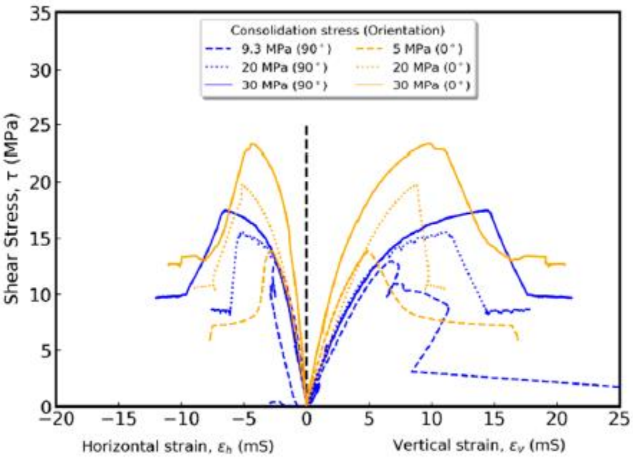


Figure 5-6: Vertical and horizontal strains versus shear stress from tests on samples oriented perpendicular to layering (blue) and parallel with layering (orange) (from Soldal et al., 2021). The drop in the shear stress after the peak indicates the formation of a failure plane.

It is understood, that depending on the formation characteristics, formations that are present in the North Sea may exhibit different behaviour in response to mechanical loading. It has been shown that generally the overconsolidation ratio (OCR) is a good indicator of the brittle or ductile behaviour. However, while both Boom clay and Draupne shale are characterised by a similar OCR, they exhibit a different response under mechanical loading. This is attributed to differences in diagenetic processes resulting in reduced or increased apparent pre-consolidation that will yield in a more or less ductile material. Regarding the Norwegian North Sea sector, mechanical tests on the Draupne formation sampled from depths greater than 2 km showed that shear-induced or tensile fractures due to overbalanced drilling may form within the formation. Nevertheless, this is not occurring at the depth of interest where shallow gas pockets accumulate.

6 Discussion and conclusions

Drilling induced damage near boreholes may take various forms with the most common and important types of failure being the shear and tensile failures accompanied by the formation of breakouts and drilling induced fractures, respectively. This is particularly true for failure under brittle conditions, while for more ductile formations, hole collapse is a more common wellbore instability (Alfred and McCaleb, 1973).

For the formation of drilling induced fractures, tensile failure occurs if the mud-weight exceeds the local fracture gradient due to overbalanced drilling. Shear failure is also a mechanism that may lead to permeability enhancement. The occurrence of both mechanisms and whether these are associated with permeability increase strongly depends on the brittleness of the formation (e.g. Evans et al., 1990; De Paola et al., 2009).

It has been discussed that weakly or normally consolidated sediments characterised by high porosity and high clay content tend to exhibit a ductile response under mechanical loading. Such response is usually not accompanied by the creation of localised permeable features like shear fractures but rather with a more homogeneous type of deformation. In addition, the presence of certain minerals such as smectite tend to increase the ductility of the material by a swelling process that decreases overconsolidation, as observed during experimental work on the Boom clay. Apparent overconsolidation that has taken place due to diagenetic processes as in the case of the Draupne formation may decrease the ductility of the material and favour deformation under brittle conditions. Similar observations have been already reported in investigation studies of barrier forming formations as creep is strongly associated to plastic deformation and increased ductility (Brendsdal, 2017 and references therein). Therefore, weakly or normally consolidated formations generally characterised by high clay content, the presence of smectite and high porosity are expected to behave in a ductile manner. In terms of hydromechanical response, claystones that have been studied in the context of nuclear waste disposal, have proven to self-seal potentially created permeable fractures in an irreversible manner due to viscoplasticity mechanisms (Bastiaens et al., 2007).

