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Natural fractures and discontinuities in a Lower Cretaceous chalk-marlstone reservoir, Valdemar Field, Danish North Sea

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ABSTRACT
Natural fractures and discontinuities have significant impact on subsurface flow conditions and thus production, of carbonate reservoirs, particularly in low-permeability sediments such as chalk-marl successions characterizing the Lower Cretaceous reservoirs in the Danish North Sea. Yet the diversity and distribution of the fractures are often poorly understood and largely underestimated. In heterogeneous, tight carbonate reservoirs, natural fractures can enhance permeability, as well as create secondary porosity and promote connectivity between reservoir compartments. The Valdemar Field, Danish Central Graben, represents the only producing field from the Lower Cretaceous in the Danish sector of the North Sea. The main reservoirs are confined to the Tuxen and Sola Formations. A new reservoir zonation is proposed based on facies characteristics and fracture patterns to consist of the lower Tuxen, middle-upper Tuxen, lower-middle Sola and upper Sola units with the Munk Marl Bed and Fischshiefer Member forming major reservoir barriers between the lower and the middle-upper Tuxen, and the lower-middle and the upper Sola units, respectively.

The reservoir intervals are of heterogeneous nature and composed of interbeds of five main facies comprising chalk, slightly marly chalk, marly chalk, chalky marlstone and marlstone. Six types of natural fractures and discontinuities are identified in the Valdemar Field based on core studies: cemented fractures, deformation bands, open fractures with plumose structures and hackle marks, shear fractures, small-offset shear fractures and rubble zones. The most dominant fracture type within all facies is the open fractures with plumose structures and hackle marks followed by small-offset shear fractures, shear fractures and rubble zones. Cemented fractures and deformation bands are less dominant. The small-offset shear fractures, shear fractures and open fractures with plumose structures and hackle marks are flow enhancing, while the cemented fractures and deformation bands are neutral or flow reducing. Rubble zones are also recorded throughout the core material. If these represent naturally fractured zones, present under subsurface conditions, they would be strongly flow enhancing. The flow-enhancing natural fractures (open fractures, shear fractures and small offset shear fractures) have densities of 7.2/m in the chalk, 5.0/m in slightly marly chalk, 3.1/m in marly chalk, 4.8/m in the chalky marlstone while they are absent in the marlstone. The flow-enhancing fractures have densities of 4.6/m in the lower Tuxen reservoir, 4.0/m in the middle-upper Tuxen reservoir, 2.7/m in the lower-middle Sola reservoir, and 7.4/m in the upper Sola reservoir. This study provides a detailed analysis of the natural fractures and discontinuities occurring the Lower Cretaceous succession of the Danish North Sea Basin, and their relation to the sedimentary facies and reservoir units.

1. Introduction

Structural discontinuities including natural fractures of various sizes and geometries are common in sedimentary rocks including carbonates and have an impact on the strength, deformation, and permeability of the rock, thus proper understanding of these features are crucial for
understanding the flow of hydrocarbons and groundwater (Van Golf-Racht, 1982; Nelson, 2001; Gudmundsson, 2011; Matthai and Nick, 2009; Salimzadeh and Nick, 2019; Sun and Pollitt, 2020; Gillespie et al., 2020).

Due to their often small size they are difficult to detect on seismic data so the understanding of natural fractures and discontinuities are often coupled to outcrop studies, core and well data. Fractures can have highly variable characteristics, and assessing their geometry, connectivity, origin, evolution and subsurface conditions makes it easier to understand.

Hydrocarbon production from the Lower Cretaceous Valdemar Field in the Danish North Sea takes place from a reservoir composed of cyclically bedded chalk, slightly marly chalk, marly chalk, chalky marlstone and marlstone. These lithologies have different mechanical properties, but all have low permeabilities (Gomord et al., 2018). Thus hydrocarbon production in this heterogeneous field is dependent on natural fractures, to act as contributors to flow (Agar and Geiger, 2015).

Classification systems of natural fractures have been proposed in several studies (Nelson, 1985, 2001; Lorenz and Cooper, 2018). These systems have been based on the origin, geometry, electrical properties as well as the potential effects of a fracture in a reservoir. Nelson (2001) propose various classification systems based on fracture origin (extension, tension or shear), the potential permeability of a fracture (open vs. filled fractures), and the structural associations of the fracture system (fault- fold- or regional related etc.). Contrary petrophysicists preferably classify fractures in image logs based on their acoustic or electric properties (conductive or resistive). Lorenz and Cooper (2018) divide fractures into two main categories considering their origin: Extension fractures and shear fractures with a palette of subcategories and modifiers. Classification systems are a useful method to categorize a spectrum of samples, and in fracture studies the used classification will be related to the overall purpose of the study with the fractures grading between categories between studies and classification schemes.

The classification system proposed in this study is based on core material from the Lower Cretaceous succession in the Danish North Sea and is applicable to similar carbonate-marl sedimentary successions. The classification scheme is based on Nelson (2001) and Lorenz and Cooper (2018) with the fracture geometry, origin and subsurface conditions guiding the distinguishing and classification of natural fractures and discontinuities in this study. Six types of natural fractures and discontinuities are classified: cemented fractures, deformation bands, open fractures with plumose structures and hackle marks, shear fractures, small-offset shear fractures and rubble zones. Deformation bands are structural features which form early (prior to lithification based on their fractures and shear fractures with a palette of subcategories and modifiers). Deformation bands are structural features which form early (prior to lithification based on their geometry) due to compaction of the sediment. Rubble zones represent structural features that are related to larger regional fault systems in the basin, and a key observation in this study have been to distinguish between natural rubble zones (by the presence of sickenlines or plumose structures on the rubble surfaces) vs. drilling induced rubble zones characterized by mechanical and even cuts on the rubble surfaces.

This study is the first to describe the natural fractures and discontinuities and their relation to facies and reservoir zones in the Lower Cretaceous Valdemar Field. No mechanical property testing has been carried out on Valdemar core, so no quantitative mechanical property data is available from these facies. Thus this study primarily focuses on fracture and discontinuity formation in relation to clay-carbonate variation within the reservoir (cf. Gomord et al., 2018). The present work may also supplement studies of fracture distribution in the Upper Cretaceous hydrocarbon-bearing reservoirs composed of chalk and argillaceous chalk (Descamps et al., 2017; Gomord et al., 2018).

