Influence of post-Danian sea-level changes and variations in sedimentation rate on overpressure build up in the clay-rich overburden in the Danish sector of the North Sea Central Graben

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INFLUENCE OF POST-DANIAN SEA-LEVEL CHANGES AND VARIATIONS IN SEDIMENTATION RATE ON OVERPRESSURE BUILD UP IN THE CLAY-RICH OVERBURDEN IN THE DANISH SECTOR OF THE NORTH SEA CENTRAL GRABEN

Ivanka Orozova-Bekkevold*, Erik Skovbjerg Rasmussen# and Niels Hemmingsen Schovsbo#

Overpressure build up in the clay-rich succession between sea floor and the top of the Chalk Group in the area around wells North Jens-1 and Fasan-1 in the Danish sector of the Central Graben, North Sea was examined by forward modelling. “Overpressure”, i.e. fluid pressure higher than hydrostatic pressure, is expressed here in terms of both the difference between pore pressure and hydrostatic pressure at a given depth and the ratio between these pressures. Pore pressure changes over time were estimated by numerical simulation of post-Danian depositional processes, incorporating sea level changes and variations in sedimentation rate. Results show that the deposition of the post-Danian (“overburden”) succession led to overpressure build up both in the overburden itself and in the underlying sediments (the so-called “underburden”). The largest estimated present-day overpressures (4.9-5.6 MPa, 23-26% above hydrostatic) occur at the base of the overburden, while an overpressure of up to 5.5 MPa was calculated to occur in the underburden. Variations in sedimentation rate appeared to have influenced the build-up of overpressure in the overburden, although no significant effect was found in the underburden.

The results indicate that more than 50% of the present-day overpressure in the overburden was generated in the last 5.3 million years, i.e. during the Pliocene and the Quaternary. When variations in sedimentation rate during the Miocene were included in the modelling calculation, this proportion increased to nearly 70%. A decrease in sedimentation rate in the mid-Miocene (Serravallian, 15-11.2 Ma) and the late Miocene (Messinian, 7.5-5.3 Ma) resulted in the dissipation of overpressures generated previously when the sedimentation rate was higher. About 60% of the overpressure generated in the Miocene developed during the Tortonian but only 14% during the Messinian.

Water depth appears to influence the overpressure magnitude. Sea level changes played a minor and short-lived role in overpressure build up. The influence of water depth was most pronounced when it was significantly greater than the thickness of the deposited sediments.

The method of overpressure estimation used in this paper may be a valuable alternative to methods based on porosity trend analysis which are widely used in the oil and gas industry.

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Key words: Overpressure, Danish Central Graben, North Sea, Cenozoic, depositional process, overburden, mechanical compaction, basin modelling, numerical forward model, finite elements approach.
industry. Both the methods used here and the results may be useful in subsurface evaluations related to carbon storage in the Danish Central Graben (e.g. project Green Sand).

INTRODUCTION

Abnormal pore pressures (i.e. pore pressure higher or lower than hydrostatic) occur in nearly all sedimentary basins in petroleum provinces worldwide (Mouchet and Mitchel, 1989). Formations with significant overpressure* (i.e. in which the pore fluid pressure is higher than hydrostatic) pose a considerable risk during drilling (Mouchet and Mitchel, 1989). It is therefore a well-established practice in the oil and gas industry to evaluate the expected pore pressures at planned well locations prior to drilling, usually with methods based on porosity trend analysis (e.g. Eaton, 1972, 1975; Gardner et al., 1974; Bowers, 1995). Pore pressure monitoring while drilling provides useful information on actual formation pressures (Mouchet and Mitchel, 1989). A number of wells in the Danish Central Graben have reported overpressures in the clay-rich Cenozoic sedimentary succession (e.g. Japsen, 1999; Jensen, 2004, Regel et al., 2017; Vejbæk, 2019, 2022). Krygier et al. (2020) found that wellbore instability related to drilling through overpressured formations in the North Sea has resulted in significant economic loss in the order of several million USD.

The Central Graben (outlined in red in Fig. 1a) is one of the most significant hydrocarbon-producing areas in the North Sea, and the Chalk Group of Late Cretaceous to early Paleocene (Danian) age constitutes a major reservoir unit. The sedimentary section overlying the Chalk Group, referred to here as the overburden, was deposited in the last 61 million years between the mid Paleocene (Selanian) and the present day. In the Danish sector of the Central Graben, this succession consists of three main lithostratigraphic units (Fig. 1b): the Rogaland Group (mid Paleocene – lower Eocene), the Hordaland Group (lower Eocene – mid Miocene), and the Nordland Group (mid Miocene – Quaternary). The Nordland and Hordaland Groups

* Overpressure is expressed here both as the difference (“OPD”) and the ratio (“OPR”) between the estimated pore pressure, \(P\), and the normal (hydrostatic) pressure, \(P_n\), at a given depth, as expressed by eq. A.7 in the Appendix (p. 216). The overpressure ratio, OPR, thus defined is a dimensionless quantity. A value of 1 means that \(P\) is equal to \(P_n\); a value of 1.2 means that the pore pressure exceeds the hydrostatic pressure by 20%. Using a dimensionless overpressure ratio is convenient given the large variety of units used to express absolute fluid pressures including MPa, bar, kPa, and psi. In addition, magnitudes of dimensionless OPR at different depths can be compared directly which is not the case when pressures are expressed in units such as MPa or bar. are composed mainly of clay-rich sediments in which smectite is the dominant clay mineral (Nielsen et al., 2015); while the Rogaland Group is dominated by tuffaceous claystones (Gold and Wagner, 1986; Jensen, 2004; Schiøler et al., 2007) and provides the seal for the underlying Chalk Group reservoirs.

It is widely accepted that rapid deposition of material upon fine-grained, fluid-saturated sediments with low permeability may result in inefficient pore fluid expulsion from these formations which can therefore become overpressured (e.g. Gibson, 1958; Audoet and Fowler, 1992; Wangen, 1993; Osborne and Swarbrick, 1997; Fowler and Yang, 1998). Previous studies have investigated the relationship between the overpressures observed in the clay-rich succession overlying the Chalk Group in the North Sea and the high post-Danian sedimentation rates (Osborne and Swarbrick, 1997; Holm, 1998, Swarbrick et al., 2002; Nordgård Bolås et al., 2004; Goffey et al., 2018; Vejbæk, 2008, 2019, 2022; Orozova-Bekkevold and Petersen, 2021). Vejbæk (2019, 2022) and Goffey et al. (2018) concluded that overpressures in the Cenozoic succession in the Danish Central Graben developed mostly during the last 10 million years, starting in the Late Miocene. However, these authors did not consider the influence on overpressure of variations in either water depth or sedimentation rate during this period.

Orozova-Bekkevold and Petersen (2021) investigated overpressure build-up in the clay-rich Cenozoic succession at well North Jens-1 in the Danish Central Graben (location in Fig. 1c). These authors simulated numerically the deposition of sediments in a shallow sea (100 m water depth) in three stages (Paleogene, Neogene, Quaternary). Their results showed that overpressures were generated at around 10-8 Ma during the late Neogene (roughly corresponding to the mid-Miocene), and overpressure build-up continued into the Quaternary. Orozova-Bekkevold and Petersen (2021) did not take account of variations in water depth in their modelling; in addition, they did not differentiate between the Eocene and the Oligocene, or between the Miocene and the Pliocene, but considered these intervals together as “Paleogene” and “Neogene” respectively. In the present study, we have refined the depositional model proposed by Orozova-Bekkevold and Petersen (2021) by introducing sea level changes together with a more detailed representation of sedimentation processes in the Danish Central Graben from the Selandian (Mid Paleocene) to the present, with a particular focus on the Miocene. We consider this model to be more realistic than those previously proposed by Goffey et al. (2018), Vejbæk (2019, 2022) and Orozova-Bekkevold and Petersen (2021) because it takes into consideration both sea level changes and variations in sedimentation rates in the studied period.
The main purpose of this study was therefore to assess the influence of variations in both water depth and sedimentation rate, especially during the Miocene, on overpressure build-up in the clay-rich succession overlying the Chalk Group at the North Jens-1 and Fasan-1 well locations in the Danish Central Graben (Fig. 1c). This area was chosen because both petrophysical logs and detailed seismic and bio-stratigraphic interpretations are available (Fig. 2) for the Miocene-Quaternary succession (Dybkjær et al., 2021). The study therefore investigates: (i) whether variations in sedimentation rate, especially during the Miocene, influenced the onset and magnitude of overpressures in the post-Danian succession in the study area; and (ii) whether water depth also played a role in overpressure development. To the best of the authors’ knowledge, this is the first study which has investigated whether coupled variations in sedimentation rate and water depth may have influenced the onset and magnitude of overpressures in the post-Chalk succession in this part of the North Sea.

**Geological settings and depositional history**

Fig. 1 shows the study area in the Danish sector of the North Sea Central Graben and the stratigraphic units above the top of the Chalk Group at the North Jens-1 well location. A NNW-SSE oriented seismic line in this area (Fig. 2) shows nearly horizontal reflectors in the post-Chalk Group succession, indicating a quiescent tectonic regime during the Cenozoic – Quaternary marked by progressive sediment deposition and burial.

The depositional history of the North Sea is relatively well understood (Konradi, 2005; Rasmussen et al., 2004, 2005, 2008, 2010, 2017; Gibbard and Lewin, 2016; Rasmussen and Dybkjær, 2014; Rundberg and Eidvin, 2016), and the infill history of the Central Graben over the last 61 million years (since the Selandian) was largely controlled by sea-level variations, regional tectonics and climate changes (Anell et al., 2012; Rasmussen, 2004, 2017). Sedimentary material was transported primarily from provenance areas to the north (Scotland, Scandinavia and the Baltic region: Konradi, 2005; Rasmussen et al., 2005, 2008, 2010; Gibbard and Lewin, 2016; Rasmussen and Dybkjær, 2014; Rundberg and Eidvin, 2016). In general, the Cenozoic succession thins towards both east and west, but factors such as local topography and the presence of salt diapirs or domes has resulted in local controls on sediment thickness (Glennie et al., 1998; Evans (Ed.), 2003).

