DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2012/23

Source Rock Development in an Evolving Half Graben: Upper Jurassic–Lower Cretaceous of Wollaston Forland, Northeast Greenland

Report Supplement to Rødryggen-1 and Brorson Halvø-1 Data Packages

Jussi Hovikoski, Morten Bjerager, Jørgen Bojesen-Koefoed & Stefan Piasecki

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

GEUS

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2012/23

Source Rock Development in an Evolving Half Graben: Upper Jurassic–Lower Cretaceous of Wollaston Forland, Northeast Greenland

Report Supplement to Rødryggen-1 and Brorson Halvø-1 Data Packages

Jussi Hovikoski, Morten Bjerager,
Jørgen Bojesen-Koefoed
& Stefan Piasecki

Confidential report

Copy No.

Released 01-07-2025

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND BUILDING

G E U S

1. Introduction

This report supplement presents integration of selected data sets of the Rødryggen-1 and Brorson Halvø-1 core data packages. The report is delivered to the participating sponsoring companies of the specific analytical programs of the above mentioned cores as described in Appendixes B2 and B3 in the collaboration agreement between GEUS and sponsoring oil companies regarding petroleum geological studies, services and data in East and Northeast Greenland.

The Rødryggen-1 and Brorson Halvø-1 cores were drilled in northern Wollaston Forland, NE Greenland, in 2009 and 2010, respectively. The Brorson Halvø-1 drill site is situated approximately 10 km to the NE from the Rødryggen-1 drill site, being located near the elevated hanging wall crest of the Permpas/Hühnerbjerg fault block (Fig. 1; Surlyk, 1978), whereas the Rødryggen-1 is located near the basin centre of the same block. The main target of the drilling in both cores was the same Kimmeridgian–Ryazanian black mudstone succession with the primary objective being to delineate the quality and lateral development of the Upper Jurassic – Lower Cretaceous source rock in an evolving half-graben system in the Wollaston Forland area.

In this report supplement, the source rock data and basin development are summarized chronostratigraphically. In addition, estimated relative sea level trend and three palaeogeographical models are presented, which represent the Kimmeridgian, the Early Volgian and the Middle Volgian–Ryazanian tectonic and palaeoenvironmental development in the Wollaston Forland area. The data are supplemented by unpublished (Appendix 6.3) and published field data.

1.1 Correlation of the cores

The correlation of the cores was primarily based on dinoflagellate stratigraphy (Appendix 6.1). Secondarily, sedimentary facies successions and GR-log signature were used within the biostratigraphic framework. The selected datum for the correlation is the contact between the Lindemans Bugt Fm and the Albrechts Bugt Member of the Palnatokes Bjerg Fm, which is visible in all of these data sets in both cores.

The correlation of the cores was not straightforward. The challenges included: 1) Biostratigraphic uncertainties implemented by sample spacing in the Lower Volgian and the kerogene rich samples, which required rough preparation; 2) the deposits of the Bernbjerg Fm. are predominantly aggradational without clear depositional trends; 3) Faulting is common particularly in the lower part of the Bernbjerg Fm, which may lead to missing sequences. Although no missing sequences were identified, faulting may have affected sequence thicknesses; 4) Nearly all key stratigraphic "surfaces" are diffuse zones; and 5) especially from the Lower Volgian upwards, the cores show contrasting depositional development, which hampers sedimentary facies-based correlations. Furthermore, simultaneously, the "cycles" become increasingly random reflecting dominance of tectonic control in their formation.

