Title : Basin settings of the Upper Jurassic Source Rock of the Southern Danish Central Graben

Author(s) : Donata Victoria Liuzzi Fernandez

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Professor(s) : Gert Jan Weltje

Supervisor(s) : Helle Krabbe

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Postal Address : Section for Geoscience Reservoir Geology
Department of Applied Earth Sciences
Delft University of Technology
P.O. Box 5028
The Netherlands

Telephone : (31) 15 2781328 (secretary)
Telefax : (31) 15 2781189
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Summary

From 3D seismic interpretation and well logs five of the strongest reflectors of the Upper Jurassic Source Rock along the Southern DGC were mapped, the markers were correlated with biostratigraphic and geochemical data. It was generated a simple 3D basin model.

The Southern DCG experienced a strong subsidence during Kimmeridgian with tilted fault blocks forming the three most important mini Basins of this area: Rosa, Poul and Igor. There was a uniform subsidence along the entire basin during the Late Kimmeridgian while the salt structures started to form in the Salt Dome Province. A large progradational system from south to north is seen, with minor retrogradations.

The subsidence rate diminished during the Volgian period and a fast regression was recorded. The Volgian is very condensed or absent in the Salt Dome Province where the salt structures pierced in a passive way.

The main HC expulsion took place in the Rosa and Poul Basin. The latest Jurassic Bo Member is not the principal source rock in the Southern Central Graben because it is immature. In this area the Lower Kimmeridgian is the main oil generator.

The Basin Modelling software calculates the maturity in the top surface of each package, and it was found that the HC expulsion rose up 40% of volume with the two artificial intralayers per package.

The statistical mean of Oil expulsion for all the TOC, HI and temperature variants range from 71500 to 154500 bbl of oil and from 110000 to 240000 bcf of gas.
Introduction

It is aimed to map the source rock of the Southern Danish Central Graben. This rock in the area has been dated from the Jurassic but its heterogeneous Rock Eval values makes us believe that it was deposited in different sedimentary environments.

In this study it is aimed to give a sedimentary sequence outline intra–Upper Jurassic so far not clear, due to the fast geometry basin modification for that period. The analysis will be carry out identifying the boundary surfaces on well logs in correlation with 3D seismic, in order to generate final “time maps”. Those parasequences will be dated and correlated based on petrophysic, biostratigraphy and geochemistry properties.

The intra Upper Jurassic surfaces will be used as input to do a basin analysis, from which a maturity model must be obtained, a quantification of the oil expelled and its burial history.
Chapter 1

1. Geological Setting of the Danish Central Graben (DCG)

On a large-scale the North Sea Rift is characterized as a three-armed system comprised of the Viking Graben (VG), Inner and Outer Moray Firth basins (IMF, OMF) and Central Graben (CG).

The Central Graben has an approximate length of 500 km from which 150 km belongs to Denmark and consist in a series of half-grabens with NNW–SSE strike. The Danish Central Graben is bounded in its east by Coffee Soil Fault.

Figure 1-1. North Sea Rift and the location of the Central Graben, and zoomed the DCG.
The coffee soil fault runs along the eastern margin of the Danish Central Graben. It can be followed on seismic up to 5 – 6 s two travel time. In general the fault plane has low dip angle around 30 – 35°. Sundsbø & Megson (1993) supports the fault appears to be planar when converted to depth. They also supports the total vertical movement of this fault is from 2.5 to 4 km in depth and it extends 6 km.

This fact can also be observed in the Coffee Soil Fault due to its broken segments with variable strike direction. In addition, the Central Graben segment with NW-SE orientation does not contain a substantial thickness of Triassic deposits but locally contains up to 4 km of Upper Jurassic shales, relating it to the variation of the slip rates along the Coffee Soil Fault (Sundsbø & Megson, 1993)).

### 1.1. Regional Geology

The North Sea Graben includes the Viking Graben, Moray Firth and Central Graben which are tectonically related with the Atlantic sea rift opening. The North Sea area was the site of a triple plate collision zone during the Caledonian orogeny. Four major tectonic events influenced the area since the Cambrian: (i) the Caledonian collision during Late Ordovician to Early Silurian, (ii) subsequent rifting and basin formation mainly identified in the Carboniferous to Permian due to the Pangea plate fragmentation (iii) Mesozoic rifting and graben formation and (iv) inversion during Late Cretaceous to Early Tertiary (Ziegler, 1990).

During the Jurassic, Errat, Thomas, & Wall, 1999 propose a polyphase rift history involving a reorientation of the kinematic axis from N–S to SW–NE. In other words a “variation on a vector triangle in the North Sea Rift” based on the isopach trends in Jurassic and Lower (see Figure 1–2).
This fact is evidenced specially in the Central Through and the Outer Moray. In the other hand, there are not explicit evidences in the CNS Graben of Danish sector of this shifting.

In the Late Cretaceous extensional structures were reactivated in a reverse sense as part of the regional inversion of basins in the southern part of the North Sea. Deposition proceeded throughout the deformation, and thickness variation in the deep marine Chalk succession is directly attributable to compressional deformation of the basin floor. The total shortening across the rift amounts to only a few percent. The structural expression of the reactivated margins is typically as low amplitude folds with minor associated reverse faulting. Compressional reactivation was restricted to basement faults, and the shallow inclination of the margin faults may have been an important factor in their subsequent reactivation. Zechstein evaporites and overpressured Jurassic shales were influenced the development of some of the compressional structures. Seismic-stratigraphic analysis of the Upper Cretaceous sequence indicates that the compressional deformation was markedly diachronous. Abrupt changes in the deformational chronology are found to occur across the transverse segment boundaries (Cartwright, 1989) (see Figure 1–3)
Figure 1-3 Summary of stratigraphic column for the Central North Sea area (modified by Errat et al., 1999 after Cayley, 1987).

1.2. Tectonostratigraphy

The pre-rift Basin evolution was characterized by a regional subsidence by thermal contraction following rift events in the latest Palaeozoic and earliest Mesozoic. There is a marked transgressive trend and marine conditions were restricted to the axial parts of the seaways in the Late Triassic and earliest Jurassic, spreading to the basin margins and the most proximal depocentres by the latest Sinemurian – Early Pliensbachian.

In the Upper Triassic succession it is shown a phase of relatively uniform regional subsidence following rift events in the Late Carboniferous – Early Permian (Figure 1–4) and the Early–Middle Triassic.

Lower Jurassic sediments are missing in some areas of the Danish Basin caused by its erosion due to uplift in the Middle Jurassic (Andsjerg & Dybkjær, 2003). Some authors attribute this uplifting to the development of rift dome extending 700 km in
Regional uplift, erosion and subsequent subsidence, onset of rifting and onlap of the previously uplifted area thus took place late Early – early Middle Jurassic times. In the Toarcian records the onset of regression and progressive basin restriction, suggest regional uplift and erosion and the reversion to terrestrial conditions in the Middle Jurassic.

The regional uplift was followed by a rifting mega-sequence at the Early – Middle Jurassic, since Surlyk & Ineson (2003). It started since Middle Jurassic peaked in the Lated Jurassic until the earliest Cretaceous. They also support the rifting opening
was not continuous but in phases of more intense rifting and block rotation alternating with more tranquil periods of regional subsidence.

Rattey & Hayward (1993) subdivided the syn-rift succession into seven regional tectonostratigraphic sequences for the Middle Jurassic—Lower Cretaceous. Later on Andsjerg & Dybkjær (2003) interpreted regional framework very compatible with the last one that will be well developed and explained in the next chapter (Statigraphic Sequence in the DCG—previous work).

Early syn-rift sedimentation was confined to narrow subsiding graben. A prominent unconformity is recorded in the uppermost Bathonian of the northern Danish Central Graben, recording a marked shift in subsidence patterns during early rifting (Andsjerg & Dybkjær, 2003).

The rift climax occurred in the Early Oxfordian—middle Middle Volgian in the Danish sector of the Central Graben, but with an important calm period in the Late Kimmeridgian characterised by regression and shoreface progradation (Andsjerg & Dybkjær, 2003, Johannessen, 2003, Møller & Rasmussen, 2003).

The late Middle and Late Volgian saw a general diminish in rift activity in the Danish Central Graben resulting in the development of more symmetrical sub-basins, associated with a general reduction in the overall sedimentation rate. Indeed, the Upper Volgian—Lower Ryazanian in the Central Graben is characterised by a relatively condensed stratigraphic package of organic-rich ‘hot shales’, associated locally with basin floor sands (Donovan et al., 1993; Ineson et al., 2003).

1.3. Lithology of central danish graben in the Jurassic

For the purposes of this work, the data is not correlated with formations, due to the lack of formation tops on the well reports. However, the lithologies are important to understand the depositional settings (see Figure 1–5).
**Lola Formation.**

- **Lithology:** claystones with organic material.
- **Color:** dark olive-grey to grey.
- **Depositional environment:** the formation consists of terrestrial origin with a low energy deposition of an offshore open marine environment.

**Farsund Formation.**

- **Lithology:** medium to dark grey claystones; they are carbonaceous and variably calcareous, and are intercalated with numerous thin beds of brownish dolomite.
- **Structures:** Towards the eastern part of the Danish Central Graben, close to the Coffee Soil Fault, the proportion of sandstones increases and there appears to be a transition locally to the sandy Poul Formation.
- **Depositional environment:** The organic matter is mainly liptinitic, and deposition took place in a relatively deep marine environment. Thin units of turbidite sandstones occur locally in the deeper parts of the basins.

**Bo Member (Ryazanian – Late Volgian).**

- **Lithology:** black to dark grey–brown, laminated claystones, which are carbonaceous and slightly calcareous to noncalcareous. It is intercalated with thin beds of dolomite.
- **Depositional environment:** Deposition occurred in a low-energy, oxygen-deficient deep marine environment. The sandstone–mudstone couplets were deposited from dilute turbidity currents (Ineson *et al.* 2003).

The Bo Member is present in the uppermost level of the Farsund Fm and it is considered as the best source rock in the Danish Central Graben Basin. It has a TOC that ranges from 3% to 8% and very high pyrolysis values of 10 - 100 kg HC/ton rock, and 200–600 HI. Nevertheless, there is a lateral variation in its thickness and organic richness, attributed to intrabasinal structural topography and the location of the sediment input centres (Ineson *et al.* 2003). This unit is 15 – 30 m thick in some sectors but truncated in some structural highs.
1.4. Statigraphic Sequence in the DCG – previous work

Andsjerg & Dybkjær, 2003 published a paper about the stratigraphic sequence of the Jurassic in DCNS. Their investigation is based on petrophysical log data, core sedimentology and biostratigraphic data from about 50 wells using seismic lines in some wells to assist the correlation.

They affirm the Jurassic basin history of the Danish Central Graben can be subdivided into seven discrete phases (this work focuses on the sequences 4 till 7):

1. Shallow marine and offshore sediments deposited in a prerift basin extending from the North Sea to the Fennoscandian Border Zone (Hettangian–Pliensbachian).
2. Uplift and erosion in association with a Toarcian–Aalenian North Sea doming event. A major hiatus represents this phase in the study area.
3. Terrestrial and marginal marine sedimentation during initial rifting (latest Aalenian/earliest Bajocian – Late Callovian).
4. Early Oxfordian – Early Kimmeridgian transgression during and after a rift pulse. The sedimentary environment changed from coastal plain and marginal marine to fully marine.
5. Regression associated with a cessation or slowing of subsidence during a structural rearrangement that took place in the Late Kimmeridgian during a break in the main rift climax. Shallow to marginal marine sandstones were deposited above an erosion surface of regional extent.

6. Deep-water mudstones deposited in a composite graben with high subsidence rates related to rift pulses (latest Late Kimmeridgian – middle Middle Volgian).