It can be observed that clayey formations such as shales or claystones will exhibit different response as a result of different formation characteristics depending on the overconsolidation ratio, clay content, porosity and diagenetic processes among others. In the general context of leakage in the North Sea, deeper formations (e.g. Draupne formation) may exhibit fracturing accompanied by permeability increase. However, it is highly probable that at shallower depths, ductile shales are present characterised by lower permeability (due to the absence of open fractures) and sealing abilities inhibiting further gas migration and the creation of a continuous leakage pathway. It has been discussed that at the shallow section of the Norwegian North Sea where methane emissions have been recorded, the present formation is the Nordland shale. Mechanical characterisation of the Nordland shale demonstrated that the material is highly ductile exhibiting an elastic – perfectly plastic response implying that the formation of fractures is highly unlikely. Therefore, drilling induced fractures proposed as a leakage mechanism in the shallow section is not a plausible scenario.

Assessing the possibility of the occurrence of drilling induced fractures in the Upper North Sea Group, it is necessary to consider the formation characteristics and the drilling conditions. Even though petrophysical analysis or mechanical testing on cores of the Upper North Sea Group has not been performed, it is possible to derive some conclusions based on the literature review performed.

The Upper North Sea Group is considered as unconsolidated or weakly consolidated (TNO report TNO2019 R11562) with a low value of OCR. In addition, existing logs from the well A15-03 show that the clay content is high with smectite and illite being the main clay minerals. It is assumed that the Upper North Sea Group is expected to behave similarly to its time-equivalent Nordland shale that was found to exhibit an elastic-perfectly plastic response not accompanied by the creation of permeable fracture-like planes. Moreover, the presence of smectite favours swelling and increased ductility of the formation. Furthermore, even deeper North Sea overburden shale formations have been found to form annular barriers and are hence more likely to act as seals to upward fluid migration than provide leakage pathways. The formation of annular barriers due to shale creep has been observed both at the laboratory scale (Enayatpour et al., 2019; van Oort et al., 2020) and in the field (Kristiansen et al., 2018; Bauer et al., 2021). Lastly, in combination with the above, the self-sealing properties of clayey formations implies that the maintenance of open fracture channels is not very probable.

Focusing on drilling induced fractures, tensile failure could occur if the mud weight exceeds the local fracture gradient. In the shallow sections of the wells in the North Sea, mud-weights are typically close to hydrostatic pressure, below the local fracture gradient, because drilling under overbalanced conditions typically leads to fluid losses (in one of the many highly permeable layers of the Upper North Sea Group) and this would be quickly addressed by the drillers. Hence, the formation of fractures due to overbalanced drilling is very unlikely at shallow depths. This is confirmed by studies that have reported that drilling induced fractures in the North Sea are only observed at deeper intervals > 2500 m (Brudy, 1998). Furthermore, drilling induced fractures would not form in the uppermost part of the well (50 to 70 m below the sea floor) because the conductor casing is pile driven into the ground and not drilled. Therefore the upper sediments will never come into contact with the drilling fluids, and therefore drilling induced fractures cannot form there. This means that migration from the shallow gas accumulation to the surface, along the outside of a well, cannot be contributed to one single mechanism (i.e. drilling induced fractures).

While it is certain that some wells leak, leakage assessment for CO_2 storage (Metz et al., 2005; Gholami et al., 2021) along poorly completed and/or abandoned wells report that leakage may occur between the cement and the inside of the metal casing, through the cement plug itself, through deterioration (corrosion) of the metal casing, deterioration of the cement in the annulus and leakage in the annular region between the formation and the cement (Moghadam et al., 2022; Gasda et al., 2004). Another study of CO_2 leakage along wellbores discusses that possible pathways are the material interfaces between rock formation and cement and/or cement and casing and/or cavities in the cementation of the wellbore annulus and/or pre-existing permeable cracks or fractures within the rock formation in the direct vicinity of the wellbore off the annulus (Bohnhoff and Zoback, 2010). It should be noted that drilling induced fractures are not included or mentioned as potential pathway and to the authors’ knowledge, no published evidence of leakage through drilling induced fractures exists in the literature.

It is concluded that there is no evidence supporting that migration through drilling induced fractures can be classified as a common and critical migration pathway in the Upper North Sea Group.

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