

Introduction

The Kraka oil Field is a salt-induced anticlinal structure located in the southernmost tip of the Danish Central Graben (Danish North Sea). It is produced through natural depletion of the Danian Ekofisk Fm, an overpressured, naturally fractured chalk reservoir. Ekofisk chalk is a mono-mineralic carbonate rock that consists of 96 - 99% calcite (CaCO_3), non-carbonate biogenic particles and small amounts of clay particles (Abramovitz et al., 2010). The Danian of the Kraka Field is divided into an upper porous zone (units D1 – D3) and a lower tight zone (D4 – D5). Porosities in the porous zone are in the range of 25 - 35%, and vary only slightly across the field (Klinkby et al., 2005). In the reservoir, silica occurs as continuous chert bands and isolated chert nodules. The matrix permeability is less than 1mD, however, the effective permeability is approximately 20 times that due to the presence of fractures.

Tectonic fractures related to halokinesis are the main permeability enhancers. Smaller fractures associated with cherts and stylolites may however be important for local permeability enhancement. Fractures in Kraka occur in swarms (Jorgensen et al., 1991). Fracture spacing, orientations and connectivity in the field are currently not well constrained.

In this extended abstract we compare fractures and fracture zones observed at different scales on core, borehole images (FMS and FMI) and ant-tracked seismic volumes, and show that we can correlate between them. BHI and core data are highly complementary. Borehole images are cheaper, provide true orientations and survey the reservoir in-situ, so we can differentiate open and closed fractures under reservoir conditions. Cores allow for direct observations, analyses at nano and micro scale and laboratory experiments. Seismic is used to map faults and fracture zones away from the borehole and to identify regional structural trends. Combining the three data types allows us to extrapolate fractures away from the borehole, and will serve as inputs into a mechanically based discrete fracture model (DFN), which will improve future well planning and EOR activities.

Method and Theory

Micro-resistivity images from FMS and FMI tools are available in one vertical well and seven horizontal or deviated wells. The surveyed wells were drilled in the time period between 1989 and 1997 and raw data has been reprocessed for this study. Due to the high resistivity of chalk, caving and tool sticking, image quality is poor in many places. Chalk sections directly below chert bands have been particularly hard to resolve, as the chert bands do not have planar surfaces and so cause errors in the pad alignment stage of processing. The cherts, being highly resistive compared to the chalk, are in turn well resolved. A large portion of the fracture swarms in Kraka are chert associated. Additionally, cherts enable depth matching between borehole images and cores, as depth shifts along wells vary by up to 8 ft

Cores are available in three of the wells logged by BHI tools: Well 1 (deviated), Well 2 (horizontal), and Well 3 (vertical). This abstract focuses on analyses from Well 1, where the core-recovery percentage is highest. Relative fracture orientations measured in core have been reoriented, depth shifted and are plotted alongside image picks.

Fracture picks from BHIs and cores are subsequently compared to a structural framework derived from seismic images. Seismic amplitude cubes acquired in 2012 have a vertical resolution in the order of 40 m. Therefore, high-fidelity information from the Kraka amplitude cube has been extracted using a gapped chromatic method that is based on structurally sharpened satellite RGB/HSV processing (Laake, 2015). The resulting structural cube serves as an input for an algorithm that systematically analyze the data, mimicking the "swarm intelligence" of ants (Pedersen et al., 2005). The algorithm extracts structural lineaments and assigns confidence levels depending on the length and width of the path of segments, to enhance subtle compaction features and small-scale faulting that are essential to the interpretation of the Kraka chalk field. The additional structural information is used as an opaque overlay on the conventional amplitude cube to guide the seismic interpretation and to avoid misclassification of noise or acquisition artifacts. Centimeter- to meter-scale fractures identified in borehole images and cores are compared to these larger structural lineations in 3D.