7. Deposition of organic-rich mudstones and turbidite sandstones during the late Middle Volgian – Early Ryazanian.

Each phase is subdivided in sequences referred according to their age, for the Lower Jurassic five sequences, for the Middle Jurassic four, and in the Upper Jurassic there were 11 sequences.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Age</th>
<th>Sequences</th>
<th>Deposition environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1</td>
<td>Hettangian–Pliensbachian</td>
<td>Hett-1, Hett-2, Sin-1, Pliens-1, Pliens-2</td>
<td>Pre-rift shallow marine deposition</td>
</tr>
<tr>
<td>Phase 2</td>
<td>Latest Pliensbachian – Latest Aalenian</td>
<td>Aalen-1, Baj-1, Bat-1, Cal-1</td>
<td>Uplift and erosion in the proto-rift phase</td>
</tr>
<tr>
<td>Phase 3</td>
<td>Latest Aalenian/earliest Bajocian – Late Callovian</td>
<td>Aalen-1, Baj-1, Bat-1, Cal-1</td>
<td>Terrestrial and marginal marine deposition during the rift initiation stage</td>
</tr>
<tr>
<td>Phase 4</td>
<td>Early Oxfordian – Early Kimmeridgian)</td>
<td>Ox-1, Ox-2, Kimm-1</td>
<td>Rift pulse related transgression</td>
</tr>
<tr>
<td>Phase 5</td>
<td>Late Kimmeridgian</td>
<td>Kimm-2, Kimm-3</td>
<td>Shallow marine deposits and changing structural patterns. Extensive sand deposition took place in the early Late Kimmeridgian in subsidence between two rift pulses. The sand deposition took over a large area with low accommodation space (in the north), which was created on the hangingwall plateau. Exposed highs and land areas outside the graben supplied the sand. Due to the decrease in subsidence in the Tail End Graben, input of finegrained sediment could catch up with accommodation space generation, probably resulting in a flat topography at the end of this phase</td>
</tr>
<tr>
<td>Phase 6</td>
<td>latest Late Kimmeridgian – middle Middle Volgian</td>
<td>Kimm-4, Volg-1, Volg-2, Volg-3</td>
<td>Deep-water mudstones in a composite graben: rift pulses and passive subsidence Renewed rifting caused rapid subsidence in the study area. Several rift pulses. Due to the high overall rate of subsidence, sand deposition associated with relative sea-level falls did not occur. The Danish Central Graben began to break up into minor subbasins.</td>
</tr>
</tbody>
</table>
Phase 7
late Middle Volgian – Early Ryazanian

Volg-4

Organic-rich mudstones and basin axis turbidites. Subsidence decreased, probably entered in an early post-rift stage. Major segments of the Coffee Soil Fault became inactive, resulting in a shallower, more symmetrical basin.
Active subsidence continued in a number of subbasins. Highly organic-rich mudstones are prominent in the deposits of this phase. The mudstones are interbedded with turbidite and debris flow sand deposits locally, in particular along the Tail End Graben – Gertrud Graben basin axis and along the eastern margin of the Tail End Graben.

Ryaz-1

The sequences tops were defined on the boundary surfaces (picked in the well logs as gamma ray sonic and resistivity), in the change of coarsening up sequences to fining up ones.

Their biostratigraphic data is mainly confined to palynomorphs due to the scarcity of other microfossil groups in most wells to be useful for detailed correlation. The biostratigraphic correlations are based on events rather than recognition of biozones.

The events used in this study are mainly last occurrence datums (i.e. first downhole appearance) of dinoflagellate cyst species. The biostratigraphic information utilised in their study includes published data (Birkelund, et al., 1983; Hoelstad, 1986; Poulsen, 1986; Johanessen, et al., 1996).

The data were derived from cutting samples. It was established a palynostratigraphic framework in the Lower Jurassic, based on a small number of events and stratigraphically diagnostic palyno-assemblages. In the other hand, the biostratigraphic resolution in the Upper Jurassic is higher due to the large sediment thicknesses, the better data quality, and the higher diversity of dinoflagellate cyst species.

Most key surfaces in the Upper Jurassic succession are picked in marine mudstones and siltstones. Of these key surfaces, only one sequence boundary (the base Kimm–2 SB) shows any sign of significant erosion. It was found high organic contents in the Upper Volgian – Ryazanian mudstones of the Bo Member (Michelsen, et al., 2003).
<table>
<thead>
<tr>
<th>Sequence</th>
<th>Biostratigraphic data</th>
<th>General description</th>
<th>Base</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kimm-2</strong></td>
<td>A latest Early Kimmeridgian to earliest Late Kimmeridgian age is indicated by the LOD of <em>Endoscrinium galereum</em> in the lower part of the sequence in Edna-1 and West Lulu-1 and the FAD of <em>Subtilisphaera? paeminsosa</em> and <em>S.? inaffecta</em> in the lower part of the sequence in Gert-1 combined with the LOD in the sequence above of <em>Stephanelytron scarburghense</em> in the Gert-2, Jeppe-1 and Lulu-1 wells</td>
<td>The HST consists of a coarsening-upwards interval of marine mudstones, siltstones and sandstones. The thickness of the sequence attains a maximum of 319 m in Cleo-1. Major depocentres for this sequence are located in the southern Tail End Graben – eastern Salt Dome Province, in the northern Tail End Graben – Søgne Basin and in the Fedan Graben.</td>
<td>Erosion surface – abrupt shift from high GR to low GR</td>
</tr>
<tr>
<td><strong>Kimm-3</strong></td>
<td>The LOD of <em>Stephanelytron scarburghense</em> in the lower to middle part of this sequence in Gert-2 and Jeppe-1 and the LOD of <em>Endoscrinium luridum</em> in the succeeding sequence (Kimm-4) indicate a Late Kimmeridgian age for this sequence</td>
<td>In the Tail End Graben (e.g. Nora-1), the TST is represented by a thin fining-upwards interval of marine mudstones. The HST typically consists of marine mudstones. In the Fedan Graben – Gertrud Plateau area and in the Søgne Basin, the HST terminates in a distinct coarsening-upwards interval, which includes silt- and sandstones (e.g. Gert-4). The thickness of the sequence attains a maximum of 387 m in Cleo-1. Major depocentres are located in the Søgne Basin, the Fedan Graben and the southern Tail End Graben – Salt Dome Province.</td>
<td></td>
</tr>
<tr>
<td><strong>Kimm-4</strong></td>
<td>A Late Kimmeridgian age is indicated for the sequence based on the LOD of <em>Stephanelytron scarburghense</em> in the sequence below combined with the LOD of <em>Endoscrinium luridum</em> close to the upper sequence boundary in Amalie-1 and Cleo-1</td>
<td>In basinal areas, the lower sequence boundary is located at the top of a coarsening-upwards interval, the Salt Dome Province and in the Tail End Graben, it often occurs in a condensed form.</td>
<td></td>
</tr>
<tr>
<td><strong>Volg-1</strong></td>
<td>The sequence is referred to the earliest Early Volgian (Fig. 3C) based on the LOD of <em>Endoscrinium luridum</em> in the sequence below combined with the LOD of <em>Subtilisphaera? paeminsosa</em> in the upper part of the sequence in a number of wells (e.g. Amalie-1, Deep Gorm-1, Gert-2, -4, Gwen-2, Ravn-2, U-1).</td>
<td>In several wells in the Salt Dome Province, the TST is missing and the MFS amalgamates with the underlying sequence boundary (e.g. Deep Gorm-1) The MFS is marked by a conspicuous peak on the gamma-ray, sonic and resistivity logs. Both the TST and HST consist of marine mudstones.</td>
<td>The boundary is situated at the turnaround point between rather indistinct coarsening-upwards and fining-upwards units.</td>
</tr>
<tr>
<td><strong>Volg-2</strong></td>
<td>The LOD of <em>Subtilisphaera? paeminsosa</em> in the sequence below (Volg-1) and of <em>Oligosphaeridium patulum</em> in the sequence above (Volg-3) indicate an Early Volgian age for this sequence. This is further supported by the LOD of <em>Cribroperidinium? longicorne</em> in the lower part of the sequence in the Eg-1 and Emma-1 wells (Fig. 3C).</td>
<td>Partly or completely eroded in most wells in the Salt Dome Province, this sequence is recognised throughout the remainder of the Danish Central Graben, including the Outer Rough and Ål Basins. The lower sequence boundary of this sequence consists of marine mudstones.</td>
<td>is rather indistinct in most wells, being located at the top of a weak coarsening-upwards trend within the HST of the Volg-1 sequence below</td>
</tr>
<tr>
<td><strong>Volg-3</strong></td>
<td>The LOD of <em>Oligosphaeridium patulum</em> in the lower part of this sequence in a number of wells (e.g. Deep Gorm-1, Elly-2, Falk-1, Gert-2, Gert-4, I-1, M-8, U-1, V-1) combined with the LOD of <em>Occisucysta bulla</em></td>
<td>It is missing locally in the south-western part of the Salt Dome Province and in the area around the Mandal High, probably due to erosion consists of marine mudstones.</td>
<td></td>
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</tbody>
</table>
in the middle to upper part of the sequence in the Bo-1, Gert-2, Gwen-2 and Ravn-2 wells indicate a latest Early Volgian – middle Middle Volgian age for this sequence. This is supported by the LOD of *Perisiesasphaeridium pannosum* in the upper part of the sequence in Gert-1 and Gert-2.

The LOD of *Seminiodinium inrribile* in the lower part of the sequence in Bo-1 and of *Semiaisphaera jurassica* in the lower to middle part of the sequence in a number of wells (e.g. Bo-1, Deep Gorm-1, Eln-1, Gwen-2, I-1, Jeppe-1, Ravn-2, W-1) indicate a middle Middle Volgian age for the lower part of the sequence. In combination with the LOD of *Egmontodinium polyplacophorum* in the middle to upper part of the sequence in the Bo-1, Deep Adda-1, E-1, I-1, Lone-1 and V-1 wells, this indicates a middle Middle Volgian to Late Volgian age for the sequence. This age assumption is supported by the LOD of one or more of the dinocyst species *Dichadogonyaulax pannea*, *Glossodinium dimorphum*, *Muderongia simplex* (the form previously referred as *Muderongia* sp. A; Poulsen & Riding 2003, this volume) and *Gochtiodinia mutabilis* within the sequence in a number of wells (e.g. Bo-1, Deep Gorm-1, E-1, Eln-1, Gwen-2, I-1, Iris-1).

The lower part of the TST typically shows a fining-upwards/coarsening-upwards pattern; in V-1, this unit is developed as a 30 m thick sandstone unit. Due to the increasingly organic-rich nature of the sediments (see below), the gamma-ray log is not considered a fully reliable grain-size indicator. The upper boundary of this sequence is commonly an erosion surface and the upper part of the HST is thus missing in many wells (e.g. Gwen-2, Jeppe-1).

In a number of wells, the sequence boundary is further marked by the abrupt base of a slightly more silty or sandy unit.

The LOD of *Egmontodinium expiratum* in the lower part of this sequence in a number of wells (e.g. Bo-1, Edna-1, Gert-2) and of *Rotosphaerotopsis thula* immediately above the ‘hottest’ part of the Bo Member (e.g. in Anne-3, Bo-1, E-1, Edna-1, Gert-2, Jeppe-1) indicate a Late Volgian – Early Ryazanian age for this part of the sequence. The uppermost part of the Farsund Formation is of Late Ryazanian age. This is indicated by the LOD of *Dingodinium spinosum* which coincides broadly with the upper boundary of the Farsund Formation in a number of wells (e.g. Deep Gorm-1, E-1, Edna-1, Jens-1, Jeppe-1, Kim-1, Lone-1, V-1; Ineson et al. 2003, this volume) and by the LOD of *Dichadogonyaulax culmula* at the same stratigraphic level in the E-1, Edna-1 and Gert-2 wells (Fig. 3C).

The distribution of the Ryaz-1 sequence corresponds to the distribution of the Volg-4 sequence (see above). The development of the ‘hot shales’ of the Bo Member within this sequence and the transition to more calcareous sediments at the top of the Farsund Formation makes sequence stratigraphic analysis problematic. In certain wells that lack such turbidite sandstones (e.g. E-1, Gert-2), the bioevents of the turbidite-bearing section are absent; this hiatus is interpreted to have resulted from erosion or sediment bypass, updip from areas in which turbidite sands accumulated (Ineson et al. 2003, this volume). The turbidite interval may represent lowstand and possibly early transgressive deposits. In areas without active turbidite transport or deposition, this interval is characterised by a gradual upwards increase in gamma-ray values, probably representing the background sedimentation of the basin (e.g. Bo-1). This increase in the strength of the gamma-ray signal culminates in the highest gamma-ray values in the entire Jurassic studied section. This interval corresponds to the ‘hot unit’ of Jensen et al. (1986), formalised as the Bo Member (Farsund Formation) by Michelsen et al. (2003, this volume). The dominant lithology is organic-rich marine mudstone; the mudstones are locally interbedded with turbidite sandstones (Ineson et al. 2003, this volume). The thickness of this interval, from the basal sequence boundary to the top of the Farsund Formation, attains a maximum of 326 m in Iris-1.

Turbidite sandstones occur above the boundary in several wells.
Chapter 2

2. Methodology

The first step was the compilation of the data as shown the box below. The project was carried out in Petrel software v. 2010.2.

- Seismic 3D from DUC +PSDM Petrel Software 2010.2
- Well logs from Petrel software 2010.2
- Biostratigraphy from Final well reports
- Geochemical information from Pyrolysis

Second, sequence stratigraphic and seismic stratigraphic interpretation were carried out iteratively. The horizons were dated with biostratigraphic data from the available wells.

The time horizons were converted to depth and transferred to a basin modelling software named Trinity 4.0. TOC and HI maps were generated from Rock-Eval data and isochrones maps (for interpolation matters) to produce maturation and expulsion maps.

With the information collected the results are (1) structural evolution within the Jurassic sequence in DCG; (2) burial history; (3) maturity maps and kitchens.

Hereafter, in the next chapter further details will be provided about those procedures in combination with some theoretical background, and the results obtained.
2.1. Geochemical Analysis

The petroleum source rock is fine-grained organic rich rock that could generate or already did generate an amount of hydrocarbon enough to form commercial accumulations of oil and gas.

