Reservoir Zonation of Lower Cretaceous Deep-water Limestones in the Danish North Sea -- New Insight from Improved Core-to-Log Correlation*

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General Statement

The Lower Cretaceous deep water limestones and marly limestones of the Danish Central Graben form a widespread, but as yet, poorly understood play. Most of the wells penetrating the Lower Cretaceous carbonates have reported shows and the potential volume of oil and gas accumulated in the Lower Cretaceous limestone is significant. At present, production from the Lower Cretaceous reservoirs is limited to the Mærsk Olie and Gas AS operated Valdemar Development, where oil is produced with flow rates of up to 3500 BOPD from long horizontal wells. Additional commercial accumulations occur in the Adda area to the east. In both areas, the reservoir is a thin, usually less than 300 feet (100 m) thick, highly heterogeneous succession of hemipelagic limestone and argillaceous limestone, lithologically comparable to the Austin Chalk.

To improve the understanding of the reservoir unit, large sets of analytical data of porosity, permeability, clay-content and hydrocarbon saturation from cores have been used to quantify core-to-log correlation. Integration of log and core data, constrained by a sequence stratigraphic framework allows the first detailed zonation of the Valdemar Field reservoir into 14 zones.

Sequence Stratigraphy

The sequence stratigraphy of the Lower Cretaceous deep water succession of the Cromer Knoll Group is based on integration of core-based facies descriptions, log stratigraphy and biostratigraphic data. Refinement and modification of the sequence stratigraphy based on detailed palynology and nannofossil work on core data from the North Jens-1 well at the Valdemar Field resulted in the recognition of eight depositional sequences. They have subsequently been traced regionally, and the sequence stratigraphy provides a detailed framework for correlation within which it is possible to evaluate lateral and depth dependent variations in reservoir properties both within the Valdemar area (Figures 1 and 2) and regionally.

The Lower Cretaceous reservoir units are limited to sequences CK 3 B CK 6. The sequences have been subdivided further based on lithological variations, and facies-dependent lateral variations in reservoir properties have been evaluated based on the recognition of sequence boundaries as time-specific surfaces (Figure 3).

