Oil production from Lower Cretaceous Chalk Play - the Valdemar Field, Denmark

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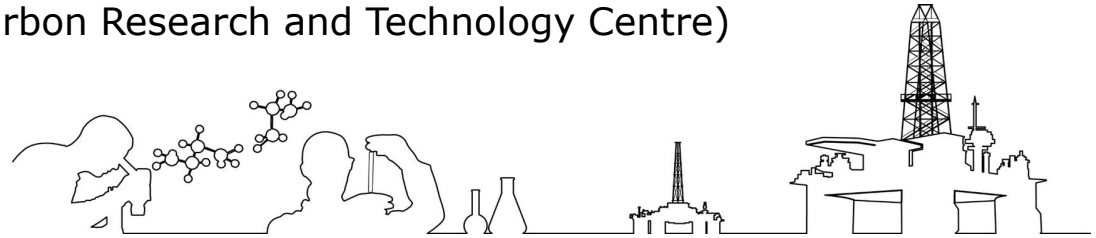
Center for Olie og Gas - DTU
The Danish Hydrocarbon Research and Technology Centre

Agenda

1. Introduction to the Centre for Oil and Gas (The Danish Hydrocarbon Research and Technology Centre)

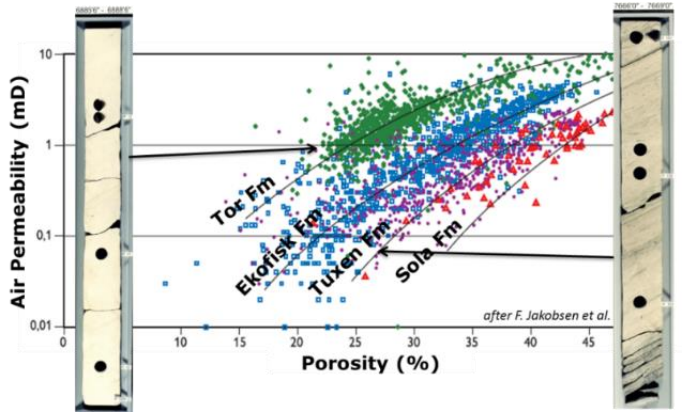


2. Lower Cretaceous Play
   - Structural Setting
   - Stratigraphic Framework

3. Valdemar Field
   - Field characteristics
   - Reservoir quality and zonation

4. Challenges & Research Hypothesis

5. Opportunities

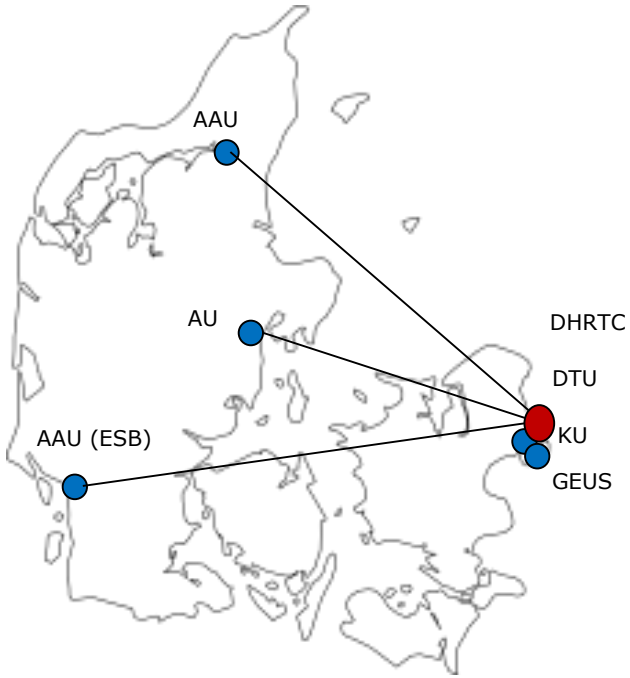


6. Summary

Centre for Oil and Gas

DHRTC Background

- The Centre is part of the Danish long-term national strategy on energy production.
- Collaboration between different Danish Universities (AAU, AU, GEUS, KU and DTU) and the Industry.



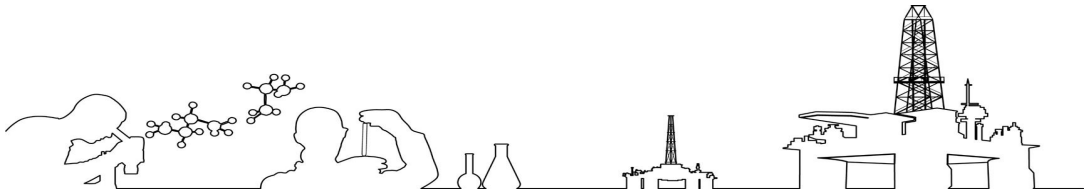
Objectives

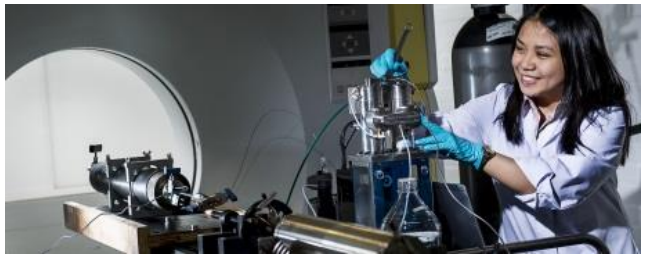
- Research and innovation can identify and qualify innovative ways to enable increased oil and gas recovery in the Danish North Sea.
  - Reservoir Characterisation
  - Enhanced Oil and Gas Recovery Processes
  - Drilling and Production Technology Concepts
  - Production Facilities and Material Research and Design
- Attract and educate professionals to the industry.

AALBORG UNIVERSITY DENMARK · AARHUS UNIVERSITY · GEUS · UNIVERSITY OF COPENHAGEN · DTU

Resources

- 1 billion DKK over 10 years, tax-deductible grant by Danish Underground Consortium (DUC).
- 50 years of data and interaction with DUC and other industries.
- Employees with many years of chalk expertise from the industry.





TOTAL · Chevron · nordsøfonden

Research at DHRTC

AWF.1 Demo Model

Advanced Waterflooding

Pilot: Kraka, Dan & Halfdan

AWF 1 2

The objective is to improve recove
modified injection water rather tha
point of view.

Naturally occurring fractures in ch
artificial pressure support. More
combination with microscopic EOR

DUC Development Plan -

The original DUC Reference case consisted o
(Ekofisk formation) with injection water supp
The new Demo case adds the element of Sma

Fracture Modelling | Compaction drive

DHRTC Hypothesis

Oil recovery in Dan, Halfdan and Kraka can b
advanced water flooding techniques, so-calle
where the composition of injection water is m
or adding salts in order to achieve an optimiz
on reduced corrosion, enhanced compaction
microscopic sweep.

Expected Key Deliverable

- Fracture prediction model (Petrel App)
- Experimentally verified updated compaction
- Upscaling workflow and Geo-modelling wor
- Updated relperm curves from coreflood exp
- High resolution scanning images of flooding
- Fundamental understanding of Smart water
- Smart water composition optimised for Scal
- Integrated THMC model (coupled Thermo-H

Natural fractures | Fracture

Corefloods (SEM & CT) | Enh

AWF.2 Demo Model

Advanced Stimulation Techniques

Pilot: Halfdan and Gorm

AWF 1 2

The objective is to identify and mature soluti
through existing development wells in order
test likely to be performed in a Gorm well in 2

Radial Jet Drilling (RJD)

This technology is used today to enhance production from on
(gas). It uses a high pressure water or acid jet to create nu
wellbore. The aim is to develop this technology further to
complex completions.

RJD chalk lab test samples

Demonstration Case (Halfdan)

4D seismic and logging data from the dedicated observation
the Tor formation, with good recovery from the upper secti
deeper region. The AWF.2 hypothesis is that RJD and induce
from the deep Tor formation in a commercial viable way by
reservoir from existing wells and by enhancing the water flood

Improve Commercially Viable Recovery

Produce faster | Produce longer

Increase Injectivity | Increase Productivity | Improve Sweep

Extensive solutions

Conventional Simulation | Modelling of Radial Jet Drilling technology | Modelling of Water Acid | Subject Matter Acid | Modelling of controlled wash solution

Coupled Thermo-Hydro-Mechanical Model with H2O

Project completed

Expected Deliverables at TRL 3

- Lab test of the behavior of RJD laterals (Stability Analysis)
- Large scale testing of the Radial Jet Drilling technology or solutions. First RJD pilot application; Gorm well
- Simulation sector model including the most promising com solution.

Gorm RJD Application

- Well: Vertical, producer
- Target: Remaining oil in Ekofisk and Tor
- Horizontal RJD Laterals

RJD laterals

Halfdan RJD Applicati

- Well: Horizontal, producers & injec
- Target: Unswept oil in deep Tor
- Vertical RJD Laterals

Producer | Monitoring well | Obse

Top Tor

RJD laterals

Water floo

Oil

TRD.1 Demo Model

Tight Reservoir Development

Pilot: Valdemar Lower Cretaceous

TRD 1

The Lower Cretaceous deep-water chalks and marly chalks of the Danish sector of the Central Graben form a widespread but, as yet, poorly understood play with large hydrocarbon accumulations. Current production is limited to the Valdemar Field and one well in Tyra LC.

The objectives is to identify methods to improve economic recovery of the Lower Cretaceous reservoir in the Danish North Sea.

DUC Development Plan - Reference Case

The currently existing DUC development plan will be used as a reference case. The new demo case will add the estimated impacts of the hypothesis.

