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Evolution of the stress and strain field in the tyra field during the Post-Chalk Deposition and seismic inversion of fault zone using informed-proposal Monte Carlo

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A B S T R A C T

When hydrocarbon reservoirs are used as a CO₂ storage facility, an accurate uncertainty analysis and risk assessment is essential. An integration of information from geological knowledge, geological modelling, well log data, and geophysical data provides the basis for this analysis. Modelling the time development of stress/strain changes in the overburden provides prior knowledge about fault and fracture probability in the reservoir, which in turn is used in seismic inversion to constrain models of faulting and fracturing. One main problem in solving large scale seismic inverse problems is high computational cost and inefficiency. We use a newly introduced methodology - Informed-proposal Monte Carlo (IPMC) - to deal with this problem, and to carry out a conceptual study based on real data from the Danish North Sea. The result outlines a methodology for evaluating the risk of having sub-seismic faulting in the overburden that potentially compromises the CO₂ storage of the reservoir.

1. Introduction

Sequestration of CO₂ in former oil and gas reservoirs can contribute to amelioration of the global increase in CO₂ emissions, and it is already in use in a limited number of sites worldwide (Bachu, 2008; Michael et al., 2010; Ringrose et al., 2017). Injection of CO₂ for enhanced oil recovery has already been utilised by the oil industry for decades, particularly in onshore North America (Gozalpour et al., 2005). CO₂ is currently stored offshore Norway, in Sleipner and Snøhvit, with ~ 1.5-10⁶ tonnes annually (Eiken et al., 2011). Pilot-projects have been carried out in Germany (Kempha and Kühn, 2013; Bergmann et al., 2016), Spain (Vilamajo et al., 2013; Ogaya et al., 2013) and Texas (Daley et al., 2008; Doughty et al., 2008), and this has greatly increased our understanding of CO₂ migration, monitoring and injection strategies in geological reservoirs.

Injection of CO₂, or any other fluid, into subsurface reservoirs might increase the risk of caprock failure and migration of fluid along faults, fracture corridors, and other pre-existing weak zones (Ogata et al., 2014a). Understanding the detection thresholds of such structures calls for careful mechanical modelling of the reservoir stress- and strain field, careful inversion of available seismic data, combined with geological knowledge from well data and outcrop data. In this way it may be possible to quantify the probability of significant CO₂ migration through the caprock, laying the ground for a meaningful risk evaluation.

During the last couple of decades considerable progress has been made in geophysical and geostatistical data analysis methods to correctly estimate model uncertainties and thereby to evaluate fault detection thresholds (Zunino et al., 2015). The goal of this pilot project is to propose a way of exploiting these methods for risk assessment in connection with CO₂ storage. Conceptual models are developed to model the time evolution of the subsurface, giving information about current and future stress fields resulting from geological processes, such as sediment deposition for example. This analysis provides the prior information to a subsequent probabilistic inversion of seismic data. Monte Carlo methods are used to simulate the noise in the data, and the noise is back-propagated through the geophysical (e.g., seismic) equations into the geophysical model, generating a model variability, and reflecting the uncertainty of the reservoir structure. Combining this approach with prior information about the mechanical properties of the reservoir, we evaluate the probability of fault migration scenarios. In this pilot project, we carry out a concrete, highly simplified numerical study of the sub-problem of estimating the density of sub-seismic faults in the overburden of an existing North Sea hydrocarbon reservoir, and established a simple probability model for releases through existing faults. The study is a starting point for developing a full-scale risk analysis system based on the principles outlined above.

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2. Geological background

The present-day stress-strain state of the subsurface is the result of complex geological and planetary processes, taking place over millions of years, such as plate tectonic movements, sedimentary deposition, climate changes, erosion, uplifting etc.

The hydrocarbon field Tyra is situated in the Danish sector of the Central Graben in the North Sea. The hydrocarbon accumulation in this field is mainly concentrated in the chalk reservoirs (Ekofisk) in the Danish sector. The most intensive sedimentary influx into the North Sea occurred during the Late Paleocene-Pleistocene (Gibbard and Lewin, 2016). The sediments, deposited in offshore environment (Schlumberger, 2007), form the present-day overburden above the chalk reservoirs in the North Sea.