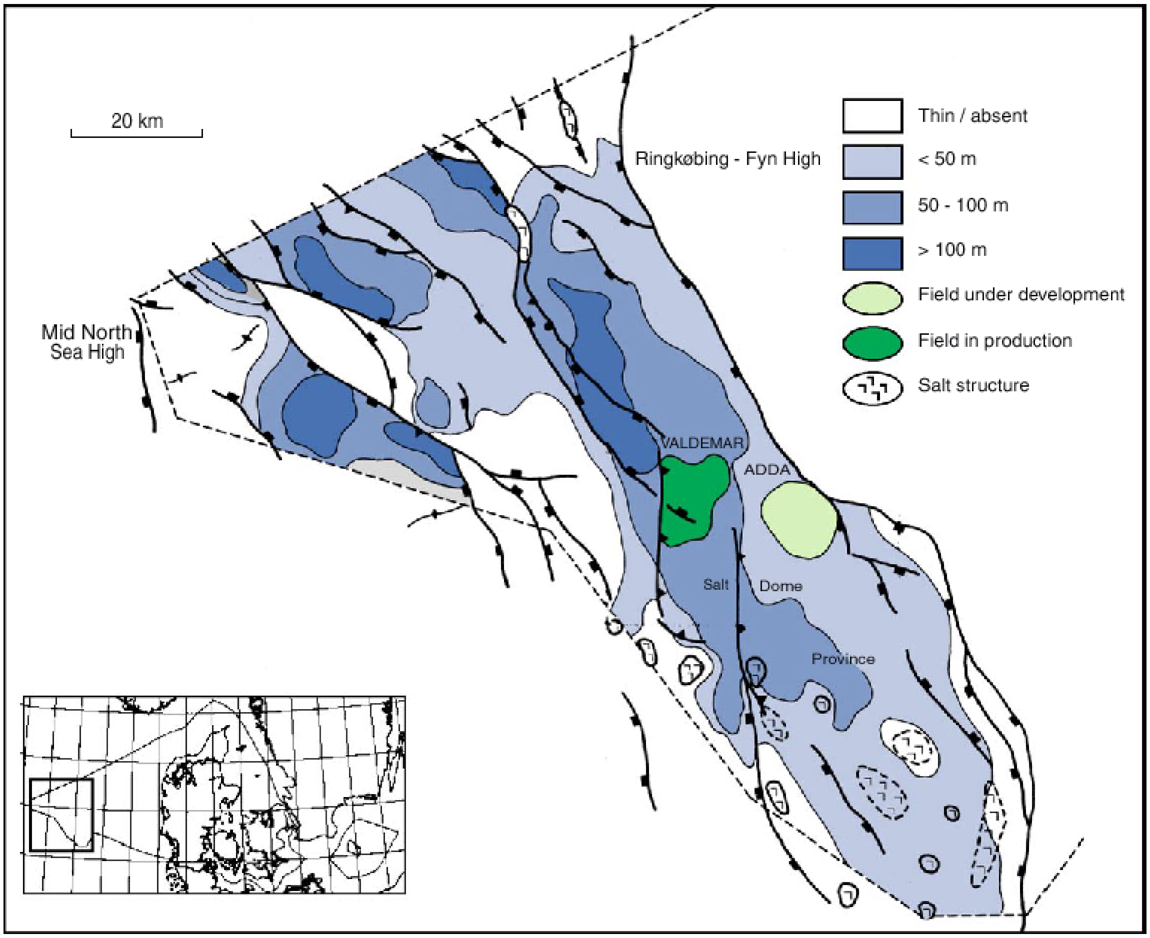

Figure 1. Distribution and thickness of the Lower Cretaceous reservoir succession in the Danish Central Graben. The location of the Valdemar Development and the Adda Field is shown.