Improve Economic Recovery of LCr

Produce faster | Produce longer | Produce cleaner

Increase Productivity | Enhance Sweep | Fluid Re-extension | Pressure Support | Improve Injectivity | Conventional simulation | Auxiliaries

Reduce Water Production | Improve Sweep Distribution | Improve Injectivity Distribution | Improve Sweep Distribution | Water Injection | Gas Injection

Demo Potential

Up to 150 MMBOE

Existing Profile - Produced and secure resources | Compaction drive | Gas solution drive | Expand into Be South | IOR/EOR | Beyond Valdemar | Fieldlife extension | Oil Production

DHRTC Hypotheses

- Natural and induced fractures can increase productivity, compaction and sweep in the Lower Cretaceous
- Understanding of Reservoir Quality distribution can improve OIIP estimates and guide new development projects
- Compaction/subsidence is an important contributor to drive mechanism
- Gas Injection can help produce longer and more
- Water Injection can reduce remaining oil through enhanced sweep as well as enhance the compaction drive

Technical description | Economic description | Prototype / simulation | Uncertainties, assumptions and risks

Expected Key Deliverables at TRL-3

- Fracture model based on updated LC rock mechanical database
- Improved understanding of Reservoir Quality distribution to assist OIIP estimates that can guide new development projects
- Update LC rock mechanical database and improve Geo-mechanical model - QC against time-lapsed seismic
- Model demonstrating the possible improvement of recovery in the Lower Cretaceous reservoir by gas injection
- Feasibility study of water injection in Valdemar

Technology Gaps

- Feasibility study on the technical and economical benefits/disadvantages of water-flooding in the tight Lower Cretaceous reservoir

Other Risks

- Still to be mapped

Collaboration Model

- DHRTC Partner Institutions:
  - KU - IGN / NBI / KEMI
  - DTU - KEMI / KT / BYG / NanoTech
  - AU Geoscience
  - GEUS
- Other partners:
  - GEO

Programme management & Technology Maturation

Jolan Shale | Cretaceous/Jurassic | Tyra Fm | Valdemar Fm | Rørdal Fm | Sola Fm | Ekofisk Fm | Tor Fm | Hod Fm | Blodøks Fm | Tuxen Fm | Sola Fm | Rørdal Fm | Ekofisk Fm | Tor Fm | Hod Fm | Blodøks Fm | Tuxen Fm | Valdemar Fm | Tyra Fm | Chalk | Marly Chalk | Organic rich marlstone | Marlstone

Air Permeability (mD) | Porosity (%)

Contacts:
Birgitte O Larsen, Technology Maturation
Ulla Hoffmann, Programme Management

CTR-1 Demo model

Increase Water Injection Availability

Pilot: Dan and Halfdan

CTR 1 2 3

The objective of this programme
development/design aspects related t

It has been identified that optimizatic
MMBOE. The produced water treatm
water cut. If successful, the project wi

DUC Development Plan – Re

The reference case takes offset in the Water inject
Development Plan for the southern DUC fields. Es
good water injection is critical to maintain reservoir

Maersk Oil have therefore established a plan to in
through an engineering upgrade project for the Da

DHRTC Hypothesis

The hypothesis is the following: "Prevent the declir
deploying big data analytics combined with functio
occurred historically following engineering upgrade

Work stream

CTR.1.A Multilevel flow modelling (MFM) and
CTR.1.B Big Data methods for identifying caus
CTR.1.C Laboratory testing and grey-box mod
CTR.1.D MFM for offshore WI installation

Technology mapping has been done to identify rel
projects and technical disciplines that may play an
success of this demo model.

Industry Data

- Dan and Halfdan WI/PWT prediction - DUC
- Dan/Halfdan WI/PWT equipment specification -
- Engineering upgrade project - DUC

Expected Key deliverables a

- MFM developed to provide online decision supp
- Validation and verification of MFM model and ap
- Fault detection and pattern recognition (Big Dat
- Optimization and control of filtration for WI syste
- Counter action plan and failure prediction throu

Demo Model Dependencies

- Demo model AWF.1 concerning EOR
  - Water Injection requirements of EOR redev
- Demo model CTR.1 concerning water managem
  - WI & PW capacity requirements
- Demo model CTR.2 concerning Maintenance
  - Platform design
  - Operation procedures

CTR.2 Demo model

Enhanced Well Chemistry & Integrity

CTR 1 2 3 4

DUC has identified the main opportunities
maintenance cost e.g. through improved s
the DHRTC is to support the DUC by ac
discipline, and by integrating new state-of-
associated with activities with greatest im
Cessation of Production (CoP).

DHRTC Hypothesis

Main hypothesis: **Combining state of the art modeling of phenomena with risk management and modularization substantially reduce OPEX.**

This will be achieved by optimized operational management and control / treatments resulting in reduce oil production loss, reduc well as improved water injection. Secondary benefits will be enhan

Supporting hypotheses are:

- Asset OPEX can be reduced through modularization of maintena
- Well uptime can be improved through activities to mitigate corr increasing well integrity
- Well cost can be reduced through preventive activities v management and prediction tool based on state-of-the-art mode and souring mechanisms
- Well recovery can be enhanced through well conformance ac production

Industry Data

- DUC operational data, intervention and workover history as well as maintenance data (Gorm/Dan/Halfdan)

Expected Key Deliverables at TRL 3

- Cost reduction by 4D maintenance planning
- Better control of scale & corrosion
- Risk based well intervention planning tool covering e.g. workover
- Methods for mitigation of reservoir souring
- Establish test facilities and validate scale and corrosion mitigatio

Demo Model Dependencies

- AWF.1 assessment of impact of EOR processes on maintenance scale and corrosion by smart water.
- CTR.1 concerning increased water injection availability on Dan a

Field Input | Models & Predictions | Statistics | Plans

Fluid Chemistry Tool | Well Data Production info Breakthrough Injection water | Risk Tool | Model Maintenance Planning and Enhanced Intervention Planning

CTR-3 Demo model

Extend Life of Potential Hub Structures

CTR 1 2 3 4

The objective is to demonstrate structural integrity of potential hub platforms to survive extreme wave loading allowing continued safe operation of the facilities to 2042 and beyond. The challenge of extended lifetime is approached through enhanced structural monitoring, evaluation of extreme wave probability and risk evaluation. Proving increased lifetime capability of the potential hub structures opens the opportunity of using the production facilities for tie-in solutions.

North Sea Development Plan – Reference Case

A number of marginal resource pools could become commercially viable to produce by use of a DUC hub platform, provided sufficient life and capacity is ensured.

In evaluating development scenarios for the Hejre field, several DUC installations were proven to have sufficient remaining fatigue life to continue operations beyond 2042. However, this evaluation did not take into account the risk of extreme waves which must be further investigated to prove the extended lifetime of the existing structures.

DHRTC Hypothesis

The research hypothesis is to combine the understanding of the structural response and of extreme waves to supplement the DUC AWARE project in reducing uncertainty in the risk analysis from which decisions on life extension, strengthening, operational restrictions etc. can be based.
Advanced methods for the analysis of actual structural response will be utilized to verify and update models and provide estimates of the condition of the structures. A unique understanding of the nature and statistics of extreme waves will result from theory and measurements at actual location and test facilities. Research on fatigue crack propagation and inspection techniques will address probability of detection of critical defect size. Improved risk-based methods for fatigue crack inspection and corrosion will be developed. Value of Information (VoI) will be employed for selecting data and measurements based on importance rather than availability. Secondary benefits will be reduced cost of structural integrity & reliability management.

Work stream

CTR.3.A Structural Integrity & Monitoring
CTR.3.B Extreme Waves
CTR.3.C Risk Modelling

Industry Data

- Tie-in development plans - DUC
- Structural integrity reports - DUC

Expected Key deliverables at TRL 3

- Actual stress statistics
- Wave statistics and monitoring data
- Structural monitoring data
- Validation for structural model assumptions
- Load model and updated statistics for extreme, breaking waves
- Probabilistic risk modelling

Technical description | Economic description | Prototype / simulation | Uncertainties, assumptions and risks

North Sea Development Plan – Reference Case

Reference case based on existing facilities being decommissioned and no availability for tie-in solutions, hence no new developments will be initiated

DHRTC Aspirations

Recovery of estimated contingent, technological and prospective resources as tie back to existing hub-structures.

Impact Aspirations

- Structural Monitoring: in 2018
- Near shore test centre: in 2019

Potential

Life extension of other infrastructure in the North Sea can be assessed based on same methodology.

HC production | Increased lifetime and recovery | Income | Costs | CAPEX | OPEX | Decommissioning | Time

Technology Gaps

- Structural State Estimation in the presence of structural non-linear behavior.
- Sufficiently fast computational methods.
- Extreme wave modelling and statistics.
- Corrosion.
- Anchor state, foundation stiffness.

Risks

- Competing project within industry and research environments.
- Solution not accepted by authorities.
- Prohibitive cost of scale testing.