An effective petroleum source rock must satisfy the requirements of quality, quantity, and thermal maturity of the organic matter. To summarize, the oil expulsion of a source rock relays in factors that must act together, as (1) type of source rock (from source of organic sediments) as kerogen type, (2) the total amount of organic carbon, (3) maturation and expulsion. There are some methods to measure the state of these factors as Rock-Eval pyrolysis (Peters, Walters, & Moldowan, 2005).

The four principal types of kerogen in sedimentary rocks include types I (very oil prone), type II (oil prone), type III (gas prone), and type IV inert.

Type I. Immature type I kerogen has high atomic H/C (~0.5), high Rock-Eval HI (>600 mg HC/ g TOC), and low atomic O/C (<0.1). Type I kerogen are dominated by lipinite macerals, although vitrinites and inertinites can occur in lesser amounts. Most type I kerogens are dominated by lipids-rich algal debris particularly in lacustrine setting (Peters, Walters, & Moldowan, 2005).

Type II. Immature type II kerogen has high atomic H/C (1.2 – 1.5), high Rock-Eval HI (300 – 600 mg Hc / g TOC), and low atomic O/C compared with type III and IV. The kerogen is dominated by lipinites and macerals but vitrinites and inertinites can occur in fewer amounts. Type II kerogen originates from mixed phytoplankton, zooplankton, and bacterial debris, usually in marine sediments. The type II kerogen accounts for most petroleum source rock, including Jurassic of the North Sea.

Type II/III. describes a transitional composition between types II and III that commonly represents a mixture of marine and terrigenous organic matter deposited in a paralic marine setting. Immature type II/III kerogen has atomic H/C and Rock-Eval HI in the range 1.0 – 1.2 and 200–300 mh HC / g TOC, respectively.
Type III. Immature type III kerogen has low atomic H/C (0.7 – 1.0), low Rock-Eval HI (50-200 mg HC / TOC) and high O/C (up to ~ 0.3). This type of hydrocarbon, usually originates from terrigenous plants, and it is dominated by vitrinites and lesser amounts of inertite macerals.

Type IV. Type IV kerogen is dead carbon showing low atomic H/C (<0.7) , low Rock-Eval HI (<50mg HC / g TOC) and low O/C. This type of kerogen is dominated by inertite macerals, and it can originate from other kerogen types that were reworked and oxidized.

Total Organic Carbon (TOC) also called organic carbon \( C_{org} \) measures the quantity (but not the quality) of the organic carbon in rock or sediment samples.

The Rock-Eval pyrolysis consists on heating the rock at 25 °C/min in an inert atmosphere. A flame ionization detector (FID) senses organic compounds generated during pyrolysis having picks or release named as \( S_1, S_2 \) and \( S_3 \).

The first peak (\( S_1 \)) represents hydrocarbons that can be thermally distilled from the rock (free hydrocarbons in the sample). The second peak (\( S_2 \)) represents hydrocarbons generated by pyrolytic degradation of the kerogen in the rock. It is an indication of the quantity of hydrocarbons that the rock has the potential of producing should burial and maturation continue. The third peak represents milligrams of carbon dioxide generated from a gram of rock during temperature at 390° C.

\( T_{max} \) is the temperature at which the maximum release of hydrocarbons from cracking of kerogen occurs during pyrolysis (top of \( S_2 \) peak). \( T_{max} \) is an indication of the stage of maturation of the organic matter.

The hydrogen index (HI) corresponds to the quantity of pyrolyzable organic compounds from \( S_2 \) relative to TOC on the sample therefore amount of HC over the total TOC \( (HI=[100 \times S_2]/TOC) \). With the increasing thermal maturation HI and TOC decreases. The oxygen index corresponds to the quantity of carbon dioxide from \( S_3 \) relative to the TOC. The production index is defined as PI- \( S_1/(S_1+S_2) \), used to characterize the evolution level of the organic matter.
Source rock data from the Jurassic was compiled from Maersk Oil in 24 wells in the area. The pyrolysis data were gathered in pIGI software in order to cluster the data of interest (Jurassic sector of the southern wells of the DCG) and to plot geochemical values to study the nature and quality of the source rock, i.e. Van Krevelen Diagram (see Figure 2–1).

**Figure 2–1 HI data plotted Vs OI from the southern wells of the DCG, used to guide about the nature of the kerogen type of the source rock.**

### 2.2. Biostratigraphy and lithology

The biostratigraphic information utilized in this study includes published data (Johannesen et al., 1996, 2003) and unpublished well reports from Maersk Oil. The biostratigraphic results are confined to palynomorphs because information from other groups of microfossils is too scarce in most wells to be useful for detailed. Most of the data were obtained from cutting samples. The table below collects biostratigraphy and lithology from the Maersk Oil reports.
Table 1: Lithology and ages from biostratigraphy. Information compiled from the well reports none published of Maersk Oil.

<table>
<thead>
<tr>
<th></th>
<th>Volgian</th>
<th>Upper Kimm</th>
<th>Lower Kimm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fasan</td>
<td>Claystone with local thin Siltstone beds and Limestone stringers. The Siltstones probably occur as thin beds and laminae - and are medium to dark brownish grey, very soft to soft, micaceous, moderately calcareous and variably sandy, locally grading to dirty Sandstone.</td>
<td>Gray shale</td>
<td>Gray shale</td>
</tr>
<tr>
<td>E-1</td>
<td>Gray shale</td>
<td>Gray shale</td>
<td>Gray shale</td>
</tr>
<tr>
<td>G-1x</td>
<td>Shale, gray, soft, calcareous, silty, micaceous, and siltstone. Some fine-grained sandstone and traces of brown dolomite</td>
<td>Shale, gray, firm, silty, calcareous, and silt, fine sand and dolomite, as above.</td>
<td>Shale, gray, firm, silty, calcareous, and silt, fine sand and dolomite, as above.</td>
</tr>
<tr>
<td>S.E. G-1</td>
<td>Claystone dark to medium grey, trace pyrite, calcareous, interlaminated with siltstone - grading sandstone dark to pale grey, very fine grained, slightly calcareous carbonate. Glaucite, pyrite, no to low visible porosity, oil bleeding. Dolomitic limestones stringers.</td>
<td>Claystone predominantly light to medium grey, soft to moderately firm, brown oil stain, Argillaceous Limestone/Dolomite medium to dark brown.</td>
<td>Claystone predominantly light to medium grey, soft to moderately firm, brown oil stain, Argillaceous Limestone/Dolomite medium to dark brown.</td>
</tr>
<tr>
<td>M-8x</td>
<td>Mudstones, light and dark grey and greenish grey, thin bedded to laminated grey interbedded mudstone. Marine middle to outer neritic.</td>
<td>Mudstones, light and dark grey and greenish grey, thin bedded to laminated grey interbedded mudstone. Marine turbid bottom environment middle to outer neritic.</td>
<td>Mudstones, light and dark grey and greenish grey, thin bedded to laminated grey interbedded mudstone. Marine turbid bottom environment middle to outer neritic.</td>
</tr>
<tr>
<td>Olga-1x</td>
<td>The silty claystone was medium to dark grey, locally light grey and contained traces of very fine sand. Local gradations to dark grey shale were present. The calcareous dolomite limestone was light grey to off-white and finely crystalline to cryptocrystalline.</td>
<td>The Kimmeridgian is predominately claystone, dark grey to medium grey to black with an occasional thin dolomite stringer, dark tan to dark red brown, very hard, predominantly microcrystalline. The upper portion from approximately 8180' to 8270' consists of marl, medium to dark grey, soft, plastic, sticky, silty, and grading to claystone as above. Trace nodular pyrite.</td>
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</table>

2.3. **Sequence stratigraphy and seismic stratigraphic interpretation**

The sequence stratigraphy analysis is based on data from 24 wells that penetrate Jurassic deposits southern of the Danish Central Graben (see Figure 2–2). For sequence stratigraphy interpretation was gathered information from: well logs (including gamma ray, sonic, neutron / density and resistivity logs); lithology logs and biostratigraphy.
Figure 2-2 Map of the area of study, southern part of the Danish Central Graben. On the map are shown the basin structure and the wells location used in this work.

The construction of the sequence stratigraphy is based on the correlation of well log patterns combined with seismic correlation. Most commonly the Gamma-Ray well logs were used for high resolution correlations but resistivity logs and density formed an important tool in some organic rich mudstone units.

It is considered that maximumflooding surfaces are the most reliable correlation surface in successions dominated by marine mudstones and therefore a potential good source rock. These surfaces were allocated on the GR logs between the fining upward and coarsing upward sequences.
The methodology was to interpret the stratigraphic boundaries from three well logs and tie them to the seismic reflectors. In addition, the well tops from Top-Jurassic as base Jurassic were provided by Maersk Oil (from the PSDM 2010 project).

A direct stratigraphic correlation among the wells was not found, possibly because of the high deformation of the basin. Therefore, three wells located in the deepest area of the Poul Basin were correlated and used as starting point.

The wells E-1, Fasan-1 and G-1 (Igor) are lined-up in the deepest area of the Poul Basin having the most complete depositional sequence of all the wells despite they don’t cover the entire Jurassic package.
The interpretation on the logs was done with high resolution. Nine well tops were identified on the Gamma ray logs and correlated using density resistivity and velocity logs (see Figure 2–3).

![Seismic cube with well logs]

**Figure 2–3.** Maximum flooding surfaces identified on the wells E-1, Fasan and G-1 from left to right.

The well tops were picked on the seismic cube, but they did not always correspond to a continuous seismic reflector. Therefore, only the well tops that corresponded to a strong and continuous coefficient of reflection were left.
The reflectors selected were mapped on the seismic cube in time. The resulted horizons were located on the other wells, while it was carried out a quality control through the patterns of density and velocity logs for each new well top.

In summary, the surfaces were identified on an iterative process between well logs and seismic continuity. Most of the wells are located on structural highs and therefore some of the sequences are very condensed or not present.

2.4. **Well – seismic tie**

The seismograms are generated as a forward 1D modeling to predict the seismic response of the Earth and being able to match the seismic responses in TWT with the well log responses in depth. A 1D synthetic seismogram is formed by simply convolving an embedded waveform with a reflectivity function. The reflectivity function can be calculated from the density log and the sonic log. The sonic log can be adjusted to check shock velocity points (see Figure 2–4).

The synthetic seismogram is meant to correlate the log responses with the proper reflectors on the seismic, and then to locate the well tops (in depth domain) on the seismic (in TWT domain). The quality of the fitting will depend on the velocities and wavelet.

![Figure 2-4 Theory behind synthetic seismogram](image)

Building synthetic seismograms require continuous and reliable log data along the entire length of the borehole. Damaged logs will create errors in the time depth relationship or...
artificial responses in the synthetic seismogram. In the majority of cases, logs will require some considerable editing before they can be used to create synthetic seismograms.

The logs used were sonic (calibrated with check-shots) and density. The editing of the logs consisted on a despike process and a harmonic average of 6–10 samples. This process was done to diminish the dolomitization effect and to decrease the frequency of the resolution (see Figure 2–6).

The waveform can be obtained mainly from two different ways. One is calculating a synthetic wavelet for which the user will input all the parameters. The other one is extracting the wavelet from the seismic response.

There are four types of analytical wavelets: Ricker, Ormsby, Klauder and Butterworth. In this job only the Ricker was used.

The workflow process for the wavelet extraction involves trying several combinations of extraction parameters, recording the results, and trying different boreholes in order to gain a better understanding of the nature of the seismic data (Synthetic wavelets/ petrel manual).

The wavelet varies according the well. Below the Cretaceous sequence it was extracted an average of a 25 Hz wavelet from the seismic cube, recalling the earth is a filter band pass.

The acoustic impedance log was deconvolved with the 25 Hz wavelet, in order to generate the first synthetic (see Figure 2–5). The synthetic was compared with the seismic response and then judged its quality, taking as reference the strong amplitude generated in the Base Chalk. The more similar the position of the reflectors the better.

![Wavelet used for general deconvolution.](image)
If the synthetic generated did not fit with the seismic cube then a more detailed process was carried out. The wavelet was extracted from a radius of 50 samples of the well (in x,y direction) and the depth block from the Cretaceous up to the end of the well log. In addition, the resulting synthetic was “stretched”, meaning fitting two strong reflectors and stretching within that interval.

The stretching method in some cases is not the most correct because it can result in a nice visualization from an out of place velocities.

The intervallic velocities obtained from the stretched synthetic were exported and compared with the check-shots ones in order to avoid artefacts. Therefore, a quality control of the resulting intervallic velocities was carried out, re-ensuring they were in an acceptable range of values (see Figure 2–6).
Figure 2-6 To the left it is well logs from Alma -1x well. It is shown the edited logs in red of density and sonic compared with the original ones in black. To the right, it is shown as example the proper fit between the seismic and the synthetic seismogram. The right figure from the well U-1x is the intervallc velocity comparison between check-shots and a stretched seismogram.
2.5. **Seismic interpretation**

The seismic used in this project consists on a 3D P-wave cube in double time scale, processed in zero phase. According with the nomenclature used for the seismic in Europe and in this project, a positive contrast of impedance “hard kick” is recorded as a negative number on the deflection or wiggle.