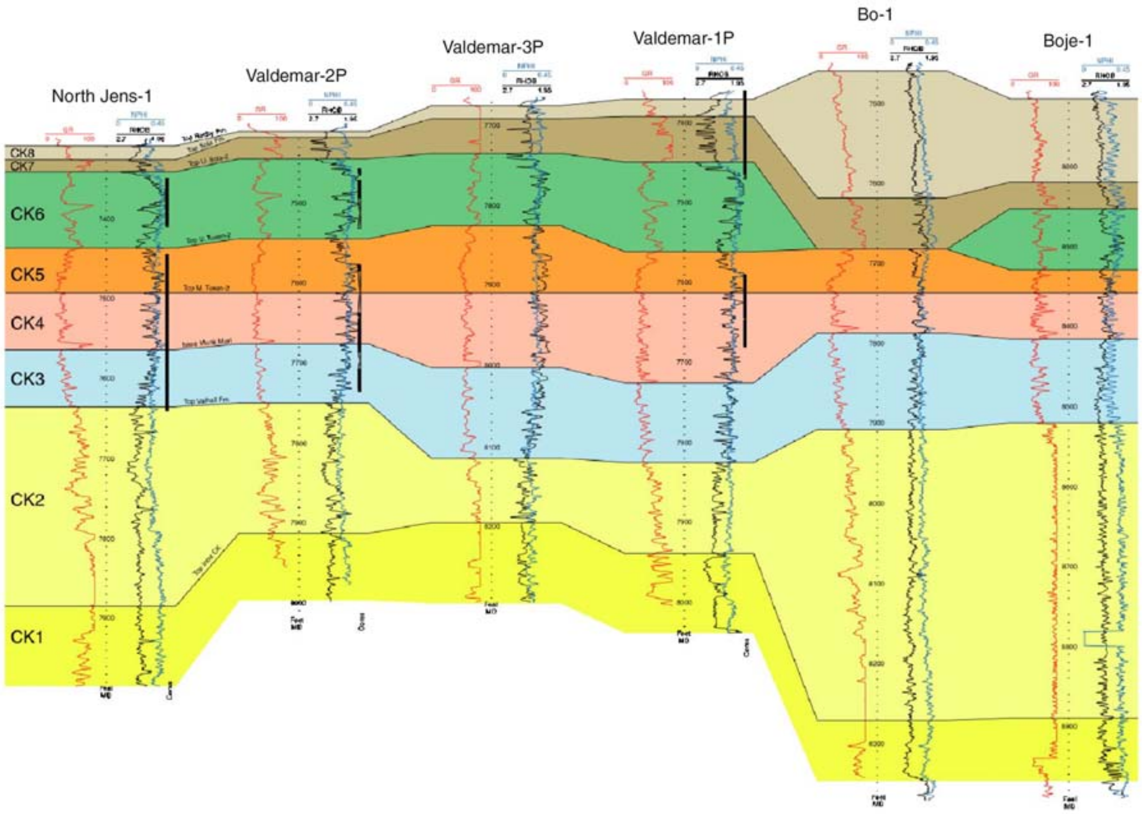

Figure 2. Log panel with wells from the Valdemar area showing the sequence stratigraphic subdivision of the Cromer Knoll Group.

Reservoir Units	Thick-ness ft	Facies	Heterogeneity		Log data				Core data		N/G ratio log/core	Por/IR ratio per 10% IR	Reservoir quality
			Bedding bed/ft	Flaser flaser/ft	Shale vol %	Crestal porosity %	Por/depth ratio p.u./100'	High porosity record.	Porosity vertical wells	Porosity horizontal wells			
Rødby	20 6-158		nd	nd	nd	14 0-23 UB	nd	-	nd	nd	0.0/0.0	-	Poor
Albian Shale	40 15-63		nd	nd	nd	8 0-25 B	nd	-	17 9-23	nd	0.0/0.0	-4	Poor
Upper Sola-2	20 0-29		0,50	0,45	30 10-68	24 0-40 T	2	-	35 8-44	nd	0.6/0.6	-5	Fair
Upper Sola-1	25 0-26		0,19	0,38	20 8-52	40 11-50 B	1	-	42 30-50	nd	0.8/1.0	-5	Good
Fischschiefer	6 0-9			laminated	48 24-68	22 11-38 T	nd	-	32 18-43	nd	0.0/0.0	-3	Poor
Lower Sola-3	10 6-15		0,45	laminated	24 10-40	33 22-43 U/B	2-3	(2H),(4H)	38 31-44	nd	0.8/1.0	-3- -5	Good
Lower Sola-2	15 9-39		0,86	laminated	29 12-51	27 7-42 B/T	2-5	-	30 23-34	nd	0.6/-	-	Fair
Lower Sola-1	20 0-26	No data			35 10-74	21 8-38 B	2-4	-	nd	nd	0.3/0.0	-	Poor
Upper Tuxen-2	25 0-31		0,29	0,19	25 12-48	24 8-33 B	2-3	3H	28 20-36	23 18-32	0.6/0.5	-6	Poor
Upper Tuxen-1	25 13-33		0,12	0,44	11 0-25	35 27-48 U	2-3	(1H), 3H	37 17-45	30 22-36	1.0/1.0	-7	Very good
Middle Tuxen-2	25 16-40		0,28	1,04	16 5-25 (47)	30 14-41 B	2	3H	32 14-45	35 24-48	0.8/0.6	-4	Fair
Middle Tuxen-1	30 24-59		0,35	0,11	15 6-30	33 15-40 U	1-3	3H	36 14-44	37 23-48	0.9/0.9	-7	Good
Munk Marl	6 3-10			laminated	30 9-62	30 27-35 U	1-2	2H, 3H	27 20-42	nd	?	?	Poor
Lower Tuxen-3	30 25-41		0,15	0,11	14 4-27	30 22-40 U	2	2H, 3H	32 15-46	25/31/43 17-47	1.0/0.9	-7	Good
Lower Tuxen-2	35 23-58		0,19	0,38	18 10-33	25 12-33	1-2	(1P), 2H	31 14-45	nd	0.8/0.7	-6	Fair
Lower Tuxen-1	20 1439		0,50	0,17	21 14-34	23 14-27 B/T	1	1P	23 14-36	nd	0.8/0.6	-5	Poor
Valhall													