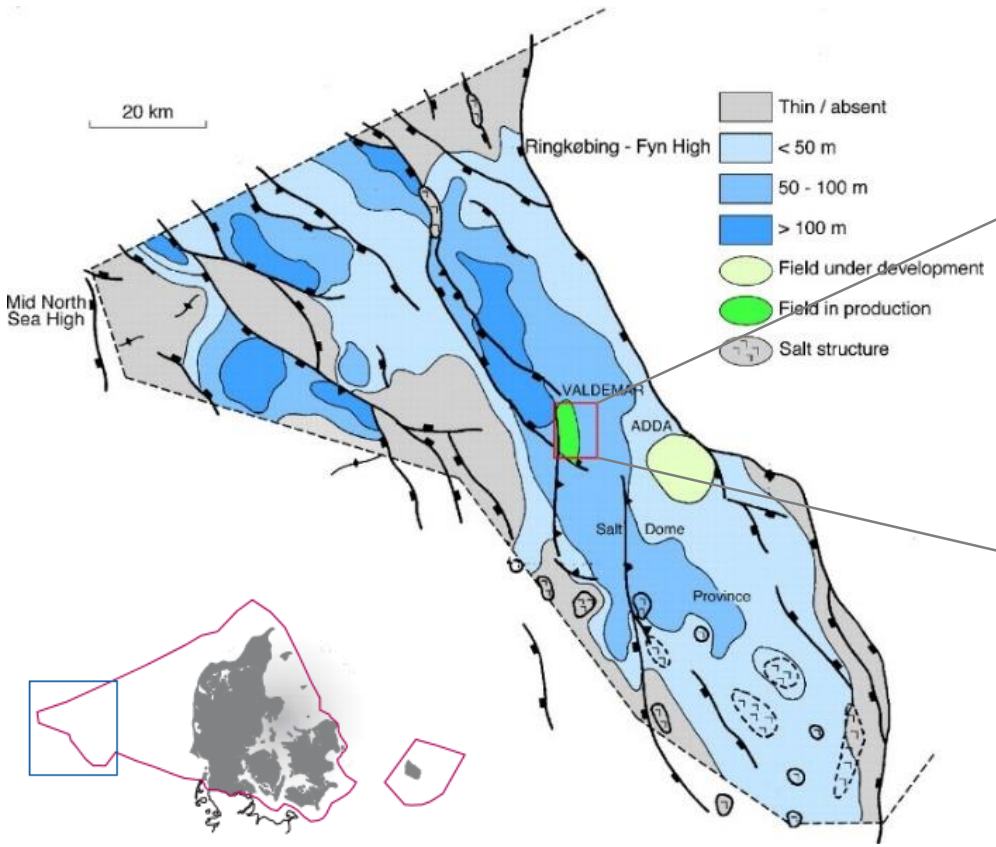
Collaboration Model

- Partner institutions:
  - DTU BYG
  - DTU MAN
  - DTU MEK
  - AU
  - AAU

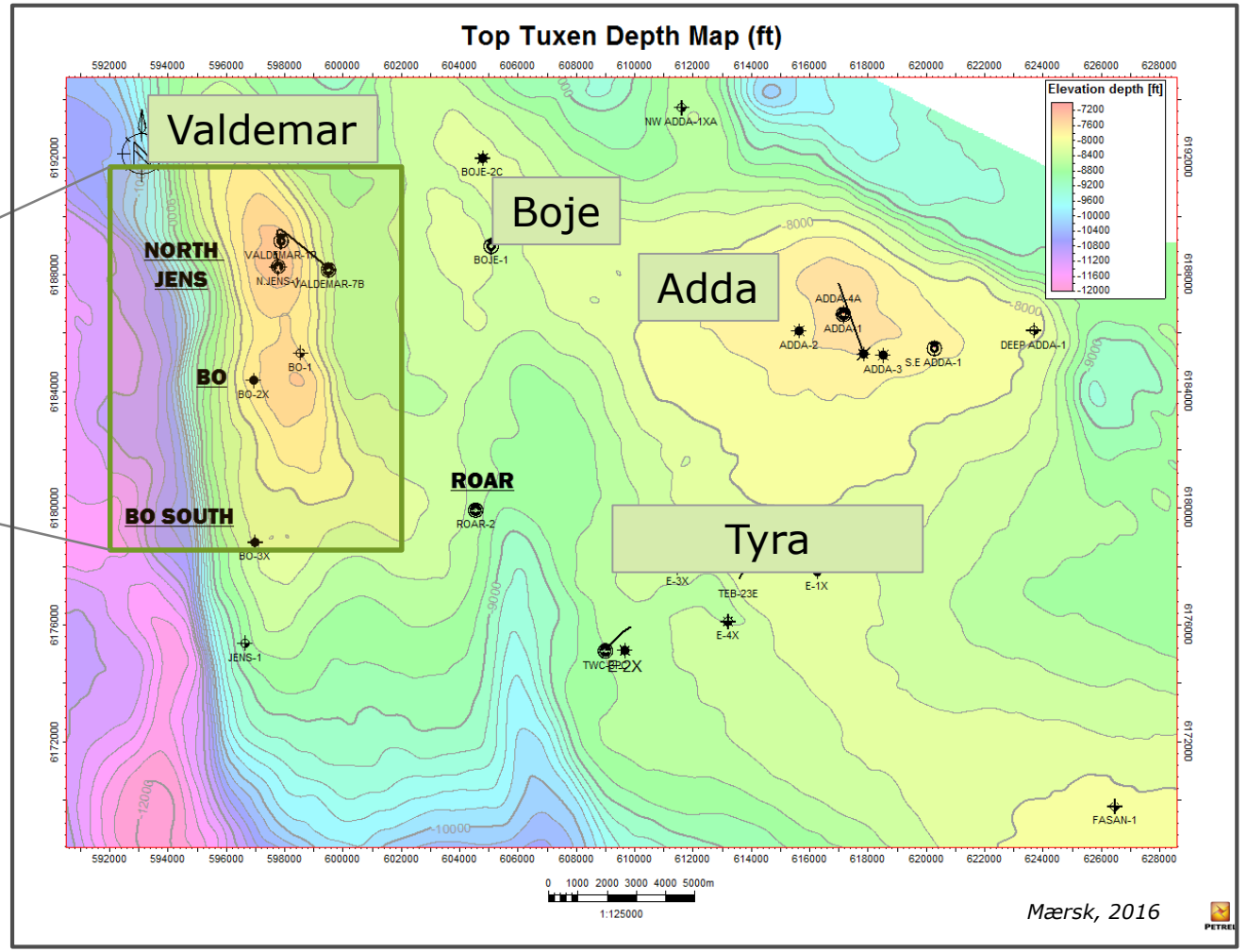
Contact: Henning Hartmann, Programme Management

Introduction – Lower Cretaceous Play

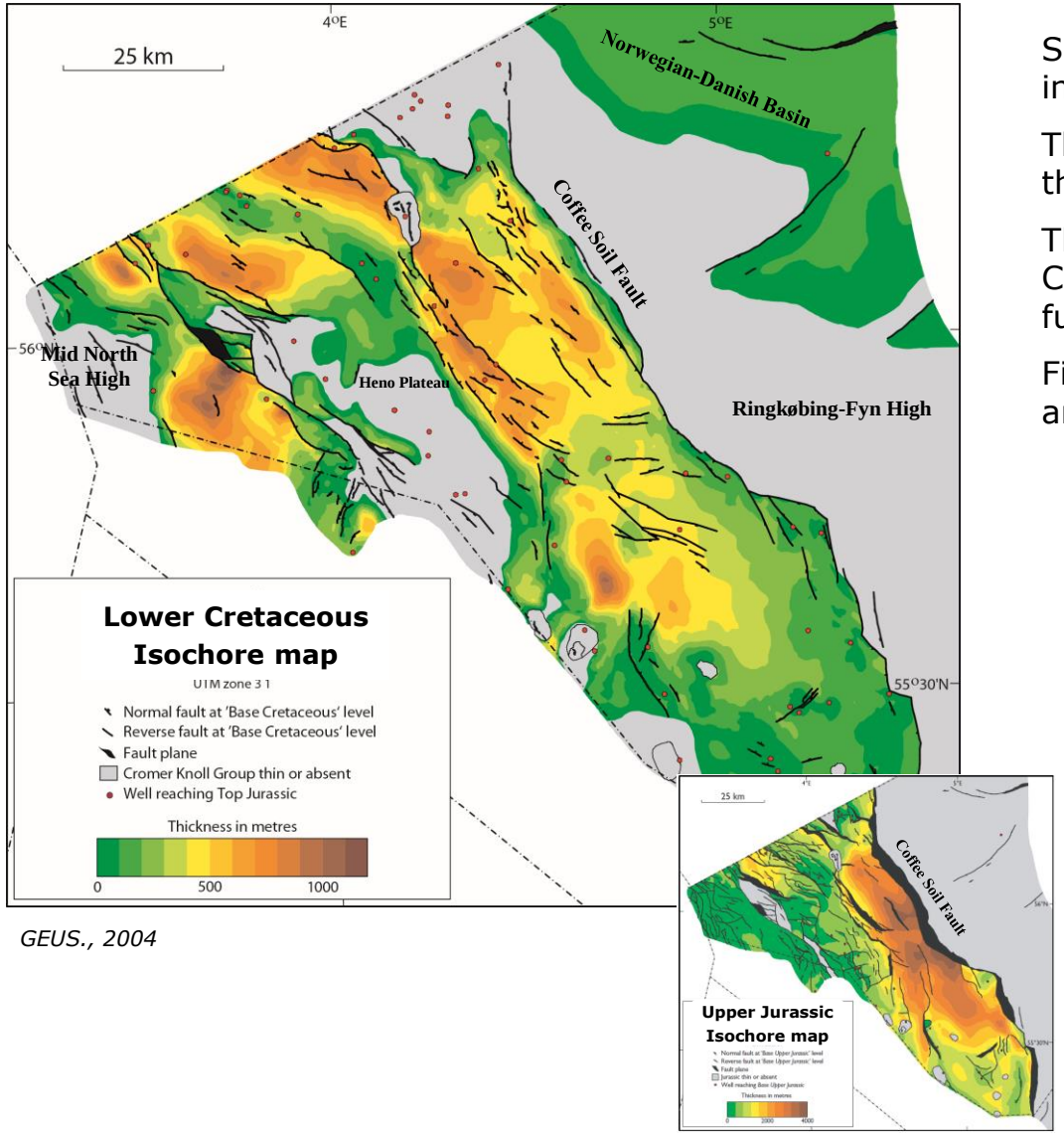
Despite representing a widespread play in the Central North Sea, production from the Lower Cretaceous chalks is currently confined to the Valdemar Field and one single well in the Tyra Field. The Valdemar field has been producing for more than twenty years and yet **significant risk and opportunities remain**.



Thickness Lower Cretaceous Tuxen/Sola Formation;
Jakobsen et. Al. 2004



Structural Setting



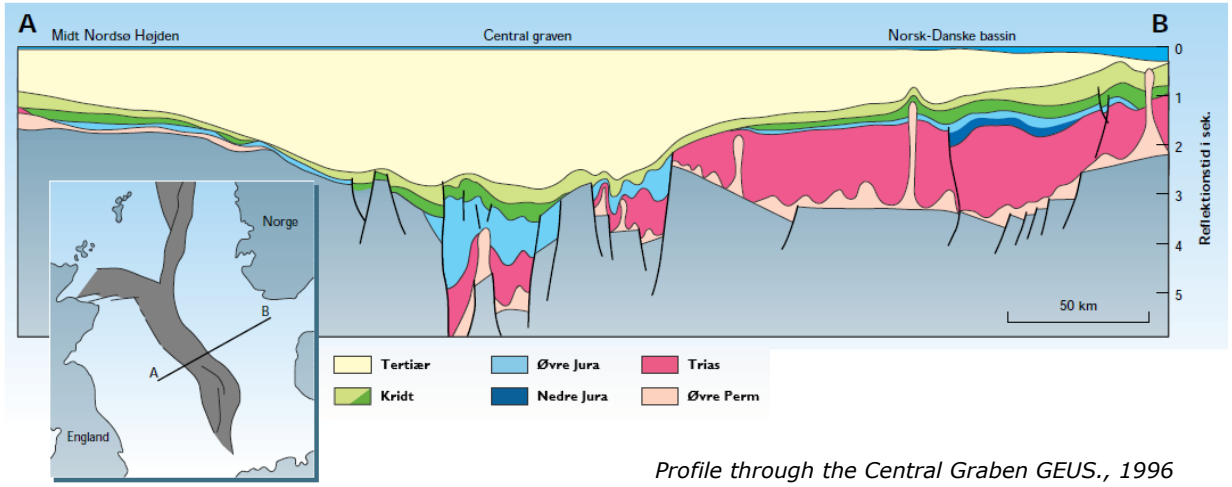
GEUS., 2004

Sedimentation during the Early Cretaceous was strongly influenced by the tectonic evolution of the area.

The extensional tectonic regime of the Late Jurassic continued in the Early Cretaceous although with reduced sedimentation rates.

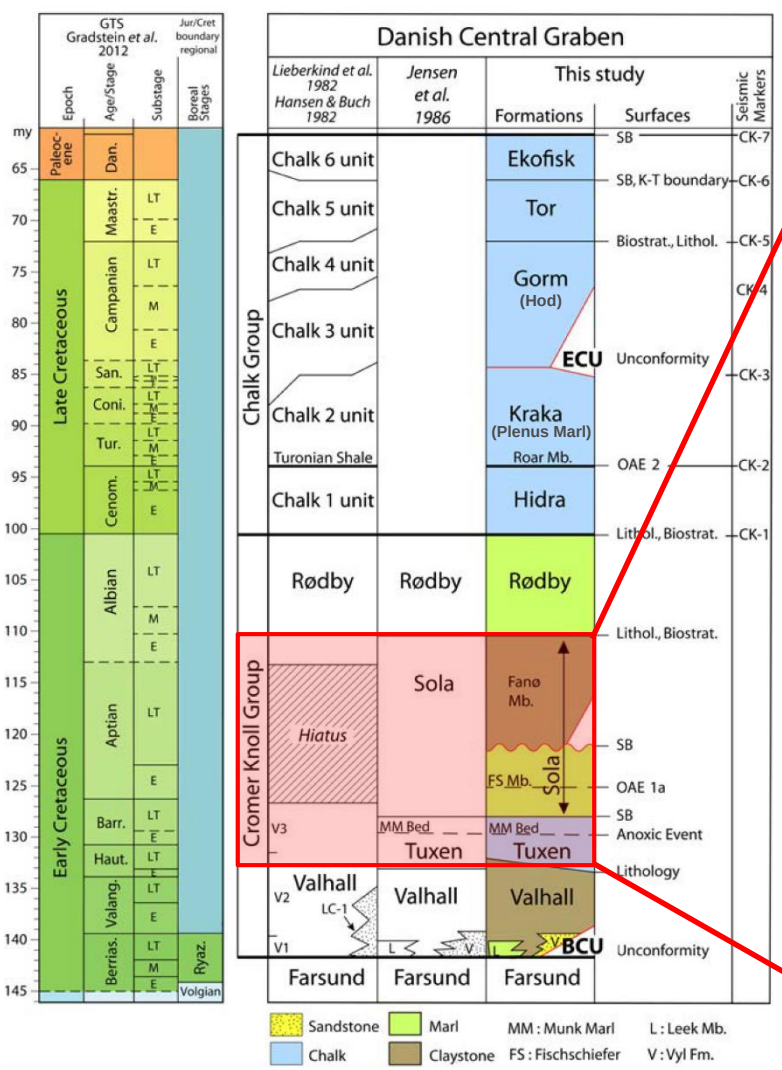
There was a slight shift from deposition concentrated along the Coffee Soil fault in the east to depo-centres also developing further to the west. Sediments accumulated in local depo-centres.