![Seismic convention](image)

**Figure 2-7 Seismic convention - red color for increase in the RC and blue for the decrease of RC.**

The seismic resolution problem can be caused by several factors: attenuation of noise in the data processing; vertical minimum thickness so wavelet used in deconvolution; horizontal minimum size from the seismic migration (Brown, 2003); and changes in the lithology producing no contrast of impedance.

The seismic interpretation was carried out in the software Petrel 2010.2, and the cube utilized was a merged between the DUC cube and PSDM. As consequence, there are lateral changes in resolution. The DUC has a better coverage of the area and it is better migrated in depth than the PSDM.

The seismic cube can be visualized and interpreted from vertical sections: inlines, crosslines or composite lines, and horizontal sections as time slices.

The seismic interpretation in this project was carried out carefully trying to honour the same reflector in 3D. Discontinuities in the same reflector were found caused by resolution, stratigraphy breaks, fault displacements or salt presence.
The subsalt imaging is a challenge specially regards the salt structure boundaries. For this seismic cube the resolution around the salt structures are optimum in general, despite the boundaries are not limited with precision since the interpretation is done in a regional context.

Pitfalls in the seismic interpretation are taken for granted. Around the salt structures it is expected to have apparent dips as well as in some fault planes, and “smiles” were found product of the miss-migration in the deepest part.

Since the reflection produced by the Chalk is very strong, the color scale based in the entire volume was shadowed in the Jurassic sequence. Then the color scale of the cube visualized was modified on limits from −20000 to 20000 respectively.

When the reflector was tracked there was discriminated between onlap and truncation as seen in the Figure 2–8.

![Figure 2–8 Illustration of concepts of seismic interpretation.](image-url)
When the layer was not continuous the tool of flattening was used. There are several areas where the seismic reflection is null, therefore it was impossible to follow the reflector through.

The interpretation was done using a combination of 2D and manual track tool in several composite lines. Depending on the continuity of the reflector and its deformation, there were interpreted with more or less coverage the lines per area. After having a good enough coverage, 3D tracking was applied.

The 3D tracking was done per sectors, meaning, enclosing an area with a polygon and auto-track that area only. Afterwards, it was done a quality control to ensure the quality of the track. If the auto-track was accepted in one area the same process was applied to the contiguous area, if not, the auto-track was undone and it was increased the coverage of manual interpretation.

The auto-tracking settings differed on the reflector status in that area, i.e. if the reflector was continuous and strong the auto-track was settled to follow a range of 30% of confidence of the amplitude, but if the reflector was very variable in amplitude it was selected the option of following the local maximum amplitude.

Any auto-tracking (even done per sectors and with different settings) contains errors and quite often it jumps even 2–3 loops in the seismic wave. Therefore, in this project the horizons in petrel will have not a perfect track along the entire reflector, in special in the non uniform zones. This error will be tolerated in this project because they are local and do not affect the shape of the horizon in the regional scale.

When the horizons were finished they had to be converted to surfaces. Therefore, using the tool in petrel named “Make/edit process“ the surface was created, using as input the horizons interpreted and interpolating them with the “Minimum curvature“ algorithm. The last one was chosen because, (1) it was the unique method that could support the massive size of the conversion, and (2) the interpolation between the already tracked points are small spots and their filling is so small that will not make a strong difference among the interpolations techniques.
Moreover, in the surface post-process it was selected to smooth by 3 clippings the final result, with the intention of eliminate or smooth the miss tracking during the auto-track process.

2.6. **Structural interpretation**

The structural deformation in the area is complicated. The deformation comes from salt movement, the rifting process previous a compression one. The area is divided in two, the salt region (Salt Dome Province) and the not salt region.

![Diagram](image.png)

Figure 2-9 This part of the basin is divided by Salt Dome Province; Igor, Poul, Rosa and Poul basin. The entire basin is limited in the east by the Coffee Soil Fault (CSF). The salt areas in the Jurassic are highlighted in blue.

The area is extremely deformed and faulted, and not all the faults were interpreted but only the main ones with strong displacement. Therefore, the structural interpretation was done iteratively with the horizon interpretation (see Figure 2-10).
In this area it is extremely important to understand the structural deformation and the faults movements in 3D, because the horizon interpretation is very sensitive to a misinterpretation caused by fault displacements.

The faults as we know are 2D planes, and turn very complex in this structural setting. To identify the faults in plain view there were used cube attributes as Variance and 3D Curvature.

The Variance calculates the variance in horizontal planes, and then smoothes it in the vertical ones. This attribute is widely recognized to be used for fault recognition.

The variance cube has the local variance as a measure of signal unconformity. For each volumetric pixel, the local variance is computed from horizontal sub-slices. If this slice is within an unbroken reflection layer, the amplitude variance will be small whereas amplitude changes due to a fault will result in a larger variance (see Figure 2–11). Next, the variance estimate is smoothed by a vertical window and amplitude normalized.
Figure 2–11. Time slice of variance cube at 2750 ms, it can be appreciated the faults as black lines some of them pointed with blue arrows.

Salt pillows and salt domes were found in the Salt Dome Province. As we can appreciate in the time slice variance above (Figure 2–11), there are faults related with the diapirism.

A salt dome becomes diapir when it pierces its overburden in three different ways: actively, passively and re-actively. Active way when the salt is breaking the layers to uplift and deform in its roof thickening. Passive is when the diapir achieve the surface and the surrounding sediments syn-deposit with the salt uplifting. And reactive diapir forms in regional extension as the isostatic response to thinning of the roof (Vendeville & Jackson, 1992) (see Figure 2–12).

Figure 2–12 Structure deformation of the three uplifting cases (taken from Vendeville & Jackson, 1992).
Active diapirs are circular or elliptical in map view, they rise above the surrounding area and they have few faults in the early stage and many in the late stage.

Hongwei et al., 2007 suggest that the active diapirism can start either with 2 master faults or three of them crossing near the dome crest. Therefore, the diapir evolution will depend on if the fault cross the salt top or detach on it. If the top of the salt is faulted there is no development of high quantities of faults in the crest, only in the central graben (see Figure 2–14). In the other hand, if the salt is not faulted then the flank grabens will develop plenty of faults.

Different cross sections through the diapir will show very different structures depending on the direction parallel or perpendicular to the master fault. As it is illustrated in Figure 2–14 the sides of the diapir will develop graben and horst structures located depending on the faulting the salt or not, and on the number of master faults.
Salt diapirs develop high complex structures to identify and it is remarkable that this brief summary does not take into account regional efforts.

2.7. Time to depth conversion of surfaces

Unlike the physicist’s definition of velocity as a vector, its usage in geophysics is as a property of a medium-distance divided by travel time. Velocity can be determined from laboratory measurements, acoustic logs, vertical seismic profiles or from velocity analysis of seismic data. Velocity can vary vertically, laterally and azimuthally in anisotropic media such as rocks, and tends to increase with depth in the Earth because compaction reduces porosity. Velocity also varies as a function of how it is derived from the data. For example, the stacking velocity derived from Normal Move Out measurements of common depth point gathers differs from the average velocity measured vertically from a check-shot or vertical seismic profile (VSP). Velocity would be the same only in a constant velocity (homogeneous) medium (Schlumberger glossary http://www.glossary.oilfield.slb.com/Display.cfm?Term=velocity).

The check-shots and VSPs are very accurate but only in depth and not representative over the area. Cubic velocities are obtained either from seismic data (usually from the NMO or Migration), or by generating a velocity model grid from the well data. The most recommended method, for heterogeneous lithologies (in special for salt related structures), is a combination of the 2D and seismic processing velocity data in order to generate a velocity grid per structure (Brown, 2003).

In this case Maersk Oil does not have migration velocities available. Instead, they have an “Initial velocity model” tied up to base Cretaceous but not properly tied to the sequence below. Now a days a velocity model is been carrying out by the company but they will not be available before this project ends up.

The generation of a velocity model that suits the Jurassic section can take several months and a new project; therefore, it was decided to use a constant velocity gradient below the Base Cretaceous as it has been used so far in the Maersk Initial Velocity Model.

Nevertheless, a new initial velocity model was done to increase the quality of the velocity in the Jurassic, taking advantage of the new horizons made in this work. For this purpose
maps of intervallic velocities (in the different horizons) were generated to diminish the error among the horizons with depth. The velocity maps were generated from an interpolation of some wells check-shots, and included in the Initial velocity model.

As result, the errors calculated were in the same range as those from the initial Initial Velocity Model. Following the Ockham's Razor principle for the purposes of this study we will use the initial Initial Velocity Model.

### 2.7.1. THE INITIAL VELOCITY MODEL

This document describes the model to be used as an initial model for the tomographic velocity model building for the regional Danish PSDM project from Maersk Oil (see Figure 2-15).

The velocity model is a simple layered \( v_0, k \) model. In the Tertiary the \( v_0 \) maps need a lateral gradient to be applicable over the whole project area.

\[
v = v_0(x,y) + kz, \quad v_0(x,y) = v_{00} + a(x-x_0) + b(y-y_0)
\]

![Figure 2-15 Velocity model used for time to depth conversion in petrel.](image)


2.8. **Basin Modelling**

Basin modelling is the process of using either proprietary or commercially available software to assess charge risk by integrating diverse geological and engineering data types into a model of one or more petroleum systems active in an area being explored. Basin models are constructed by integrating various types of geological and geochemical data (e.g., see Welte et al., 1997, for a review).

The conceptual model of the basin modelling is the reconstruction of the geologic history of the basin from paleo-time to present day by subdivision of geologic history in “events”. Therefore, the tasks are generating models of compaction, temperature, maturity, HC generation and expulsion and migration and accumulations.

The thermal maturation history components of models are usually calibrated with various petrographic and geochemical thermal maturity parameters measured on rocks (e.g., vitrinite reflectance data, Rock-Eval data, apatite fission track data, fluid inclusion data) and oils (e.g., biomarker maturity parameters).

The response of the source rocks to increasing maturation (i.e., when in the maturation history a source rock generates hydrocarbons, and how the relative proportions of oil vs. gas change with increasing maturation) is modelled using source rock kinetics data. The critical importance of using appropriate kinetics data in constructing a model has been reviewed by numerous authors (Jarvie, 1991; Espitalie et al., 1993; Andresen et al., 1993; Welte et al., 1997).

Either 1D, 2D, or 3D basin modelling (basin modelling) may be performed. The choice of model type and sophistication depends on the data available, the project goals, and the time/ funding available to construct the model.

For this project it was performed a 3D basin model, to obtain a maturation model of the source rock and its HC generation. The software utilized was Trinity 4.0.

The maturation is a diagenetic process during which organic matter undergoes two types of changes: mobile products (gas, liquids) are given off, and condensation of the solid
residual products takes place during their aromatization (Peters, Walters, & Moldowan, 2005).

The terms “oil window” and “gas window” define the depths within which, a source rock will generate and expel oil or gas depending on the type of kerogen. High maturity can have a considerable effect upon source rock characteristics and may cause an underestimation of the potential of a source rock.

Following, the input data for the project is explained in detail.

The data requirements for the model input are:

- Structure maps (depth) imported from petrel.

- Absolute Ages. With the identification of the geological period it was given the absolute age.

- Temperature of the basin.

- Concepts on basin evolution. We know it is a rifting process and the sediment water interface temperature is 5 °C, but it was not included the paleo water depth, nor heat flow history.

- Source rock distribution. As type, thickness, TOC and HI.

2.8.2. TEMPERATURE

The temperature in depth was calculated as a unique gradient for the entire basin. The data was provided by Maersk Oil of 15 wells. The surface temperature was fixed at 5 °C.

This temperature generalization drags errors into the final maturation maps. In order to quantify the range of maturation values, three Vitrinite reflectance maps were created each one with different curve gradient within the data range. As result maturity maps are identified with low gradient (cold), average gradient (avr) and a high gradient (hot) (see Figure 2–16–Figure 2–17).
ROCK TYPE

Facies analysis was not incorporated in this job. In the Late Jurassic the sedimentation has been identified as shallow marine to deep with consistency in shale presence (see Table 7).

In the Basin Modeling software it is possible to set the source rock properties per package as shown in the Figure 2-18. The expulsion values used were the default program ones.

The kerogen types are assumed by the rock description and the regional geology setting. In the package from Top Oxfordian – Horizon 8 it was assumed a kerogen type II/III since it was deposited on shallow marine it can have sediments of terrestrial origin. In the other hand it is recognized that from Horizon 8 up to base Cretaceous the environment
corresponds to deep marine, for which it is assumed to be kerogen type II of aquatic marine shale.

Figure 2.18 Setting of the properties per packages within the source rock, in the software Trinity 4.0

2.8.4. STRUCTURE AND THICKNESS MAPS (DEPTH)

As explained in the Chapter 2.3, five horizons were interpreted within the Jurassic.