Chalk
Low argillaceous chalk
High argillaceous chalk
Chalky marlstone
Marlstone
Claystone
Pebbly mudstone

U: Unimodal
B: Bimodal
T: Trimodal

Figure 3. Petrophysical and sedimentological parameters for the Lower Cretaceous reservoir units.

Reservoir Zonation, Facies, and Compartments

The reservoir zonation was initially based on well logs and core data from the vertical North Jens-1 well that allowed 14 reservoir units to be distinguished. The zonation was then extended to include all (11) conventional wells in the Valdemar Field area and subsequently the 34 wells penetrating the Lower Cretaceous succession within the Danish Central Graben. In the Valdemar area, individual units range in thickness from 0B59 feet (0B18 m), with an average from 6B35 feet (2B11 m) and the log-based units are accordingly below seismic resolution.

The reservoir interval consists of deep-water chalk and argillaceous chalk interbedded at a variety of scales with marlstone. Seven depositional facies have been distinguished in the North Jens-1 well using a modified JCR (Joint Chalk Research) classification: 1) Chalk; 2) Marly chalk (a. Low argillaceous chalk; b. High argillaceous chalk); 3) Marlstone (a. Chalky marlstone; b. Marlstone); 4) Claystone; and 5) Pebbly chalk.

The individual reservoir zones are internally heterogeneous, and quantification of average reservoir properties are based on core data. The reservoir units are a composite of two or more of these facies and show variable degrees of heterogeneity in the form of lamination, bedding or flasers (Figure 3). The best reservoir properties are recorded in units dominated by chalk and low argillaceous chalk whereas units dominated of marlstone, high argillaceous chalk and claystone form poor reservoirs and may act as internal barriers.

The reservoir units have been ranked into four categories: poor, fair, good and very good, based on their characteristics combined with estimates of net/gross ratios. Due to the heterogeneity of the reservoir units, the classification is based on average values, with a bias towards data from conventional wells as the horizontal wells do not provide information in the vertical direction.

The reservoir is divided into two stratigraphic compartments separated by a low porosity and clay-rich limestone interval corresponding to the Upper Tuxen-2 and Lower Sola-1 units. The lower compartment is internally heterogeneous and consists of two zones (the Lower Tuxen-1, -2 and -3 units and the Middle Tuxen-1, -2 and Upper Tuxen-1 units), separated by the Munk Marl unit. The upper compartment is also internally heterogeneous, the Lower Sola-2 and -3 reservoir zone is separated from the Upper Sola-1 and -2 reservoir zone by the Fischschiefer unit.

Porosity Relationships

Porosity was found to have a direct relationship to clay content, and the porosity/clay relationship has been estimated for each reservoir unit by plotting core porosity versus insoluble residue (IR)(Figure 4). The data plot on two parallel trend lines with an offset of approximately 10 p.u. indicating different relationships between the absolute values for IR (clay content) and porosity in the two stratigraphic compartments, but a similar reduction of porosity of 5-7 p.u. per 10 % increase in IR (clay).

The difference in clay/porosity relationship between the two stratigraphic compartments is possibly facies controlled; the lower compartment is more intensely bioturbated and there is therefore a higher risk of destruction of coccosphere plates into single crystals and higher degree of clay-chalk mixing than in the upper compartment.