Finally the basin was inverted in Late Cretaceous creating anticlinal traps.

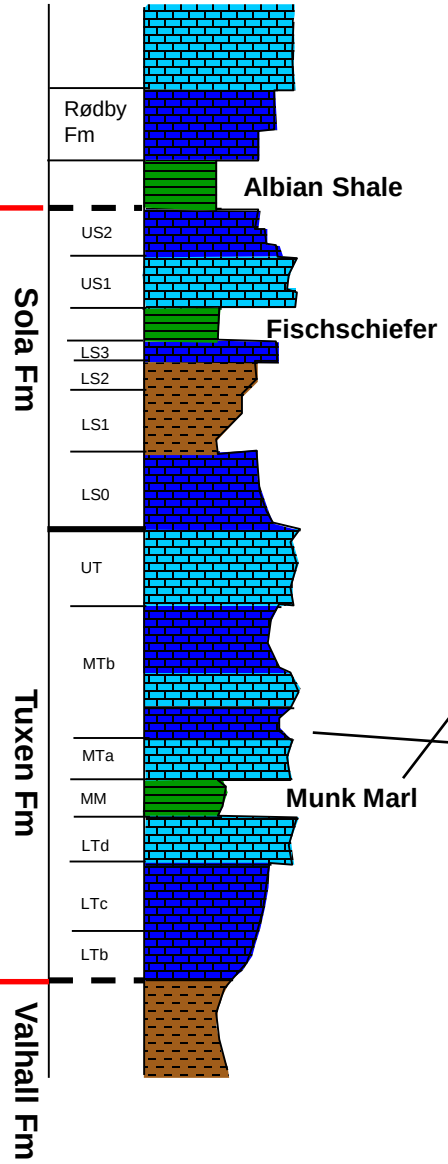


Profile through the Central Graben GEUS., 1996

Stratigraphic Framework



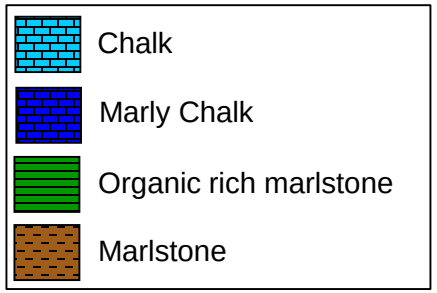
Van Buchem et. Al., 2017



The Lower Cretaceous reservoir section is divided into the Sola Formation and the Tuxen Formation.

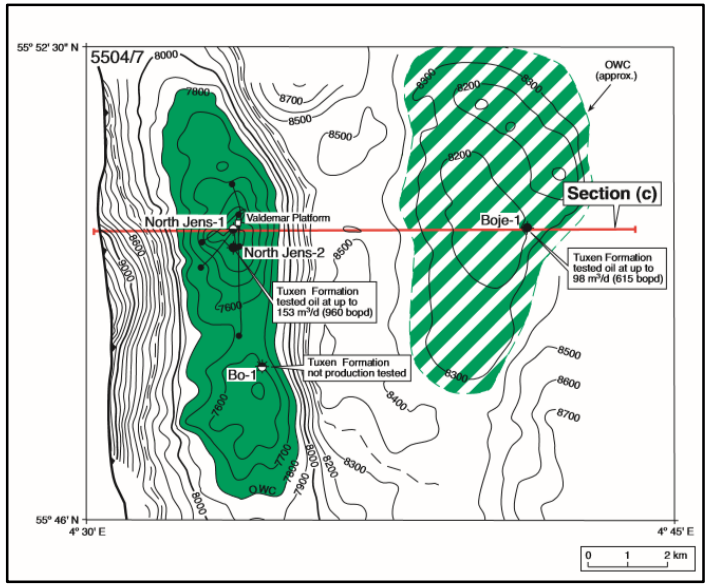
The section is composed of interbedded chalk, marly chalk, organic rich marlstones and marlstone.

Munk Marl - organic rich marlstone



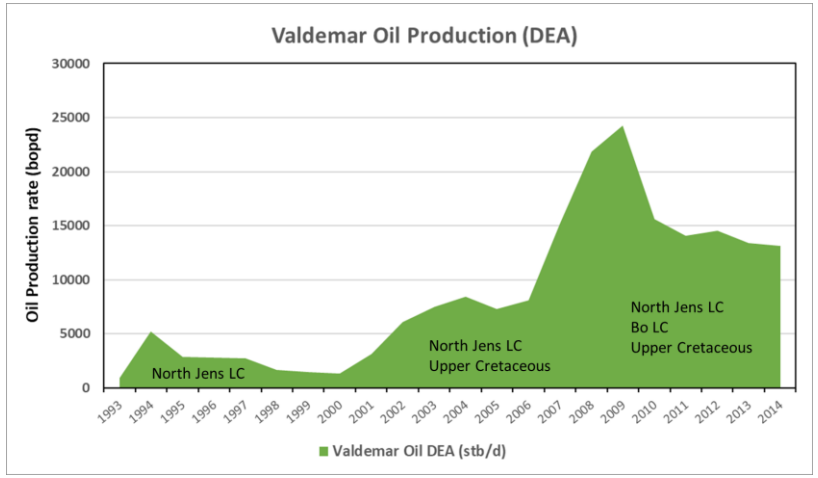
Middle Tuxen - heterogeneous and layered - marly chalk/chalk

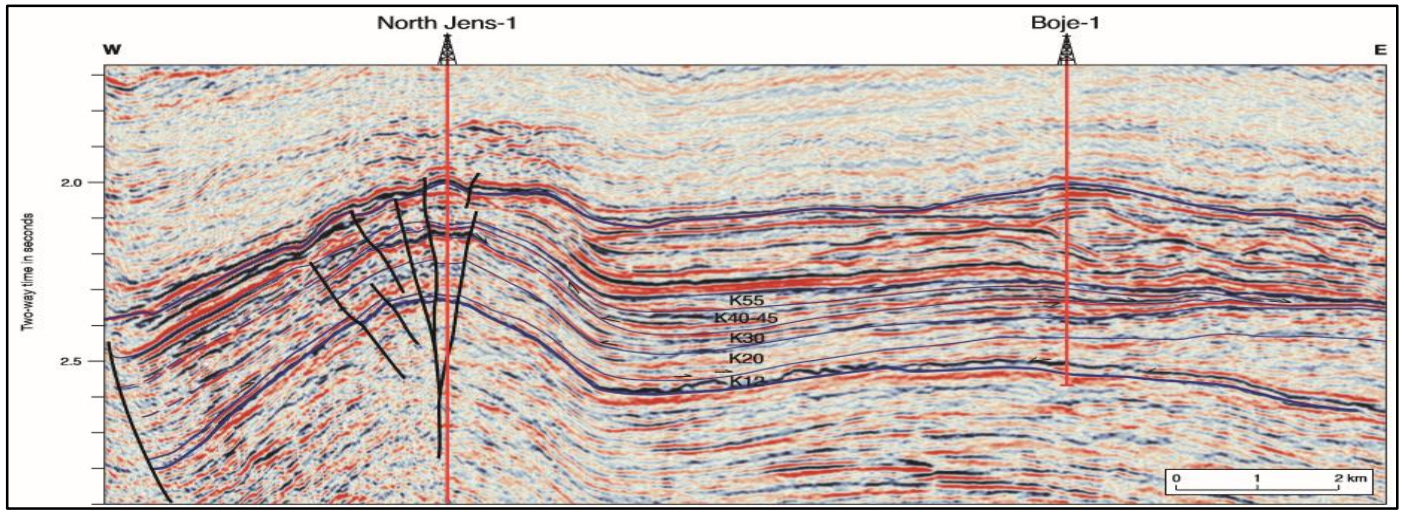
The Valdemar Field



Field Information

Type:	Complex inversion anticline
Discovery date:	1977 (Bo-1 well)
Field start-up	October 1993
Top reservoir:	~2200m
Formation:	Tuxen/Sola Formation
Reservoir thickness:	95m
Net pay:	75m
Porosity:	15-35%
Permeability:	Below 1mD





Field Volumetrics:

Area:	15 km2
In Place volumes:	~700MMstb
Recovery factor:	10-25%
Production (end 2017)	~80MMbbls *(including Upper Cretaceous production; ENS 2017)*

Production mechanism: Primary depletion and likely some addition of compaction

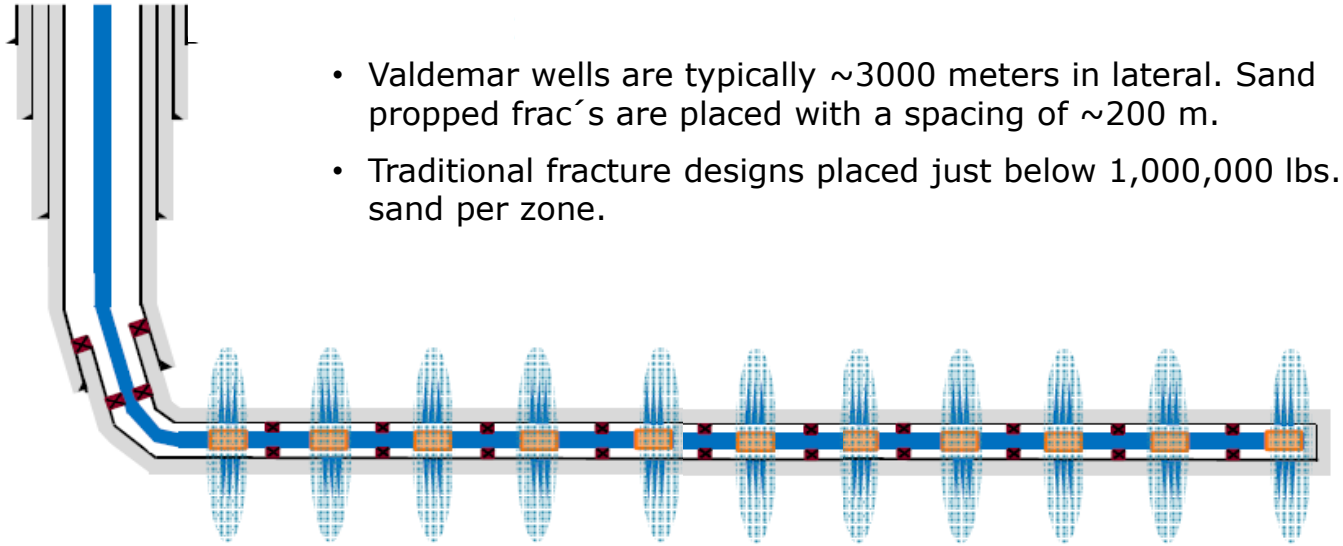
Figures and numbers from Millenium Atlas, 2004

The Valdemar Field

The Valdemar Field is produced from 16 horizontal wells and is today the fourth largest oil producing field in the Danish Underground Consortium (DUC).