2. Geological setting

2.1. Structural setting

The Danish Central Graben is part of the larger regional North Sea Central Graben rift complex in the axis of the North Sea basin (Gowers and Sabse, 1985; Vejbaek, 1986; Vejbaek and Andersen, 2002; Japsen et al., 2003; Møller and Rasmussen, 2003; Van Buchem et al., 2018).

The Danish Central Graben is bounded by the Mid North Sea High to the west and the Coffee Soil Fault to the east (Fig. 1) and consists of a series of eastward dipping, NW–SE trending half-grabens separated by structural highs (Japsen et al., 2003; Møller and Rasmussen, 2003). During the Middle Jurassic and Early Cretaceous, the Danish Central Graben experienced regional extension and fault-controlled subsidence due to sinistral transtensional strike-slip movements along NNW–SSE trending faults (Vejbaek and Andersen, 1987). During the initial syn-rift stage, subsidence took place to the east along the north–south linearities of the Coffee Soil Fault with deposition of Middle Jurassic fluvial and deltaic sediments (Japsen et al., 2003; Møller and Rasmussen, 2003; Glad et al., 2018). During the Kimmeridgian, a rise in sea level was accompanied by a significant increase in subsidence rates, causing a shift towards a NW–SE trend resulting in depocenters to move westwards, accompanied by deposition of marine shales known as the Forsund Formation that are the main source rock for the Valdemar Field (e.g. Ineson et al., 2003; Michelsen et al., 2003; Ponsaing et al., 2020).

Deposition of the Lower Cretaceous sediments took place in local grabens formed by thin skinned extension, detaching along the top of the Zechstein salt and controlled by the lateral distribution of the Zechstein salt (Hansen et al., 2021).

At the end of the Early Cretaceous, the hitherto governing NE–SW extension regime changed to a NNE–SSW compressional state with NW–SE dextral transpression occurring simultaneously, resulting in phases of inversion of increasing intensity during the Late Cretaceous and Palaeogene (Vejbaek and Andersen, 2002). The Early Cretaceous collapse grabens were inverted (thin-skinned inversion), creating the present topography of the Base Cretaceous Unconformity (Hansen et al., 2021) (Fig. 1).

2.2. Valdemar Field

The Valdemar Field is situated in the central part of the Danish Central Graben, north of the Salt Dome Province (Fig. 1). An inverted, N–S trending anticline dominates the structure of the area that is characterized by two structural highs, around the wells North Jens-1 to the north and Bo-1 to the south, separated by a saddle point (Fig. 1).

The North Jens area of the Valdemar Field has experienced a larger degree of inversion making it structurally more complex than the Bo area. Two large fault populations are present in the northern part of the field, striking WNW–ESE and NNW–SSE and interfering with each other. The WNW–ESE oriented faults are related to the south-western boundary of the Tail End Graben and the NNE–SSW oriented faults form the western margin of the Salt Dome Province. In the Bo area, the fault populations are more unidirectional being dominated by faults striking NNE–SSW, which could be due to the location of the Bo high being farther south and thus more distant from the Tail End Graben boundary. The dynamic evolution of the faults and associated fractures is related to formation of both the graben and inversion structures. However, they are yet not fully understood in the context of the complex interaction between deep crustal and thin skinned deformation.

Production in the Valdemar Field occurs from two non-interacting stratigraphic Lower and Upper Cretaceous reservoir units with the principal production located in the Lower Cretaceous units (Jakobsen et al., 2004, 2005). The Lower Cretaceous reservoirs are confined to the Tuxen and Sola Formations within the Cromer Knoll Group, a marine succession covering the majority of the Danish Central Graben and reaching a thickness of over 900 m in the main deponents (Fig. 2).

Discovery of the Valdemar Field dates to 1977 with the discovery of the Bo-1 well followed by the discovery of the North Jens area in 1985, and in 1993 the Lower Cretaceous reservoir came on stream (Danish Energy Agency, 2018). Field delimitation is approximately 100 km². Currently 21 wells operate the field (16 in the Lower Cretaceous); some
wells are drilled horizontally to follow the north-south trending crest of the anticline in a parallel pattern, while others are vertical. The wells are completed with induced sand propped fractures, around 10–15 per well, to improve stimulation of the low permeability formations. During active years on stream (1993–2020), a total of 14,115 thousand m$^3$ oil, and 6905 Nm$^3$ of natural gas have been produced from the Valdemar Field (Danish Energy Agency webpage, 2021).

The Lower Cretaceous reservoirs are heterogeneous and are composed of interbedded chalk, slightly marly chalk, marly chalk, chalky marlstones and marlstones. Source rocks are primarily organic-rich shales of the Farsund Formation (Ponsaing et al., 2020). The Tuxen Formation of Hauterivian–Barremian age (Fig. 2) has a thickness of 50 m in the North-Jens area and is composed of interbedded layers of marly chalk, slightly marly chalk and chalk with subordinate chalky marlstone and marlstone; the formation is divided into two broadly equal parts by a 2 m-thick interval of organic-rich dark marlstones referred to as the Munk Marl Bed (Ineson, 1993; Jakobsen et al., 2005). In the North Jens-1 region, the Barremian–Albian Sola Formation (Fig. 2) has a thickness of around 35 m; the lower part of the formation is primarily composed of marly chalk and chalky marlstones with subordinate marly chalk while the upper part is characterized by interbeds of slightly marly chalk and chalk. A distinctive 2 m thick unit of laminated dark marlstones (Fischschiefer Member) separates these two parts of the Sola Formation. The succession is capped by a ca. 5 m thick mudstone unit, previously termed the Albian Shale (Ineson, 1993; Jakobsen et al., 2005) but recently formally defined as the Fano Member (Van Buchem et al., 2018).

### 3. Methodology

The foundation of this study is the sedimentary cores drilled across the Valdemar Field, many of them have been cut in half to aid inspection of fractures and sedimentary characteristics (Fig. 2).