In Trinity 4.0 the HC expulsion is calculated based among others on maturity. The maturity in this program is not volumetric calculated but only on the horizons used as input. This situation produce a miss-estimation of the HC expulsion since the maturity in the top of a sequence is different than in the bottom.
In order to minimize this error, each unit was subdivided in three equal thickness, incorporating 2 artificial intra layers (see Figure 2–19).

Consequently, inside one unit it will be calculated the maturity in three horizons.

The horizons from the sea level bottom had to be included in order to obtain a proper burial history (provided by Maersk Oil).
2.8.5. ABSOLUTE AGES:

Absolute ages were assigned to the horizons in the software Trinity 4.0 as shown in the list below.

- sea-floor (0)
- tu_pico_ft.DAT (2.5)
- tl_pico_ft.DAT (3.6)
- u_mio3_ft.DAT (5.33)
- m_mio_ft.DAT (11.6)
- l_mio_ft.DAT (15.97)
- o安庆_ft.DAT (23.03)
- tm_eoc_ft.DAT (33.9)
- bChalk (99.6)
- BCU (145)
- bbo Member (145.1)
- Hz-surface (145.5)
- SF_MFS.2a_Converted (145.66)
- SF_MFS.2b_Converted (145.86)
- HI-surface (146)
- SF_MFS.4a_Converted (147)
- SF_MFS.4b_Converted (148)
- HB-surface (149)
- SF_MFS.8a_Converted (150.23)
- SF_MFS.8b_Converted (151.48)
- HD-surface (152.7)
- SF_MFS.9a_Converted (153.7)
- SF_MFS.9b_Converted (154.7)
- HTonc-surface (155.7)

2.8.6. TOC AND HI:

Again, Trinity 4.0 takes as input TOC and HI discrete maps for the HC generation; therefore, it is not used as input TOC and HI volumes.

The software calculates from one TOC and HI map, the expulsion per total organic content in the unit volume. TOC and HI values from each well (see Tables 2–6; Figure 2–20–Figure 2–22) were RMS averaged as per depth per unit and spatially interpolated.
Figure 2-20 Example of the RMS average in HI and TOC values at Alma-1x well.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>TOC averaged from all the wells</th>
<th>HI averaged from all the wells</th>
</tr>
</thead>
<tbody>
<tr>
<td>2–4</td>
<td>2,1</td>
<td>240</td>
</tr>
<tr>
<td>4–8</td>
<td>1,79</td>
<td>263</td>
</tr>
<tr>
<td>8–9</td>
<td>2,1</td>
<td>240</td>
</tr>
<tr>
<td>9–Top Oxf</td>
<td>1,66</td>
<td>206</td>
</tr>
</tbody>
</table>

Table 2 TOC and HI from wells averaged per unit

<table>
<thead>
<tr>
<th>Package 2–4</th>
<th>TOC Harmonic average within the package</th>
<th>HI Harmonic average within the package</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fasan</td>
<td>1,98</td>
<td>283</td>
</tr>
<tr>
<td>E-1x</td>
<td>2,75</td>
<td>232.9</td>
</tr>
<tr>
<td>Alma 1-x</td>
<td>1,25</td>
<td>241</td>
</tr>
<tr>
<td>G-1</td>
<td>2</td>
<td>130</td>
</tr>
<tr>
<td>Avr</td>
<td>2,1</td>
<td>240</td>
</tr>
</tbody>
</table>

Table 3 Harmonic average of HI and TOC per well in Intra Volgian (H2–H4).
Table 4 Harmonic average of HI and TOC per well in Lower Volgian (H4–8).

<table>
<thead>
<tr>
<th>Package 4–8 Well</th>
<th>TOC Harmonic average within the package</th>
<th>HI Harmonic average within the package</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fasan</td>
<td>1.51</td>
<td>275</td>
</tr>
<tr>
<td>Alma</td>
<td>0.64</td>
<td>171</td>
</tr>
<tr>
<td>M–8x</td>
<td>1.17</td>
<td>162</td>
</tr>
<tr>
<td>G–1</td>
<td>2</td>
<td>140</td>
</tr>
<tr>
<td>Skjold Flank</td>
<td>2.31</td>
<td>185</td>
</tr>
<tr>
<td>N–22</td>
<td>3.12</td>
<td>646</td>
</tr>
<tr>
<td>Avr</td>
<td>1.79</td>
<td>263</td>
</tr>
</tbody>
</table>

Table 5 Harmonic average of HI and TOC per well in Late Kimmeridgian (H8–H9).

<table>
<thead>
<tr>
<th>Package 8–9 Well</th>
<th>TOC Harmonic average within the package</th>
<th>HI Harmonic average within the package</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alma</td>
<td>1.11</td>
<td>210</td>
</tr>
<tr>
<td>M–8x</td>
<td>1.98</td>
<td>170</td>
</tr>
<tr>
<td>Skjold Flank</td>
<td>2.41</td>
<td>140</td>
</tr>
<tr>
<td>N–22</td>
<td>2.14</td>
<td>385</td>
</tr>
<tr>
<td>Avr</td>
<td>1.79</td>
<td>240</td>
</tr>
</tbody>
</table>

Table 6 Harmonic average of HI and TOC per well in Early Kimmeridgian (T. Oxf–H9).

<table>
<thead>
<tr>
<th>Package Top Oxf–9 Well</th>
<th>TOC Harmonic average within the package</th>
<th>HI Harmonic average within the package</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alma</td>
<td>0.89</td>
<td>149</td>
</tr>
<tr>
<td>A–3</td>
<td>1.21</td>
<td>170</td>
</tr>
<tr>
<td>Skjold Flank</td>
<td>2.24</td>
<td>105</td>
</tr>
<tr>
<td>N–22</td>
<td>2.3</td>
<td>400</td>
</tr>
<tr>
<td>Avr</td>
<td>1.66</td>
<td>206</td>
</tr>
</tbody>
</table>

In this project it is assumed the deepest the paleo-basin the higher the TOC and HI content. It is because the sedimentation rate in those zones are higher and shale prone,
leaving a good opportunity for preservation and deposition with higher organic content and more likely in an anoxic environment.

The paleo-water depth is unknown but it is assumed the basin floor had a similar shape as the isochrone maps.

Based on the previous formulation it was generated one map of HI and TOC per unit, using the method of kriging interpolation of the values (RMS averaged) per well in combination with co-kriging of the isochrone maps. The co-kriging have a correlation coefficient around 0.5 – 0.7 and it was set a maximum value of 6 in TOC and 600 in HI (see Figure 2-21). The values were chosen from the range of values of TOC and HI and also assuming good source rock below the values of the Bo Member.

The correlation coefficient was evaluated visually depending on the result; in some cases the result map had an extremely wide area of maximum values, and then for this case the coefficient was changed to a higher value and re-generated the map. The maps share the same boundary than the horizon interpreted. The Figure 2–21 is a representative example of the parameter settings for HI of horizon H8 in Petrel on the “Make/edit surface” tab.

![Figure 2-21 Example of the setting for the generation of HI map on the package, with Kriging interpolation with thickness of the package as co-kriging.](image)

The resulting maps (see Figure 2–22) were imported into Trinity 4.0 and labelled as “Property maps”.

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With all the data on the software maturation maps of Vitrinity, HC expulsion history, burial history and oil and gas expulsion maps were calculated.

Figure 2-22 In the top are the maps of HI and TOC over the package 8–9. In the bottom it is the isochrone map to show the strong correspondence of it with HI and TOC values trending, respecting the averaged values over depth shown in the figure bottom right.
Chapter 3

3. Results

Five horizons were mapped named as 2, 4, 8, 9 and Top Oxfordian (Figure 3–1; Figure 3–3) from young to old. They are the strongest seismic reflectors that mark the boundary of different seismic depositional features as can be appreciated in the intersection view SW–NE in the Poul Basin (see Figure 3–1).

The well tops were tied to seismic using synthetic seismograms and there were chosen the correspondent seismic reflectors that complies: (1) mappable along the entire area as a soft kick; and (2) the ones that are boundaries of reflector patterns. The last one is understood as the stratigraphic boundary between two different sedimentary systems or stages.

A correlation of the MFS among the well E–1 Fasan –1 and G–1 was not clear, except by the horizon 4. Consequently, there was used the pertaining seismic reflector to correlate along all the wells (see Figure 3–1).

Due to the stratigraphic composition of the basin in addition with the structural deformation, the reflectors are not necessary a MFS, but it is ensured the reflector interpreted belongs to a stratigraphic boundary.
Figure 3-1. SW-NE intersection line. It can be appreciated the horizons interpreted mark the boundary of differently organized packages.
The sonic and density neutron logs do not vary substantially through the stratigraphic interval, indicating that gross lithological variation within the Farsund is small. Nevertheless, the Horizon 4 limits a change in the trending of the resistivity increasing. In addition, the cyclicity of the dolomitisation below the Horizon 4 is higher than above, which tells about differences in anoxicity and clay content in the depositional environment.

In summary, the Upper Jurassic sequence was divided in five packages (see Figure 3-1 and Figure 3-3).
Figure 3-3. Five reflectors within the Upper Jurassic being used as main correlation tool among the wells.
3.1.1. DATING PACKAGES

The biostratigraphy analysis in the Fasan-1 (from Fasand final report performed by Fugro Robertson) is one of the most recent and it limits the intra Upper Jurassic age subdivisions with the top Kimmeridgian in 10816 ft (see Table 7).

<table>
<thead>
<tr>
<th>EARLY CRETACEOUS AND LATE JURASSIC</th>
<th>md [ft] from</th>
<th>to</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late Ryazanian</td>
<td>8760.656</td>
<td>8990.164</td>
</tr>
<tr>
<td>?Late Volgian - Ryazanian</td>
<td>8990.164</td>
<td>9045.902</td>
</tr>
<tr>
<td>Late Volgian</td>
<td>9045.902</td>
<td>9249.18</td>
</tr>
<tr>
<td>?Early - Middle Volgian</td>
<td>9249.18</td>
<td>9832.787</td>
</tr>
<tr>
<td>Early Volgian</td>
<td>9832.787</td>
<td>10816.39</td>
</tr>
<tr>
<td>Late Kimmeridgian</td>
<td>10816.39</td>
<td>12472.13</td>
</tr>
</tbody>
</table>

Table 7 Biostratigraphic division of the Jurassic and early cretaceous in well Fasan-1.

From the biostratigraphic correlation with the well tops Horizon 8 was identified as the top of the Kimmeridgian sequence, the horizon 4 is the top of the Early Volgian and the Horizon 2 is intra Middle Volgian (Figure 3–4).

In the well A–3 there were dated the deepest reflectors. The H9 is near but not exactly the top Lower Kimmeridgian and the Top Oxfordian as the base (Figure 3–4).

In general the well biostratigraphy information has low detail in the Jurassic sequence.
Figure 3-4. Date of packages intra Upper Jurassic from Fasan-1x well biostratigraphy
Figure 3-5. Maps in TWT of the 4 reflectors interpreted intra Upper Jurassic. As dated the horizon 2 is intra Middle Volgian, horizon 4 top Early Volgian; horizon 8 top Kimmeridgian; horizon 9 top Lower Kimmeridgian. [1] Diapirsm effect that generates elevation of the horizon; [2] mini basin generated.
3.1. Maps of reflectors intra Upper Jurassic in TWT

The interpreted horizons are showed in the Figure 3-5 and they range from 1800 ms to 4200 ms TWT. In every case, the south part of the basin is uplifted and higher than the north. In the south west of the Horizon 9 there is an elliptic shape (Figure 3-5) probably caused by salt withdrawn. The not interpreted zones in the Horizons 8 and 4 are due to salt presence in the south.

Towards the North the reflections are not continuous or clear, for which the interpretation was not done. Towards the south the horizons are truncated and not present (see Figure 3-6).

Figure 3-6 Contour of horizon truncations toward south and west.
3.1.2. GEOCHEMICAL FEATURES

As demonstrated by Swanson, 1961, uranium in sedimentary rocks is typically bound to organic matter and the positive correlation between gamma radioactivity and total organic carbon (TOC).

Ineson, et al., (2003), studied these relations in the Bo Member finding a clear increase in the overall gamma-ray values beneath and within the Bo Member as result of an increased content of uranium, showing that thorium and potassium have little variation. They affirm the uranium may also be concentrated in biogenic phosphate material, however, and since such debris is common in the organic-rich mudstones of the Bo Member, this may provide an additional contribution to the total gamma response.

Nevertheless, not direct correlation was found between the GR and the TOC response in the overall Upper Jurassic (see Figure 3–7). The wells plotted were E-1x, G-1, M-8x and Alma-1x in TOC vs Vsh. Based on the Ineson, et al., (2003) conclusions it can be said that this package of Jurassic source rock must have low uranium content in the highest TOC packages in each well probably due to the lack of biogenic phosphate material.