Correlation of Core and Borehole Images

In the BHI data from the Kraka Field, sinusoids representing bedding (chalk and marl) are continuous across borehole images. Most fractures are however only represented by partial sinusoids, either because they are short or because they are only partially open or cemented. Comparison with core data, when available, is imperative in determining which partial signals should be picked. Lessons learned from cored wells are transferrable to BHI-surveyed wells without core.

The advantage of core is that we can identify smaller-scale stylolite associated fractures that are not detectable on images because the image resolution is about 1-2mm. Most open chert associated fractures are however visible, due to the large resistivity contrast between cherts and water-based drilling mud. The length of the chert-associated fractures depend on the size of the chert band or nodule, and varies between 10 and 50 cm in Well 1.

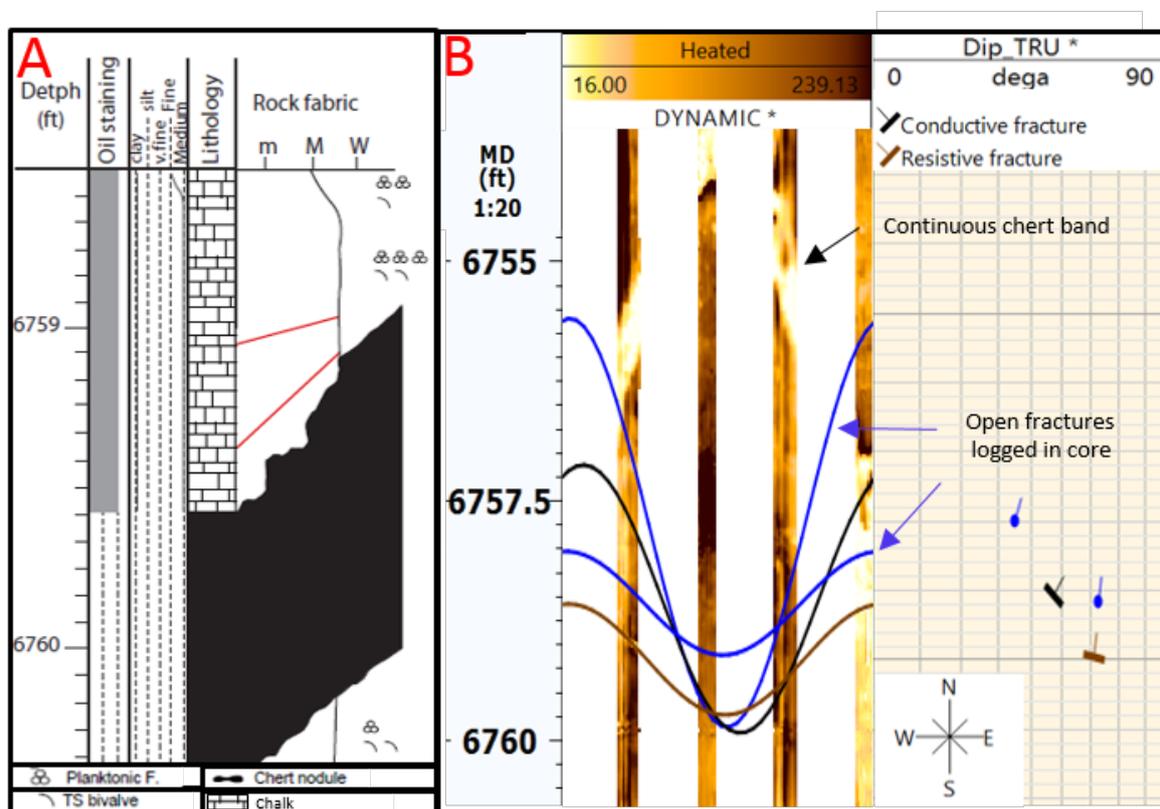


Figure 1 Core log (a) with faults in red and Core-to-BHI correlation (b) of fractured interval in Well 1