The studied cored sections were from the North Jens-1, Valdemar-1, Valdemar-2 and Valdemar-3 wells (Fig. 2). North Jens-1 is subvertically drilled making it ideal for fracture and facies analysis along the well. All these cored sections are located in the northern area of the Valdemar Field, and all cores are of an overall quality allowing three-dimensional investigations of the fractures and facies. The cores have diameters between 10 and 30 cm. The North Jens-1 cored section, comprising a ca. 90 m (295 feet) thick interval, spanning the stratigraphic interval from the Valanginian to the Aptian thus covering most of both the Tuxen and Sola Formations (Fig. 2).

Each natural fracture observed in these cores was classified and its location (measured depth along the wellbore), dimensions and host facies were recorded. The main challenge in fracture analysis is to distinguish between natural and drilling induced fractures (cf. Lorenz and Cooper, 2018; Kulander et al., 1990). Following the criteria proposed by Lorenz and Cooper (2018), natural fractures commonly show:

(i) mineralization  
(ii) similar orientation and geometries to mineralized fractures  
(iii) no geometric relationship with the core surface  
(iv) plumes, steps or slickenlines that have axis that are not parallel to the core axis.  
(v) planar geometry inclined to the core axis.

Whereas drilling induced fractures can be characterized by:

(i) rough, unmineralized, fresh breaks  
(ii) curving or bending towards the core surface, so they intersect it perpendicularly or at a tangent  
(iii) Plumes that are parallel to the core axis and bend as they approach the core edge  
(iv) Fracture planes that are consistently normal or parallel to the core axis.

Using this approach, observed structural discontinuities were classified into likely natural fractures and probable drilling-induced fractures. The same criteria were also used to assess whether rubble zones
are based on the Geologic Time Scale 2020 (Gale et al., 2020). Field and thus this study is primarily based on studies of this core. Absolute ages represent the most continuous and complete core record through the Valdemar available, however the quality of the cores are varying. The North Jens-1 well core material represent. Material from both the Tuxen and Sola reservoirs are for this study, distributed with 47 measurements in lower Tuxen, 70 in middle-middle Sola and 21 in the upper Sola reservoir intervals.

The Valdemar Field has hitherto been divided into 12 reservoir units (Jakobsen et al., 2005). However this study proposes a new reservoir zonation so that four main reservoir intervals are defined: lower Tuxen, middle-upper Tuxen, lower-middle Sola and upper Sola (Fig. 3).

4. Sedimentary facies

4.1. Chalk

Chalk (pelagite) is white to off-white, occasionally light yellow relatively pure nannofossil chalk without significant presence of clays, except for isolated solution seams (Fig. 4A). Certain levels in this facies are rich in nannoconids (Mutterlose and Bottini, 2013), but overall coccoliths dominate the composition of the facies. The chalk is homogeneous and generally structureless with faint mottingle due to bioturbation. Observed trace fossils include: Chondrites, Planolites and Thalassinoides. Part of the chalks are oil stained giving the rock a yellow to brown colour. In North Jens-1, chalk units vary in thickness between a few cm and a few m and make up 13% of the full core length. Lower Tuxen contains 10% chalk, middle-upper Tuxen contains 25% chalk, lower-middle Sola contains 0% chalk and upper Sola contains 4% chalk. Lithological transitions are both gradational or sharp, and chalk frequently occurs in close association with slightly marly chalk and marly chalk. Where the gradational boundaries are typically developed between the various chalk facies, the sharp transitions are more abundant when marlstone and chalk alternate.

4.2. Slightly marly chalk

The slightly marly chalk (pelagite/hemipelagite) has an overall cream, white to light grey colour with dark grey clay and organic material dispersed in the chalk matrix or concentrated as clay flasers and burrow fills. Most intervals are strongly bioturbated (cf. Damholt and Surlý, 2004) with a pronounced mottled fabric whilst others have abundant, clearly distinguishable, burrows (Fig. 4B). Trace fossils comprise Chondrites, Planolites, Thalassinoides and Zoophycos. In North Jens-1, units vary in thickness between 10 cm and 1–2 m and make up 30% of the full core length. Slightly marly chalk constitute 35% of the lower Tuxen as well as the middle-upper Tuxen reservoir units, while the facies only constitutes 4% of the lower-middle Sola and it dominates the upper Sola reservoir unit by constituting 70%. Slightly marly chalk frequently occurs in close association with chalk and marly chalk.

4.3. Marly chalk

The marly chalk (pelagite/hemipelagite) is light to medium grey and clay material can be concentrated in laminae and burrow fills, occur as clasts, or be dispersed throughout the sediment. Trace fossils comprise Chondrites, Planolites, Thalassinoides and Zoophycos.

The lithology is typically strongly to weakly mottled due to bioturbation, however intervals with laminations, clay flasers and burrows with clay fill are present (Fig. 4C). Intervals with slump structures and clay clasts indicate remobilization after initial deposition (cf. Andersen and C. Glad et al. page 4.5). Preliminary analyses indicate that the grey tone of the rocks are only a crude indicator of carbonate/clay ratio since organic matter and disseminated pyrite also contribute to colour. The grey tone is only a relative indicator of carbonate/clay ratio and we refrain from suggesting absolute values. The grey-scale analysis is supported by microscopy and visual inspections of texture and sedimentary structures in the sedimentary cores. There is a lack of direct continuous measurements of mechanical properties for the suite of lithologies composing the Lower Cretaceous reservoir rocks in the North Sea. However comparing to studies of similar lithologies it is to be expected that chalk will have more brittle conditions, whereas higher concentrations of clay and organic matter will result in reduced stiffness, friction coefficient and rock strength as well as more ductile conditions of the layer (Gomord et al., 2018).

Fig. 2. Stratigraphy of the Early Cretaceous formations in the Danish North Sea. To the right five cores North Jens-1, Valdemar-1, Valdemar-2 and Valdemar-3 are shown corresponding to the stratigraphic intervals that their core material represent. Material from both the Tuxen and Sola reservoirs are available, however the quality of the cores are varying. The North Jens-1 well represents the most continuous and complete core record through the Valdemar Field and thus this study is primarily based on studies of this core. Absolute ages are based on the Geologic Time Scale 2020 (Gale et al., 2020).