**Paleocene – Eocene**

During the early Cenozoic, Paleocene* and Eocene, the Danish sector of the North Sea (Fig. 1c) was

* Note that the term “Paleocene” in this paper refers to the Selandian and Thanetian (mid and late Paleocene, 61-56 Ma).
Overpressures in the Danish sector of the North Sea Central Graben

Overpressures in the Danish sector of the North Sea Central Graben were dominated by the hemipelagic deposition of clay-rich sediments with varying amount of biogenic material (Michelsen et al., 1998; Nielsen et al., 2015). Water depths were probably >500 m in the central North Sea Basin. The source area for most of the clay was the North Atlantic and Greenland (Larsen et al., 2003) where volcanic activity produced ash which was transformed into smectite in a marine environment (Nielsen et al., 2015). During the early Oligocene, more coarse-grained sediments began to be deposited indicating the erosion of uplifting topography in the hinterland (e.g. Scandinavia). Deltas prograded to the south of Scandinavia (Schiøler et al., 2007; Śliwińska et al., 2014) and clay-rich sediments were deposited to the west of the main deltaic systems (Hansen et al., 2004, 2008; Hübscher, 2016). Therefore, most of the preserved Oligocene succession was deposited in a marine shelf and slope environment.

**Miocene – Quaternary**

The Savian tectonic phase in the early Miocene (Pharaoh et al., 2010) resulted in changes to patterns of sedimentation in the North Sea Basin, and large-scale fluvio-deltaic systems began to prograde SW from Scandinavia. Thick packages of alternating muds and sands were deposited in wave-dominated deltas, while more mud-rich sequences were deposited in contourite systems to the west of the main delta complexes (Rasmussen et al., 2010). The morphology of the deltaic systems indicates sea-level changes of the order of 25 to 35 m (Rasmussen, 2017); however, a significant sea level fall at the Oligocene-Miocene boundary was probably of the order of 70 m (Miller et al., 2005). Increased subsidence of the North Sea Basin occurred in the middle Miocene (Koch, 1989), and marginal land areas were flooded by marine waters despite a global sea level fall of 70 m (John et al., 2011). Fully marine conditions lasted for more than 7 million years, spanning the late middle and early late Miocene, in the NE portion of the basin.

Meanwhile to the SE, fluvio-deltaic systems developed in front of the rising Carpathian Mountains in the late Miocene (Oszczypko, 2006; Standke, 2006; Kuhlmann, 2007). Initially, the North Sea Basin was...
decoupled by the Alpine chain from this foreland basin; but fluvial systems sourced from the Carpathian Mountains and the Alps were established in the late Miocene. By the end of the Pliocene, large-scale fluvial systems supplied sediments to the southern North Sea Basin (Kuhlmann, 2007). The associated sediment load in the central and southern North Sea Basin probably enhanced the subsidence rate. Deltaic progradation resumed by the end of the Pliocene, and sediments derived from Scandinavia dominated Quaternary deposition.

The Miocene – Quaternary depositional history of the North Sea can be summarized as follows. Sediments deposited during the Tortonian (11.8 to 7.2 Ma) originated from source areas to the east and SE during the Pliocene (5.3 to 2.6 Ma) (Rasmussen, 2004; Rasmussen et al., 2005; Rasmussen et al., 2017; Dybkjær et al., 2021). After the Pliocene, the North Sea Basin tilted due to uplift of the Fennoscandian Shield which resulted in increased rates of subsidence and sedimentation in the central Graben area. The highest rate of sediment input from the Fennoscandian Shield into the North Sea occurred during the late Pliocene – Pleistocene (Rasmussen et al., 2008; Rasmussen and Dybkjær, 2014). Reworking of pre-Quaternary sediments was associated with major tilting of the eastern margin of the North Sea Basin around 1 Ma, and resulted in an up to 1 km thick pile of Quaternary deposits in the Danish North Sea (Rasmussen et al., 2005; Knox et al., 2010; Ottesen et al., 2018).

Sea level variations
Water depths in the Central Graben were approximately 800 m until the early Miocene (23 Ma). Rasmussen (2004) reported a sea-level change of around 100 m between the Oligocene – Miocene transition (23-21 Ma) and the mid Miocene (14-13 Ma). The effect of the sea level fall of around 70-100 m in the middle Miocene (John et al., 2011) was outpaced by accelerated subsidence (Rasmussen, 2004, 2017). At the end of the Miocene (5.3 Ma), the water depth dropped to approximately 150-200 m and then to about 70-100 m at the end of the Pliocene (Rasmussen, 2004, 2017). The present-day water depth in the Danish Central Graben (Fig. 1c) varies between 40 m in the south and 80 m in the north.

MATERIALS AND METHODS
Numerical forward simulation of the deposition of the overburden (i.e. the successions between top-Chalk Group and sea floor) in the Danish Central Graben is used as a predictive model which estimates how the pore pressure evolves during sedimentation. The modelling framework was introduced by Orozova-Bekkevold and Petersen (2021) and uses a finite element approach to assess pore pressure changes as a result of consolidation and compaction in a layer of fine-grained, clay-rich and water-saturated material from the moment of its deposition at the sea floor to its burial to about 2200 m depth. This set-up was chosen, because at the North Jens-1 and Fasan-1 well location (Fig. 1), the sediments from seafloor to the top of the Chalk Group are clay-rich and approximately 2000-2200 m thick and were deposited in the last 61 Ma from the Selandian (mid Paleocene) to the present. This period is referred to henceforth as the “post-Danian”. Sediment deposition was modelled in time as a discrete process: the first layer was deposited on a pre-existing domain, the so-called “underburden”, at time $t = 0$ and new layers of material were added on top at given time steps (e.g. 200,000 model years) until a prescribed stratigraphic horizon (i.e. elevation above the base of the domain) was reached. The horizon was determined by the thickness of a given stratigraphic unit. The water column, with an appropriate depth on top of the sediment pile, including the underburden at time $t = 0$, was included in the simulation. This assured that the material on the top of the sediment pile was fully water-saturated at any time. Simulation of deposition as a number of discrete layers is a simplification of the depositional process but was adopted in order to reduce computational time and cost.

Modelling assumptions
The material composing both the underburden and the overburden (the deposited succession) was assumed to be a homogeneous and isotropic, porous, clay-rich medium and fully water-saturated. The sediments were modelled as a clay-rich medium because the post-Danian lithostratigraphy in the study area is dominated by a shale/claystone (smectite-rich) succession from sea floor to a depth of 1500-2000 m. Both the material of the pre-existing (at time $t = 0$) domain and that of the layers building the overburden were modelled as a soft, poro-elasto-plastic medium, with the so-called the SR3 model (Peric and Crook, 2004; Crook et al., 2006a,b; Thornton and Crook, 2014), a modification of the Cam Clay Model (Roscoe and Burland, 1968).

All sediments were assumed to be at their maximum burial depth at any given time, and the effects of erosion, uplift and/or other tectonic events were not included in the modelling. The maximum stress was assumed to be vertical and to be caused by the weight of the overlying strata. The horizontal stress was assumed to be isotropic and was estimated as a fraction of the vertical stress (see equations A.1 and A.2 in the Appendix: pp 215-217). This assumption reflects a condition of “passive tectonics” in the study area, i.e. the absence of active large-scale deformation other than that due to loading by the overlying material.
Burial-related deformation was assessed assuming plain strain conditions. The material composing the overburden was assumed to be unconsolidated at the time of deposition and to have high initial porosity; while that composing the underburden was assumed to be consolidated and to have lower porosity.

Changes in mechanical rock properties, strain-stress fields and in pore fluid flow due to sediment consolidation and compaction during burial are described in the Appendix (pp. 215-217). Further details can be found in papers by Peric and Crook (2004), Crook et al. (2006a,b), Thornton and Crook (2014) and Orozova-Bekkevold and Petersen (2021). Material properties and parameters used in the modelling and in the Appendix equations are given in Table 1 and Table 2.

Only mechanical compaction (i.e. porosity reduction) was considered. Lithologic variations and/or thermal effects leading to diageneis and/or hydrocarbon generation were not included but could be integrated in future models.

**Geometry**

For simplicity and to reduce computational time, both the under- and the overburden were represented by a 500 m wide 2D column. The underburden was assumed to be 200 m thick; the overburden was about 2200 m thick at its maximum. A relatively modest width of 500 m was chosen in order to satisfy the assumptions of material isotropy and homogeneity (i.e. all layers were composed of the same soft, fine-grained clay-rich material).

**Initial and boundary conditions**

Initially, at time $t = 0$ before the onset of sedimentation, the water column above the underburden was taken to be either 100 m or 800 m deep, depending on the depositional model used. The underburden was then allowed to settle under gravity for a duration of approximately 10 million model years.

The only external force acting was therefore the gravitational load of the overlying strata and the water column; this force was applied at the top of the sediment pile and acted vertically downwards. Both the under- and overburden domains were fixed at the sides, and the underburden was also fixed at the bottom, i.e. no deformation was allowed across the basal boundary or across the sides although material was able to deform within the domains. Pore fluids were allowed to flow both vertically and horizontally within the domain in accordance with Darcy’s law (equation A.9), but no fluid charge from exogenous sources (successions outside the domain) was permitted. In other words, no additional fluid (e.g. from areas lying outside the under- and overburden) beyond that already in place was allowed to flow into the sediments.

After the end of deposition, the sedimentary column was allowed to settle under gravity for a duration of approximately 10 million model years.