Thus, the present-day stress-strain state of the Post-Chalk overburden in the North Sea is mainly the result of the sedimentary deposition. In addition, the weight of the thick overburden affects the stress-strain field of the underlying strata. In addition, reservoir depletion, caused by hydrocarbon production, leads to stress and strain changes both in the reservoir and the overburden. Among the examples are the subsidence experienced in the Tyra field (Plischke, 1994; Schützens et al., 2019) and the Ekofisk (Sulak and Danielsen, 1989) fields.

The overburden provides the reservoir seal and hosts significant part of the infrastructure (wells, pipelines etc.); an accurate analysis of its integrity and/or strength is of great importance. One very important parameter is the fracture pressure of the seal – if the pressures at the top of the reservoir exceeds the fracture pressure of the seal, a breach will occur and the reservoir fluid will escape.

Thus, the stress state of the overburden together with its elastic properties are crucial parameters to consider, with respect to its integrity, when evaluating the risk of leakage of reservoir fluid (CO₂ or hydrocarbons).

Seismic reflection data is used extensively in the oil and gas sector for imaging and characterizing the subsurface. Reflected energy and arrival time of reflected waves provides information on elastic properties in specified locations and allows us to map geological formations on large and smaller scales, only limited by the resolution of the data.

Seismic resolution implies the capability of distinguishing between different geological micro-structures. Some geological features such as small faults and fractures are below the seismic resolution threshold. Recognition of small-scale structures helps us to study thin layers and small faults and fractures are below the seismic resolution threshold.

2.2. Seismic inversion

In our inversion approach, our aim is to produce subsurface models representing relevant physical characteristics of the caprock in the chosen area. In this study, we compute acoustic impedance models consisting of homogeneous layers whose impedances were tied to wells with velocity and density logs. If \( m \) denotes the model parameters (in our case acoustic impedances in a grid covering a vertical 2D section of the reservoir), \( d \) is the data, and \( g \) is the function representing conversion of impedance to reflectivity, followed by convolution with the wavelet and 2D post-stack migration, then calculation of the seismic data (here 2D post-stack, migrated data) from the impedance model can be expressed as:

\[
d = g(m).
\]

We use a probabilistic formulation of the inverse problem (Tarantola and Valette (1982)), where we seek the probability distribution for the model \( m \) that combines information from the data with any available prior information about \( m \).

Formally, if the prior probability density \( \rho \) expresses the probability of models based on non-seismic information, and the likelihood function \( L \) measures the degree of fit between the observed data and synthetic data calculated from the elastic reservoir model, and \( k \) is a normalization constant, then:

\[
\rho(m) = k \cdot L(m).
\]

is the desired probability density for \( m \). In our case, our prior probability distribution \( \rho(m) \) assigns probabilities to \( m \) according to the following assumptions:

1. Only homogeneous, layered impedance models with sharp boundaries, calibrated to well information in the area, have nonzero a priori probability. All such models are a priori equiprobable.
2. Layer boundaries are “smooth” (limited height changes between horizontally neighbouring grid points), except for randomly selected locations where they are intersected by faults. Limitations on height variations away from fault intersections, as well as maximum changes at fault locations, are determined from inspection of the seismic data.
3. The probability distribution of sub-seismic faults is assumed to be equal to the (normalized) distribution of shear (differential) stress in the reservoir.
4. Both the distribution of shear (differential) stresses and fault angle limits are given by our modelling of the deposition of the overburden over geological time (see details below).

The prior probability distribution \( \rho(m) \) enters into our calculations, not as a mathematical expression, but through a Monte Carlo algorithm that generates samples from \( \rho(m) \).

Our Likelihood Function \( L(m) \) is given by

\[
L(m) = C \exp \left( -\frac{1}{2} (d_{\text{obs}} - g(m))^T C_0 (d_{\text{obs}} - g(m)) \right)
\]

where \( d_{\text{obs}} \) are the (noisy) observed data, and \( C_0 \) is the covariance matrix of the noise. In this study we assume white noise: \( C_0 = \sigma^2 I \), where \( \sigma_0 \) is the standard deviation of the seismic noise, and \( I \) is the unit matrix.

Since the prior probability distribution \( \rho(m) \) is not given as an explicit mathematical expression (but only through a Monte Carlo sampling algorithm), we sample the posterior probability density using an Extended Markov-Chain Monte Carlo (MCMC) algorithm (Mosegaard and Tarantola 1995; Tarantola, 2005; Zunino et al., 2015). Our algorithm is augmented with an Informed Proposal strategy (Khoshkholgh...
et al., 2021a,b), allowing us to perform Monte Carlo inversion with a very large number of model parameters (here $\sim 3.3 \times 10^6$).