4. Sedimentary facies

Lithological identification is based on visual inspection of core
4.4. Chalky marlstone

Chalky marlstone (pelagite/hemipelagite) is medium to dark grey and is moderately to heavily bioturbated (cf. Damholt and Surlyk, 2004) and bioturbation comprises *Asterosoma, Chondrites, Palaeophycus* and *Thalassinoides*. The bioturbated intervals are interrupted by cm-thick layers of mm-thin even lamination. Certain intervals of this facies is characterized by ‘leopard chalk’ fabric. Slump structures and clay clasts suggest remobilization after initial deposition of the facies (cf. Ander-skouv and Surlyk, 2011). In North Jens-1, units of this lithology vary in thickness between thin beds of a few cm and up to 10’s of cm and make up 15% of the full core length. Chalky marlstone constitutes 16% of the lower Tuxen, 6% of the middle-upper Tuxen, 41% of the lower-middle Sola and only 2% of the upper Sola reservoir units. The facies frequently occurs in close association with marlstone and marly chalk.

4.5. Marlstone

The marlstone facies (pelagite/hemipelagite) is a dark grey to black marlstone in some intervals grading into a calcareous mudstone with a relative high amount of organic content indicated by its dark colour. Black intervals are predominantly laminated comprising mm-thick parallel laminations (Fig. 4D). However, weakly to heavily bioturbated intervals occur. Trace fossils comprise *Planolites* and *Chondrites*. Fragments of belemnites and bivalves are present throughout the facies. This facies is particularly notable in the Munk Marl Bed of the Tuxen Formation and the Fischschiefer Member of the Sola Formation, in both intervals alternating with lighter chalky marlstones. The Munk Marl Bed is an almost black finely laminated pyritic marlstone with 8–14% organic carbon. The fine thin laminae in the Munk Marl Bed are characterized by alternating lighter and darker layers with the light layers being inferred to be composed of nannofossils predominantly while clay is the main constituent in the dark layers (Heldt et al., 2012). The Fischschiefer is a laminated black marlstone-calcareous claystone rather similar to the Munk Marl with scattered pyrite and a few trace fossils, primarily *Chondrites*. According to Mutterlose and Bottini (2013), the unit contains up to 8% organic carbon. In North Jens-1, beds of marlstone vary in thickness between a few cm and up to 10’s of cm and comprise 11% of the full cored thickness. Marlstone is absent in the lower Tuxen and upper Sola reservoir units, while it only constitutes 3% of the middle-upper Tuxen and 21% of the lower Sola reservoir units. Marlstone frequently occurs in close association with marlstone and marly chalk.

5. Fracture characterization

A total of 470 natural fractures and discontinuities were recorded throughout the North Jens-1 core, with the majority of natural fractures and discontinuities being concentrated in the chalk-rich facies. Six different types of fractures were seen in the North Jens-1 core: cemented (mineralized and sealed) fractures, deformation band, open fractures with plumose structures and hackle marks, shear fractures, small-offset shear fractures and in addition, there are numerous rubble zones which may be related to structural features or represent drilling induced features (Fig. 5 A, B, C, D, E and F respectively). Fractures observed in other

| Chronostratigraphy (age) | Lithostratigraphy | Stratigraphic compartments | Reservoir zones (Jakobsen et al., 2005) | Reservoir intervals (This study) |
|--------------------------|-------------------|-----------------------------|--------------------------------------|---------------------------------|
| Cenomanian               | Rødby Formation   | Barrier interval            | Rødby                                |                                 |
|                          |                   |                             | Albian Shale                          | upper Sola                      |
| Albian                   | Sola Formation    |                             | Upper Sola-2                          |                                 |
|                          |                   |                             | Upper Sola-1                          |                                 |
|                          |                   |                             | Fischschiefer Member                  |                                 |
|                          |                   |                             | Middle Sola-3                         |                                 |
|                          |                   |                             | Middle Sola-2                         | lower-middle Sola               |
|                          |                   |                             | Middle Sola-1                         |                                 |
|                          |                   |                             | Lower Sola-1                          |                                 |
| Barremian                | Tuxen (upper)     | Barrier interval            | Upper Tuxen-1                         | middle-upper Tuxen              |
|                          |                   |                             | Middle Tuxen-2                        |                                 |
|                          |                   |                             | Middle Tuxen-1                        |                                 |
|                          |                   |                             | Lower Tuxen-3                         |                                 |
|                          |                   |                             | Lower Tuxen-2                         |                                 |
|                          |                   |                             | Lower Tuxen-1                         | lower Tuxen                     |

Fig. 3. Overview of the Lower Cretaceous reservoir zonation of the Valdemar Field defined by Jakobsen et al. (2005) and its correlation to lithostratigraphic units and stratigraphic compartments Jakobsen et al., (2005). The reservoir zonation defined in this study differs somewhat from Jakobsen et al., (2005) as the Munk Marl Bed and Fischschiefer Member are here considered barriers for fracture propagation and growth thus functioning as fracture barriers.
cores from the Valdemar Field are briefly described thereafter.

The shear fractures and small-offset shear fractures are distinguished by their displacement. Small-offset shear fractures are characterized by having two fracture planes (sides) that can be matched up without a significant gap whereas shear fractures are characterized by having an offset which extends beyond the core dimensions. On this basis it can be estimated that the shear fractures have greater apertures under subsurface conditions. Rubble zones are recorded, and categorized as natural fractures, as they represent structural features most likely the damage zone of a fault which is inferred from e.g. the presence of slickenlines, plumose structures and/or cement on the rubble rock pieces.

There is a complete lack of stylolites within all facies. These are commonly known features in the Upper Cretaceous – Danian chalks of the Danish North Sea (e.g. Fabricius et al., 2008).

5.1. Cemented fractures

Cemented fractures, are fractures filled by a combination of gouge, clay, and minerals (calcite and pyrite most commonly). They are short (lengths ranging between 4.5 and 22 cm) and in most cases are fully contained within the core. Although in some cases they extend across the entire core width (Fig. 5A). They have apertures of 0.4 mm–3 cm which are partially or fully cemented. The cementation of the fracture results in significantly reduced local permeability (Wennberg et al., 2016).

A total of eleven cemented fractures are observed in North Jens-1 constituting 2% of all natural fractures (Fig. 6). They are distributed with 3 occurrences in marly chalk, and 4 occurrences in both slightly marly chalk and chalk (Fig. 3). Due to the limited observations of this fracture type, fracture densities have not been calculated. Cemented fractures are known from other North Sea fields (e.g. LeveilleKnipeMore et al., 1997) such as the Danian Ekofisk Formation of the Kraka Field (Glad et al., 2020).