**Well data and material (rock) properties**

The main properties used to assess pore pressure changes were density and/or porosity in conjunction with permeability (see Appendix 1). Since we simulated the deposition of a 2000-2200 m thick sedimentary column, density and/or porosity data from the sea floor to a depth of ca. 2200 m was required. Where direct porosity measurements are not available, they can be estimated from density and/or acoustic velocity data (Eaton, 1969, 1972, 1975; Gardner, 1974; Bowers, 1995; Fjær et al., 2008). Consequently, the main criterion in selecting wells for this study was that: (i) the well penetrated a thick Cenozoic shale/claystone succession; and (ii) that density, porosity and/or velocity/sonic data were available from as close to sea floor as possible. As suitable wells, Orozova-Bekkevold and Petersen (2021) identified the North Jens-1 and 1/2-1 wells in the Central Graben (locations in Fig. 1), and site 646 of Leg 105 of the Ocean Drilling Program (ODP) in the Labrador Sea south of Greenland (Arthur et al., 1985) (hereafter referred to as ODP well 646). Similar to the Danish Central Graben, sediments at ODP well 646 are of Quaternary-Cenozoic age with a predominantly clay/silt-rich lithology. Also, they are currently at their maximum depth of burial and no erosion, uplift or other tectonism has occurred here since deposition (Arthur et al., 1985). Moreover, the well 646 region experienced high sedimentation rates after the end of the Miocene, as did the Danish Central Graben, with thick Quaternary (approximately 275 m) and Pliocene (about 230 m) sections (Arthur et al., 1985).

Another suitable well, Fasan-1 (location in Fig. 1c), at which petrophysical logs were available for the post-Danian succession, was identified near North Jens-1 (data courtesy of GEUS). These additional log data extended the data-set used in this study down to a depth of 3500-3700 m.

The data-set used therefore consists of petrophysical logs (gamma-ray, sonic, bulk density, neutron porosity) from the three Central Graben wells (labelled in red in Fig. 1c) and from ODP well 646. Core measurements were only available from the ODP well. We used gamma (GR) logs in the Central Graben wells to distinguish clay-rich (GR >50 API) and clay-poor (GR < 50 API) lithologies. The Chalk Group successions in wells Fasan-1 and North Jens-1 (at 2000-2400 m depth: Jensen, 2004; Gold and Wagner, 1986) were excluded from the data-set. Clay-rich sediments in the ODP well 646 were identified by the dominant minerology (Arthur et al., 1985). By combining data from the ODP well with those from the Central Graben wells, we...
obtained a data-set for the clay-rich lithology from sea floor down to a depth of about 3700 m. The data-set allowed us to constrain initial values (at time $t = 0$) of input parameters such as bulk density and porosity. Porosity was estimated from the bulk density, $\rho$, by:

$$\varphi = \frac{\rho_{gr} - \rho}{\rho_{gr} - \rho_{water}}$$

(eq. 1)

in depth intervals for which no bulk density logs were available; but where sonic logs were acquired, the bulk density was calculated from the acoustic velocity (Gardner, 1974).

**Pore pressure and overpressure**

Table 1 and Table 2 show parameter values used in equations A.1-A.12 (given in the Appendix) for non-consolidated clay and for the more consolidated underburden. We used both the Biot coefficient (Regel et al., 2017) and the permeability (Orozova-Bekkevold and Petersen, 2021) varying with porosity to estimate the effective stress (eq. A.3), the pore pressure (eq. A.6) and the fluid flow at a given time step (eq. A.11). The initial porosity and permeability assigned to the underburden accounts for possible effects due to diagenesis and/or fracturing.

**Overpressure** is defined as fluid pressure above hydrostatic and is expressed (eq. A.7) as the difference ("OPD") and the ratio ("OPR") between the estimated pore pressure, $P_p$, and the hydrostatic pressure, $P_h$.

**Numerical models of post-Danian deposition**

The post-Danian succession at the North Jens-1 and Fasan-1 wells was deposited in a marine environment with changing water depths with varying sedimentation rates (see above).

For this study, the post-Danian was modelled as a number of depositional stages, each with its own duration, following the six main Cenozoic series: Paleocene (Selandian to Thanetian), Eocene, Oligocene, Miocene, Pliocene and Quaternary (i.e. Pleistocene and Holocene together).

Since the focus of the study was the influence of variations in Miocene sedimentation rate on...
overpressure development, an alternative model was created in which the six Miocene ages (Aquitanian to Messinian) were treated as separate depositional stages. This model was called the “multi-stage Miocene” model; the model described above which treated the whole of the Miocene as one stage was called the “single-stage Miocene” model. The multi-stage Miocene model therefore had eleven stages: Paleocene, Eocene, Oligocene, Aquitanian, Burdigalian, Langhian, Serravallian, Tortonian, Messinian, Pliocene and Quaternary.

The thickness of the Paleocene (61-53 Ma), Eocene (53-33.7 Ma) and Oligocene (33.7-23 Ma) successions were obtained from the stratigraphic column at the North Jens-1 well (Fig. 1b; Gold and Wagner, 1986), and chronologies were based on the International Chronostratigraphic Chart version 2021/05 (Cohen et al., 2013-2021). Chronologies and thicknesses of the Miocene (23-5.3 Ma), Pliocene (5.3-2.6 Ma) and Quaternary (2.6 Ma to present-day) successions (Fig. 1b) were from Dybkjær et al. (2021). A simplified mean depositional rate (in metres per million years) for each stage was then obtained by dividing the respective unit thickness by the duration in million years (Table 3).

Sediment deposition in the respective stage was modelled as a discrete process by adding one layer every 200,000 model years (i.e. 5 layers per 1 million years) until the prescribed thickness was obtained. An exception was made for the Oligocene (duration 10.7 million years) and, in the case of the multi-stage Miocene model, the Aquitanian (duration 2 million years), since the corresponding sedimentary successions are very thin (Table 3). Deposition during these stages was modelled by only 5 and 2 layers respectively. Thus, variations in sedimentation rate were incorporated into the simulation both in terms of the duration of the depo-stages, the thickness of the respective sequences, and the number of discrete layers added in each stage.

Appropriate water depths were then assigned for each depositional stage (Table 3).

The duration in million years, the present-day thicknesses, the water depth, and the number of discrete layers for each depositional stage used in the numerical simulation are given in Table 3. The table illustrates variations in sedimentation rates and water depths. For the single-stage Miocene model, the average sedimentation rate for the Miocene (duration of 17.7 million years, thickness of 795 m) is about 45 m/million years, similar to that of the Burdigalian in the multi-stage Miocene model.

**Finite elements forward modelling**

Finite element model software Elfen (ELFEN, Rockfield Software Ltd; Crook et al., 2003; Peric and Crook, 2004; Crook et al., 2006a) was used to simulate numerically the development of the post-Danian sedimentary column at the North Jens-1 location. The finite elements solution was semi-coupled: the mechanical field (i.e. changes in strain, stress, porosity, permeability etc. during burial) was solved explicitly; and the fluid field (i.e. the movement of pore fluids, so-called seepage) was solved implicitly; then the two solutions were coupled (aligned) at regular time steps (for example, every 0.01 million model years).

**Finite elements mesh**

At time t = 0 before the onset of sediment deposition, the pre-existing underburden – a 2D column 200 m high and 500 m wide – was divided into 124 equilateral triangular elements with sides of 50 m. Triangular elements were added and the mesh was updated when a new layer was deposited, as described in Peric and Crook (2004) and Crook et al. (2006a, 2006b).

At the end of the simulation, the 2D sediment column was approximately 2100-2200 m thick and 500 m wide. The final mesh consisted of about 1550 elements.

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**Overpressures in the Danish sector of the North Sea Central Graben**

**Table 3. Multi-stage Miocene depositional model. Mean depositional rates were derived from the present-day thicknesses and the respective stage durations.**

<table>
<thead>
<tr>
<th>Deposition Stage</th>
<th>Age [Ma] from-to</th>
<th>Duration [MY]</th>
<th>Present-day thickness [m]</th>
<th>Mean depo rate [m/MY]</th>
<th>Nr of layers</th>
<th>Water depth [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial: Pre-existing base</td>
<td>61.0 – 53.0</td>
<td>8.0</td>
<td>165</td>
<td>21</td>
<td>40</td>
<td>800</td>
</tr>
<tr>
<td>1: Paleocene (Mid – Late)</td>
<td>53.0 – 33.7</td>
<td>19.3</td>
<td>230</td>
<td>12</td>
<td>97</td>
<td>800</td>
</tr>
<tr>
<td>2: Eocene</td>
<td>33.7 – 23.0</td>
<td>10.7</td>
<td>20</td>
<td>2</td>
<td>5</td>
<td>800</td>
</tr>
<tr>
<td>3: Oligocene</td>
<td>23.0 – 21.0</td>
<td>2.0</td>
<td>10</td>
<td>5</td>
<td>2</td>
<td>650</td>
</tr>
<tr>
<td>4: Miocene-1, Aquitanian</td>
<td>18.5 – 15.0</td>
<td>3.5</td>
<td>165</td>
<td>47</td>
<td>18</td>
<td>450</td>
</tr>
<tr>
<td>5: Miocene-2, Burdigalian</td>
<td>15.0 – 11.2</td>
<td>3.8</td>
<td>60</td>
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<td>19</td>
<td>550</td>
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<tr>
<td>6: Miocene-3, Langhian</td>
<td>11.2 – 7.5</td>
<td>3.7</td>
<td>285</td>
<td>77</td>
<td>18</td>
<td>350</td>
</tr>
<tr>
<td>7: Miocene-4, Serravallian</td>
<td>7.5 – 5.3</td>
<td>2.2</td>
<td>160</td>
<td>73</td>
<td>11</td>
<td>150</td>
</tr>
<tr>
<td>8: Miocene-5, Tortonian</td>
<td>5.3 – 2.7</td>
<td>2.6</td>
<td>330</td>
<td>127</td>
<td>13</td>
<td>75</td>
</tr>
<tr>
<td>9: Miocene-6, Messinian</td>
<td>2.7 – 0</td>
<td>2.7</td>
<td>460</td>
<td>170</td>
<td>14</td>
<td>40</td>
</tr>
</tbody>
</table>
Sensitivity to variations in water depth and to changes in the Miocene sedimentation rate

The influence of water depth on overpressure generation was investigated by running the simulation with the multi-stage Miocene model twice: once with a constant water depth of 100 m for all stages, and a second time with variable water depths (Table 3).