The TOC response was not correlated with uranium logs due to scarcity of spectral logs in the area.
In the software pIGI plots of T-max vs Depth of the Jurassic sequence were generated in 6 wells in order to identify the maturity of the source rock. First it is important to take into account that most of the wells with geochemical data are located in the highest structures for production purposes, therefore, they are not representative of the overall basin. The oil window range shown in the graphic (green area) is automatically settled by the software but it can change with the kerogen type (see Figure 3–8). It can be seen that based on this graphs around the 40% of the rock is already in the oil window and the rest is still immature.

Figure 3–8 Graph of maturity showing in green the oil window. Graph set by pIGI software.
In the same software it was plotted the $S_2$ Vs TOC in order to have a better appreciation of the kerogen type. Most of the data is concentrated near the zero axis. As explained in the previous chapter, if the rock has already generated HC the values of HI are going to decrease and also the $S_2$. Therefore the kerogen type graphs are tricky to interpret if the rock is not immature. For this reason it is used the T-max Vs HI diagram, plotting the data in one diagram with the circle size corresponding to its TOC and the next one with the $S_2$. There is data below the T-max 435 °C (then immature data) with organic matter from the 3 types of kerogen mainly of type III. The Late Jurassic and Oxfordian is usually present in nearer the type III, but the Kimmeridgian is present in between type II and type III and the Volgian tends to be type I or type II. The volgian data is located near the 440 °C for which it is possible to be type I and be degenerating with maturation to type II.
Based on the geochemical data and on it is concluded the Kimmeridgian rock to be type II/III, and the Volgian more possible be type II.
3.1.3. TIME – DEPTH CONVERSION

The time to depth conversion from the horizons were controlled or compared with the depth to time conversion from the wells information. It is well known that the check-shots velocities are very reliable and with a minimal error compared with a regional cube velocity model. In the following Table 8 there are shown the errors in feet of the horizon conversions compared with the wells.

Table 8 Table of error in the velocity conversion $d_z$-Surface converted – checkshots [ft]

<table>
<thead>
<tr>
<th>Well identifier</th>
<th>Surface</th>
<th>$dH_2$ [ft]</th>
<th>$dH_4$ [ft]</th>
<th>$dH_8$ [ft]</th>
<th>$dH_9$ [ft]</th>
<th>$dT_Oxf$ [ft]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADDA-1</td>
<td>Horizon 2</td>
<td>-197.32</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALMA-1X</td>
<td>Horizon 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALMA-2X</td>
<td>Horizon 2</td>
<td>24.38</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DEEP-ADDA-1</td>
<td>Horizon 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E-1X</td>
<td>Horizon 2</td>
<td></td>
<td>92.95</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FASAN-1</td>
<td>Horizon 2</td>
<td></td>
<td>-19.35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JENS-1</td>
<td>Horizon 2</td>
<td></td>
<td>-70.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S.E.IGOR-1</td>
<td>Horizon 2</td>
<td></td>
<td>126.89</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-3</td>
<td>Horizon 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALMA-1X</td>
<td>Horizon 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALMA-2X</td>
<td>Horizon 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DEEP-ADDA-1</td>
<td>Horizon 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E-1X</td>
<td>Horizon 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FASAN-1</td>
<td>Horizon 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M-8X</td>
<td>Horizon 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N-22X</td>
<td>Horizon 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N.JENS-1</td>
<td>Horizon 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S.E.IGOR-1</td>
<td>Horizon 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SKJOLD-FLANK-1</td>
<td>Horizon 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-3</td>
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<td></td>
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<tr>
<td>ALMA-1X</td>
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<td>ALMA-2X</td>
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<td>195.29</td>
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<tr>
<td>ELLY-2</td>
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<td></td>
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<td></td>
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<tr>
<td>ELLY-3</td>
<td>Horizon 8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FALK-1</td>
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<td></td>
<td></td>
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<td>FASAN-1</td>
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<td></td>
<td></td>
<td></td>
<td>-51.19</td>
<td></td>
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<tr>
<td>G-1(IGOR)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>280.46</td>
</tr>
<tr>
<td>JENS-1</td>
<td>Horizon 8</td>
<td></td>
<td></td>
<td></td>
<td>-334.04</td>
<td></td>
</tr>
<tr>
<td>N-22X</td>
<td>Horizon 8</td>
<td></td>
<td></td>
<td></td>
<td>-477.53</td>
<td></td>
</tr>
<tr>
<td>N.JENS-1</td>
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<td></td>
<td></td>
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<tr>
<td>Olga-1X</td>
<td>Horizon 8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S.E.IGOR-1</td>
<td>Horizon 8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>159.26</td>
</tr>
</tbody>
</table>
As shown in the error map (Figure 3-9), the wells located to the north have the highest error values up to 400 ft in some cases. In addition, it is remarkable the error increases with the depth as expected. Also, high error values are found in the salt deformation area which is expected due to first the location of the wells on the top or flank of the salt structures which have high velocities that are not taken into account in the velocity model applied.
Figure 3-9 Comparison of time depth conversion from wells (checkshots) and horizons (initial velocity model) in feet.
A burial history graph was generated from the software Trinity 4.0. The burial history is slightly different in the north and south with the same shape over time (see Figure 3-10). The total deposition thickness in the north is roughly 40% higher than in the south, and the Upper Jurassic deposition in the south is only around 37% of the thickness in the north.

The burial history reconstruction at the southern DCG illustrates the deepest burial in the Poul Basin. In the Upper Jurassic there are two different rates of sedimentary deposition, being the highest in the early period, and it decreased substantially from the Early Cretaceous. It is important to mention this model is not taking into account the erosion or hiatus caused by the inversion in the Cretaceous. Moreover, it can be summarized a strong period of subsidence during Jurassic, a relative calm period from the Cretaceous up to Miocene.

Figure 3-10. Burial history of southern DCG. In the top the burial history of the Poul basin in the north, and in the bottom the burial history in the Salt Dome Province in the south.
Figure 3-11 Maturity maps of Vitrinite. Horizon 2 (Intra M. Volgian) top right, Horizon 4 (Top E. Volgian) top left, Horizon 8 (top U. Kimmeridgian) bottom left, Horizon 9 (top L. Kimmeridgian) bottom right.
The Vitrinite Reflectance was calculated in the Trinity 4.0 software; generating maps that depict three different maturation levels for organic matter in the sedimentary rocks (see Figure 3-11). The Ro values correspond, generally, to the onset of oil generation, the onset of gas generation, and immature. Vitrinite reflectance values between 0.7 – 1.2 are in oil window, 1.2–2.0 are in wet gas window, while those with values >2 are in dry gas zone.

Different maturity maps were obtained from the different temperature gradients (hot, cold, average). From the “average temperature” model is interpreted the source rock the south is still immature, but in the north it is not.

The kitchen area grows in extension toward the deepest layers being barely mature in the youngest one. The Upper Jurassic Source Rock is mostly in the HC generation windows but not entirely.

The Figure 3-12 illustrates how the best kitchen area does not overlap the highest values of TOC and HI. The expulsion takes place only where the high values areas of the 3 components overlaps.

The Vitrinite Reflectance maps were compared with the laboratory studies of the well Deep Adda. The Ro values are in the same range in the average temperature model (Table 9). The highest error goes from 0.55 (model) to 0.92 (lab), which can be critical at local scale. In the layer H4 the laboratory value is higher than the map, meaning that possibly the modelled maturation is under-estimated Figure 3-12.
Figure 3–12 Basin modelling maps of the Horizon 4 or top E. Volgian. Top left is the Vitrinite map, top right Hi map; bottom left TOC map, and bottom right the final oil expulsion map area.
Table 9 Vitrinite Reflectance Vo from Basin modelling (avr temperatures) compared with laboratory results

<table>
<thead>
<tr>
<th>Well</th>
<th>Surface</th>
<th>Data from Horizons</th>
<th>Data from Laboratory</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Depth</td>
<td>MD</td>
</tr>
<tr>
<td>ALMA-2X</td>
<td>Horizon 2</td>
<td>-8153.05</td>
<td>9449.49</td>
</tr>
<tr>
<td>G-1 (IGOR)</td>
<td>Horizon 2</td>
<td>-8544.38</td>
<td>8691.15</td>
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<tr>
<td>JENS-1</td>
<td>Horizon 2</td>
<td>-9894.64</td>
<td>10013.64</td>
</tr>
<tr>
<td>ALMA-2X</td>
<td>Horizon 4</td>
<td>-8266.02</td>
<td>9590.45</td>
</tr>
<tr>
<td>DEEP-ADDA-1</td>
<td>Horizon 4</td>
<td>-9698.18</td>
<td>9826.18</td>
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<tr>
<td>M-8X</td>
<td>Horizon 4</td>
<td>-7443.2</td>
<td>7541.15</td>
</tr>
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<td>A-3</td>
<td>Horizon 8</td>
<td>-7894.01</td>
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<td>A-3</td>
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</tr>
<tr>
<td>G-1 (IGOR)</td>
<td>Horizon 9</td>
<td>-10511.8</td>
<td>10660.96</td>
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<tr>
<td>M-8X</td>
<td>Horizon 9</td>
<td>-8103.38</td>
<td>8201.8</td>
</tr>
</tbody>
</table>

The total expelled oil depends on the values settled for TOC, HI and temperature. The following tables are values summary of the combination of those factors

Table 10 Oil and gas expulsion from TOC, HI maps and hot gradient

<table>
<thead>
<tr>
<th>TOTAL EXPULSION</th>
<th>OIL</th>
<th>174290 mmbbl</th>
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</thead>
<tbody>
<tr>
<td>GAS</td>
<td></td>
<td>317529 bcf</td>
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</table>

Table Oil and gas expulsion from TOC, HI maps and cold gradient

<table>
<thead>
<tr>
<th>TOTAL EXPULSION</th>
<th>OIL</th>
<th>34598 mmbbl</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAS</td>
<td></td>
<td>14027 bcf</td>
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</tbody>
</table>
Table 11 Oil and gas expulsion from TOC and HI maps and averaged temp

<table>
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<th>TOTAL EXPULSION</th>
<th>OIL</th>
<th>118234 mmbbl</th>
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</thead>
<tbody>
<tr>
<td>EXPULSION</td>
<td>GAS</td>
<td>131711 bcf</td>
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</tbody>
</table>

Table 12 Oil and gas expulsion from average temperatures and constant HI and TOC

<table>
<thead>
<tr>
<th>TOTAL EXPULSION</th>
<th>OIL</th>
<th>144515 mmbbl</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXPULSION</td>
<td>GAS</td>
<td>144515 bcf</td>
</tr>
</tbody>
</table>

The total HC expulsion calculated from the 5 interpreted horizons are 129167 mmbbl of oil and 81012 bcf of gas, in contrast with the inclusion of the 2 added intra-packages horizons with 180092 mmbbl of oil and 151114 bcf of gas; these expulsions are calculated under the same pyrolysis and temperature settings. In conclusion, doubling the number of horizons the expulsion calculation is 40% higher, and therefore if volumetrically calculated the total expulsion is higher than the shown in this project.

Figure 3-13 Oil expulsion graph per horizon.
Figure 3–14 Gas expulsion graph per horizon.

From the Figure 3–13 the deepest horizons are the ones that generated more HC. In the oil expulsion table it is remarkable the expulsion of the H4b is higher than H8 due to the change of the kerogen type. The oil expulsion from all the results obtained from the combination of TOC HI and Temperature were statistically measured (see Table 13). Separately, HC expulsion range was calculated with the different temperature slopes, keeping the same TOC and HI maps as shown in the Table 14.

Table 13 Statistics of HC expulsions from the results of the combination of TOC, HI and Temperatures.

<table>
<thead>
<tr>
<th></th>
<th>OIL EXPULSION [mmbbl]</th>
<th>GAS EXPULSION [bcf]</th>
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<tbody>
<tr>
<td>Mean</td>
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<td>169092.8</td>
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<td>Standard Error</td>
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<td>28653.7245</td>
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<tr>
<td>Median</td>
<td>112304.5</td>
<td>158717.5</td>
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<tr>
<td>Standard Deviation</td>
<td>65356.78</td>
<td>90611.03288</td>
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<tr>
<td>Range</td>
<td>187679.5</td>
<td>250189</td>
</tr>
<tr>
<td>Minimum</td>
<td>16462.5</td>
<td>67340</td>
</tr>
<tr>
<td>Maximum</td>
<td>204142</td>
<td>317529</td>
</tr>
<tr>
<td>Confidence Level(95.0%)</td>
<td>41525.72</td>
<td>64819.228</td>
</tr>
<tr>
<td></td>
<td>(mmbbl)</td>
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<td></td>
</tr>
<tr>
<td>Mean</td>
<td>76416</td>
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<tr>
<td>Standard Error</td>
<td>41818</td>
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<tr>
<td>Median</td>
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<td>Standard Deviation</td>
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<td>Range</td>
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<td>Minimum</td>
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<tr>
<td>Maximum</td>
<td>180092</td>
<td></td>
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<tr>
<td>Confidence Level(95.0%)</td>
<td>531000</td>
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</table>
Chapter 4

4. Basin history

The aim in this chapter is to have a rough sequence of the basin development. Nevertheless, since we are dealing with an extensional system that changed into compressional, some of the evidences or rifting structures were shadowed by inversion as fault reactivation and salt deformation.