5.2. Deformation bands

Deformation bands appear in cores as networks of dark brown light lines that have apertures of around 1 mm. They usually have a small offset to the host rock and may exceed lengths of several cm (Fig. 5B). Deformation bands represent original primary structural features which formed early as a result of compaction (cf. Wennberg et al., 2016). Deformation bands are narrow zones of cataclasis (where the sediment particles are crushed or broken). They have a shear offset, although it is usually small (sometimes just a few mm or less). The relative displacement across the fracture plane can be closed or offset by relative shear. They are compaction features corresponding to local pore space collapse.

Rather than being classified as a natural fracture deformation bands are considered as a structural discontinuity which formed early as the sediment underwent compaction (Wennberg et al., 2013, 2016; Minde and Hiorth, 2020).

Deformation bands constitute 10% of the total fractures in North Jens-1 with 52 occurrences (Fig. 6). There are 17 occurrences in chalk, 10 in marly chalk and 25 in slightly marly chalk (Table 1). Deformation bands have the highest density in chalk with 1.5/m, while slightly marly chalk are less dense with 0.9/m and marly chalk with 0.4/m while they are absent in marlstone (Table 1).

5.3. Open fractures

Open fractures with plumose structures and hackle marks interpreted by fractography provide insight about fracture propagation and direction (e.g. Woodworth, 1896). These structures represent, dilatant mode I opening, fractures created by opening driving stress and indicate the presence of fluid overpressure in the reservoir during their formation (Lorenz and Cooper, 2018). The axes of the plumes record the direction of the fracture propagation (Lorenz and Cooper, 2018). The open fractures are best recognized by their fracture plane visible on the surface of a core piece (Fig. 5C). On core pieces it is often only part of the structure that is visible, often due to broken core. The plumose structures have apertures varying between 4 and 12 cm. The plumose structures and hackle marks are parallel to bedding, and they can in some cases be observed to be flanked by one or two fringe zones of small en-échelon
Fig. 5. Fracture types and discontinuities in the Valdemar Field. A: Cemented fracture. The fracture has an aperture of around 15 mm, and is filled with a combination of clay and calcite minerals. The saw marks on the sides of the core are artificial. Upper Sola Formation, North Jens-1 core. B: Deformation bands concentrated in a dense network showing considerable geometrical variations along the fracture planes, which is partly the result of variable angles between the fractures and the core surface. Middle-upper Tuxen Formation, North Jens-1 core. C: Open fracture with plumose structure and hackle mark. The open fractures with plumose structure and hackle mark occur frequently throughout the North Jens-1 core. Lower-middle Sola Formation, North Jens-1 core. D: Shear fracture with slickenlines along the fracture plane. The aperture of the fracture (extension of the slickenlines) suggests the fracture has a throw beyond the restrictions of the core dimensions. Middle-upper Tuxen Formation, North Jens-1 core. E: Small-offset shear fracture here recognized by the fracture plane indicated by dashed lines. Lower-middle Sola Formation, North Jens-1 core. F: Rubble zone characterized by clasts varying between silt and pebbles in size with the majority of the clasts being granules in size (around 2–4 mm) with some clasts exceeding several cm in size. The presence of sheared slickenlines on some of the clasts indicate that the rubble zone formed naturally while more sharp cuts to the surface of the clasts would suggest a mechanically induced nature for the broken up part of the core.
Natural fractures illustrated by their percentage and occurrences. The fracture type is important to distinguish between the natural open fractures with plumose structures and hackle marks and drilling induced plumes. The induced fractures form after the core is cut and show plume patterns that curve to become normal to the outer core surface suggesting that the core surface was free at the time of discing (Lorenz and Cooper, 2018).

With 246 occurrences, the open fractures with plumose structures and hackle marks are the most abundant natural fracture type observed in the North Jens-1 core and constitute 53% of the total fractures (Fig. 6). The open fractures with plumose structures and hackle marks are the most abundant fracture type in all facies. The fracture type is distributed through the North Jens-1 core with 80 occurrences in slightly marly chalk, 69 cases in chalk and 49 and 48 occurrences in marly chalk and chalky marlstone, respectively (Table 1). Chalk has the greatest density, as occurrences measured along the core per meter, of marly chalk and chalky marlstone, respectively (Table 1). Chalk has the highest density in slightly marly chalk with 0.9/m, in chalk the fracture density is 0.3/m and 0.5/m in marly chalk while marlstone have a fracture density of 0.2/m (Table 1).

5.5. **Small-offset shear fractures**

Small-offset shear fractures are recognized as a separation in the core creating a crevice with slickenlines along the fracture wall (Fig. 5E). They are planar features defined by having an unfilled (open) aperture, they occur both as singular structures or within networks of several fractures that either occur alongside each other or branching of one another. Small-offset shear fractures are distinguishable from shear fractures by having an offset which can be traced within the core dimensions in contrast to the shear fractures that have their offset beyond the core dimensions. They range in length from between 4 cm and 32 cm, although as some of the fractures are not fully traceable through the core dimensions they may very likely exceed the maximum length measured.

Small-offset shear fractures are widely recognized in carbonate reservoirs and have a significant influence on fluid flow, and may locally create a permeability contrast (e.g. Föppelreiter and Balzarini, 2005; Bourrié, 2010).

Small-offset shear fractures constitute 17% of the natural fractures in the North Jens-1 core with 77 occurrences (Fig. 6). They are most frequent in slightly marly chalk (30 occurrences) and marly chalk (23 occurrences) and are also present in chalk and chalky marlstone with 12 occurrences in each of these facies (Table 1). The fracture type has a density of 1.0/m in chalk, 1.1/m in slightly marly chalk, 0.8/m in marly chalk and 0.9/m in chalky marlstone, while they are absent in the marlstone (Table 1).