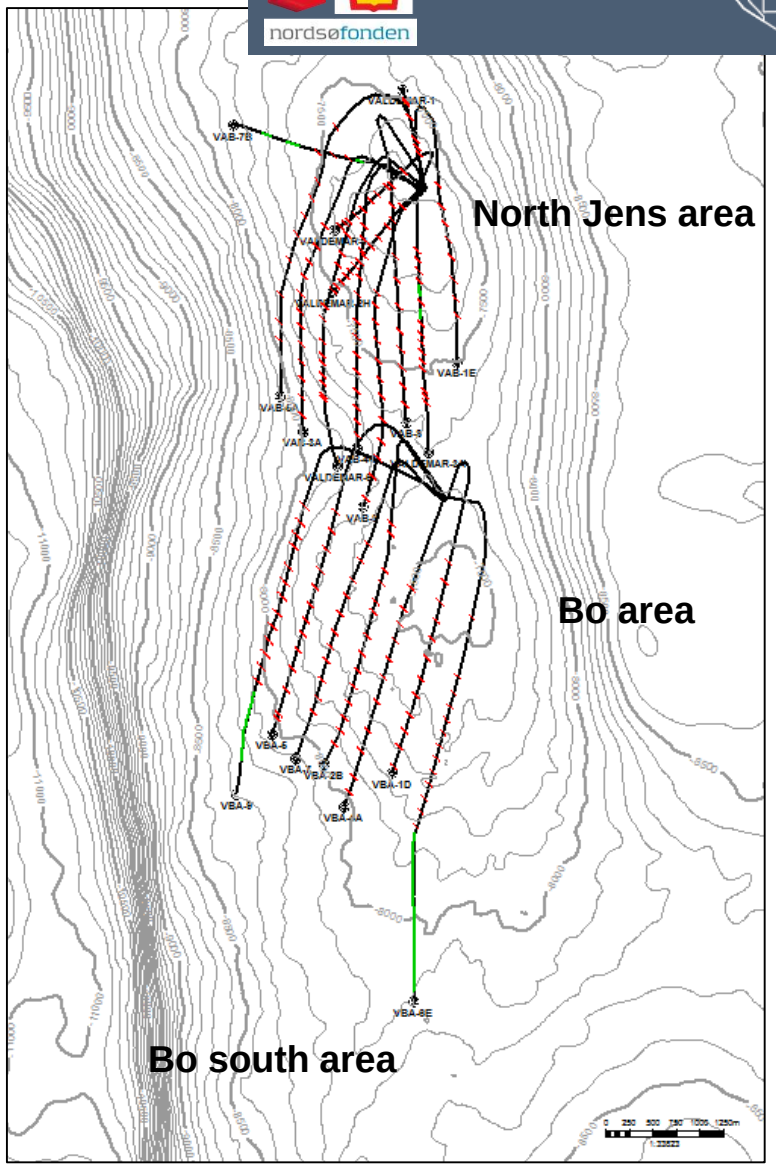
- 9 producers in the North Jens area and 3 abandoned wells
- 7 producers in the Bo area
- Bo South undeveloped

- All wells are completed with sand propped frac´s
- Some zones acid stimulated.



- Valdemar wells are typically ~3000 meters in lateral. Sand propped frac´s are placed with a spacing of ~200 m.
- Traditional fracture designs placed just below 1,000,000 lbs. sand per zone.

Horizontal well with sand propped frac´s

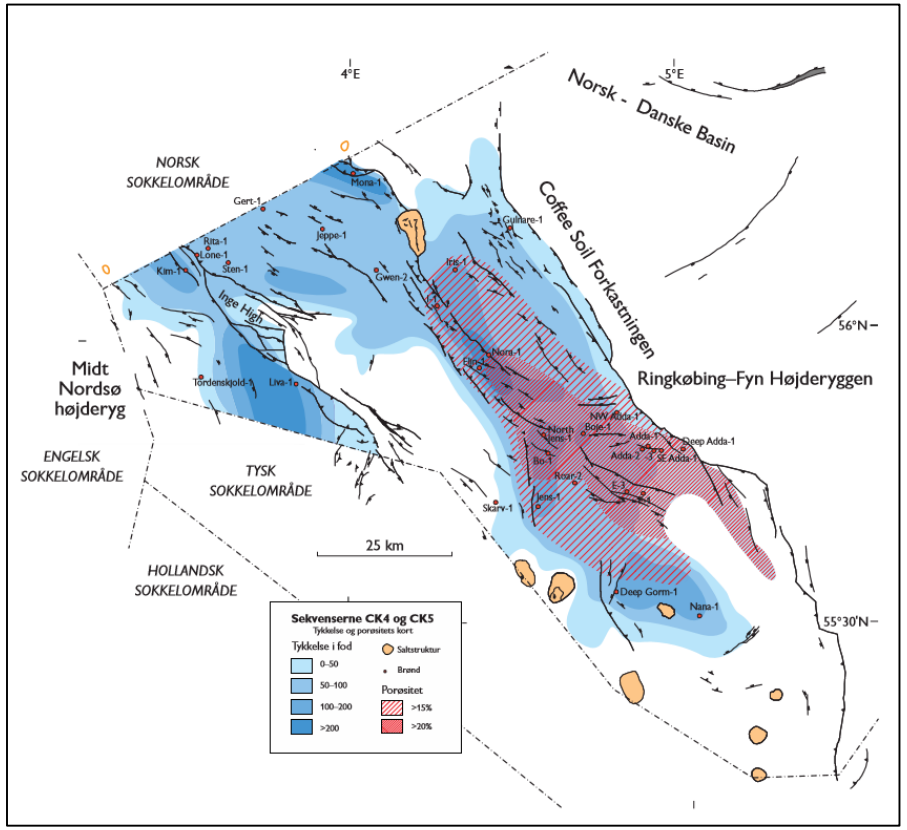


Reservoir Quality

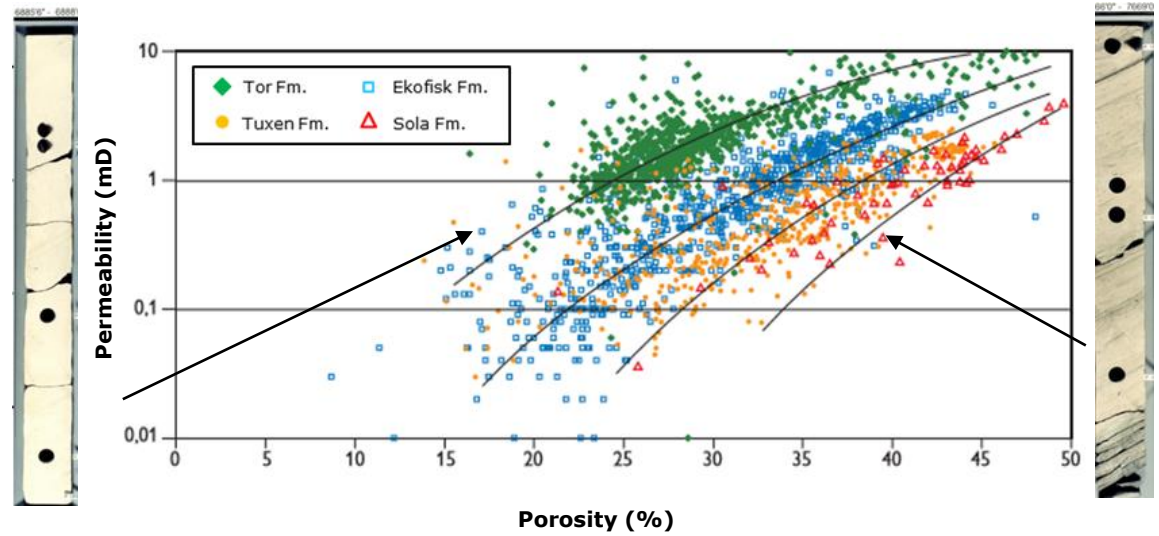
The Lower Cretaceous reservoir is very different from the Upper Cretaceous Chalks (Ekofisk & Tor Formation).

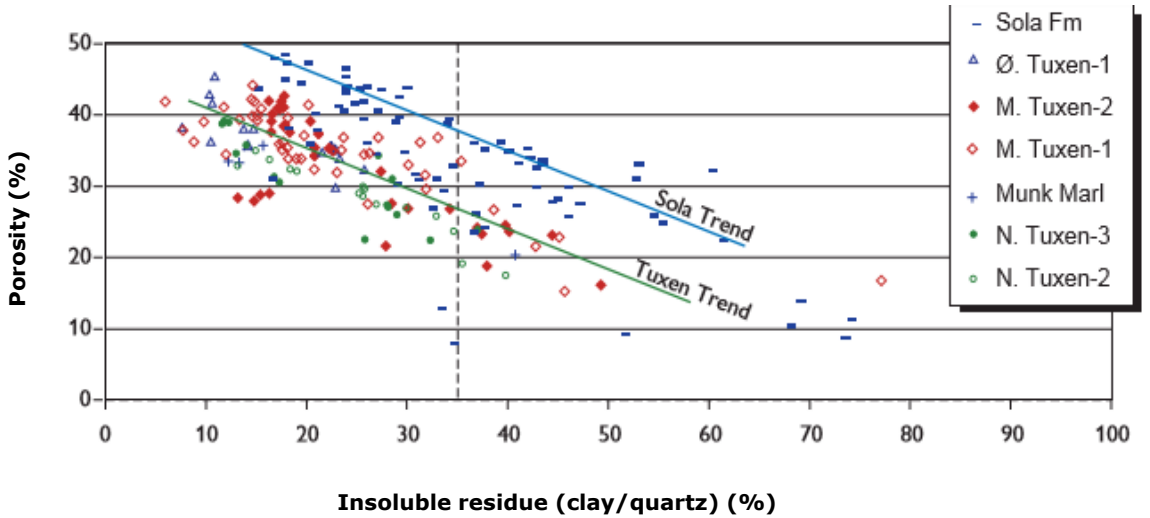
It is a lot more heterogeneous and permeabilities are much lower and the clay content is very high.