In addition, the influence of variations in the Miocene sedimentation rate for the build-up of overpressure was investigated by running the simulation with the two depositional models (“single stage” and “multi-stage” Miocene models) with a constant water depth of 100 m for all stages.

Validation of the predicted overpressure

A pore pressure gradient (PPG) plot was found in the Fasan-1 well completion report (Figure 3.9.1 in Jensen, 2004: the report can be obtained from geus.dk) and we extracted the pore pressure gradient values manually from this plot (hence the accuracy may be uncertain). Although no details were given as to how exactly this PPG was derived, this is the only available information about the actual in-situ pore pressure in the study area, and we used it for qualitative validation of our estimates. We used also the relative density of the drilling fluid (the so-called mud weight) found in the well completion report of Fasan-1 (Jensen, 2004).

Pore pressure gradients are often derived either from drilling data (e.g. the drilling fluid pressure) or from analysis of porosity trends (e.g. Eaton, 1974; Mouchet and Mitchel, 1989) with respect to a reference depth such as mean sea level or sea floor. However, no information was found in Jensen (2004) as to how exactly the reported Fasan-1 PPG was obtained; neither was the reference depth datum reported (e.g. mean sea level, rotary table elevation or seafloor).

In addition, in our modelling we used a water density of 1035 kg m$^{-3}$ (Table 1), accounting for the salinity of both marine and formation waters. By contrast units of relative density (specific gravity, equivalent mud weight) used to express pore pressure gradients and drilling fluid pressures in the oil and gas industry are defined with respect to the density of fresh water at 4°C ($999.94$ kg m$^{-3}$). In order to account for the differences in water density, we multiplied the manually extracted PPG values by ($999.94/1035$), but this probably introduced additional uncertainties.

Thus, only qualitative validation (comparing general trends) rather than quantitative validation (comparing actual magnitudes) was possible.

RESULTS

This section summarizes the main outcomes of the numerical simulation of post-Danian deposition in the Danish Central Graben.

Input data and porosity-depth profile in the Danish Central Graben

The profiles in Fig. 3 show the variations versus depth of bulk density (a, left) and porosity (b, middle) for the clay-rich post-Danian succession in the wells studied, together with (c, right) the variation in final porosity of all the wells.

The figure shows that in the depth interval from 600 m to 800 m, there is a very good match between the densities and the porosities for the shale/clay sequences in ODP well 646 and in well 1/2-1 (red and blue dots, respectively). This is in spite of differences in local conditions at the well sites and in the data acquisition tools. Between depths of 1200 and 2700 m, the well 1/2-1 data are in good agreement with data from the Fasan-1 and North Jens-1 wells. The data from well 1/2-1 was therefore used to fill in the gap in the Chalk section between depths of 2000 m and 2300 m in the Fasan-1 and North Jens-1 wells. Thus from sea floor to approximately 700 m, the profiles are based on data from ODP well 646; from 700 m to around 1200, data was from well 1/2-1; from 1200 to 2000, data came from the Fasan-1 and North Jens-1 wells; from 2000 to 2300 m (the Chalk section in the Fasan-1 and the North Jens-1 wells), data was from well 1/2-1; and below 2300 m, the data came from well Fasan-1 only (Figs 3a, b).

Two distinct trends of density and porosity versus depth can be observed (Figs 3a and b). Between sea floor and 300-350 m, there is a rapid change of density and porosity versus depth (black dashed lines); whereas between ~350 m and 3700 m, the change versus depth is much slower (purple dashed lines). The gradients of the trend lines are related to the material coefficients $\lambda$ and $\kappa$ (given in Table 1) used in Appendix equation A. 4.

A hypothetical final porosity-depth trend (Fig. 3c; dashed red curve) was created in order to indicate the average expected porosity at any given depth. The trend can be described with the following equation:

$$\phi = 0.01175 + 0.626e^{(-0.00125\times D)}$$

where $\phi$ is the porosity expressed as a fraction, and D is depth in metres below sea floor.

Between sea floor and a depth of 300-350 m, porosities are 0.6 to 0.75 (Fig. 3b, c). Observed porosity then decreases rapidly to about 0.4-0.45 at 600-700 m. Between 800 m and 2400 m, the majority of the data points shows porosity values of around 0.4 to 0.5, comparable to those at 600-700 m. Below 2400 m, the porosity decreases again and is about 0.2 at 2300 m depth.

In the intervals between sea floor and ~700-800 m and below 2400-2500 m, the porosity is relatively well aligned with the expected average values (red dashed
Overpressures in the Danish sector of the North Sea Central Graben

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curve in Fig. 3c); while between 800 m and 2400 m, the majority of data points show higher porosity than expected. Seismic data (for example Japsen, 1999) suggest that in the Central Graben, the top of intervals with abnormally high porosities are at ~800 to 1200 m.

Present-day pore pressure and overpressure
We reported the estimated pore pressure, \( P_p \), and the overpressure (as both OPD, the difference between \( P_p \) and hydrostatic pressure; and as OPR, the ratio of the two pressures) as 1D plots versus depth. To avoid possible boundary effects due to possible distortion of elements along the sides of the modelled domain, values were extracted along a vertical profile line in the middle of the modelled sedimentary column at equidistant (20 m) points.

Fig. 3. Profiles versus depth of shale density (a) and shale porosity (b) from the wells studied. The ODP data (red dots) are from core measurements, the Central Graben data (blue, green and black dots) are from density and neutron porosity logs. The porosity estimated from density is plotted in yellow. Dashed lines show tentative trends (see text for details). The equation in the right panel describes the dashed trend line.

Fig. 4 (a, left) shows estimated present-day pore pressure (red curve), the hydrostatic pressure (in blue) and the difference (OPD, in red) between the two (in MPa), together with corresponding overpressure ratios (b, right, blue and red curves) versus depth for the multi-stage Miocene model with variable water depths. The green curves in Fig. 4b are as follows: dashed – the PPG in Fasan-1 as reported in the well report; solid – the PPG corrected for water salinity; and dotted – the mud weight. The pale blue rectangle at the top of the columns illustrates the water depth (40 m) for the Quaternary. The “wiggles” in the estimated pressure and overpressure ratio profiles correspond roughly to the boundaries between the stratigraphic units. The central panel in Fig. 4 shows the present-day thickness of the stratigraphic units.
Below ~600-700 m, the estimated pore pressure (Fig. 4a) is higher than hydrostatic; the difference (black curve in Fig. 4a) becomes significant (> 1 MPa) below 1000 m, reaching 4.5-5.6 MPa in the section between 1900 and 2100 m.

The trend is emphasized in the corresponding profile of overpressure ratio (OPR) in Fig. 4b. The model predicts that mild overpressure (2-5% above hydrostatic: Fig. 4b) may occur in the lower part of the Pliocene section. The estimated overpressure ratio is more pronounced in the Miocene section: it is around 1.1 (i.e. 10% above hydrostatic) at the base of the Tortonian (about 1300 m depth) and about 1.16 at the base of the Miocene (at around 1700 m depth). The highest overpressure ratio, approximately 1.23 (i.e. 23% above hydrostatic), is found in the lower Eocene/upper Paleocene successions between depths of 1900 m and 2050 m. Below 2050 m, the estimated
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Overpressure decreases slightly and is 1.22 (i.e. 22% above hydrostatic) in the underburden.

To validate the prediction, the estimated OPR was compared to the pore pressure gradient (PPG, dashed and solid green curves in Fig. 4b) in well Fasan-1 (Jensen, 2004). As mentioned earlier, the PPG values are uncertain and information and/or data on how this gradient was derived were not available. It is possible that the PPG was derived using the mud weight used in well Fasan-1 (dotted lines in Fig. 4b), but this is speculation.

Thus, the estimated pore pressure could only qualitatively be compared to the PPG in Fasan-1. Both the estimated OPR (plotted in red) and the Fasan-1 PPG increase with depth in the overburden and decrease slightly in the underburden. The OPR indicates that the onset of overpressure (OPR>1) occurs at around 600 m depth, in the middle of the Pliocene sediments; while the Fasan-1 PPG points to the onset of overpressure at ~900 m depth in the upper part of the Miocene (Messinian) succession. The OPR is highest in the Paleocene section and reaches a maximum at the boundary between over- and the underburden. The Fasan-1 PPG is highest in the Eocene interval and decreases below the Eocene-Paleocene boundary (Fig. 4b). The lack of information regarding how the PPG was derived does not allow these differences to be analysed.

Overpressure build-up during deposition

Numerical modelling allowed changes in pore pressure and the build-up of overpressure during sediment deposition to be investigated. The profiles in Fig. 5 show estimated overpressure ratios, OPRs, at the end of each depositional stage for the multi-stage Miocene model with variable water depths. The numbers in blue show the maximum overpressure, expressed in % and in MPa above hydrostatic, and the corresponding depth (in metres below mean sea level) at the end of each stage.

During the Paleocene (Fig. 5, top left), moderate (about 2%, 0.3 MPa above hydrostatic) overpressure developed only in the underburden. At this time, the underburden had lower porosity and permeability than the newly-deposited and not-yet compacted overburden material (Tables 1, 2). During the Eocene, minor (1.4%, 0.2 MPa above hydrostatic) overpressure developed in the overburden while that in the underburden decreased slightly from 2% to about 1.4% above hydrostatic. At the end of the Oligocene, the estimated pore pressure was less than 1% (0.1 MPa) above hydrostatic throughout the entire sedimentary column.

Moderate overpressure (2%, 0.2 MPa) developed during the Aquitanian (23-21 Ma), and reached 3.6%, about 0.6 MPa, above hydrostatic at the end of the Langhian (15 Ma). The low sedimentation rate during the Serravallian (15-11.2 Ma) corresponded to a reduction of overpressure to less than 2% (0.3 MPa) at the end of the period. Overpressure build-up resumed during the Tortonian (11.2-7.5 Ma), reaching 6.2% at the end of this period and 7.2% at the end of the Messinian (5.3 Ma), 1.1 and 1.2 MPa above hydrostatic, respectively. The process accelerated significantly during the Pliocene (5.3-2.7 Ma) and the Quaternary (2.7 Ma to present), with predicted maxima of 15% (2.9 MPa) and 23.3% (5 MPa) above hydrostatic at the end of the respective periods.