During the Triassic the sediment package is considerably thicker in the Coffee Soil Fault (CSF) (south) being the responsible of the main subsidence of the half graben (see figure 4-1). Otherwise, the Callovian-Oxfordian package has not its thickest part next to the CSF, evidence of a structural change.

It is believed that the Lower Jurassic is barely present in this area because its sediments were eroded during the thermal dome uplift.

Based in the location of the depocenters in the Jurassic time, it is inferred the subsidence was ruled mainly by block tilting, and listric faults. In order to understand the deformation in the Lower Jurassic in the basin it is necessary to interpret the basement rupture caused by the rifting process. Two main composite lines were selected, one perpendicular to the CFS (figure 4-2) and the other parallel (figure 4-1), crossing the Poul Basin.

The faults of the basement (caused by block tilting) are pretty decoupled from the sequence above. In the composite line B it can be identified normal faults from tilted blocks. The displacement of hanging wall subsidence are not major except by the fault A.1 located in the north, which had a strong displacement, indicating to be active for a longer period than the others.

The blocks tilted can be observed more clearly in the figure 4-2, from right to left we can observe: (1) an echelon structure pertaining to the Poul plateau; (2) block tilted toward
NNE producing strong displacement; (3) roll over structure over the listric fault dipping towards north; (4) listric inverted fault.

In order to follow these structures in map view it was generated a time slice of Variance Attribute at 5000 ms (see figure 4-2). At this level we are cutting the Triassic sequence which is quite coupled with the basement faulting. The darker colouring corresponds to deformation meaning faulting or bending (highest variation per cell). The roll-over deformation western to the Fault N-S joins to the south with the Gorm salt pillow and together can be followed along 43 km. The clearer region corresponds to the tilted block that rules the highest subsidence in the Lower-Middle Jurassic and early Late Jurassic. It is delimited in the north and south by a two different listric faults dipping to the north, to the west the listric fault with the roll over structure, to the east with the hanging wall of an echelon structure.

Roughly described, the unit between Base Callovian – Top Oxf has strong subsidence due to the block tilting. This package, and the previous one thinness up in the south of the A.1 fault (Figure 4-1) and thickens up to the north of it, evidencing this fault was active in a normal way from the Triassic
Figure 4-1 Intersection window in TWT parallel to the CFS.
Figure 4-2 At the top it can be seen an intersection seismic window in TWT almost perpendicular to the CSF. To the left it is a time slice of a variation cube at 5000 ms. It can be observed on the Triassic sequence the main deformations that limit the Poul basin.
4.1. **Lower Kimmeridgian (Top Oxfordian – Horizon 9)**

The first seismic impedance reflector that can be followed after the strong erosional surface of the Base Callovian is identified as Top Oxfordian, dated from biostratigraphy (see Figure 3-4). This reflector hasn’t a strong marker in the well logs to identify it properly on them.

The horizon 9 is intra Lola formation intra Kimmeridgian date and it can be followed along the entire basin. This package is recognized from cuttings and cores, to consist of mudstones and claystones.

There is a correspondence between the reflection amplitude and the time-depth map, so the amplitudes are smaller in the deepest regions (usually northern) and stronger in the shallower (southern in the Salt Dome Province) (see bottom right of the Figure 4-3). It is suggested the layers are more condensed in the south with more homogeneous deposition.

Based on the time-isochrone maps four depocenters were identified.

The first one is in the Igor Basin. It is suggested an important movement of the CSF that produced accommodation, which was filled out with this package of sediments. In addition, the salt possibly migrated from this area thanks to buoyancy, towards Dan Structure.

The second depo is in the north and it is created by an active displacement along a listric fault A.1 (see Figure 4-1). This fault had a strong displacement from the Triassic and its continuous movement generated secondary faults, ruling the subsidence of this package.

The third depocenter is in the current Poul Basin with an azimuth approximately north south, running parallel to the CSF at 11 km of distance. It is inferred the CFS for this period was not the main subsidence driver but in the other hand the block tilting.
The block faults from the basement ruled the subsidence with no propagation towards this package. This suggests a plastic deformation on the package below that avoids the transfer of the efforts in a brittle way to the packages overlying.

The fourth depocenter is very interesting and it is located in the Rosa Basin. In the isochrone map there is a thinning area (purple color) towards the Rosa Basin and a lack of interpretation among Rosa and Poul Basin (see figure 4–3). This is because the seismic was shadowed by structures of tectonic inversion when the listric fault was reactivated, which does not allow the interpretation of those horizons.

Based on the thick deposition in the Rosa Basin for this period it is inferred there was a normal movement of the listric fault, or hanging wall block tilted.
Figure 4-3 Top left top L. Kimmeridgian (H9) in TWT. Top right isochrone map of this unit. Bottom left surface converted in depth ranging from 6000–21000 ft of depth. Bottom right is an amplitude attribute over the surface with the amplitude RMS averaged in +/- 10 ms of the exact amplitude value.
Figure 4–4 Progradational structures in the Poul Basin. Shelf breaks marked spatially in the figure below. Top figure is seismic section flattened in the H8 or top Kimmeridgian, and below, a time slice of the flattened section.
Figure 4-5 Well log response of GR, sonic and density of some wells of the unit Lower Kimmeridgian
It is observed radial faulting to the Kraka structure in the Salt Dome Province (see Figure 4–3). This suggests an active phase of the diapirism and therefore, it started to pierce up after the deposition of this package. The O–1 structure didn’t produce main structural deformation and so probably deformed in a passive way. In the Dan structure also can be observed strong faulting caused by the after salt deformation.

Exploration wells are mainly located in the highest zones of the basin and/or the most deformed ones, as expected for oil discoveries. Then, the well information of this package is constrained to the south area and the diapir flanks, which both are discontinous and deformed. This package is very dolomitized as seeing in the well-logs with very frequent spikes in the logs (see Figure 4–5).

Seismic stratigraphy structures can be identified in the margin of the Poul Basin and deeper. Some structures are clinoforms dipping towards the north. The stratigraphical sequences are ruled with progradation towards the north (Figure 4–4) with some minor retrogradation in between, from which it can be distinguished SB’s and MFS’s. (see Figure 4–7). The Sequence Boundaries are recognized for having erosion over the package bellow and downlaps.

This fact can carry some consequences to this package. (1) the horizon interpreted as top Lower Kimmeridgian (H9) is in fact a SB instead of a MFS as it was meant to be; (2) the depocenter in Poul Basin has an apparent migration to the north, due to the lack of physical mass that was eroded; and (3) we are dealing with an active possible shelf sedimentary environment.

The geochemical values range in this package are 0.5–8 w.t. % TOC, HI 60–290 mg HC/g TOC, 1–4.30 mg/g S2. As explained before there is no geochemical data of this package in the deepest part of the basins. In general pyrolysis trends don’t have a straight correlation along the wells or with the other well logs.

Based on the geochemical studies this package is considered good source rock. Based on the stratigraphy evidence and previous descriptions of the Lola Formation, it is believed
this source rock was sedimented on a shallow marine environment, then it was catalogued as kerogen type II/III.

In the basin modeling this package is located in a HC generation window with large areas in oil window and gas window. The main maturation is as expected is in the north part of the basin, and it produces the highest HC expulsion among the entire source rock (see Figure 4–6).

In the horizon 9 the mature zone covers 1539 km² (63% of interpreted surface) and 184 km² (11% interpreted surface) of post-mature; the surface with oil expulsion covers 402 km² (31% of the area) increasing with depth, concentrated mainly in the Poul and Rosa Basin (Figure 4–6). This package (including the layer subdivision) expels approximately 51752 mmbbl of oil and 102402 bcf of gas.

Figure 4–6 Oil expulsion map of the unit H9–H9a. Major expulsion in Poul Basin and Rosa Basin.
Figure 4-7 Seismic stratigraphy intersection flatted in Top Kimmeridgian (H8). In red there are the SB and in green the MFS.
4.2. **Upper Kimmeridgian (Horizon 9 – Horizon 8)**

The horizon 8 is a marker that limits a change in the amplitudes on the seismic cube; this horizon is itself a strong reflector with very high amplitudes that can be easily followed along the entire basin. Towards the south it is truncated and therefore non-existent in the maps. It is also identified as top Kimmeridgian.

The lithology recorded in the well description is the same as above, mudstones and claystones as part of the Lola Formation.

The subsidence for this period is more consistent over the entire basin. The Igor Basin shifts its depocenter away from the CSF because secondary faults drive the subsidence for this period. The shape of the subsidence in the Poul Basin is elongated towards the north achieving the deepest zone in the hanging wall of the echelon structure of the Poul Plateau.

The horizon 8 was not interpreted in the Rosa Basin because the reflector became discontinuous and with high frequency. Then depocenters in this area will not be discussed.

Skjold and Dan structure were in active diapirism while Kraka was thinning up. From which it can be concluded the Skoild and Dan are younger than this package deposition and Kraka is already uplifting with the O-1 salt structure.

The south has progradational sequences, as in the previous package, towards the north (see Figure 4–7). In a time slice parallel to the Horizon 8, it was possible to follow the shelf break along the basin and study how the progradation took place from the salt province into the Poul Basin. The shelf breaks are in the border of the Poul basin for this period, as they run perpendicular to the CFS.

As mentioned before the lithologies recorded on the well report are mudstones and *claystones*. 
In the classic stratigraphic subdivision, the progradation is related to a sediment supply higher than the accommodation, in this case, the accommodation is produced by the rifting system.

Towards the north of the Danish Central Graben Johannessen, et al. (2010), propose clastic supply to the basin from the Ringkøbing-Fyn High (eastern of CFS). It is possible that this sedimentary supply from this high continues towards the south as for example from Poul Plateu. Then we can say probably there was more than one direction of sediment supply in the basin.

This feature makes our source rock very different quality laterally.

The geochemical values in this package range to 0.7 – 13 w.t. % TOC, HI 75 – 320 mg HC/g TOC, mg/g 0.5 – 19 S2. As explained before there is no geochemical data of this package in the deepest part of the basins. The values of this package locate it in a good quality source rock.

The rock equivalent in the north of the basin for this time is still the Lola formation and there is no reason to believe we are dealing with a different formation (Andsbjerg & Dybkjær, 2003)
Figure 4-8 Top left top U. Kimmeridgian (H8) in TWT. Top right isochrone map of this unit. Bottom left surface converted in depth ranging from 7500–18000 ft of depth. Bottom right is an amplitude attribute over the surface with the amplitude RMS averaged in +/-10.
As in the Lower Kimmeridgian we remain in the same sedimentary system of shallow marine for which it is catalogued as kerogen type II/III.

In the well Fasan it is found a strong correlation among the TOC values and stratigraphy. As shown in the Figure 4-9 for the Kimmeridgian period there is an increasing of TOC with depth, which is explained by the progradational sequence in this region. Therefore the sedimentary deposition is coming from deeper (higher TOC) to shallower (lower TOC) as it corresponds from old to young.

![Figure 4-9 Correlation of stratigraphy and geochemical changes along the well Fasan](image)

In the horizon 8 the mature zone covers 1390 km² (61 % of interpreted surface) and 35 km² (2% of the surface) of post-mature with oil expulsion covering 402 km² (29 % of the area) increasing with depth, concentrated mainly in the Poul Basin in the flank of the CSF and Rosa Basin (Figure 4-10). This package (including the layer subdivision and the other averaged settings) expels approximately 30397 mmbbl of oil and 16545 bcf of gas.
Figure 4-10 Oil expulsion map of the unit H8-H8a. Major expulsion in Poul Basin and Rosa Basin legend in mmbbl.

4.3. Lower Volgian (H8-H4)

From the H8 upwards, the seismic feature changes, and the amplitude of the reflectors become stronger, more continuous and organized.

The H4 is also a continuous and high amplitude reflector. This horizon in the well logs is has an inflexion of the density and sonic well log, with higher density and lower sonic.

This package pinches out toward the south, and so it is either very condensed or not present in the Salt Dome Province. The lithology of this unit is the Farsund Formation, which is the best source rock in the Central Graben.

The progradational sequence continues towards the north, and the subsidence occurs only in the north of the Poul Basin (see Figure 4-12).
Except by Skjold the salt structures are already uplifted and passively going up.

It is deformed by secondary faults which are disconnected from the primary ones and the older rocks. In the figure below it can be observed a horst that was tilted and its block crest eroded (see Figure 4–14).

The subsidence at the north of the Poul Plateau is complicated. In general secondary faults, produced from major listric fault movement, rule the subsidence in this area (Figure 4–11).

![Image](image_url)

Figure 4–11 Secondary faults ruling subsidence as it can be observed near by the well E–1 and G–1.