We use the seismic convolutional model as the forward model, which produces the seismic data by convolving the 2D reflectivity image with a 2D-wavelet used as the point-spread function. The reflectivity is computed from the seismic impedance, which is a product of density and velocity. We assume here that the density is roughly proportional to the velocity (Lithostratigraphic Chart of the Central North Sea, 2014). In order to simulate the residual, horizontal smearing left in the data after (an unavoidable imperfect) migration, we use the 2D wavelet shown in Fig. 1 where the variation in time is a zero phase Ricker wavelet with a dominant frequency of 50 Hz, and the horizontal variation has a width (full width at half maximum) of 20 m. For the sake of simplicity, we will assume in this study that the wavelet is constant everywhere in the depth domain, and hence the modelling can be carried out with time $t$ replaced by depth $z$.

### 2.3. Fault detection limit from seismic data

Using probabilistic models for evaluating the fault density in a certain area, we can assess the likelihood of CO2 migration in the reservoir. One of the first investigations of possible leakage risks and safety of CO2 underground injection was conducted by Holloway (1997), and probabilistic methods for risk assessment of such problems has become more and more popular during years (Kopp et al., 2010; Smith et al., 2011; Zunino et al., 2015).

In this study we use a simplified probabilistic approach to locate areas of increased risk of fracturing in the cap rock. We use a Monte Carlo method to generate small subseismic faults escaping the resolution limit of the data, but at the same time having a fault density proportional to the prior probability density derived from the differential stresses. The differential stresses were calculated from finite elements forward modelling of the Post-Chalk Deposition (see below).

In this study we use Informed Proposal Monte Carlo in order to integrate (1) prior knowledge about strain and stress fields and fault and fracture probability models in the reservoir, and (2) information from observed seismic data, to provide uncertainty analysis and to assess the probability of CO2 migration. The aim is to contribute to probabilistic models that could appraise possible CO2 leakage through faults in the overburden.
2.4. Finite elements modelling of the deposition of water-saturated clay-rich porous material

The deposition of the clay-rich overburden in geological time is modelled in terms of a finite element method, using the software Elfen (ELFEN, Rockfield Software Ltd.). The framework and the theory behind the software are given in details in Crook et al. (2003), Peric and Crook (2004), (Crook et al. (2006a, 2006b), Thornton and Crook (2014).

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

$$\text{div}(\sigma_p) + [(1 - \phi)\rho_s + \phi \rho_f] (g - a_s) = 0.$$  

The pore fluid (water only) flow over geological time is represented with a transient equilibrium equation:

$$\text{div}\left(\frac{k(\phi)}{\mu}(g - a_s)\right) = [\phi/K_f + (\alpha - \phi)/K_s] \frac{\partial P_f}{\partial t} + \alpha \frac{\partial \varepsilon_v}{\partial t}$$

where:

- $\sigma_p$ is the effective stress; $\rho_s$ and $\rho_f$ are the solid and the fluid density, respectively.
- $g$ is the Earth’s gravitational acceleration, $a_s$ is the acceleration of the solid phase, $P_f$ is the fluid pressure, $\phi$ is the porosity, $k(\phi)$ is the porosity-dependent permeability, $K_f$ is the fluid bulk modulus, $K_s$ is the frame bulk modulus, $\alpha$ is the Biot’s coefficient and $\varepsilon_v$ is the volumetric strain.

The bulk modulus of a non-consolidated clay is expressed as a function of the mean effective stress $P'$ (Thornton and Crook, 2014):

$$K = K_0 + \frac{(1 - A)P_{co}}{\kappa} \exp\left[\frac{\phi_0 - \phi}{\lambda(1 - \phi_0)(1 - \phi)}\right] + \frac{A'\sigma'}{\kappa (1 - \phi)}$$

where.

- $\phi_0$ is the initial porosity, $K_0$ is the initial bulk modulus and $P_{co}$ is the initial pre-consolidation pressure.
- $A$ is a weighting factor, $\kappa$ and $\lambda$ are material constants.

3. Data and methods

Well and 2D seismic data from the Tyra Field were kindly provided by DHRTC. One of the criteria to select wells for the study was the availability of density and sonic logs in the overburden.

We used petrophysical logs and well reports for the following wells: Deep Adda, E1-X, Fasan-1, South East Adda (Fig. 2). The wells are located in the Danish sector of the Central Graben, approximately 200 km west from the city of Esbjerg.