Areas with good porosity are locally restricted.



Tor Fm. **Tuxen Fm.**





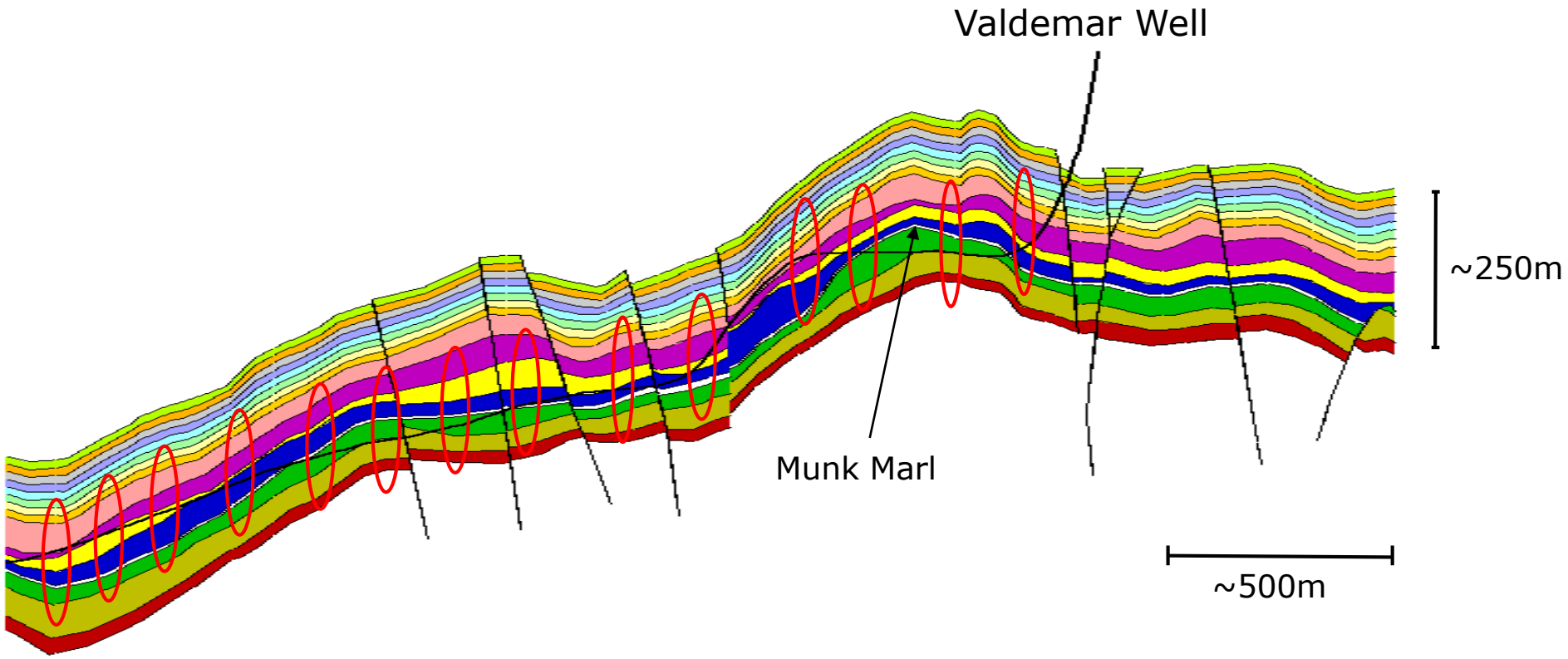
Figures taken from GEUS, Geology, 2003

Reservoir Zonation

The reservoir section is divided into 16 different zones including the organic rich mudstone layers.

The reservoir can be followed across the entire Valdemar Field with the help from biostratigraphy. The zonation is based on differences in porosity, permeability and clay content.

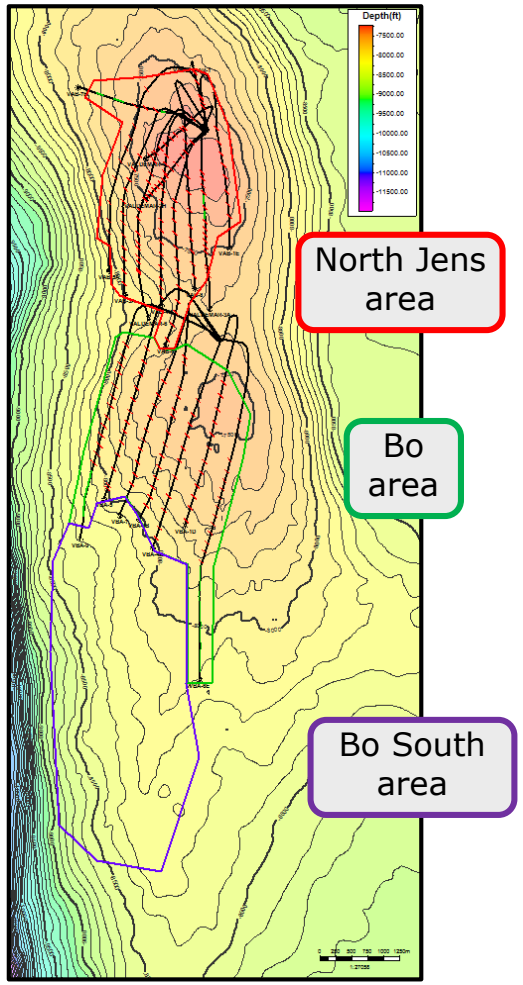
Long horizontal wells are designed to target the layers of best reservoir quality. Completion with sand propped frac's to connect different layers and to connect across the Munk Marl.



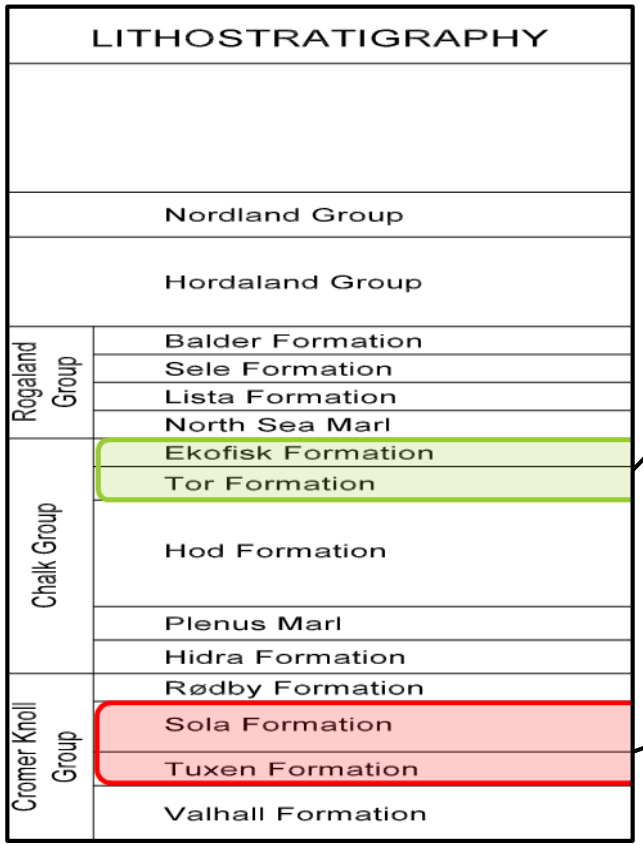
Challenges

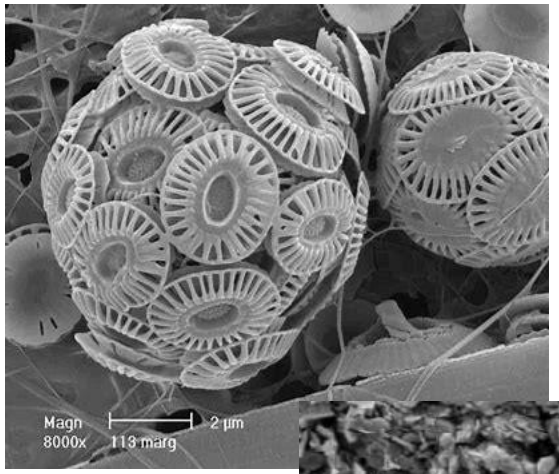
The recovery factor for the Lower Cretaceous has so far been **relative low and uneven** across the Valdemar Field area.

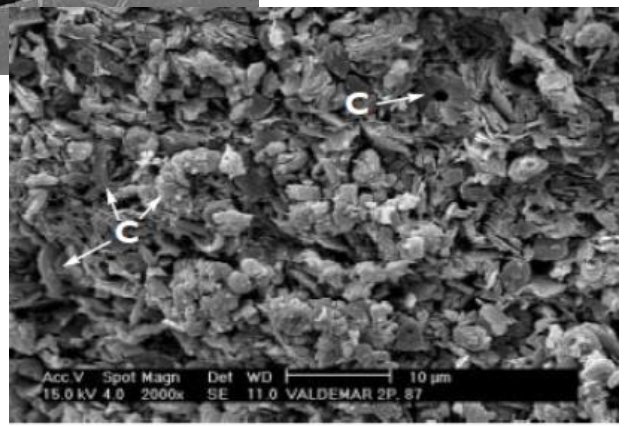
STOIIP is currently expected more or less the same, but **North Jens is today prognosed to recover twice as much oil as the Bo area.**



Another challenge is the rather limited **fundamental understanding** of the Lower Cretaceous marly chalk reservoir compared to the more clean Upper Cretaceous chalk.