5.6. **Rubble zones**

Rubble zones are sections of broken core, typically tens of centimeters to a few meters thick. They may represent either fault zone or a fracture corridor, or damage due to the drilling process. It is difficult to distinguish natural rubble zones created by faults or closely spaced fractures from drilling induced rubble zones. However, the surfaces of broken core pieces in natural rubble zones often exhibit staining and dimensions. Shear fractures in this study are commonly recognized by their fracture plane and by the presence of slickenlines (Fig. 5D). The slickenlines are generally continuous and parallel features and characterized by clay smearing in some cases.

There are 45 occurrences in North Jens-1 constituting 10% of all fractures in the core (Fig. 6). The primary occurrences of shear fractures are restricted to slightly marly chalk and marly chalk with 24 and 14 occurrences respectively, while they occur 3 and 4 times in chalky marlstone and chalk respectively (Table 1). Shear fractures have the highest density in slightly marly chalk with 0.9/m, in chalk the fracture density is 0.3/m and 0.5/m in marly chalk while marlstone have a fracture density of 0.2/m (Table 1).

### Table 1

Overview of the fracture density for each fracture type distributed in the facies along the North Jens-1 core. Due to the limited amount of cemented fractures, and the uncertainty of the length and background (natural or induced) of the rubble zones fracture densities have not been deemed relevant for these two types. Furthermore the combined fracture density for the flow-enhancing fracture types has been calculated. Occurrences of each fracture type pr. facies is also noted and summarized by amount and percentage for the entire North Jens-1 core at the base of the table.

| Natural fractures Facies | Cemented fractures (occurrences) | Deformation bands (occurrences) | Open fractures with plumose structures and hackle marks (occurrences) | Shear fractures (occurrences) | Small-offset shear fractures (occurrences) | Rubble zones (occurrences) |
|--------------------------|---------------------------------|---------------------------------|---------------------------------------------------------------|------------------------------|------------------------------------------|---------------------------|
| Chalk                    | n = 4                           | n = 17 1.5/m                    | n = 69 5.9/m                                                  | n = 4 0.3/m                  | n = 12 1.0/m                             | n = 9                      |
| Slightly marly chalk     | n = 4                           | n = 25 0.9/m                    | n = 80 3.0/m                                                  | n = 24 0.9/m                 | n = 30 1.1/m                             | n = 10                     |
| Marly chalk              | n = 3                           | n = 10 0.4/m                    | n = 49 1.8/m                                                  | n = 14 0.5/m                 | n = 23 0.8/m                             | n = 17                     |
| Chalky marlstone         | n = 0                           | n = 0                           | n = 48 3.7/m                                                  | n = 12 0.2/m                 | n = 10 0.9/m                             | n = 3                      |
| Marlstone                | n = 0                           | n = 0                           | n = 0                                                        | n = 0                        | n = 0                                    |                           |
| North Jens-1             | 11                              | 52                              | 246                                                           | 45                           | 77                                       | 39                        |
| (occurrences)            |                                 |                                 |                                                              |                              |                                          |                           |
| North Jens-1 (percentage) | 2%                              | 10%                             | 53%                                                          | 10%                          | 17%                                      | 8%                        |
look weathered, and may show slickensides, plume and hackle marks or cement, while induced rubble zones can be jagged and fresh looking. Rubble pieces in the North Jens-1 core range from silt to pebble sized rock pieces with some larger fragment of cobble size occurring in the zones (Fig. 5F). The majority of the rubble zones are primarily composed of pebble sized particles (2–64 mm) with around 10% of the clasts being smaller or larger.

There are 39 rubble zones in North Jens-1 thus constituting a total of 8% of all observed fractures (Fig. 6). Approximately 14% of the complete North Jens-1 core is composed of rubble zones. The zones predominantly occur in marly chalk, slightly marly chalk and chalk with 17, 10 and 9 occurrences respectively while only 3 rubble zones are assigned to the chalky marlstone facies. Due to the large intervals the rubble zones can span they often extend across facies, and where obvious facies transitions occur they count half for each of the respective facies (Table 1).

5.7. Fractures in other cores

The upper cored section in the Valdemar-1 well (Fig. 2) covers the uppermost part of the Upper Sola Formation and is of low quality. There are only seven fracture types, including rubble zones, present: (i) three occurrences of rubble zones (ii) three small-offset shear fractures and (iii) single open fracture with plumose structure and hackle mark that are all found in chalk facies except for one small-offset shear fracture and one rubble zone interval that occur in slightly marly chalk.

The lower cored section of the Valdemar-1 well (Fig. 2) covers the Tuxen Formation and 22 natural fractures were recorded: (i) one cemented in chalk (ii) five deformation bands of which four are in chalk and one occurs in slightly marly chalk (iii) four small-offset shear fractures (three in slightly marly chalk, one in marly chalk) (iv) two open fractures with plumose structures and hackle mark in chalk and (v) 10 rubble zone intervals (two in marlstone, one in chalky marlstone, one in slightly marly chalk and five in chalk).

The cored section of the Valdemar-2 well (Fig. 2) spans short intervals of the Tuxen Formation, Fischerschiefer Bed and overlying Sola Formation and has a total of 51 natural fractures: (i) Three cemented fractures in chalk, (ii) ten networks of deformation bands of which eight are in chalk and two in slightly marly chalk, (iii) six small-offset shear fractures, four in chalk and two in slightly marly chalk, (iv) Seven open fractures with plumose structures and hackle marks, four in slightly marly chalk and three in chalk, (v) Sixteen rubble zones; seven in chalk, eight in slightly marly chalk and one in marlstone, (vi) Nine shear fractures, eight in chalk and one in slightly marly chalk.

Valdemar-3 (Fig. 2) covers the Barremian spanning the middle- and upper Tuxen Formation with 119 natural fractures occurring. i) One deformation band network in slightly marly chalk. ii.) Four small-offset shear fractures of which two are in chalky marlstone and two in slightly marly chalk. iii.) 84 open fractures with plumose structures and hackle marks distributed with three in chalky marlstone, two in marly chalk, two in slightly marly chalk and 77 in chalk. iii.) Five rubble zones of which two are in chalky marlstone, one in marly chalk and two in chalk. V.) Shear faults occur 25 times distributed by six in marly chalk, four in slightly marly chalk and fifteen in chalk.