The well reports of the four wells (Jensen, 2004; Rong et al., 1985; Kleist et al., 1977), hold very useful information about the lithological composition of the overburden in the Tyra field. The Post-Chalk
Fig. 4. Sketch of the location of the considered seismic profile, the seismic data, and the main reflective horizons, derived from seismic interpretation and the corresponding stratigraphic units and geological age. The steep sections of the horizons representing the tops of the Jurassic and the Lower Cretaceous sections probably indicate the presence of faults.
overburden is approximately 2000 m thick and is represented by three main groups: the thick Nordland and Hordaland Groups, composed mainly of smectite-rich shales (Nielsen et al., 2015), and the much thinner Rogaland Group.

The upper (most shallow 0–500 m depth) part of the Nordland Group consists of predominantly Quaternary sand/clay mixtures, while the lower part consists predominantly of claystone with occasional thin limestone layers (Jensen, 2004). The Hordaland Group consists predominantly of clay-rich (shale) formations, in some interval interbedded with thin limestone layers (Jensen, 2004). The Rogaland Group is situated at the top of the Chalk Group and thus represents the seal for the reservoir with thin limestone layers (Jensen, 2004). The Rogaland Group is characterized by tuffaceous claystone, in some interval interbedded with thin limestone layers (Jensen, 2004). The Rogaland Group is situated at the top of the Chalk Group and thus represents the seal for the reservoir with thin limestone layers (Jensen, 2004).

The layers were deposited one-by-one on the top of the underlying ones until the height of the respective horizon (Fig. 4) was reached. At the end, the deposition of the last layer, a ‘settling’ period of the duration of 0.5 My was introduced to simulate conditions of relaxation with no deposition.

The Jurassic and Cretaceous sections were modelled as deposited in one chunk and were “allowed” to settle under gravity, before the onset of the Post-Chalk deposition. The material, composing the Upper Jurassic (stage 1 in Table 2) is assumed to be consolidated shale, while the Lower Cretaceous to Top Danian (stage 2) is assumed to be composed by consolidated sandstones. The stratum between Top Lower Cretaceous and Top Danian can be seen as a proxy for a reservoir.

It is assumed that the deposited material composing the Post-Chalk overburden is unconsolidated clay, fully saturated with water. All materials are considered to be.

### Table 1
Tentative assignment of the reflective horizons to stratigraphic groups an geological age.

<table>
<thead>
<tr>
<th>Horizons, from Fig. 4</th>
<th>Stratigraphic Group/Formation</th>
<th>Numerical Age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea Bed/Top Quaternary</td>
<td>Top Nordland Gp</td>
<td>0.00</td>
</tr>
<tr>
<td>Top Pliocene</td>
<td>Mid Nordland Gp</td>
<td>2.60</td>
</tr>
<tr>
<td>Top Miocene</td>
<td>Lower Nordland Gp</td>
<td>5.30</td>
</tr>
<tr>
<td>Top Oligocene</td>
<td>Upper Hordaland Gp/Mid Lark Fm</td>
<td>23.00</td>
</tr>
<tr>
<td>Top Eocene</td>
<td>Lower Hordaland Gp/Top Horda Fm</td>
<td>33.90</td>
</tr>
<tr>
<td>Top Ypresian (Mid Eocene)</td>
<td>Top Rogaland Gp</td>
<td>47.80</td>
</tr>
<tr>
<td>Top Danian (Early Eocene)</td>
<td>Top Chalk/Top Ekofisk Fm</td>
<td>61.60</td>
</tr>
<tr>
<td>Top Upper Cretaceous</td>
<td>Top Shetland Gp/Top Tor Fm</td>
<td>66.00</td>
</tr>
<tr>
<td>Top Lower Cretaceous</td>
<td>Top Cromer Knoll Gp</td>
<td>100.0</td>
</tr>
<tr>
<td>Top Jurassic</td>
<td>Top Tyne Gp</td>
<td>145.0</td>
</tr>
</tbody>
</table>