Plots of porosity versus permeability for Maastrichtian, Danian and Lower Cretaceous samples show a distribution of data following 3 different trend lines (Figure 5). The trends are related to different matrix textures which again are controlled by the composition and pore-geometry of the rocks. The size of the pore throats in the Lower Cretaceous is approximately 1/3 of what is found in the Upper Cretaceous Chalk so the capillary entry pressure and irreducible water saturation are considerably higher in the Lower Cretaceous than in the Upper Cretaceous.

The analytical data indicate a linear relationship between porosity and clay content along with an exponential relationship between porosity and permeability. The porosity was found to be dependent on pressure as well, and the carbonates in the Valdemar Field are undercompacted due to high pore pressure. Based on corrected log data, it is evident that porosity also is depth-dependent (Figure 6) and that reservoir quality limestones (porosity > 20%) are restricted to depths less than 9000 feet (3 km).

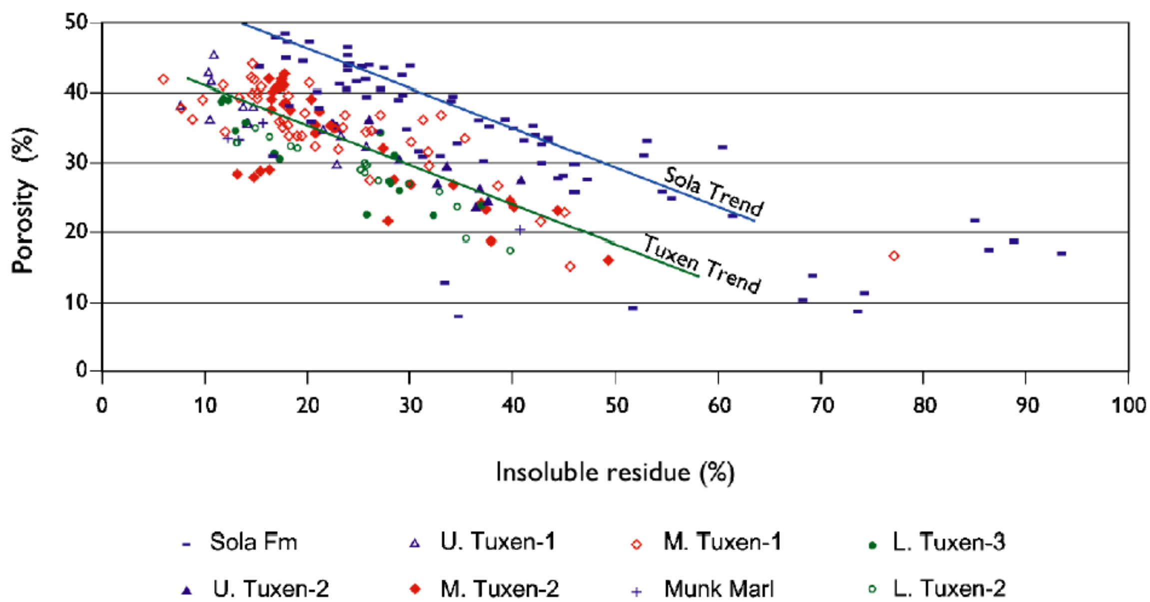

Figure 4. Porosity versus insoluble residue relationship for the various reservoir units. Different trend lines for the Sola and Tuxen Formations display the variation between the two stratigraphic formations.