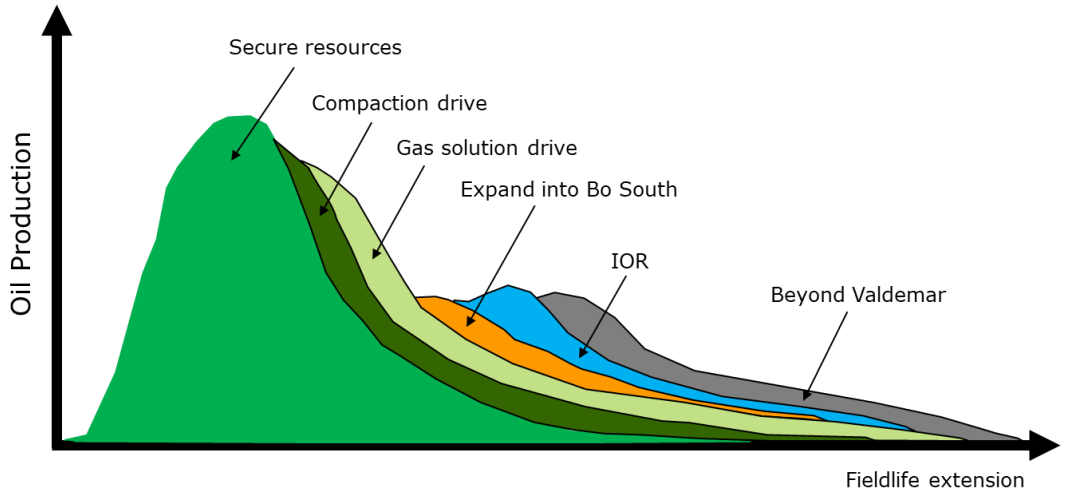


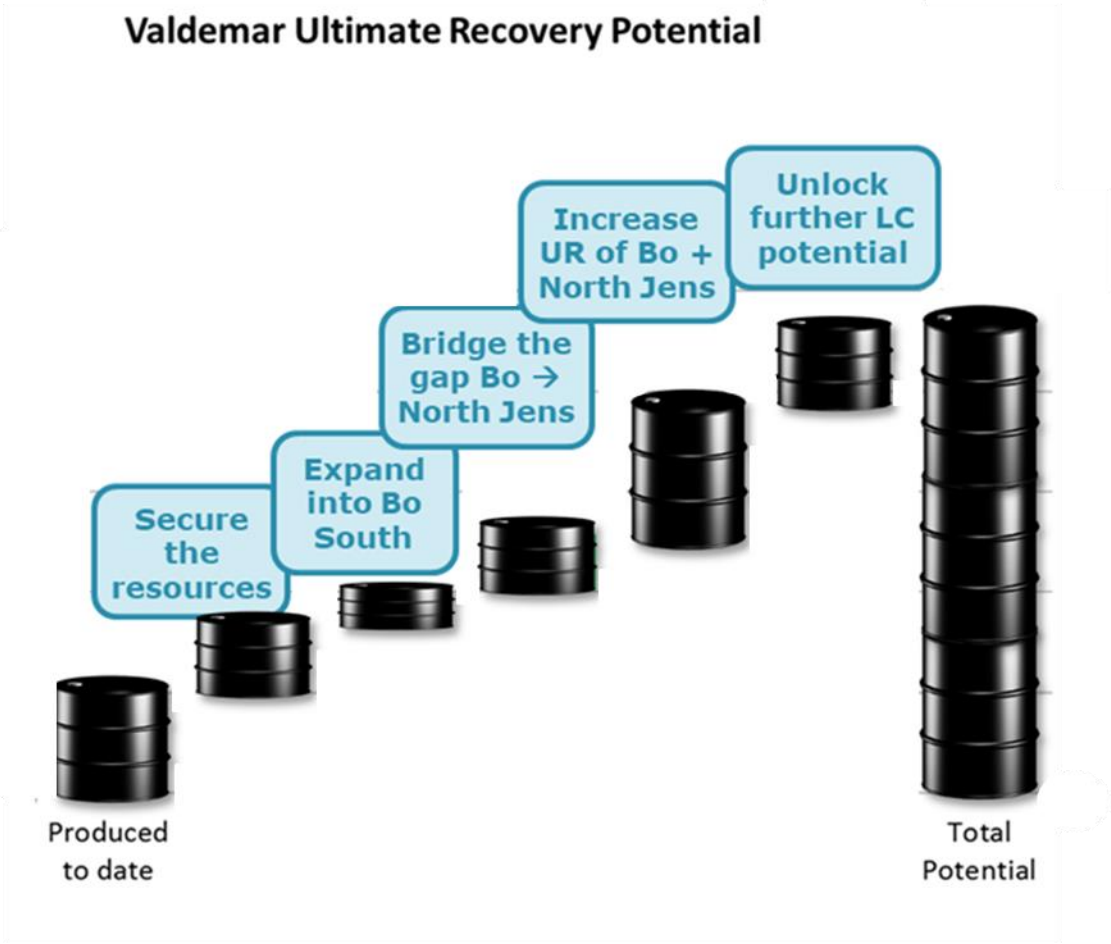
Mærsk, 2016

Opportunities

It is believed that research can help/complement with:

- Bridging the gap between North Jens area & Bo area (understand well performance)
- Decisions on how to expand into Bo South
- Increasing ultimate recovery of both the North Jens and the Bo area
- Unlocking further Lower Cretaceous potential

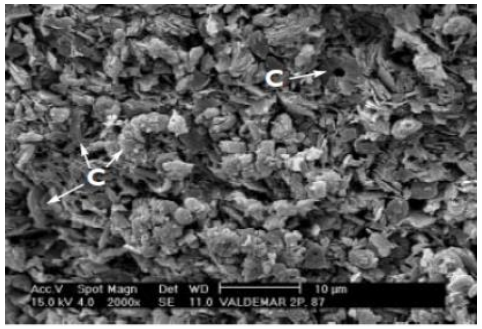


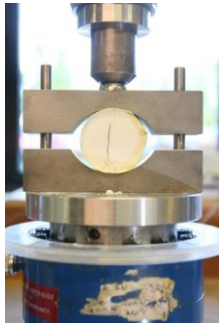


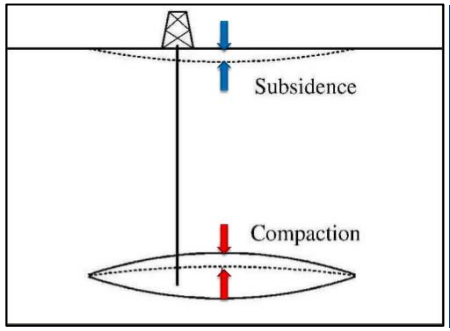
Mærsk, 2016

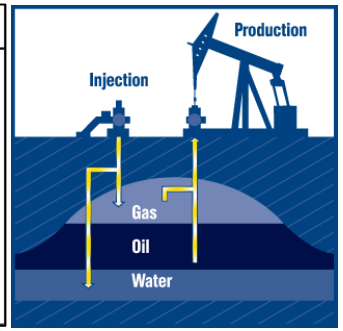
Hypotheses (DHRTC currently working with)

- **Natural and induced fractures** can increase productivity, compaction and sweep in the Lower Cretaceous
- Better understanding of the **Reservoir Quality distribution** can improve OIIP estimates and guide new development projects
- **Compaction/subsidence** is an important contributor to drive mechanism
- **Gas Injection** can help produce longer and more in Lower Cretaceous reservoirs









Natural and induced fractures

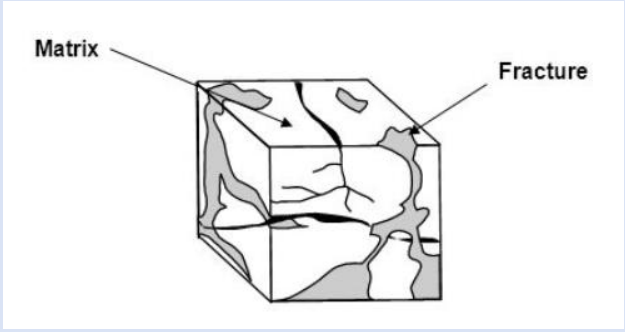
Challenges:

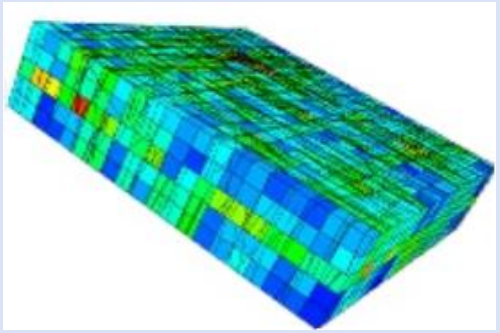
How do we position new wells in optimal ways? How do we develop new areas?

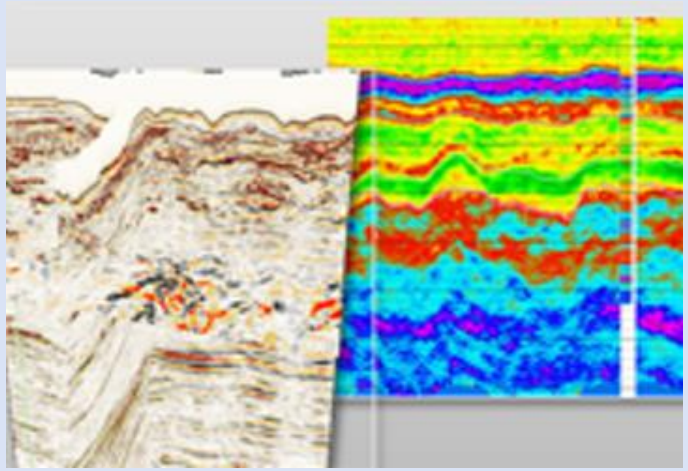
Can we get a better at predicting the permeability multipliers that are needed in our reservoir models to be able to history match?

Ongoing Research:

- Dynamic tectonic evolution of the greater Valdemar area – assessing the stress field and modelling of the deformation intensity > **better fracture models**
- Test the capabilities of a geomechanically driven Discrete Fracture Network (DFN) model
- Tailored processing schemes for optimized imaging based on seismic signals







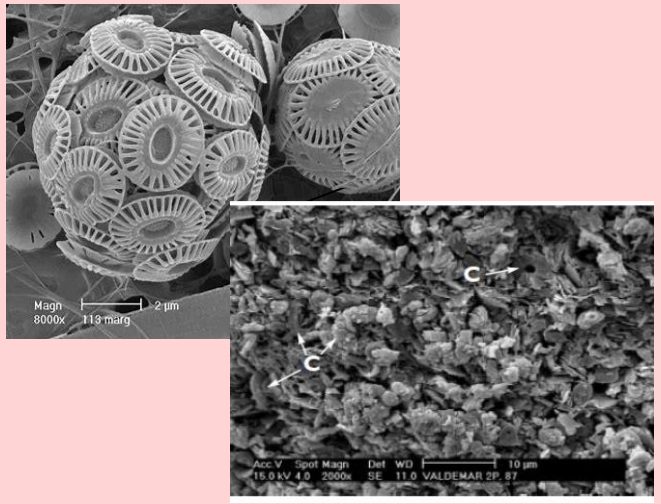
Reservoir Quality distribution

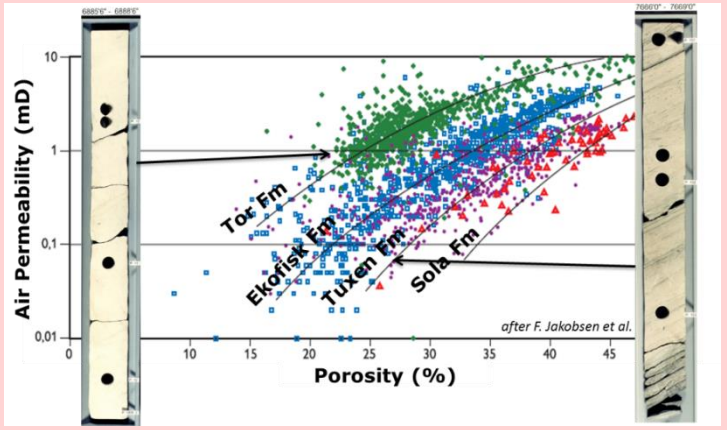
Challenges:

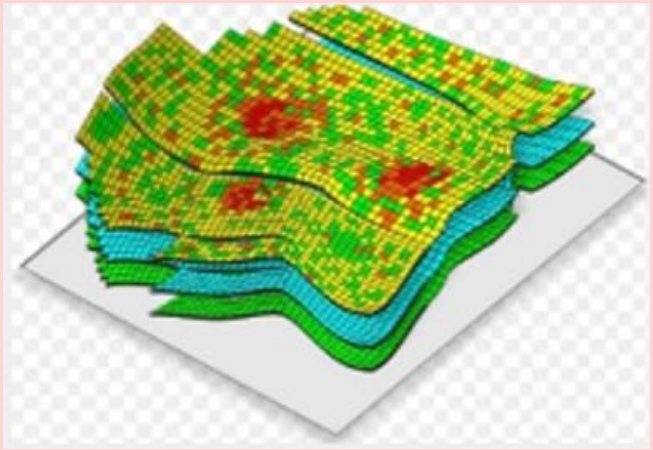
Property modelling is not well aligned with current facies/geological model. Difficult to predict properties away from wells into undeveloped areas. Uncertainties on OOIP.