### Table 2
Main deposition stages with duration (in Million Years, MY) and present-day thickness.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Geological Period</th>
<th>Duration [MY]</th>
<th>Nr of layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Pre-existing base</td>
<td>Upper Jurassic</td>
<td>0.1 - Settling under gravity</td>
<td>1</td>
</tr>
<tr>
<td>2: No detailed modelling</td>
<td>L. Cretaceous</td>
<td>1.0 - Settling under gravity</td>
<td>1</td>
</tr>
<tr>
<td>3: No detailed modelling</td>
<td>U. Cretaceous – Eocene</td>
<td>1.0 - Settling under gravity</td>
<td>1</td>
</tr>
<tr>
<td>4: No detailed modelling</td>
<td>Ypresian (L. Eocene)</td>
<td>8.0</td>
<td>4</td>
</tr>
<tr>
<td>5: No detailed modelling</td>
<td>Mid to Late Eocene</td>
<td>19.3</td>
<td>5</td>
</tr>
<tr>
<td>6: No detailed modelling</td>
<td>Oligocene</td>
<td>10.7</td>
<td>5</td>
</tr>
<tr>
<td>7: No detailed modelling</td>
<td>Miocene</td>
<td>17.7</td>
<td>5</td>
</tr>
<tr>
<td>8: No detailed modelling</td>
<td>Pliocene</td>
<td>2.7</td>
<td>2</td>
</tr>
<tr>
<td>9: No detailed modelling</td>
<td>Quaternary</td>
<td>2.6</td>
<td>2</td>
</tr>
<tr>
<td>10: No detailed modelling</td>
<td>Post-depo settling</td>
<td>Projected 0.5 MY after present</td>
<td>Not used</td>
</tr>
</tbody>
</table>

Fig. 3 shows the lithology columns and, respectively, the depth coverage of the sonic logs acquired in the four above mentioned wells. The figure illustrates very well the challenges related to the availability of log data in the overburden. In all four wells, no sonic data were acquired in the shallow section from sea bed to approximately 500 m depth. In the well E–1X, sonic log was acquired only in the reservoir (chalk) section. The best coverage of the overburden is provided by the sonic logs in the wells South East Adda and Fasan-1. By combining these two logs, we were able to extract information for the overburden from approximately 500 m—2200 m depth, i.e the Hordaland and the Rogaland Groups.

The sonic logs were used to derive the density and the porosity of the material as described in Orozova-Bekkevold and Petersen (2021). The evolution of these properties in time is driven by the rate of deposition and subsequent burial of fully saturated material, as described in Crook et al. (2003), Peric and Crook (2004), Crook et al. (2006a, 2006b), Thornton and Crook (2014), Orozova-Bekkevold and Petersen (2021).

3.1. Finite elements forward modelling of the Post-Chalk Deposition

A 2D subsurface geometry was derived from seismic interpretation of the main reflective horizons down to (approximately) 2500 m depth below sea bed. The delineation of the 2D seismic profile used in the inversion, the main reflective horizons and the corresponding stratigraphic units are shown in Fig. 4. The bottom of the domain was set to 2500 m below sea. The lateral (horizontal) extension is approximately 2000 m. It was assumed that the horizons correspond roughly to the stratigraphic groups/formations and the geological age given in Table 1. The overburden section is composed by the strata above the Chalk Group (given in blue on Fig. 4, bottom right). The steep sections of the horizons representing the tops of the Jurassic and the Lower Cretaceous sections probably indicate the presence of faults.

In the present model, the overburden was deposited upon a pre-existing domain (called also underburden), composed by the strata from Top Jurassic to Top Danian, Fig. 4. Thus, the pre-existing domain is composed by the units (Fig. 4) Tyne (grey), Cromer Knoll (green) and Chalk (blue). The horizons from Top Ypresian to Top Quaternary (Fig. 4, Table 1), were used to define the depositional stages in the time evolution of the Post-Chalk period.

The post-Chalk deposition was modelled using the approach, recently presented by Orozova-Bekkevold and Petersen (2021). Each stage is defined by specific duration in millions of years and a prescribed number of discrete depositional layers, composing the respective section. The duration in time and the number of discrete layers used for each depositional stage are summarized in Table 2.

Since the focus of this study was the Post-Chalk overburden, the geological evolution of the Jurassic and the Cretaceous sections pre-existing base (sedimentary deposition, tectonic events, erosion, uplifting, etc.) was not modelled in details at this stage. In addition, we lacked data related to material properties and timing of past tectonic events for these sections.

The layers were deposited one-by-one on the top of the underlying ones until the height of the respective horizon (Fig. 4) was reached. At the end, after the deposition of the last layer, a ‘settling’ period of the duration of 0.5 My was introduced to simulate conditions of relaxation with no deposition.