6. Reservoir units

The Lower Cretaceous chalk reservoir succession of the Tuxen and Sola Formations in the Valdemar Field is subdivided into 14 units (Fig. 3; Jakobsen et al., 2005). The three functioning reservoir compartments are according to Jakobsen et al. (2005): (1) the lower Tuxen beneath the Munk Marl Bed, comprising the Lower Tuxen-1, Lower Tuxen-2 and Lower Tuxen-3 zones, (2) the upper Tuxen composed of the Middle Tuxen-1, Middle Tuxen-2 and Upper Tuxen-1 zones (and locally Lower Sola-1) and (3) the Sola (Middle Sola-2, Middle Sola-3, Fischerschiefer Member, Upper Sola-1, Upper Sola-2 zones). The remaining zones are marlstone-rich including the Middle Sola-1 and the Munk Marl Bed and considered to represent poor reservoir or baffles/barriers (Jakobsen et al. 2004, 2005). In the North Jens-1 well, these three reservoir compartments are 21 m, 28 m and 11 m thick, respectively; the Upper Tuxen-1 zone, considered the optimum reservoir zone by Jakobsen et al. (2004, 2005), is approximately 7.5 m (25 feet) thick.
A new classification of the reservoir units is given here in order to aid the description of the natural fractures (Fig. 3). This slightly revised approach has been selected as natural fractures neither developed nor propagated within the Munk Marl Bed and the Fischschiefere Member, and thus these two intervals acted as barriers for the formation and growth of natural fractures. The new reservoir intervals are: the lower Tuxen interval (identical to the lower Tuxen in Jakobsen et al., 2005), the middle-upper Tuxen interval (identical to the upper Tuxen in Jakobsen et al., 2005), the lower–middle Sola interval (comprising the barrier interval of Lower Sola-1 and Middle Sola-1 and reservoir zone Middle Sola-2 and -3 of Jakobsen et al., 2005), and finally an upper Sola interval (comprising Upper Sola-1 and Upper Sola-2 zones in Jakobsen et al., 2004, 2005).

These reservoir intervals have the following thicknesses in the North Jens-1 core: the lower Tuxen interval (7633–7564 feet, 21 m), the middle–upper Tuxen interval (7557–7467 feet, 28 m), the lower Sola interval (7464–7393 feet, 13 m), and the upper Sola interval (7386–7350 feet; 11 m).

The lower Tuxen reservoir interval is primarily composed of equal amounts of marly chalk (39%) and slightly marly chalk (35%) associated with chalk (10%) and chalky marlstone facies (16%) (Fig. 7). This reservoir interval has the lowest measured average porosity with a value of 27.2% while the average permeability of 0.73 mD is the third lowest (Fig. 8).

The middle-upper Tuxen reservoir interval is composed of marly chalk (31%), slightly marly chalk (35%), chalk (25%), chalky marlstone (6%) and marlstone (3%) (Fig. 7). The reservoir interval has the highest average permeability of 1.9 mD and an average porosity of 34.4% which is the third lowest (Fig. 8). The middle-upper Tuxen-1 reservoir zone, considered alone, is composed of chalk (59%), slightly marly chalk (23%), marly chalk (15%) and chalky marlstone (3%) and thus constitutes the most chalk-rich reservoir unit. The average permeability for the middle-upper Tuxen-1 unit is 3.9 mD while the average porosity is 38%.

In the lower Tuxen reservoir interval, a total of 150 natural fractures were recorded with the small-offset shear fractures (31%) being abundant while open fractures with plumose structures and hackle marks (22%) as well as deformation bands (19%) and shear fractures (15%) are common and rubble zones (8%) and cemented fractures (5%) are rare (Figs. 7 and 9).

In the middle-upper Tuxen reservoir interval, a total of 145 natural fractures and discontinuity distribution are examined in relation to the reservoir intervals described above (Fig. 7). For each reservoir interval it is determined which fracture types are rare (<10%), common (10–30%) or abundant (>30%) of the total amount of registered fractures within the interval. A total of 470 natural fractures were recorded in the North Jens-1 cored section; these are distributed relatively evenly throughout the cored section, but are more frequent in the chalk-rich facies and completely absent within the marlstone (Fig. 6).

In the lower Tuxen reservoir interval, a total of 150 natural fractures were recorded with the small-offset shear fractures (31%) being abundant while open fractures with plumose structures and hackle marks (22%) as well as deformation bands (19%) and shear fractures (15%) are common and rubble zones (8%) and cemented fractures (5%) are rare (Figs. 7 and 9).
fractures were recorded with the open fractures with plumose structures and hackle marks (52%) being abundant while shear fractures (14%), small-offset shear fractures (12%), rubble zones (11%) and deformation bands (10%) are common and cemented fractures (1%) are rare (Fig. 7).

Considering only the Upper Tuxen-1 reservoir zone, a total of 19 natural fractures were recorded, with rubble zones, shear and small-offset shear fractures being relatively common.

In the lower-middle Sola reservoir interval, a total of 77 natural fractures were recorded with the open fractures with plumose structures and hackle marks (79%) being the most abundant group. Rubble zones (8%), small-offset shear fractures (5%), deformation bands (4%), shear fractures (3%) and cemented fractures (1%) are rare (Fig. 7).

In the upper Sola reservoir interval, a total of 98 natural fractures were recorded with the open fractures with plumose structures and hackle marks (78%) being the most abundant group while small-offset shear fractures (9%), deformation bands (6%), rubble zones (5%), shear fractures (1%) and cemented fractures (1%) are rare (Figs. 7 and 10).

7.2. Natural fractures and sedimentary facies

The abundance of the different categories of natural fractures within the five main facies has been assessed (Fig. 11); due to the complete lack of natural fractures in the marlstones, this lithology is not represented.
Hence for each facies it is determined which fracture types are rare (<10%), common (10%–30%) or abundant (>30%) relative to the total number of fractures registered in that facies in the North Jens-1 core. There are too few cemented fractures to carry out statistical analysis on fracture density. Rubble zones are not included in the fracture density statistics as they may cover several meters of core, and extend across facies boundaries.

In chalk, cemented fractures, deformation bands and shear fractures are rare, small-offset shear fractures are common while open fractures with plumose structures and hackle marks occur abundantly. Chalk constitutes 11.7 m of the total core length in North Jens-1 and the fracture density is 5.9/m for open fractures with plumose structures and hackle marks, 1.0/m for small-offset shear fractures, 1.5/m for deformation bands and 0.3/m for shear fractures (Fig. 11).