If no additional deposition occurs in the next 10 million years, overpressures will dissipate and only the formations below approximately 1450 m (i.e. the Langhian-Paleocene successions) will be moderately overpressured (4-6%, 1.1-1.3 MPa, above hydrostatic).

Influence of variations in water depth and of variations in the Miocene sedimentation rate

The influence of variations in water depth was evaluated by comparing in the multi-stage Miocene model the results obtained with a constant water depth of 100 m with the results obtained with a variable water depth. The sensitivity of pore pressure to variations in the Miocene sedimentation rate were investigated by comparing the outcomes of the single-stage and multi-stage Miocene models, both with a constant water depth of 100 m. To illustrate overpressure build-up in time, we extracted pore pressure values at two specific depths: one roughly in the middle of the underburden, and the other at the base of the overburden. These two depth levels were chosen because they were present throughout the modelled time period. Model results are illustrated in Fig. 6 in which estimated overpressure ratios at the two depth points are plotted versus time: that in the underburden in blue and that at the base of the overburden in red.

The upper and middle panels of Fig. 6 show the estimated overpressure over time for the single-stage Miocene and the multi-stage Miocene models, respectively, both with constant water depths of 100 m, while the bottom panel shows the results of the multi-stage Miocene model with variable water depths. All three panels illustrate similar overpressure trends. The modest overpressure generated during the Paleocene was dissipated by the end of the Oligocene. Overpressure then began to build up again from the beginning of the Miocene (Aquitanian, 23-21 Ma, from 38 to 40 million model years), and the process accelerated significantly in the mid-Miocene (Tortonian, ~9 Ma, at about 50 million model years). Overpressure build-up then intensified in the Pliocene and Quaternary, reaching a maximum of 23-26% (5-5.6 MPa) above hydrostatic at present. Overpressures are expected to dissipate in the future with the cessation of deposition.

Maximum values of the estimated overpressure ratios at the end of the Miocene, the Pliocene and...
Fig. 5. Estimated overpressure ratios (OPR) at the end of each depositional stage beginning with the end-Paleocene (top left). Depth is in metres below mean sea level. The pale blue polygons represent the water column; the yellow polygons represent the sediment pile including the underburden. The dashed horizontal lines outline the approximate tops of the sediments deposited in previous stages. The numbers in blue show the maximum overpressure (in % and MPa above hydrostatic) at each stage and the respective depth.

at the present day for the three model cases are compared in Table 4. The influence of water depth is most clearly seen in the underburden (blue curves in Fig. 6) during the first depositional stage (Paleocene), when the overburden was still very thin. In the case of a water depth of 100 m (top and middle panels of Fig. 6), overpressure in the underburden developed at around 2.5 million model years (roughly 58.5 Ma). The overpressure ratio reached 1.064 (i.e. 6.4% above hydrostatic) at around 4-5 million model years (57-56 Ma), and then decreased to approximately 1.043 at the end of the Paleocene. With greater water depths (800 m: lower panel of Fig. 6), the initial high overpressure in the underburden is most likely due to the initialisation of the model: at time 0, only the already consolidated underburden (i.e. with lower porosity and permeability, Table 1 and 2) existed. Otherwise a modest overpressure of about 2% was estimated at the end of the stage.

In both water-depth cases, no noticeable overpressure developed in the overburden during the Paleocene.
Overpressures in the Danish sector of the North Sea Central Graben

After the Paleocene, the two water-depth models led to similar trends in overpressure evolution versus time at both depths. Pore pressure was nearly hydrostatic from the Eocene to the end of the Oligocene (53-23 Ma, 8-38 million model time years), with a build-up of overpressure starting in the early Miocene (23-21 Ma) with some differences related to variations in sedimentary rate during the Miocene.

In the single-stage Miocene depositional model (Fig. 6, top panel), mild overpressure (1-1.6% above hydrostatic) was estimated at both depths from the beginning (23 Ma, at about 38 million model years) to about the middle of the Miocene (11 Ma, 50 million model years). After that time, the build-up of overpressure accelerated significantly. In the late Miocene, roughly 7.5 Ma, the estimated pore pressure exceeded hydrostatic by 4-5% (OPR of ~1.04-1.05), and from that point increased steadily to the end of deposition.

In the case of the multi-stage Miocene depositional model (Fig. 6, middle panel), a moderate overpressure (1-1.6% above hydrostatic) was estimated at both depths from the beginning (23 Ma, at about 38 million model years) to about the middle of the Miocene (11 Ma, 50 million model years). After that time, the build-up of overpressure accelerated significantly. In the late Miocene, roughly 7.5 Ma, the estimated pore pressure exceeded hydrostatic by 4-5% (OPR of ~1.04-1.05), and from that point increased steadily to the end of deposition.

In the shallow-water case (middle panel, Fig. 6), a moderate overpressure was estimated in the Aquitanian (23-21 Ma); while in the deeper-water case (bottom panel, Fig. 6), moderate overpressure was predicted to occur approximately 2 million model years later, during the Burdigalian (21-18.5 Ma). In all cases, the most significant overpressure developed after the end of the Messinian, during the Pliocene (5.3 to 2.7 Ma) and Quaternary (2.7 Ma to present).

The model with variable water depths estimated slightly lower overpressures during the Miocene, and slightly higher overpressures at the present day, compared to the model with a constant water depth of 100 m (middle and lower panels, Fig. 6). It is interesting to note the differences in estimated present-day overpressures: a water depth of 100 m resulted in a slightly higher overpressure compared to that estimated for a 40 m water depth; maximum OPR values were 1.26 and 1.23 (26 and 23% above hydrostatic), respectively.

The three segments of Table 4 describing the different models are each composed of two columns; the left-hand columns show estimated overpressure ratio at the end of the Miocene, the Pliocene and at the present day respectively. The right-hand columns show the percentage contribution to the overpressure by each depositional stage up to the present day. In the single-stage Miocene model with a constant water depth of 100 m (left side, Table 4), the maximum estimated overpressure ratio was approximately 1.12 (12% above hydrostatic) at the end of the Miocene (5.3 Ma), 1.19 at the end of the Pliocene (2.7 Ma), and is 1.25 at the present day. Thus about 46% of the present-day overpressure was generated during the Miocene, 31% during the Pliocene and 23% during the Quaternary.

In the multi-stage Miocene depositional model with a constant water depth of 100 m (middle section in Table 4), the estimated maximum overpressure ratios at the end of the Miocene (1.09) and the Pliocene (1.15) are lower compared to those for the single-stage Miocene model, while the present-day values are nearly the same (1.25 versus 1.26). In this case, about 34% of the present-day overpressure was generated during the Miocene and 25% during the Pliocene, with 41 % during the Quaternary.

For the multi-stage Miocene depositional model with variable water depths (right side in Table 4), similar proportions of the estimated present-day overpressure were generated during the Miocene (31%), the Pliocene (34%) and the Quaternary (35%).

All three cases therefore suggest that a significant proportion (up to 46%) of the present-day overpressure may have developed during the Miocene. However, all the models suggest that more than 50% of the overpressure was generated during the Pliocene and Quaternary, periods which were characterised by high sedimentation rates.

Table 4. Maximum values of the estimated overpressure ratios (OPR) at the end of each stage from the Miocene to the present-day for the three models.

<table>
<thead>
<tr>
<th>Epoch</th>
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Fig. 6. Overpressure build-up over time expressed as a ratio (OPR, = Pp / HydroP). Upper panel: the single-stage Miocene model with constant water depth of 100 m. Middle panel: the multi-stage Miocene model with constant water depth of 100 m. Lower panel: the multi-stage Miocene model with variable water depth. The overpressure in the underburden (110 m above the base) is plotted in blue, while the overpressure at the base of the overburden (230 m above the base) is given in red. The horizontal dashed lines mark the two depths at which the overpressure was extracted.
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The profiles of present-day overpressure (expressed as both a pressure difference, OPD, and a ratio, OPR) versus depth estimated with the three models are compared in Fig. 7. The three cases resulted in very similar values of the estimated present-day pressures: pore pressure exceeds hydrostatic at depths greater than 600-800 m below sea floor, i.e. the overpressure onset is in the middle part of the Pliocene section. Pore pressures in the uppermost (Quaternary to mid-Pliocene) section are equal to hydrostatic, while the section between the mid-Pliocene and Paleocene (Selandian) is overpressured. The Miocene is characterized by an overpressure ratio varying from around 1.1 (10%, 1 MPa above hydrostatic) at the top of the section (upper Messinian) to about 1.15-1.2 (15-20%, 3-4 MPa) at the base (in the Aquitanian succession). The highest overpressure ratio, up to 1.23-1.26 (23-26%, 4.8-5.6 MPa above hydrostatic) was estimated at the base of the overburden in the Paleocene (Selandian-Thanetian) section. Deposition of the overburden resulted in overpressures of about 21%-23% (around 5-5.5 MPa) in the underburden.

The model with variable water depths in conjunction with multi-stage Miocene deposition is considered here to best represents the post-Danian sedimentary process in the study area in the Danish Central Graben. The model suggests that the Pliocene and the Quaternary contributed almost equally to about 70% of the present-day overpressure, while approximately 30% of the overpressure was generated in the Miocene.

Fig. 7. Present-day overpressure estimated with the three modelling case scenarios. Depth is in metres below sea floor. Left: sketch of the single-stage Miocene depositional model with constant water depth; middle: the estimated present-day overpressure in terms of difference (Pp-HydroP) and of ratio (PP/HydroP). Right: sketch of the multi-stage Miocene depositional model with variable water depth.
DISCUSSION

Post-Danian sedimentation in a study area around the North Jens-1 and Fasan-1 wells in the Danish Central Graben was simulated numerically in order to examine the generation and evolution of overpressure in the clay-rich successions overlying the Chalk Group. The simulation incorporated details of post-Danian sea-level changes and variations in the sedimentation rate in this area derived from biostratigraphic and seismic interpretations (Rasmussen, 2004, 2017; Rasmussen et al., 2005; Ponsaing et al., 2020; Dybkjær et al., 2021). This model was more realistic than that proposed in the previous study by Orozova-Bekkevold and Petersen (2021).