Ongoing Research:

- A quantified link between depositional processes/environments and reservoir properties
- Understanding the fundamental control on the distribution of clay minerals
- Models to predict reservoir heterogeneity from un-cored sections using cuttings – better database
- Spectral decomposition as a tool to de-risk (reservoir thickness, contacts etc.)







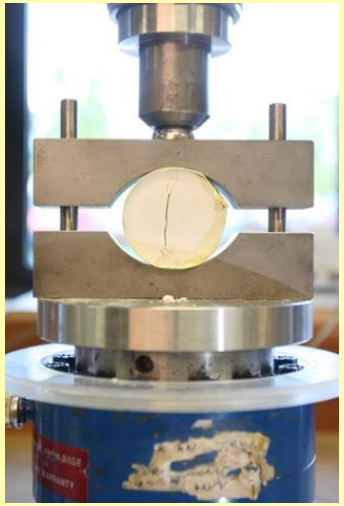
Compaction and subsidence

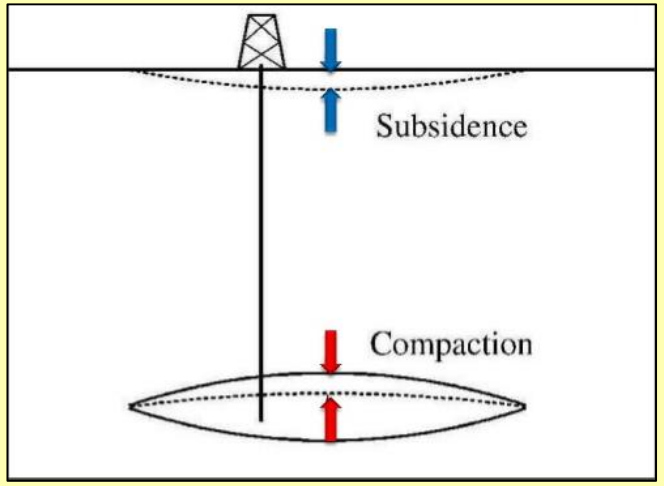
Challenges:

Do our reservoir models predict compaction correctly?

Ongoing Research:

- Updated Lower Cretaceous Rock Mechanical database (new cleaning methods)
- Understanding the effect of depletion with respect to fracturing and pore collapse – QC against 4D
- Effect of mineralogy and degree of cementation on rock mechanics properties
- Effect of water flooding – water weakening





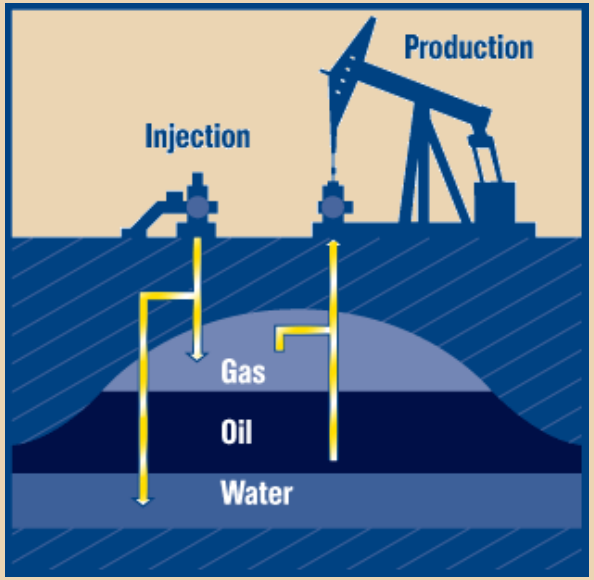
Gas Injection

Challenges:

Uncertainties on relative permeability properties. Uncertainties on the PVT in Valdemar. Uncertainty on recovery gain that can be expected from gas injection.

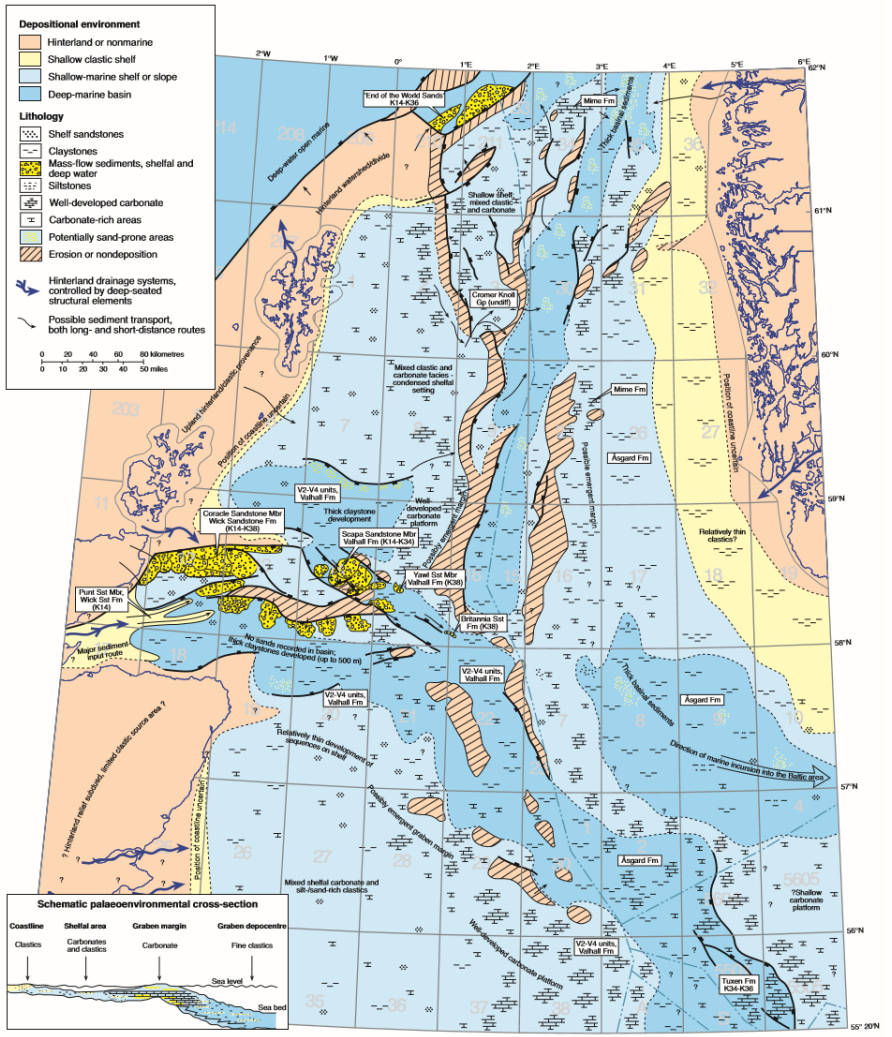
Ongoing Research:

- Estimation of increased recovery with gas injection using different injection gasses
- Improved characterisation of the relative permeability parameters
- Important to understand the drivers for an economic business case



Cretaceous Play - Norway

The Sola and Tuxen Formation is **widely distributed in the Norwegian and Danish sectors**. In the Norwegian sector it is developed in the Central Graben and in parts of the Norwegian-Danish Basin



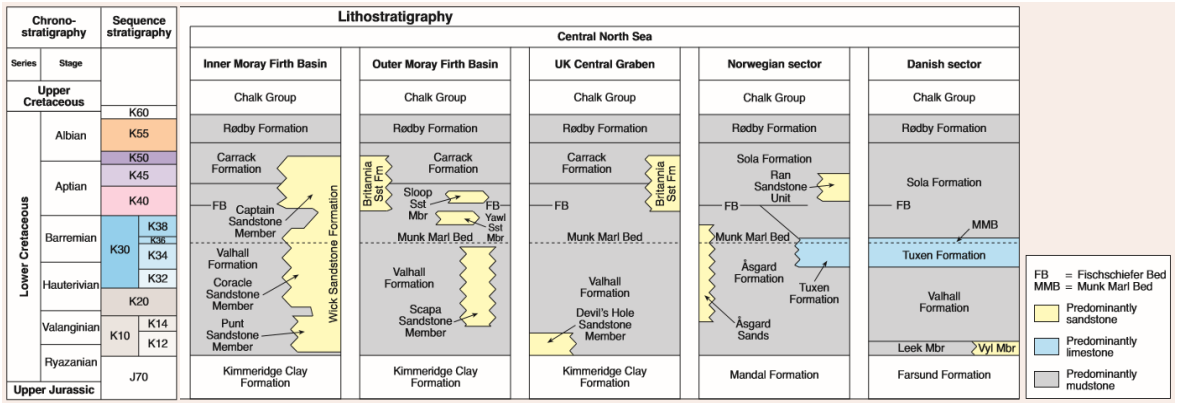
Palaeogeograpic map of the K14-K38 depositional sequence. Millenium Atlas, 2004

Looking at NPD there are 81 wells listed that have penetrated the Tuxen Formation. None of the wells had Tuxen as a target. Even more wells penetrated the Sola Formation.

Thickness varies between 1-100m for the Tuxen Formation and 20-200m for the Sola Formation.

Examples:

- 1/3-8 with shows in Sola Formation
- 2/11-1 reference well for Sola Formation – no shows
- 2/11-7 shows reported from Limestones in Lower Cretaceous
- 2/6-2 reference well for Tuxen Formation – tight water bearing



Millenium Atlas, 2004

Getting the Lower Cretaceous into play

Despite representing a **widespread play**, production from the Lower Cretaceous chalks is currently confined to the Valdemar Field and one single well in the Tyra Field in Denmark.

The Valdemar field has been producing for more than twenty years and yet **significant risk and opportunities remain.**

The Sola and Tuxen Formation is also widely distributed in the Norwegian sector and could be an **opportunity**.

At DHRTC we believe that **Research and Innovation** in close cooperation with the Industry can help identify and qualify innovative ways to enable **increased oil and gas recovery** from the Lower Cretaceous reservoir.

Thank You
For Your Attention