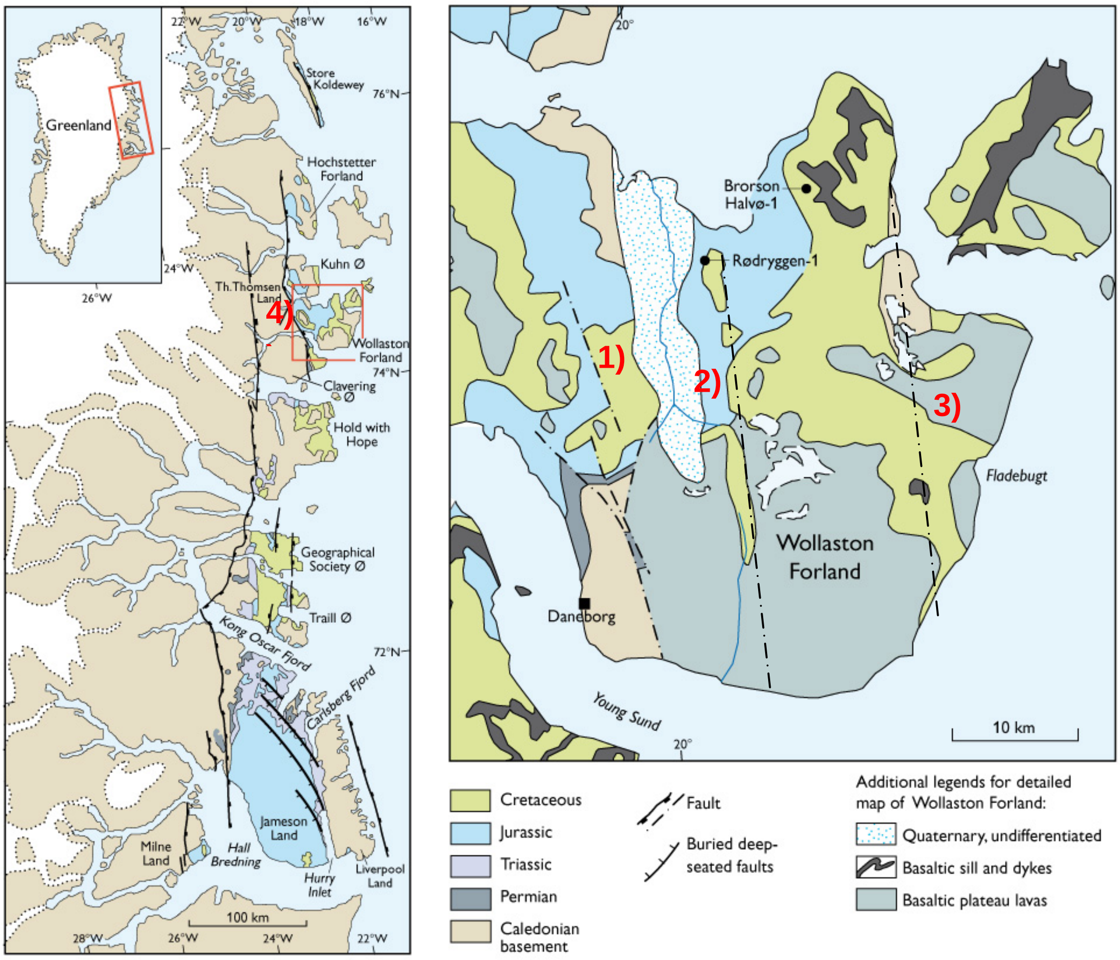
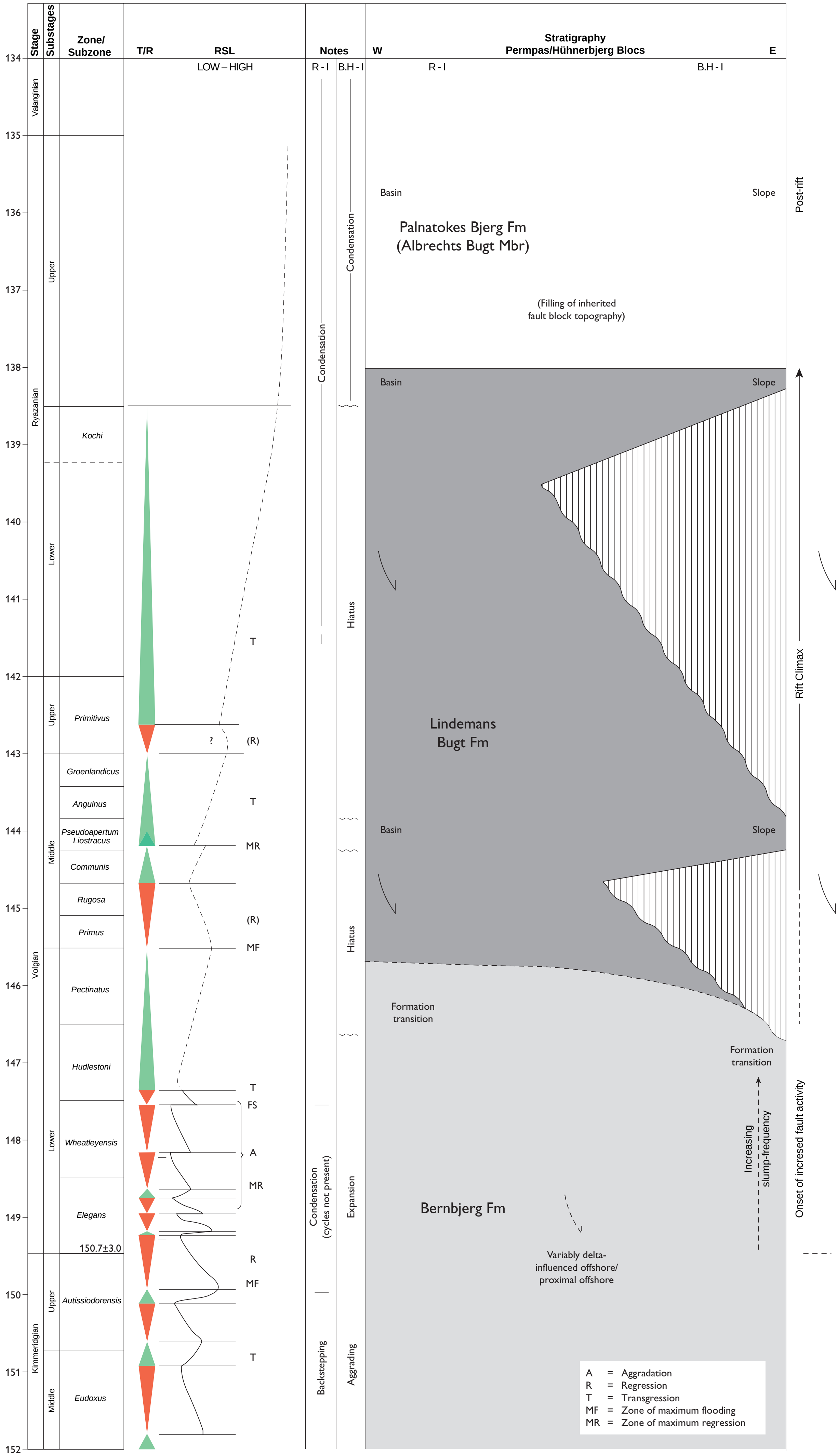


