Introduction

Naturally fractured low permeability rocks are economically important around the world as hydrocarbon reservoirs, aquifers, geothermal prospects and sites for CO2 storage, amongst other applications. Fluid flow through such rocks is very much dependent on the properties of both individual fractures (e.g. aperture, roughness, length and orientation) and those of the fracture network (e.g. fracture intensity, distribution, and connectivity).

In most cases, however, only very limited information is available about fractures in the subsurface; they are too small to be imaged on conventional seismic data, and boreholes provide only 1 dimensional data (i.e. no information on fracture length and connectivity) with limited coverage. Recent advances in seismic processing (e.g. ant tracking; Pedersen et al. 2002) have raised the possibility of identifying larger fracture corridors and smaller faults, which can form important fluid conduits. Aabo et al. (2020) apply these techniques to the Kraka field, a hydrocarbon field producing from a fractured chalk reservoir offshore Denmark, and show a good correlation between lineations observed on ant-tracked seismic data and resistive fractures identified in borehole images. By correlation with core, these resistive fractures are interpreted as large tectonic fractures, containing crystalline calcite cement and well-developed slickensides, indicating shear displacement.

Modelling the propagation of fractures provides a predictive method for characterising subsurface fracture networks, based on knowledge of the mechanical properties and deformation history of the geological structures in question. A method for doing simulating growth of layer-bound fracture networks over large geological structures has been developed by Welch and Lüthje (2018a, b) and Welch et al. (2019). In this study, we apply this method to the Danian reservoir unit in the Kraka field, and compare the results with the ant-tracked seismic borehole image data.

Method

The method of Welch and Lüthje (2018a, b) and Welch et al. (2019) uses linear elastic fracture mechanics theory to simulate the nucleation and propagation of layer-bound fractures. It assumes an initial population of small, circular microfractures that grow in response to the stress concentration around the edge of the fracture, that is induced when a horizontal extensional strain is applied to the layer. It also assumes that these fractures cannot propagate into the adjacent layers, so when they reach the top and bottom of the fractured layer, they instead propagate horizontally, forming elongated layer-bound macrofractures. Following subcritical fracture propagation theory (e.g. Atkinson 1984), the rate of macrofracture propagation is proportional to the stress concentration at the fracture tips, which is determined by the applied horizontal strain and the stiffness of the layer. As the macrofractures propagate they may also interact and become deactivated, either due stress shadow interaction with nearby parallel fractures, or intersection with orthogonal or oblique fractures.

This fracture network generated by this method can be represented explicitly, as a Discrete Fracture network (DFN) model, but it can also be represented implicitly by fracture property data, e.g. fracture density (P30 and P32), fracture size distribution functions, and indices of fracture connectivity and anisotropy. The key inputs required are the geometry of the fractured layer, the mechanical properties of the layer (especially stiffness), and the orientation and magnitude of the applied horizontal strain. Both the mechanical properties and the applied strain may vary laterally across the structure.

The Kraka structure comprises an anticline formed over a large (c.5x8km) salt pillow (Figure 1). For this study, the layer geometry is taken from the static model of the Kraka reservoir constructed by Total E&P Denmark (TEPDK). We have assumed that the fractures formed during uplift of the anticline, and hence that the chalk was fully lithified at the time of deformation. Mechanical property tests on the Danian chalk show that its stiffness is correlated with porosity, so the stiffness data used in this study was calculated from the seismically-derived porosity data, calibrated against mechanical test results on core samples (Frederic Amour pers. comm.). This shows generally high stiffness values (typically c.2.5GPa) but with a few patches of exceptionally high stiffness (up to 15GPa). The horizontal strain was calculated by backstripping the stratigraphy overlying the salt pillow, flattening...
each horizon in turn, and calculating the strain tensor required to deform the reservoir layer from its initially flat geometry to its present day geometry. We have not applied strain relaxation (i.e. inelastic creep processes) in this study.

![Figure 1:](image)

Figure 1: Discrete fracture network model showing layer-bound fractures in the Danian chalk layer in Kraka generated by geomechanical simulation, after c.1.2ma (left) and c.15ma (right); note that fractures form first on the flanks of the structure, and that most areas a primary fracture set develops first, followed by a secondary set of connecting fractures. Contours show the depth to the top of the Kraka structure, blue disks show resistive fractures identified on borehole images in horizontal wells by Aabø et al. (2020).

Results

The Danian chalk is separated from the underlying Maastrichtian chalk by a hardground that acts as a fluid barrier, while it is overlain by Tertiary shales that provide a seal. There is also some evidence that the upper Danian has a higher porosity and is mechanically distinct from the lower Danian. We therefore ran one model in which the layer-bound fractures spanned the entire Danian chalk layer (see Figure 1), and another in which they were restricted to the upper Danian chalk layer.

Comparison of the results with the borehole image and seismic data show a good correlation in orientation and density between the layer-bound fractures in the models, the resistive fractures in the borehole images and the lineations on the ant-tacked seismic data (Figures 2 and 3). The models assume two fractures sets, striking perpendicular to the minimum and maximum horizontal stress respectively. The generally good agreement in orientation therefore suggests that the backstripping method accurately reproduces the historical horizontal stress orientation.

One advantage of simulating the fracture network evolution is that we can examine the intermediate stages of fracture growth, to determine which of these best match the observed fracture geometry. In this case we see that fractures first develop in the high strain areas on the flanks of the Kraka structure, only later developing over the crest. Furthermore, initially only a single fracture set develops perpendicular to the minimum horizontal stress; only later does a second set of short connecting fractures develop perpendicular to the maximum horizontal stress. The borehole image data shows a high fracture density on both the crest and the flanks of the Kraka structure, with fractures perpendicular to both the minimum and maximum horizontal stress directions, suggesting that the fracture network in Kraka is near fully developed.
As expected, the fractures spanning the entire Danian layer show a larger spacing (and thus lower fracture density) than the fractures restricted to the upper Danian layer. This larger spacing is more consistent with the spacing of the resistive fractures in the borehole images and the lineations on the ant-tracked seismic data, implying that the large shear fractures in Kraka span the entire Danian layer.

**Figure 2:** Close-ups comparing the layer-bound fractures in the Danian chalk layer in Kraka, generated by geomechanical simulation (in pink) with the resistive fractures identified on borehole images in horizontal wells by Aabø et al. 2020 (blue disks).

**Figure 3:** Close-ups comparing the layer-bound fractures in the Danian chalk layer in Kraka, generated by geomechanical simulation (in pink) with the ant-tracked seismic data, and the resistive fractures identified on borehole images in horizontal wells by Aabø et al. (2020). In the left hand pictures, the simulated fractures are removed for clarity. Note the close correlation between the preferred orientation of the modelled fractures, the resistive fractures from borehole images, and the lineations observed on the ant-tracked seismic data.
Conclusions

In this study we have demonstrated that it is possible to generate a DFN by geomechanical simulation that corresponds well with observed fracture data from borehole images and ant-tracked seismic data. Key to obtaining this good match is an accurate understanding of the strain history of the structure in question (which can be obtained by backstripping), an accurate knowledge of the mechanical properties, and an accurate delineation of the mechanical layer containing the fractures. Further work is ongoing to calibrate this method against other structures and lithologies. It is hoped that in future this will provide an accurate method of modelling fluid flow through fracture networks where only limited direct data is available for fracture characterisation.

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References