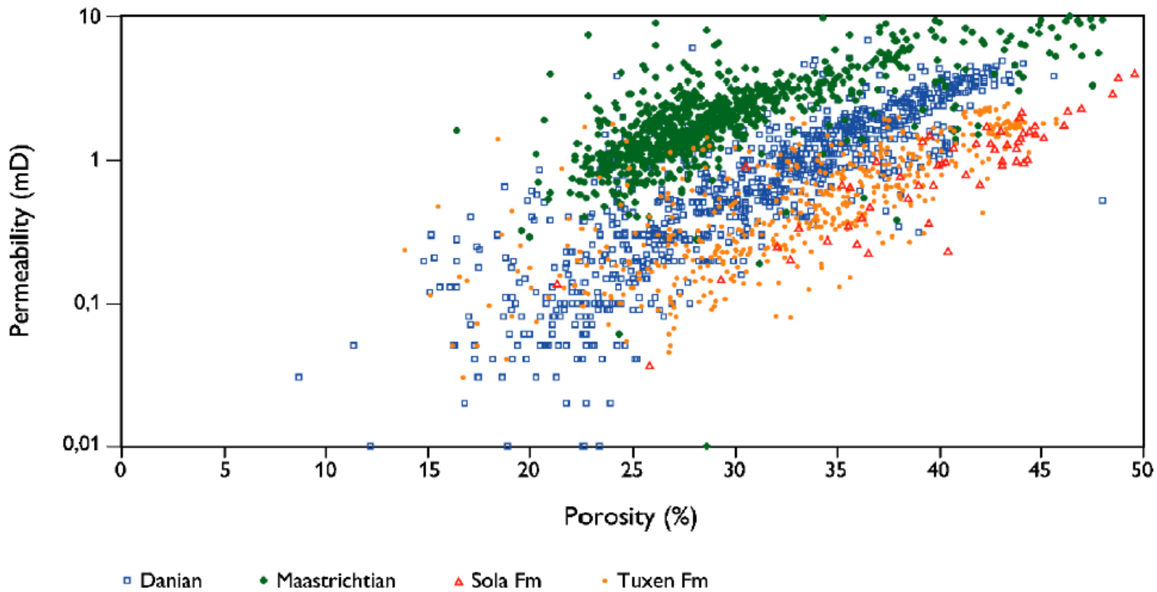

Figure 5. Comparison of Upper and Lower Cretaceous porosity-permeability data.

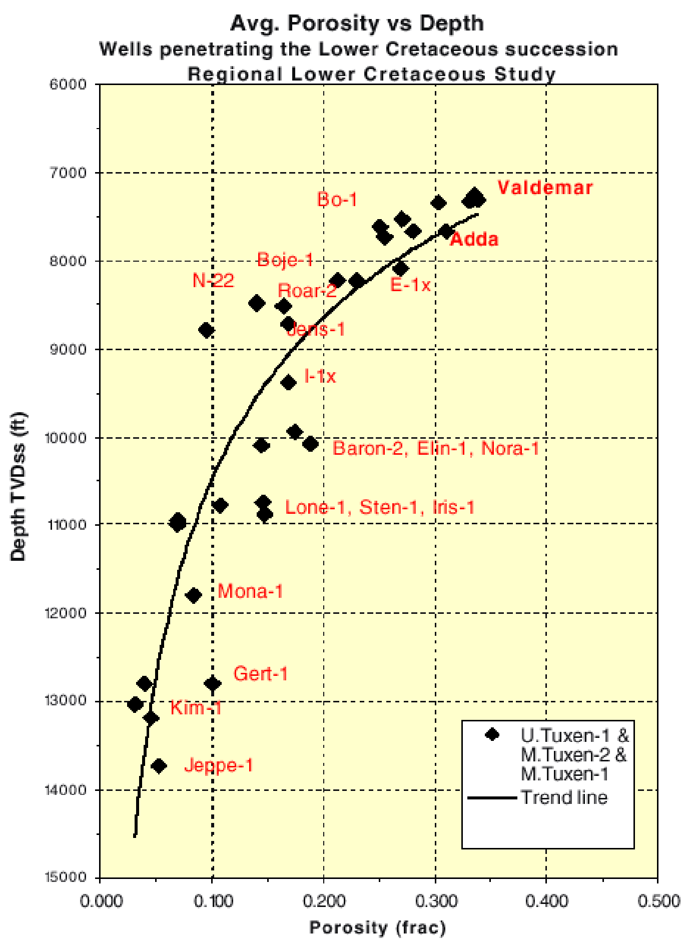

Figure 6. Porosity/depth trend for the upper part of the Tuxen Formation. Based on well data and interpretation of wireline log data.