The Jurassic and Cretaceous sections were modelled as “deposited” in one chunk and were “allowed” to settle under gravity, before the onset of the Post-Chalk deposition. The material, composing the Upper Jurassic (stage 1 in Table 2) is assumed to be consolidated shale, while the Lower Cretaceous to Top Danian (stage 2) is assumed to be composed by consolidated sandstones. The stratum between Top Lower Cretaceous and Top Danian can be seen as a proxy for a reservoir.

It is assumed that the deposited material composing the Post-Chalk overburden is unconsolidated clay, fully saturated with water. All materials are considered to be.
• isotropic and homogeneous;
• fully saturated with water;
• and at any given time, the sediments are at their maximum burial depth.

Clay diagenesis and other chemical and temperature effects are not modelled at the current stage.

Initial and boundary conditions: The main force acting upon the domain is the gravity. The gravitational load originates at the top of the sediments and acts downwards. This setup is considered representative for the Cenozoic Period in the North Sea basin, where no major tectonic events (uplift, erosion, collision, subduction etc.) occurred, and thus the maximum stress is caused only by the weight of the deposited material and acts in the vertical direction. Uniaxial compaction (i.e., plain strain conditions) is assumed.

The vertical stress, $S_v$, resulting by the weight of the overlaying sediments is assumed to be the maximum stress. The horizontal stresses are assumed to be isotropic, and in the absence of tectonic forces, it is derived from the vertical stress and the so-called effective stress ratio $K_{eff}$ is ($Mathews and Kelly, 1967$);

$$S_h = K_{eff} \times S_v.$$

The domain below the overburden (Jurassic to Danian, stage 1–3 in Table 2) is not allowed to deform at the bottom, along the top and across the sides.

The deposited material is modelled as a fully water saturated porous medium. The formation water can flow both vertically and horizontally within the domain, but there is no fluid flow from outside sources. The water does not flow through the bottom and no capillary and temperature effect are taken into account at this stage.

Meshing: The finite element mesh is generated by an advancing front algorithm, adding new elements as the geometry expands, following the deposition of new layers of material ($Crook et al. (2003); Peric and Crook (2004); Crook et al. (2006a; 2006b)$). The elements are triangular, with initial size of 100 m. The size of the elements is rescaled during the simulation, depending on the estimated plastic strain at a given step:
plastic strain exceeding 2 results in diminished element size.

At the beginning of the simulation, before start of the deposition, the finite elements mesh consists of around 120 equilateral triangular elements with sides of 100 m. At the end of the simulation, the mesh consists of around 6750 elements with sizes ranging from 50 to 100 m. The model geometry and the finite element mesh at the beginning and the end of the deposition is summarized in Fig. 5.

4. Results

This chapter is divided in two sections: the first dedicated to the results from the finite elements modelling of the overburden deposition; the second one incorporates the results from the seismic inversion.

4.1. Evolution of the stress and strain state of the subsurface during the Cenozoic deposition

The estimated changes in time in the subsurface stress-strain fields as result of the overburden deposition in the last 61 My are reported in this section.

Fig. 6 shows the evolution of the shear stress during the deposition of the overburden. Negative values mean that the shear force direction is against the respective coordinate axis direction. Here, the X-axis direction is left to right, the Y-axis direction is bottom-up. When we refer to “large” or “small” shear stress values, we refer to the absolute magnitude of the stress.

The top-left panel of Fig. 6 shows the estimated shear stress at the end of the Lower Cretaceous, while the panel in the centre of the top row in Fig. 6 (labelled “Top Chalk – 61 Ma”) corresponds to the stage just before the onset of the Cenozoic deposition, approximately 61 Million years Ago (Ma). These two stages were not modelled in details, they do not represent geological processes, just a kind of theoretical settling under gravity, as explained in the “Data and Methods” section. Thus, the respective estimated shear stress magnitudes should be considered as indicative. The other panels, starting from the top-right one, display the estimated shear stress at the end of each depositional stage.

As the figure shows, the largest shear stress was estimated along and above the very steep shoulders of the deepest horizon, corresponding to the boundary between the Upper Jurassic and the Lower Cretaceous. Relatively high shear stress magnitudes were also estimated in the lowest strata, roughly corresponding to the Chalk reservoirs, while the shear stress estimated in the overburden was low. It is interesting to observe that in the 0.5 MY after the end of deposition, the projection suggests that the subsurface continues to react and a re-distribution of the shear stress might occur, especially in the deepest layers (right bottom corner of the plot).