Porosity and density of Central Graben sediments at the sea floor

Because the Central Graben wells (North Jens-1, Fasan-1 and well 1/2-1) did not collect porosity and/or density logs from the sea floor, data from the comparable ODP well 646 in the Labrador Sea was used to provide data for shallow sediments from 0 to about 7-800 m below seabed (Fig. 3). The figure shows that the density and porosity data for the clay-rich succession at the ODP site are in good agreement with the data from the Central Graben well 1/2-1, despite the different local conditions as well as the different acquisition tools used and the major differences in the water depth – which was 3450 m at ODP site 646 (Arthur et al., 1986) versus 40 to 70 m for the Central Graben wells (Gold and Wagner, 1986; Phillips Petroleum, 1989; Jensen, 2004). This similarity allowed a porosity-density dataset to be assembled for the entire section from seafloor down to a depth of about 3700 m, and for the density and porosity values of sediments at the sea floor to be constrained (i.e. at zero effective stress and/or at time t = 0). Core measurements from the ODP well 646 showed bulk densities of between 1.40 and 1.60 g/m³ and porosities of ~0.65-0.8 at the sea floor (Fig. 3). At depths of ~600 to 700 m, the density and porosity measured at the ODP well 646 are around 2.0 g/m³ and 0.45, respectively.

Vejbaek (2022) derived a bulk density of about 1.92 g/m³ and 0.47 porosity at zero effective stress (i.e. at sea floor: see figure 8 in Vejbæk, 2022), assuming the presence of a 500 m thick ice cover during the Pleistocene. We obtained similar values – porosity of 0.45-0.50 and density of about 1.9 g/m³ – by extrapolating the data from the Central Graben wells in our dataset (see the purple trend lines in Fig. 3a and 3b) without any consideration of glaciation.

However, the measurements in the ODP well, integrated in our dataset, show significantly different porosity and density at the seafloor (i.e. at zero effective stress): 0.65-0.8 and 1.40 to 1.60 g/m³, respectively. This underlines the importance of having porosity and density data for the shallow sediments from the sea floor down to about 1000 m depth.

Vejbaek (2022) discussed uncertainties in the porosity of sea floor sediments in relation to possible effects due to North Sea glaciation during the last Ice Age. This author assumed a 500 m thick Pleistocene ice sheet in the Central Graben, which, if resting on the sea floor and not floating, would produce a load upon the underlying sediments, thus enhancing consolidation and compaction. The load produced by a 500 m thick ice sheet with a density of ~ 0.917 g/m³ would be about 4.5 MPa. The water depth at the ODP site 646 is around 3450 m (Arthur et al., 1986), which, for a sea water density of 1.035 g/m³, results in a load of about 35 MPa at the sea floor, i.e. much larger than that produced by a 500 m thick ice sheet.

The load produced by sea water or by an ice sheet adds to the total stress, i.e. the external force acting upon the underlying sediments. Thus, it affects (eq. A.3 in the Appendix) the effective stress, which is the part of the load supported by the solid frame inside the sediments. At the sea floor, no matter how large is the water column load, the effective stress is 0 because the sediments are fully water-saturated and are not consolidated, and particles are in suspension (i.e. no solid frame has yet formed). However, it is not clear if an ice sheet resting on non-consolidated deposits will result in an effective stress greater than zero at the top of the sediments, and thus cause compaction (i.e. porosity reduction) in the underlying material. Until this question is clarified, it seems reasonable for Quaternary sea floor sediments in the Central Graben to be given bulk density and porosity values which are similar to those of Quaternary sediments at the ODP site 646 – in the order of 1.50-1.60 g/m³ and 0.70-0.8, respectively, and not 1.92 g/m³ and 0.47 as suggested by Vejbæk (2022).

Porosity-depth profile in the Central Graben as an indicator of undercompaction

On the porosity-depth profile (Fig. 3b), two trends can be distinguished: a shallow trend (0 to 300 m) with rapid porosity reduction, and another trend below 400 m with slower porosity reduction. The shallow trend relies on data from the ODP site 646 well. Fig. 3b shows that there is little decrease in porosity between approximately 700 and 2400 m, indicating that a significant amount of fluid is trapped in the pore space, thus preventing compaction. The high volume of pore fluid present in the sediments leads to the development of abnormal pore pressures (Dickinson, 1953; Gibson, 1958; Audet and Fowler, 1992; Wangen, 1993; Bowers, 1995; Osborne and Swarbrick 1997; Burris, 1998; Fowler and Yang, 1998; Japsen, 1999; Swarbrick et al. 2002; Yang and Aplin 2007; Vejbæk 2008, 2019, 2022).
Analysis and verification of estimated present-day overpressure

The estimated overpressure is validated by comparing it to other sources related to in-situ pore pressure determinations. The only data related to in-situ pore pressure evaluation in the study area was the pore pressure gradient reported in the completion report of well Fasan-1 (Jensen, 2004). As mentioned earlier, the PPG values were extracted manually from Figure 3.9.1 in Jensen (2004) and thus may include some uncertainty. In addition, there are no details in this well report as to how exactly this PPG was derived: from porosity trend analysis, from the mud weight used and/or from other considerations including the reference depth.

The overpressure ratio, OPR, as estimated here (eq. A.7) is a dimensionless variable, similar to a pore pressure gradient (PPG), expressed in the units of "specific gravity" (or "equivalent mud weight:emw", see eq. A.8) widely used in the oil and gas industry. However, there are some differences; for example, pore pressure gradients are defined with respect to a reference depth (such as mean sea level or the elevation of the drilling rig), while OPR is not; in addition, in the industry, the unit "specific gravity" indicates relative fluid density with respect to the density of fresh water at 4 °C (eq. A.8), while we used the density of sea water (i.e. 999.944 versus 1035 kg m⁻³). These uncertainties and differences only allowed a qualitative analysis of trends to be made, but not a quantitative comparison between the actual magnitudes of the estimated OPR and the pore pressure gradient in the Fasan-1 well.

As shown in Fig. 4b, both the estimated present-day overpressure ratios (plotted in red) and the Fasan-1 pore pressure gradient (plotted in green) show a similar trend: they increase in depth in the overburden and decrease slightly in the underburden. The estimated OPR indicates that the onset of overpressure (OPR > 1) occurs at around 600 m depth, in the middle of the Pliocene sediments; while the Fasan-1 PPG points towards a depth of 900 m in the upper part of the Miocene (Messinian) succession. The estimated OPR reaches a maximum in the lower part of the overburden, in the Paleocene, while the Fasan-1 PPG is highest in the Eocene and decreases below the Eocene-Paleocene boundary (Fig. 4). However, the lack of information regarding how the pore pressure gradient in Fasan-1 was derived, together with the uncertainties related to its magnitude (described above), do not allow the differences between the estimated OPR and the PPG to be analysed.

A moderate overpressure (less than 0.4 MPa, 2-5% above hydrostatic) was found around 600-700 m below sea floor, rising to about 10% (0.5 MPa) at 800 m (Fig. 4b and Fig. 7). This is in line with the general consensus (Vejbæk, 2009, 2012; Japsen, 2018; Goffey et al., 2018) that at the present day the onset of abnormal pore pressures in the Central Graben occurs at a depth of 800 to 1200 m. Maximum predicted overpressures occur at the boundary between the overburden and the underburden (Figs 4 to 7), and are probably related to differences in the porosity and permeability of the respective sediments. Estimated present-day pore pressures (Fig. 4a) are in reasonably good agreement with the finding of Vejbæk (2019, 2022), who reported a formation pressure of about 27-30 MPa at 2000 m depth in well Bertel-1 (figure 1 in Vejbæk, 2019), while our simulation gave a value of about 26 MPa (Fig. 4a) at that depth. However, there are some differences in the modelling approaches used. Vejbæk (2019, 2022) only considered the vertical stress (due to the load of the overlying layers), and estimated the effective stress, σ’, using the Terzaghi equation which implies a Biot coefficient of 1. In our modelling, we estimated σ’ (equation A.3) by also including the horizontal stress and a Biot coefficient varying with porosity (Table 2). We estimated the changes in pore pressure and in the effective stress taking into account both the bulk moduli of the rock framework and that of the fluid as well as the Biot coefficient (equation A.6). This means that in our modelling, bulk density changes are influenced both by mechanical compaction and retardation in compaction due to inefficient fluid expulsion (dewatering); while in other basin modelling approaches, these changes are derived by empirical compaction trends, similar to that in Fig. 3, expressed with eq. 2.

Vejbæk (2022) used a basic transient pressure equation to estimate the pore pressure, linking compaction to increased effective vertical stress as a result of pressure dissipation. In our modelling, we used total effective stress including a horizontal component (eq. A. 3); and the estimated pore pressure is influenced both by mechanical compaction and the delay in compaction due to inefficient fluid expulsion (eq. A. 11). In addition, we used a horizontal permeability equal to the vertical permeability (following the assumption of an isotropic and homogeneous material), thus allowing the fluid to flow horizontally. However, according to Darcy’s law (Appendix equation A.9), the fluid flow in a given direction is also determined by the stress difference in that direction. Given the assumptions regarding initial horizontal stress isotropy and material homogeneity and isotropy, the stress difference in the horizontal direction is much smaller than that in the vertical direction, resulting in much slower horizontal fluid flow than vertical fluid flow (data not shown).

In addition to the transient pressure equations, we coupled the sea level to the sedimentation process thus accounting for changes in both the depositional rate and the water depth.
Orozova-Bekkevold and Petersen (2021) estimated higher maximum present-day overpressure ratios (1.35–1.36) than those in the present study (1.23–1.26). They used a coarser depositional model with only three depositional stages – Paleogene (Eocene–Oligocene, duration 33 million model years), Neogene (Miocene–Pliocene, duration 21 million model years), and Quaternary (duration 1.6–2.0 million model years) – and a constant water depth of 100 m for each stage. In addition, Orozova-Bekkevold and Petersen (2021) used triangular elements with 100 m sides while smaller triangular elements with 50 m sides were used in the present study, which therefore had a finer finite elements mesh.