Figure 1 shows a logged core interval (a) with corresponding BHI section (b) from Well 1. The core interval contains two natural fractures, represented by blue tadpoles in the BHI. Both fractures are open (non-cemented) in the core, but are recognized as natural fractures by the presence of slickensides. The logged fractures coincide with one open (conductive) and one closed (resistive) fracture picked on the borehole image. The conductive fracture is associated with the continuous chert band, while the resistive feature is believed to represent a tectonic fracture. The relative timing of silica formation and salt doming in Kraka is yet to be determined. However, as one of the closely-spaced fractures is cemented, while the other is not, it is reasonable to assume that they represent different fracture-generations.

The dip and azimuth of both fractures identified in BHI match the orientation of the fractures logged in core within 12°. Small discrepancies are to be expected, as core must be reoriented manually to calculate true orientations, so fracture orientations from BHIs are commonly considered the most reliable, while the presence and type of fractures can be identified in the core.

Correlation of Seismic and Well Data

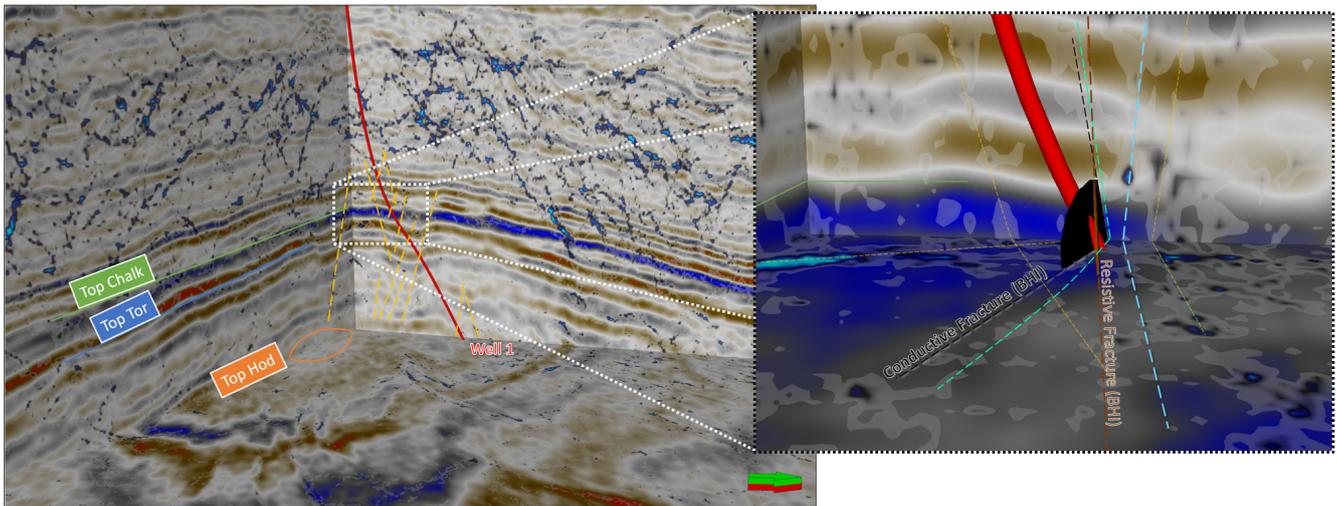


Figure 2 Seismic overlaid with ant-tracked chromatic structural cube and close-up of interpretation compared to BHI fracture discs.

In figure 2 we show the ant-track as transparent overlay over the seismic amplitude. The Top Hod to Top Chalk interval and the highly fractured overburden in the Kraka field are imaged. The z-plane in figure 2 cuts the inner chalk reservoir on Top Hod level. On this plane several lineations can be identified that strike radially relative to the anticlinal reservoir structure. The primary reservoir between Top Tor and Top Chalk shows several discontinuities and amplitude variations. On the cross-section we see conjugate inclined ($< 45^\circ$) faults cut through the reservoir and extend into the overburden and the underlying chalk package. Amplitude variations within the reservoir reflect compaction effects and possibly the influence of fluids saturation. The overburden is heavily fractured with low-throw (15m) conjugate faults that are highlighted with high confidence levels (blue) by the ant-tracking algorithm. The faults are parallel with a spacing between 50 m and 100 m and may be reactivated during depletion. This dynamic overburden must be corrected for in 4D seismic analysis.