If the shear (differential) stress exceeds the strength of the material, it might result in fracturing of the formation. Thus, the zones with larger

Fig. 6. Evolution of the Shear Stress [MPa] during the deposition of the overburden. Depth is in meters, below sea bed. The horizons are at their present day-depth. Shear Stress is given in MPa. Negative values mean that the shear force direction is against the respective coordinate axis direction.
as absolute value) shear stress might be considered being at higher risk of fracturing. The largest shear stress magnitude is estimated at present time when the overburden build-up is completed, but the zones where it is found are smaller. If no further deposition is going to occur in the next 0.5 MY, the medium relaxes and the magnitude of the shear stress could decrease.

The results presented in Fig. 6 suggest that fracturing is most likely to occur in the Lower Cretaceous section, especially above the steep shoulders of the anticline-like structure. The concentration of large (between 1 and 2 MPa in absolute values) shear stress along and above these shoulders, might be related to the geometry of the boundary between the Jurassic and the Lower Cretaceous itself. For comparison, the estimated shear stress along and above the much smoother boundaries in the overburden, above Top Chalk, is nearly 0. These steep sections might be related to existing faults; thus, concentration of high shear stress might indicate a risk for fault-reactivation.

When considering the time aspect, it looks like that the largest spatial extension of relatively high shear stress (and therefore, the likelihood of fracturing) might have occurred at the end of the first depositional stage, the Ypresian (53 Ma). As the deposition proceeded, the areas of high estimated shear stress seem to “shrink” and concentrate mainly in the Lower Cretaceous, along and above the steepest parts of the shoulders of Top Jurassic. Even at present, middle panel of the lowest row in Fig. 6, it seems that these areas might be at the highest risk of fracturing.

Fig. 7 shows the evolution in the effective strain during the burial process. The effective strain could be interpreted as a deformation accumulated during the Post-Chalk sedimentation. The maximum values were estimated in the overburden, along the Danian-Ypresian boundary, in the strata which form the top seal of the Upper Chalk reservoirs (panels on the middle row in Fig. 7). The very intensive sedimentary fluxes in the Pliocene and the Quaternary (left and middle panels on the lowest row in Fig. 7) seems to increase the effective strain in all strata between Top Chalk and Top Miocene, while the strain in both the Pliocene and the Quaternary strata is nearly 0. This is, probably, related to the fact that the effective stress in these new sediments is still nearly 0. In the projected post-deposition period (the right bottom plot in Fig. 7), the strain continues to increase and also in the Pliocene strata.

4.2. Seismic inversion

A 2D seismic profile is chosen from the Tyra field in the Danish part of the North Sea. There are two well logs located in the chosen area: E-1X and Deep Adda. By simple interpretation, and from the well
information, a velocity function was generated. This velocity model was considered as a 1st order approximation to the most likely velocity field, and as a basis for estimation of the modelization error distribution, both of which are needed for the informed proposal Monte Carlo algorithm (see Khoshkholgh et al., 2021a, 2021b). Perturbing the model in each Monte Carlo iteration is a combination of warping or deforming the layer boundary shape, perturbing and changing the velocity value in each layer, and introducing subseismic faults and fractures in the overburden according to the fault and fracture probability.

Fig. 8 shows a 2D seismic profile from the Tyra field that was used in this study. Fig. 9 shows the velocity model obtained by simple interpretation (a 1st order approximation to a best-fitting solution). The standard deviation of modelization errors (the difference between the 1st and 2nd order reflectivity estimates) is shown in Fig. 10. In Fig. 11 the prior fracture probability model, obtained from the stress field, is shown.

The 1st order approximation to the velocity model is chosen as the starting model for the inversion. The maximum velocity perturbation is chosen as 1 percent of the maximum velocity and the maximum displacement in warping is chosen as 5 pixels. Warping happens in a square window centred at a randomly selected point. The size of the window is 200 by 200. The maximum and minimum fault angles are 12° and 36° respectively.

Fig. 12 shows two different realizations from posterior model distribution. The posterior fault/fracture density, derived from samples of the posterior (Mosegaard and Tarantola, 1995), is shown in Fig. 13.
5. Discussion and conclusion

The main purpose of this study was to study possible risks, in terms of probability of fracturing or fault re-activation, related to seal integrity. Two modelling approaches were combined – a seismic inversion was used to interpret major seismic reflection horizons, which then were used to constrain the geometry of the main chrono-stratigraphic boundaries in the Tyra field.