**Influence of variations in sedimentation rate on overpressure build-up**

The rate of sediment deposition appeared to influence the build-up of overpressure. In general, overpressure dissipated during stages with sedimentation rates which were lower than those during preceding periods (Figs 5 and 6). For example, the moderate overpressure estimated at the end of the Paleocene (Fig. 5) dissipated during the Eocene and the Oligocene; and the overpressure generated in the Tortonian (11.2–7.5 Ma) decreased at the beginning of the Messinian (7.5–5.3 Ma).

If no deposition takes place in the Central Graben, the present-day overpressure will slowly dissipate; after 10 million model years (Figs 5 and 6), only moderate overpressure (maximum 1.06) will remain and only below a depth of 1500 m (Fig. 5).

**Overpressure and variations in the Miocene sedimentation rate**

Similarly to Vejbaek (2019, 2022), we found that since the Tortonian (11.2–7.5 Ma; Figs 5 and 6), the pore pressure and the corresponding overpressure in the clay-rich post-Danian succession in the Central Graben increased significantly. The results show that moderate overpressure started to build up in the early Miocene, but periods with slow sedimentation during the Miocene (Fig. 5, and middle and bottom panels in Fig. 6) may have influenced both the timing of the onset of the overpressure as well as its magnitude. In the multi-stage Miocene model, the mild overpressure build-up from the Aquitanian to the end of the Langhian was dissipated during the Serravallian, and the Tortonian overpressure was dissipated partially in the early Messinian. Thus, Tortonian deposition contributed mostly to the overpressure build-up during the Miocene while the Messinian contributed only modestly.

It appears that periods with low rates of deposition in the Miocene led to an interruption in the build-up of overpressure, resulting in a lower end-Miocene overpressure magnitude. This reduction served to enhance the contributions made during the Pliocene and the Quaternary to the estimated present-day overpressure.

**Overpressure and water depth**

Comparing the results for the multi-stage Miocene models with constant (100 m) and variable water depths (Fig. 7, dashed and dotted curves), it seems that water depth may influence the magnitude of the estimated overpressures. The overpressure estimated with the model with variable water depth (dotted curve) is lower than that in the model with constant water depth (dashed curve), expressed respectively as a pressure difference and an overpressure ratio by up to about 1 MPa and 0.05 (5%).

However, the mechanism is not easy to explain as various factors may be involved. One factor could be the nature of the numerical simulation in which layers were deposited instantaneously. Thus for example, the uppermost layer in the Quaternary was added just before the end of the stage, but the system may still not have reached equilibrium at the present day. Another factor could be the contribution of the weight of the water column to the total load acting at a given depth; a greater water depth will result in a higher load, i.e. higher total stress acting upon the solid framework. If the total effective stress exceeds a given threshold, it could trigger pore fluid expulsion; if not, the pore fluid will not be squeezed out of the porous medium and overpressure will be generated. Since the modelling framework accounts for a delay in fluid expulsion, the time at which the effective stress magnitude reaches the required threshold may influence the onset (timing) of compaction.

The influence of water depth was most visible at the end of the Paleocene (Fig. 6), when the sedimentary column was less than 500 m thick. The model with 100 m water depth predicted a maximum overpressure ratio of 1.057, while the model with 800 m water depth, excluding the high value at time t = 0 (when only the underburden existed) results in an overpressure ratio of 1.02 (lower panel in Fig. 6). A column of 100 m water results in a load of about 1 MPa, while an 800 m column leads to a load of ~8 MPa. Thus, the greater load on the sediments in a deeper-water basin may “squeeze” pore fluids out of the underlying succession more efficiently than the smaller load due to a shallower water column. This mechanism is also conditioned by the permeability. In the models presented here, only the intrinsic (matrix) permeability of the material was used and so-called “secondary” permeability, i.e. the permeability increase resulting for example from diagenesis or hydraulic fracturing, was not taken into account. Further studies are needed in order to better understand the mechanism(s) by which water depth may influence the overpressure.
Material (rock) properties, and modelling assumptions and limitations

We modelled the sedimentary succession only as a clay-rich material because this is the dominant lithology of the post-Danian sequence in the Central Graben. Other lithologies (sandstones, limestones, chalk, volcanic tuffs, marls) and organic materials were not included. The reason was that such lithologies are in general restricted to thin beds (a few metres thick) within the thick, clay-rich sequence and as such do not alter the overall behaviour of the sediment pile. In addition and as pointed out by Vejbæk (2022), using a homogenous clay-rich material reduced the risk of interpreting changes in overpressure as being due to lithological changes. Neither were the effects of shallow gas pockets, including biogenic gas accumulations, investigated – firstly because they generally occur in sand-rich reservoir rocks (which were not included in our modelling); and also because they are not relevant for mechanical compaction. However, different lithologies could easily be incorporated in the modelling framework in future studies.

The modelled domain was represented by a 2D column which was only 500 m wide, since assumptions about the isotropy and homogeneity of the material with horizontal boundaries between the chronostratigraphic layers were reasonably fulfilled within such a relatively narrow domain. However, the model could easily be upgraded to a more complex geometry when appropriate data become available in the future. In addition, the simple geometry used reduced computational time and costs.

The evolution in time of the pore pressure in a fully-saturated, clay-rich sedimentary succession during burial was investigated with respect only to mechanical compaction, i.e. to changes in the so-called primary porosity of the material. Porosity changes and/or water release due to clay diagenesis, mineral transitions, cementation of pore space and fracturing were not simulated, mainly because of a lack of data. In addition, clay diagenesis occurs at temperatures above 60-80°C which in the Central Graben occur at depth greater than 2500 m; however in this study a depth interval down to only 2200 m was modelled. These processes could easily be incorporated into the model in the future and when data of sufficient quality become available.

The applied numerical approach to simulate the sedimentary process and to estimate pore pressure changes in time uses first principles and was not based on regression analysis and/or correlations with petrophysical logs (e.g. Dickinson, 1953; Gardner et al., 1974; Eaton, 1975; Bowers, 1995; Japsen, 1999; Vejbæk, 2019, 2022). Explicit and simplistic porosity-depth and porosity-effective stress regressions were not used. Instead, changes in bulk density, porosity and the related permeability during burial were calculated interactively using Appendix equations A.1-A.12. At each time step, the dynamic interplay between the weight of the overlying sequences including the water column, the stress-strain changes, and the pore fluid flow was taken into account.

No calibration of any type was used (i.e. tuning of input parameters) to improve the estimated overpressures. For example, employing other permeability values would have resulted in different overpressure values by virtue of Darcy’s law (equation A.9).

Uncertainties

A simulation, no matter how sophisticated, will never replicate in full detail complex geological processes taking place over millions of years. The results presented here are therefore affected by uncertainties which are difficult to quantify exactly. The estimated numerical magnitude of the formation pressure depends on the values of the input parameters, especially the permeability, the depositional rate and the water depth, as well as more general assumptions such as the “passive” tectonic regime, the isotropic and homogeneous nature of the clay-rich material, isotropic horizontal stress, and the discrete numerical simulation of the sedimentation process. Uncertainties in permeability-porosity relationships have been discussed by many authors (e.g. Yang and Aplin, 2007; Mondol et al., 2008; Neuzil, 2019; Vejbæk, 2019, 2022; Orozova-Bekkevold and Petersen, 2021). We used the permeability-porosity relationship proposed by Orozova-Bekkevold and Petersen (2021); the values are roughly in the middle of the uncertainty limits, as shown in Fig. 3 in that paper.

The exact numerical value of the estimated pressures also depends on the finite elements approach used, and to a certain extent on the size and shape of the finite elements and the associated grid. In finite element modelling, the magnitude of a given variable is calculated at the nodes of the finite elements mesh, and extracting values at other locations involves interpolation or extrapolation.

Integrating data from a number of Central Graben wells with those from the ODP well 646 in the Labrador Sea allowed us to constrain the material properties at the sea floor and at time t = 0, including (Table 1) bulk density, porosity, bulk modulus, the pre-consolidation pressure, $P_{pc}$, and the parameters $\lambda$ and $\kappa$ used in equation A.4. However, no information was available regarding the precision and accuracy of the acquisition tools used to record the petrophysical logs. Thus, uncertainties with these input parameters were probably to some extent reduced but were not completely eliminated.
CONCLUSIONS

In spite of the inherent uncertainties, the forward finite elements modelling approach presented here appears to be a useful numerical tool to simulate, test and quantify how different factors may influence pore pressure evolution over geological time scales of tens of million years. The deposition of the clay-rich, post-Danian succession in a study area in the Danish Central Graben was modelled numerically to investigate the build-up of overpressure (i.e. pore pressure greater than hydrostatic pressure at a given depth) both in the overburden itself and in the underlying sediments (the “underburden”). Maximum overpressure values (23-26%, 5-5.6 MPa above hydrostatic) were found to occur at the base of the overburden, while overpressures of up to 22% or 5.5 MPa were calculated in the underburden. Variations in the sedimentation rate, especially during the Miocene, appeared to influence overpressure build-up in the overburden, while no significant effect was found in the underburden.

Model results indicate that mild overpressure was generated during the Paleocene (61-53 Ma), the Eocene (53-33.7 Ma) and the early Miocene (33.7-15 Ma). A slow-down in sedimentation in the mid-Miocene (Serravallian, 15-11.2 Ma) and late Miocene (Messinian, 7.5-5.3 Ma) resulted in dissipation of the overpressures generated in preceding stages with higher sedimentation rates. About 60% of the overpressure built-up in the Miocene was generated during the Tortonian, while the Messinian contributed only 14%. Taking account of the significant variations in sedimentation rate during the Miocene, about 30 to 34% of the estimated present-day overpressure was generated in the Tortonian – Messinian (11.2 to 5.3 Ma), while the Pliocene (5.3-2.7 Ma) and the Quaternary (2.7 Ma to present day) contributed equally with about 35% each of present-day overpressure.