From seismic stratigraphy is interpreted a fast regression, probably caused by a rise in the relative sea level. The regression is followed throughout this sequence except for a wedge located in the top of the Top Kimmeridgian (H8). This wedge was penetrated by the well Fasan – 1, and finding fine sands probably from turbidite deposition.
In the basin modelling this layer is in oil window and small areas in the gas window. In the horizon 4 the mature zone covers 962 km² (52 % of the surface) and the oil expulsion cover the same area increasing with depth, concentrated mainly in the Poul Basin in the flank of the CSF and Rosa Basin (see Figure 4–15). This package (including the layer subdivision and the other averaged settings) expels approximately 30397 mmbbl of oil and 16545 bcf of gas.
Figure 4-12 Top left top Lower Volgian (H4) in TWT. Top right isochrone map of this unit. Bottom left surface converted in depth ranging from 7500-16500 ft of depth. Bottom right is an amplitude attribute over the surface with the amplitude RMS averaged in +/- 10
Figure 4-13 Interpreted stratigraphic boundaries along the basin and across the width. In red SB’s and in green MFS’s. Some sequences are not existent in the uplifted areas, therefore the stratigraphic sequence cannot be found in all the wells but only in the deepest parts as E-1, Fasan and G-1.
Figure 4-14 Tilted block from secondary faults. It can be appreciated the erosion of the exposed sequence of the block.

Figure 4-15 Oil expulsion of the Unit H4-H4a. Major expulsion in the north of the Poul Basin and in the Rosa Basin. Legend in mmbbl.
4.4. **Early Middle Volgian (Horizon 4-Horizon 2)**

This package pertains to the Farsund Formation. From seismic stratigraphy it is observed the slope angle is less steep than in the package below. It is proposed an increase of the relative sea level (dealing now with deeper sedimentary depositional system) and a decrease of the rifting opening rate in the Poul Basin.

Due to the lack of accommodation in the mini basins except Rosa, it is believed the rifting opening was lower for this period. Therefore, the sediment loading seems to be enough to cover almost entirely the Poul and Rosa Basins.

The salt piercing and uplifting seems to happen for this period, with erosion or hiatus in the south of the basin and deposition in the North.

Due to the deep sea depositional system, it is inferred this package belongs to the kerogen type II.

A strong correlation among the TOC values and stratigraphy was found in the well Fasan. As shown in the Figure 4–9 for the Volgian period the TOC decreases with depth, explained by the transgressional sequence in this region. Therefore the sedimentary deposition is coming from shallower (lower TOC) to deeper (higher TOC) as it corresponds from old to young

In the horizon 2 the mature zone covers 277 km² with oil expulsion increasing with depth, concentrated mainly in the Rosa Basin (Figure 4–16). This package (including the layer subdivision and the other averaged settings) expels approximately 30397 mmbbl of oil and 16545 bcf of gas.
Figure 4-16 Oil expulsion of the Unit H2-H2a. Major expulsion in the Rosa Basin. Legend in mmbbl.
4.5. The Bo Member

The Bo member is localized usually in the top of the Volgian. In this area of study the Bo member is recognized in the well E-1 with 11 ft of thickness just underlying the BCU reflector. This layer is inexistente in the well G-1x for which it is believed it is truncated even northern than the H2. On seismic it is not possible to follow it or identify it due to resolution matters.

This project aim to be in regional scale, but it is well known by previous literatures and the wells E-1 and Fasan, that this layer can have a strong influence in the HC expulsion.

Since this reflector cannot be interpreted from seismic, it was followed a different approach. The BCU reflector was cut within the H2 boundary and added into the Basin Modelling software with source rock properties constant as listed: (1) kerogen type II; (2) HI 700 mg/g, (3) 6 % TOC and (4) averaged temperatures.

The HC expulsion is 542 mmbbl and gas 68 bcf in an area of 3378 km$^2$. In this model it was not taken into account neither the variability of the pyrolysis nor the thickness difference of the Bo which makes this a very optimistic model. Even though the rocks have still not achieved their top maturation point to expulse its entire potential, it represents a 0.4% of oil expulsion over the entire Upper Jurassic expulsion of the source rock. Still if the Bo Member is expelling HC it is done mainly on the Rosa Basin.
Figure 4-17: Oil expulsion of the Bo Member unit. Major expulsion in the north of the Poul Basin and in the Rosa Basin. Legend in mmbbl.
4.6. Comparison with previous works

The subdivisions of the Upper Jurassic by Andsjerg & Dybkjær (2003) have some coincidence with this work. The correlation among their subdivisions (see Figure 4–19) does not correspond always with the same reflector for example among the wells E–1 and G–1 in their Kimm4, Volgian2 (see Figure 4–19). But in general describes similar sequences than in this work.

The environment deposition subdivision in Andsjerg & Dybkjær (2003) work is the same than proposed in this one, except by in their positioning of the Kimm4 which they describe as deep marine and in this work it is proposed to be shallow marine at least in the Southern Danish Central Graben.

It is agreed in this work with Andsjerg & Dybkjær (2003), that Kimmeridgian pertains to shallow marine environment and Volgian to deep marine, and the Relative Sea Level curve they proposed for the Danish Central Graben has a strong coincidence with the proposition of this work, recording a fast rising of it for the Volgian period (Figure 4–18). Over their well top Kimm2 they describe a HST and in this work it is believed it is a combination of TST and HST.

![Figure 4–18 Comparison of the relative sea level curve of Andsjerg & Dybkjær, 2003 and other authors. Modified from Andsjerg & Dybkjær, 2003.]}

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Figure 4-19 Seismic intersection with Sequence Boundaries well tops locations from Andsjerg & Dybkjær, 2003 (in left side of each well and cursive font), and the Surfaces identified in this work (right side of each well).
5. Discussions

The southern part of the DCG experienced a strong subsidence during the Upper Jurassic. It is believed the tilted fault blocks resulted during rifting process in the Kimmeridgian formed the main depocenters.

As showed in the burial history, the subsidence rate decreased during Volgian period on which the main subsidence was ruled by secondary faults and the CSF.

Probably the subsidence in the Salt Dome Province stopped in the Late Kimmeridgian, because of the scarcity of Volgian sediments in this area, while the salt structures uplift at this time.

A large progradational system from south to north is seen, with minor retrogradations. Regionally, Maximum Flooding surfaces were identified and local Sequence Boundaries. In the Volgian, the sequence stratigraphy is characterized with transgressive system.

The presence of the shelf breaks during the Kimmeridgian refers to a depositional environment possible of shallow marine. It is believed Volgian was deposited under deep marine due to the fast transgression recorded for this period, the geochemical properties of kerogen type II, and the presence of deep marine mudstones. The sedimentary environment is also supported by other authors as Andsjerg & Dybkjær (2003), but it is remarkable in the Kimmeridgian the absence of data with typical shallow marine sediments as carbonates or sandstones.

In case of being shallow marine during Kimmeridgian it should be possible to find more than mudstones in lithology and structures as deltas, fan etc and in the Poul Basin structures as turbidite fans for example. For this purpose it is proposed to make further studies on seismic as enhanced local interpretation of the reflectors, flattened cubes, and seismic attributes.

The Fasan -1 well recorded very fine sandstones in a wedge located over the top Kimmeridgian reflector (Lower Volgian) as part of a turbiditic system. Therefore it is possible to encounter more turbidite systems within the Poul Basin in the Kimmeridgian.
The mini basins as Rosa, Poul and Igor are present and formed from before Upper Jurassic deposited.

Rosa Basin has its highest subsidence previous Upper Jurassic with a strong pulse later in the Middle Volgian. Poul Basin has a depocenter migration from south to north along the Upper Jurassic. Igor Basin is formed as consequence of primary or secondary faults caused by the CSF and stops subsiding in the Late Volgian. The mini basin in the boundary exists with an elliptic shape only in the Lower Kimmeridgian, and then it is hard to follow the reflectors in the sedimentary package.

The main HC expulsion is located in the Rosa and Poul Basin. The Bo Member differently than in the North (Ineson, Bojesen-Koefoed, Dybkjær, & Nielsen, 2003), is not the principal source rock in the Southern Central Graben because it is immature. In this area the Lower Kimmeridgian is the main oil generator.

In the basin it is recommended to carry out a facies analysis based on sequence stratigraphy and assign geochemical attributes to each in order to generate more realistic TOC and HI variations, as showed in the well Fasan -1.

In the basin modelling the maturation calculation is a variable that strongly affects the hydrocarbon expulsion. The maturation comes attached with the gradient of the temperature in depth; therefore two inputs are very sensitive for the hydrocarbon expulsion: temperature gradient and depth of the horizons.

Regarding the temperature gradient measurements they were averaged along the entire basin which it might not be realistic. Using the maps of TOC and HI (with maximum of 7 and 600 respectively) and different temperature gradients it was calculated an oil generation range from 34000bbl to 170000 bbl.

The HC expulsion rose up 40% of volume with the addition of two artificial intralayers per package. This tremendous change can be explained because the maturation of each package is calculated based on the top layer, but if we add up more layers the maturation with depth is higher and because it is in the oil and gas window the values of expulsion are higher. Then it is expected that with a volumetric calculation of the maturation (finite difference) the HC expulsion will be higher than calculated in this project.
And regarding the depth of the horizons in this work we are dealing with maximum error estimated of 400 ft. The maturation sensitivity changing this parameter was not calculated, but it is expected to have an impact.

The expulsion peak time is not reliable in this work for two reasons. First, the TOC and HI were averaged per package. This average as showed is not real, it is a good approximation to calculate the total oil generation, but it is not right to calculate the time of expulsion. One thin layer of high organic content expulses the HC faster than a low organic content layer, and if averaged it gives an expulsion time not real. Second, the inversion of the Cretaceous was not incorporated into the model, so the rate of subsidence has a null slope of a period of time and it has to be higher post-Cretaceous, possibly this time does not affect too much the expulsion peak since the rock was not mature for this time, but still it is an error that has to be taken into account or calculated. The expulsion peak time does not affect the total HC calculated up to today in this model.

The certainty of the basin modelling is attached to the quality and certainty of the inputs. As it was tough in a Basin Modelling course “Garbage in, garbage out”. Since the inputs drag many errors the basin modelling is not taken as a warranty of exact calculations but to have a good idea of the kinetics of the basin and the range of expulsion that we are dealing with, especially for exploration matters. For this reason statistics were calculated.

The statistical mean of Oil expulsion for all the TOC, HI and temperature variants range from 71500 to 154500 bbl of oil and from 110000 to 240000 bcf of gas.
6. Recommendations

It is believed that an interpretation of the faults in the basement and Triassic in 3D can give a more accurate structural history deformation of the basin and in the Jurassic.

A more extensive study of seismic stratigraphy can be used to identify packages of progradations and regressions, looking for more evidences of the environment of deposition.

The generation of more geophysical attributes can be important in order to locate geological structures as rivers, fans, deltas etc.

If it is possible to have a better understanding of progradation and regression surfaces it can be attributed a trending of TOC and HI with depth per package. If it is possible to attribute facies to the packages it can be attributed TOC and HI values in order to generate maps with more realistic approach and have less error in the HC generation calculation.

It is known that a project to generate of a velocity cube for the Jurassic package is being carried out, and when finished it is recommended to re-convert the horizons from time to depth and include them in the basin modelling project.

Utilize software that calculates the maturation in volume and not in 2D, can give a better approximation of HC generation.

Including the Cretaceous inversion and salt dome uplift in the Basin Modelling can be useful to have idea about the oil peak generation.
7. Conclusions

- The southern part of the DCG experienced a strong subsidence during the Upper Jurassic. It is believed the rifting process during the Kimmeridgian resulted in tilted fault blocks forming the main depocenters.
- The subsidence in the Salt Dome Province stopped in the Late Kimmeridgian,
- A large progradational system from south to north is seen, with minor retrogradations, and regionally were identified Maximum Flooding surfaces and locally Sequence Boundaries. In the Volgian is recognized a transgressive system.
- The presence of the shelf breaks during the Kimmeridgian refers to a depositional environment possible of shallow marine. It is believed Volgian was deposited under deep marine due to the fast transgression recorded for this period, the geochemical properties of kerogen type II, and the presence of deep marine mudstones.
- The mini basins as Rosa, Poul and Igor are present and formed from before Upper Jurassic.
- Rosa Basin has its highest subsidence previous Upper Jurassic with a strong pulse later in the Middle Volgian.
- Poul Basin has a depocenter migration from south to north along the Upper Jurassic.
- Igor Basin is formed as consequence of primary or secondary faults caused by the CSF and stops subsiding in the Late Volgian.
- The main HC expulsion is located in the Rosa and Poul Basin.
- The Bo Member differently than in the North is not the principal source rock in the Southern Central Graben.
- Using the maps of TOC and HI (with maximum of 7 and 600 respectively) it was calculated an oil generation range from 34000 to 170000 bbl.
- The HC expulsion rose up 40% of volume with the two artificial intralayers per package.
- The statistical mean of Oil expulsion for all the TOC, HI and temperature variants range from 71500 to 154500 bbl of oil and from 110000 to 240000 bcf of gas.
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8. Bibliography