A forward numerical finite elements model was used then to simulate the evolution in time of stress and strain in the Tyra field as a result of the deposition of the approximately 2000m-thick clay-rich Post-Chalk overburden in the last 61 Million years.

A simplified probabilistic analysis of a seismic 2D profile across the Tyra reservoir, intersecting the E1-X and Deep Adda well sites was carried out. The focus was on the detection limit of the data, and the result was a map of faulting and fracturing probabilities across the area.

![Fig. 12. Two realizations from the posterior probability density. The two models show examples of the variability in the impedance model permitted by the seismic data within their uncertainty. The variability is expressed in differences in layer boundary locations, subseismic faults, and layer velocities, and reflects the uncertainty of the subsurface model. The model uncertainties originate from data uncertainties and uncertainties in the prior information used in the calculations.](image1)

![Fig. 13. Smoothed density of subseismic faults and fractures above Top-Chalk level, as seen in the posterior model realizations. The colour scale above Top-Chalk level (which is the sharp boundary at the bottom) indicates the probability at each point of being intersected by a fault or a fracture. The plot is an approximate representation of the posterior fracture probability distribution.](image2)
The result is a combination of seismic information with information about stress fields, derived from the subsurface evolution model.

Given the intrinsic uncertainties in the seismic data, non-unique solutions to the inverse problem and the challenges of representing and simulating numerically geological processes lasting millions of years, we consider this modelling as being conceptual.

Since the resolution of even the best quality seismic data does not allow to detect small fractures and faults, our conceptual model can be used to identify areas of stress-strain concentration, not detectable by seismic data, which possibly can be at increased risk of fracturing and probable fault re-activation, especially in the cap rock (immediate overburden).

The finite elements simulation indicated that the deposition of thick clay-rich Cenozoic Overburden in the last 61 MY on the top of a pre-existing structure could have produced significant shear stress in the strata below the Overburden, especially in the Lower Cretaceous, which is not immediately below the overburden. The largest values of the shear stress were estimated above and along the very steep sections at Top Jurassic.

Areas of high shear stress could be at higher risk for fracturing, thus if the steepest sections of the Lower Cretaceous-Jurassic boundary represent faults, a fault re-activation along and above them might have occurred in the past. And our estimates indicated that the possible risk of fracturing along these areas remains high also at present day.

The largest effective strain (deformation) was estimated in the sections above Top Chalk, which forms the seal of the Chalk reservoir.

The very intensive sedimentation in last 5.3 My seems to lead to significant increase and re-distribution in both the shear stress of the deepest strata and the strain accumulated in the overburden.

The projection in time after end deposition showed that the strain-stress field continues to evolve even if no new sedimentation is occurring.

The stress-stress field, estimated with the present model is believed to correspond to natural state of the subsurface, i.e., the state before any kind of human intervention.

It should be kept in mind that the model of the evolution of the subsurface presented here is conceptual and was used mainly to illustrate the importance of the Cenozoic deposition for the present-day subsurface stress-strain field. The model can be improved by including further details.

Based on this study, we currently cannot make very detailed conclusions about the actual conditions at specific locations in the Tyra field. Both the subsurface evolution model and the seismic analysis were highly simplified and important processes, such as anisotropy in stress and rock properties, the pre-Cenozoic geological and tectonic history, the effect of temperature and capillary phenomena were not included in the current study. A notable weakness in the seismic analysis is the lack of accurate data modelling (waveland estimation and wave simulation), a simplified modelling of geological layering, fault geometry and velocity/impedance distribution, and that we have not included anisotropy of rock properties, which may be derived from full waveform data or AVO/AVAI data. An investigation of anisotropy may contain valuable information about rock fracturing, and should be taken up in future studies.

The outcome of the study is, however, encouraging. We have proposed a new way of analysing caprock integrity of reservoirs for CO2 storages. Our subsurface evolution model potentially allows us to predict current and future changes in a reservoir, and our probabilistic approach to seismic data analysis allows our numerical model of the stress field to be integrated with seismic information, producing fault/fracture probability maps that are ready to be included in a quantitative risk analysis.

Credit author statement

Sarouyeh Khoshkholgh: Conceptualization, Software development, seismic inversion. Ivanka Orozova-Bekkevold: Conceptualization, stress-strain modelling, Software development. Klaus Mosegaard: Conceptualization, Software development, seismic inversion.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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