It seems that water depth may influence the magnitude of estimated overpressures immediately after the deposition of a new layer, but the effect is transient. The mechanism is not easy to explain as various factors related for example to the physical characteristics of the input parameters and to data availability and to the numerical simulation itself may be important. More studies are required to investigate this problem.

The method outlined in this paper could be a used to assess overpressure generation and its variation over time in basins other than the North Sea Central Graben. It could be used to test the influence of factors such as water depth and rate of deposition on overpressure generation and can be used both for academic purposes (e.g. to investigate precisely when an overpressure originated) and also more practically, for example to provide a pore-pressure profile as required in the planning and execution of drilling operations. The results and methodology presented here could also be relevant for carbon storage activities in the Danish Sector of the Central Graben such as Project Green Sand.

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Declarations

Ethical statements: The funders had no role in study design, data analysis, decision to publish, or preparation of the manuscript.

Data availability: Data for the wells Fasan-1 and North Jens-1 are available from GEUS (https://geus.dk); for well 1/2-1 from the Norwegian Petroleum Directorate (https://npd.no); for the ODP well 646 from the International Ocean Discovery Program (https://iodp.tamu.edu).

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Authors’ contributions

Ivanka Orozova-Bekkevold conceived the idea to use numerical forward modelling of the Cenozoic deposition to test the hypothesis of overpressure build-up in the post-Danian overburden of the North Sea. She developed the methodology, selected and retrieved the relevant well data and collated the data. Ivanka performed the calculations, the analysis and the interpretation of the results, and prepared the manuscript. This includes all tables, figures (except Figure 2, the seismic cross-section) and the original draft of the manuscript.

Erik Skovbjerg Rasmussen facilitated the data collection, provided Figure 2, the sea level changes and the stratigraphic sequencing of the Cenozoic and in particular, the Miocene. He produced the description of the geological and stratigraphic set-up for the North Sea, the interpretation and the discussion of the results,
critically reviewed and edited the manuscript. He significantly contributed to the introduction, geological background, discussion and conclusions.

Niels Hemmingsen Schovsbo facilitated the data collection, significantly contributed to the manuscript with the geological and stratigraphic background, the interpretation and the discussion of the results. He critically reviewed and edited the discussion and conclusion sections of the manuscript.

All authors commented on previous versions of the manuscript, then read and approved the final manuscript.

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1. Appendix: Theoretical Background

Detailed description of the computational framework and methods used to model the changes in the mechanical properties and the pore pressure during the burial of fully saturated clay-rich material can be found in Thornton and Crook (2014), Peric and Crook (2004) and Orozova-Bekkevold and Petersen (2021).

**Vertical, horizontal and effective stress**

The vertical stress is caused by the weight of the sediments and is estimated as:

\[ \sigma_v = g \cdot \int_0^D \rho(z) \, dz \]  

(A.1)

where \( g \) is the Earth’s acceleration (9.81 \( m/s^2 \)), \( \rho(z) \) is the density at depth \( z \), and \( D \) is the total depth of interest.

In the absence of active tectonic forces the horizontal stress is isotropic, i.e. \( \sigma_x = \sigma_y = \sigma_h \) and can be derived from the vertical as:

\[ \sigma_h = -\frac{1}{1-\nu} \sigma_v = C_{eff} \sigma_v \]  

(A.2)

where \( C_{eff} \) is the so-called “matrix stress coefficient”, or effective stress ratio (Matthews and Kelly, 1967), related to the Poisson ratio, \( \nu \).

The vertical and the horizontal stresses are the forces (per unit area), acting upon the sediments, thus the average total stress is \( \sigma = \frac{\alpha \sigma_v + 2 \alpha \sigma_h}{3} \).

Inside a fully saturated porous material, part of the total stress is carried by the solid frame, the so-called effective stress, the other part - by the fluid filling the porous space. It is the effective stress, that causes compaction, since only the solid frame can deform (the fluids just flow away).

The mean effective stress is defined as:

\[ \sigma' = \sigma - \alpha P_o \]  

(A.3)

where \( \alpha \) is the Biot’s coefficient and \( \sigma = \frac{\alpha \sigma_v + 2 \alpha \sigma_h}{3} \) is the mean total stress.

**Bulk modulus**

The change of the bulk modulus with the mean effective stress \( \sigma' \) is defined as (Thornton and Crook, 2014):

\[ K = K_o + \frac{(1-A)Pco \rho_o}{\kappa} \left[ \frac{\varphi_o - \varphi}{\lambda(1-\varphi_o)(1-\varphi)} \right] + \frac{A \sigma'}{\kappa(1-\varphi)} \]  

(A.4)

where \( K_o \) is the initial bulk modulus (at time or depth 0), \( A \) is a weighting factor, \( \kappa \) and \( \lambda \) are material constants and \( P_{co} \) is the pre-consolidation pressure (Table 1).

**Pore Pressure**

The hydrostatic pressure (called also normal pressure) of a column of water at given depth, \( H \), is calculated as:
\[ P_n = \rho_{\text{water}} \cdot g \cdot H \]

where \( \rho_{\text{water}} \) is the water density, \( g \) is the Earth’s acceleration (9.81 m/s\(^2\)) and \( H \) is the height of the water column.

In undrained conditions, the pore pressure, called also formation pressure (i.e. the fluid pressure inside the pores of a saturated porous material) changes as function of the change in the mean effective stress, \( \sigma' \) (Fjaer et al., 2008):

\[ \Delta P_p = B \Delta \sigma', \text{ where the Skempton coefficient, } B \text{ is expressed as } B = \frac{\alpha K_f}{\alpha K_f + \varphi K_s} \]

where \( K_f \) is the fluid bulk modulus, \( K_s \) is the frame bulk modulus and \( \alpha \) is the Biot’s coefficient.

**Overpressure**

Overpressure is defined as pore pressure, \( P_p \), larger than the water hydrostatic pressure, \( P_n \).

It is expressed as the difference and the ratio between \( P_p \) and \( P_n \), at given depth, \( H \):

\[ \text{Overpressure} = P_p - P_n; \quad \text{Overpressure ratio, OPR} = \frac{P_p}{P_n} = \frac{P_p}{H\cdot g \cdot \rho_{\text{water}}} \]

The so-defined overpressure ratio (OPR) is a dimensionless quantity. OPR of 1 means that the pore pressure, \( P_p \), is equal to the hydrostatic pressure, \( P_n \). A value of, for example 1.2, means that the pore pressure \( P_p \) is exceeding the hydrostatic pressure \( P_n \) by 20%.

The term “specific gravity” (sg) and “equivalent mud weight” (emw), widely used in the Oil & Gas industry, refer to the relative density of given material (e.g. drilling fluid) with respect to the density of fresh water at 4 °C, 999.994 kg m\(^{-3}\); it is dimensionless:

\[ \text{Specific gravity [sg] (or emw)} = \frac{\rho_f}{\rho_{\text{fresh water @4^\circ C}}} \]

Both specific gravity and equivalent mud weight are dimensionless.

In the Oil & Gas industry, subsurface pressures (formation (pore) pressure, fracture pressure, overburden pressure) gradients (PPG, FG, OBG) are often given in sg (or emw) in order to compare it to the pressure exercised by a drilling fluid with density \( \rho_f \) inside the wellbore.

Fluid flow, \( Q \), of a mono-phase fluid (water), without taking into account changes in bulk modulus, is often expressed by the Darcy’s law:

\[ Q = -\frac{k A \Delta P}{\mu L} \]

(A.9)
where $k$ is the matrix permeability (independent of viscosity), $A$ is the cross-section area, $L$ is the length of the section, $\Delta P$ is the pressure difference at the two ends of the section, and $\mu$ is the fluid viscosity.

In the modelling presented here, the formation fluid (i.e. the water filling the pore space) can flow both in vertical and horizontal direction, depending on the parameters in the Darcy’s equation.

**Time evolution and coupling of the mechanical and seepage fields**

The non-consolidated clay material composing the overburden is represented as a fully saturated poro-elasto-plastic material. The mechanical field (the solid part) is solved explicitly, while the seepage field is solved by implicit time integration schemes and the two fields are coupled at given time intervals (Thornton and Crook, 2014).

The mechanical properties of the water-saturated medium, were expressed as:

$$\text{div}(\sigma') + [(1-\varphi)\rho_s + \varphi P_f] \cdot (g_a) = 0 \quad (A.10)$$

and the fluid (water only) flow over geological time is represented with a transient equilibrium equation, taking into account changes in the bulk modulus, $K$:

$$\text{div}\left[\frac{k(\varphi)}{\mu} \nabla P_f - \rho_f (g \cdot a_s)\right] = \left[\frac{\varphi}{K_f} + (\alpha - \varphi) / K_i\right] \frac{\partial P_f}{\partial t} + \frac{\partial \varepsilon_v}{\partial t} \quad (A.11)$$

where $g$ is the Earth’s acceleration (gravity) and $a_s$ is the acceleration of the solids, $\sigma'$ is the effective stress; $\rho_s$ and $\rho_f$ are the solid and the fluid density, $P_f$ is the fluid pressure, $\varphi$ is the porosity, $k(\varphi)$ is the porosity-dependent permeability, $K_f$ is the fluid bulk modulus, $K_i$ is the frame bulk modulus, $\alpha$ is the Biot’s coefficient and $\varepsilon_v$ is the volumetric strain, which can be expressed as function of porosity, bulk modulus and effective stress as:

$$\varepsilon_v = 1 - \frac{\varphi_0}{1-\varphi} - \frac{1}{K} \sigma' \quad (A.12)$$

At each time, $t$, the effective stress and the porosity at given depth are determined by the load of the overlying strata and the fluid flow (eq. A.1-A.12).

Thus, our modelling framework does not rely on empirical compaction trends (porosity-depth profiles) as the ones shown in Fig. 3, but accounts for and couples both mechanical changes AND retardation in compaction due to inefficient fluid expulsion (eq. A10, A11).

We believe that our results and methods can be very useful and relevant also with relation to the carbon storage activities in the Danish Sector of the Central Graben (Project Green Sand).