The close-up in figure two highlights the faulting at reservoir depth. The z-plane was adjusted to reflect the middle Danian data. Cross-cutting faults along the wells are easily identified.

High-confidence features along the well may be production related. The close-up also increases the visibility of lower confidence features from the ant-track algorithm. These also reflect low-throw conjugate faulting cutting the reservoir and compaction related features are highly visible in this display.

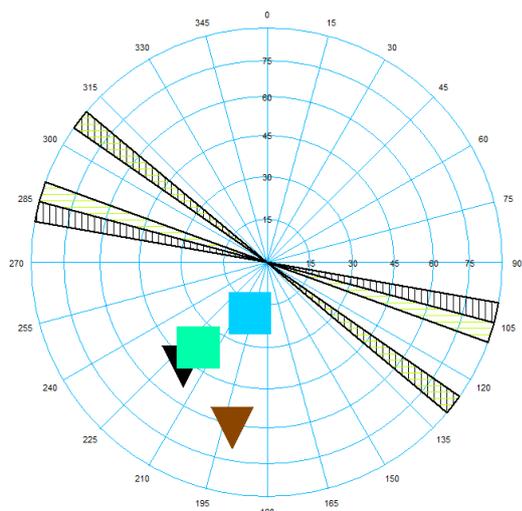


Figure 3 Rose diagram with stereonet overlay, representing BHI picks as triangles and seismic fault as squares

Along Well 1 cross-cutting faults are clearly visible. In the close-up, the two fracture picks from the BHI (Fig. 1) are imaged as discs corresponding to dip angle and azimuth. The Kraka reservoir is highly fractured and heterogeneities are clearly visible as amplitude variations on a seismic scale.

The dip and the dip-azimuth of the conductive fracture (black) corresponds well to the fault (green) from the seismic interpretation. The dip-azimuth of the resistive feature (brown) aligns with the seismic feature (blue), the dip angle deviates, however. The rose diagram in figure 3 shows the azimuth at a 5° interval coinciding for both fractures. The stereonet overlay also confirms

the qualitative assessment that the dip angle of the resistive fracture is steeper than that of the turquoise fault plane and a good match of the conductive fracture with the blue fault plane.

These results show that seismic data and careful post-processing shows stress trends that are reflected at the subseismic scale by BHI and core data. Seismic data is not capable of distinguishing open and closed fractures. Parallel and conjugate faults (yellow) in figure 2 strengthen the case of a consistent regional stress field that scales down to local stresses observed at the BHI and core scale. These can serve as input to building a field scale DFN.

Conclusions

Integrated comparisons of core, borehole image and seismic structural data in the Kraka Field indicate that:

- Many of the fractures seen on core can also be identified on borehole images, especially chert associated fractures. However stylolite associated fractures identified in core are not visible on borehole images. Chert associated fractures, extensional fractures and faults are commonly represented by partial sinusoids in BHIs, suggesting they are either short or only partially open or cemented.
- Borehole images are imperative in distinguishing cemented and open fractures, and thus better constrain fluid flow along the fracture network.
- Chromatic method and ant-track algorithm allows us to image subtle faults, fracture zones and compaction features not obvious on amplitude cubes.
- Structural features picked on BHIs correlate to large-scale regional trends and to features picked on ant-tracked seismic data. This allows us to extrapolate them away from the wellbores and calibrate 3D models (e.g. discrete fracture network models).

This integrated study proves invaluable in testing assumptions in building fracture models and the subsequent upscaling process.

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