In slightly marly chalk, the cemented fractures and deformation bands are rare, small-offset shear fractures and shear fractures are...
Six different natural fractures and discontinuities are recognized in the cores drilled in the northern part of the Valdemar Field. Small-offset shear fractures, shear fractures and open fractures with plumeose structures and hackle marks are considered to be flow enhancing while cemented fractures and deformation bands are most likely neutral or flow reducing (Bourbiaux, 2010; Wennberg et al., 2016; Ferrill et al., 2017; AlQuaimi and Rossen, 2019; Havez et al., 2021). Rubble zones that are naturally occurring under reservoir conditions will also act as flow enhancing zones. Such zones have not been considered for statistical purposes in this study, however, due to both their thickness and lithology-crossing character as well as some uncertainty as to whether they are induced or natural in the cores.

Natural flow-enhancing fractures in the sediments are distributed with the following densities: 7.2/m in chalk, 5.0/m in slightly marly chalk, 3.1/m in marly chalk and 4.8/m in chalky marlstone. No fractures were observed in the marlstones, which seem to have acted as barriers for fracture propagation. The relative brittle nature of the more carbonate-rich facies provides better mechanical properties of the lithology for natural fractures to grow and propagate within, whereas the mechanical ductile conditions of the more clay-rich facies seem to restricted fracture formation. However, the chalky marlstone facies does not follow this pattern, and have a relative frequent occurrence of natural fractures and discontinuities as this facies is typically heavily silicified (characterized by the 'leopard chalk' fabric) making it more brittle. The relatively high density of flow-enhancing fractures in chalky marlstones results also from the frequent presence of open fractures which occur closely spaced and are usually quite small in dimensions compared to similar fractures in the other facies.

The four reservoir intervals defined here are all composed of various proportions of chalk, slightly marly chalk, marly chalk, chalky marlstone and marlstone. Chalk constitutes 10% of all facies in the lower Tuxen interval, 25% in the middle–upper Tuxen and 4% in the upper Sola interval while chalk is absent from the lower-middle Sola reservoir interval. Considering the Upper Tuxen-1 reservoir zone (Jakobsen et al., 2005) in isolation, corresponding to the uppermost 7.5 m (25 feet) of the middle-upper Tuxen reservoir interval, chalk constitutes 59%. Since the chalk facies contains the highest density of flow enhancing natural fractures, it is to be expected that the Upper Tuxen-1 zone, would be the best hydrocarbon-producing reservoir level in the field (cf. Jakobsen et al., 2004).

Densities of the flow-enhancing fractures are 4.6/m in the lower Tuxen reservoir interval, 4.0/m in the middle–upper Tuxen reservoir interval, 2.7/m in the lower–middle Sola reservoir interval, and 7.4/m in the upper Sola reservoir interval. Thus somewhat surprising a relatively low density of flow-enhancing fractures was recorded in the middle-upper Tuxen reservoir interval considering the high proportion of chalk in this interval. A possible explanation is that the chalk facies form relatively thin layers often interrupted by beds rich in clay and organic material against which the fractures terminate, resulting in reduced fracture propagation and development.

The lower-middle Sola reservoir interval contains a significant proportion of clay-rich lithologies (chalky marlstone and marly chalk) and has relative low densities of flow-enhancing fractures, while the upper Sola reservoir interval has a significantly higher proportion of chalk-rich facies including chalk and slightly marly chalk as well as relative high densities of flow-enhancing fractures. These differences in density of natural fractures suggest that the clay-carbonate ratio of the facies in the reservoir interval probably related to their mechanical properties is an important factor controlling fracture formation and development.

This study shows that small-offset shear fractures, open fractures and shear fractures have the highest density in the chalk facies, with a density of 7.2/m, which supports the suggestion of lithology (clay content), and thus mechanical properties, was one of several parameters controlling development of these fractures. This conclusion is supported by the fact that no natural fractures and discontinuities are present in marlstone comprising the Munk Marl Bed and the Fischschiefer Member. However even though there is an absence of natural fractures in the marlstone intervals in the North Jens-1 core, particularly the Munk Marl Bed and Fischschiefer Member, there is a presence of sub-horizontal slickensided shear surfaces in other cores (e.g. Valdemar-2, Bo-2, Bo-3).
9. Conclusions

- Six types of natural fractures and discontinuities are identified in core material drilled in the Lower Cretaceous Valdemar Field: Cemented fractures, deformation band, open fractures with plumeose structures and hallmark marks, shear fractures, small-offset shear fractures and rubble zones. The distribution of fractures is recorded with respect to five broad facies (chalk, slightly marly chalk, marly chalk, chalky marlstone, and marlstone) and in relation to four informal reservoir intervals used in this study: lower Tuxen, middle-upper Tuxen, lower-middle Sola, and upper Sola.

- The small-offset shear fractures, shear fractures and open fractures with plumeose structures and hallmark marks are considered to be flow-enhancing, while the cemented fractures and deformation bands are most likely neutral or flow reducing comparing the fracture types to experimental and numerical studies. Rubble zones, if formed naturally, can constitute enhanced flow zones.

- The flow-enhancing natural fractures have densities of 7.2/m in chalk, 5.0/m in slightly marly chalk, 3.1/m in marly chalk, 4.8/m in the chalky marlstone, while they are absent in marlstone. The flow-enhancing fractures have densities of 4.6/m in the lower Tuxen reservoir interval, 4.0/m in the middle-upper Tuxen reservoir interval, 2.7/m in the lower-middle Sola reservoir interval, and 7.4/m in the upper Sola reservoir interval.

- Flow-enhancing fractures are more prone to develop and propagate in the chalk-rich facies, and terminate against clay- and organic-rich layers. There is an absence of natural fractures in the marlstone facies and natural fractures truncate against even mm-thin layers marlstone. Fracture density in the various facies is suggested to be controlled by their mechanical properties with the highest density in the relatively brittle chalk-rich facies and none in the more ductile marlstone.

- The middle-upper Tuxen reservoir interval and in particular the uppermost part of this interval has a relative high relative high proportion of chalk and contains common flow-enhancing structures including rubble zones and is thus considered to have the best reservoir properties.

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