Figure 1. Study area showing the studied cores and main faults: 1) Kuppel fault; 2) Permpas Fault; and 3) Hühnerbjerg Fault. The Dombjerg Fault (4), which was the main coastline position controlling fault during the Late Jurassic is situated near the left margin of the inset figure and is marked on the regional map. The Permpas-Hühnerbjerg block(s) was bounded by the Kuppel and Hühnerbjerg Faults, which probably represented the main controlling faults in the studied block during the Late Jurassic. Modified after Surlyk (1978; 2003)



GØ02_02_142_JHOV.eps

Figure 2 (previous page). Stratigraphic chart of the Permpas-Hühnerbjerg block(s) showing inferred T/R cycles and RSL trend. See Appendix 6.1 for the correlation and GR-signatures.

The interpreted facies successions are illustrated as T/R (transgressive/regressive) cycles in Figure 2. Considering the challenges mentioned above, these cycles should be considered only as rough estimations of the main depositional and relative sea level trends. The data behind depositional interpretations are presented in the core reports, and are not repeated here.

2. Basin Development

2.1 Kimmeridgian

The Kimmeridgian palaeoenvironmental development is similar in both cores, suggesting possibly an eustatic control and more or less a single basin. The interval shows the strongest deltaic-influence in the studied cores and contains abundant coal fragments and plant debris. The biomarker analysis shows an elevated content of retene (marker for gymnosperms) in the Rødryggen-1 core in this interval. The Kimmeridgian is interpreted to represent transgressive systems tract (see below).

The deposits comprise 2–3 T/R cycles ~15–~25 m-thick, which are best developed in the Brorson Halvø-1 core (Fig. 2). The cycles are backstepping in the Rødryggen-1, whereas in the Brorson Halvø-1 they show a more aggradational pattern until the Late Kimmeridgian. Depositional environments ranged mainly from delta-influenced proximal offshore (Rødryggen-1) to offshore (Brorson Halvø-1) settings during the Eudoxus Zone. Minor flooding at the top of Eudoxus Zone led to facies change to bioclasts-rich offshore sedimentation in both cores.

During the Autissiodorensis Zone, the depositional system reached storm wave base at least during late progradational phases. From this time onwards, the Brorson Halvø-1 records somewhat shallower environments than the contemporary intervals in Rødryggen-1 despite of its location further offshore from the main coastline. This is interpreted to reflect minor uplift along the Hühnerbjerg fault crest (Figs. 1 and 3). The interpretation is supported by locally occurring minor slump intervals and field data from the Brorson Halvø area, which show occasional presence of gravity-flow sandstones that occur in laterally limited finger-like channels (Appendix 6.3) being in line with localized fault-generated relief.

The upper part of the Kimmeridgian recorded a prominent eustatic transgression and a zone of Maximum Flooding (Fig. 2). The depositional environment graded into dysoxic-anoxic offshore setting in the both cores. This change is particularly well reflected in the character of the Rødryggen-1 core source rock (interval around 190 m).

A generalized palaeogeographic/depositional model for the Kimmeridgian of the Wollaston Forland is presented in Figure 3. The model assumes that the depositional system showed some similarities with modern mud-dominated coastal sedimentary systems coupled with more specific features of the Late Jurassic seaway of E-NE Greenland. Requirements for the formation of mud-dominated coastlines today are the presence of a fine-grained riverine source(s) and along-coast dispersal of sediments. Suitable river systems include complexes of minor rivers and/or large, suspension-load-dominated rivers that are associated with wide, low-gradient alluvial plains (e.g., Amazon, Mississippi–Atchafalaya, Yangtze, Ganges, and Po rivers). Potentially, wide low-gradient coastal plains were formed in the NE Greenland margin during the Late Oxfordian – Kimmeridgian transgression (Surlyk, 1993; this study), which onlapped the peneplained Middle Jurassic deposits. The coastline was likely heterolithic or muddy, and influenced by wave dissipation caused by mud-plumes and low depositional gradient (e.g., coast of Louisiana).

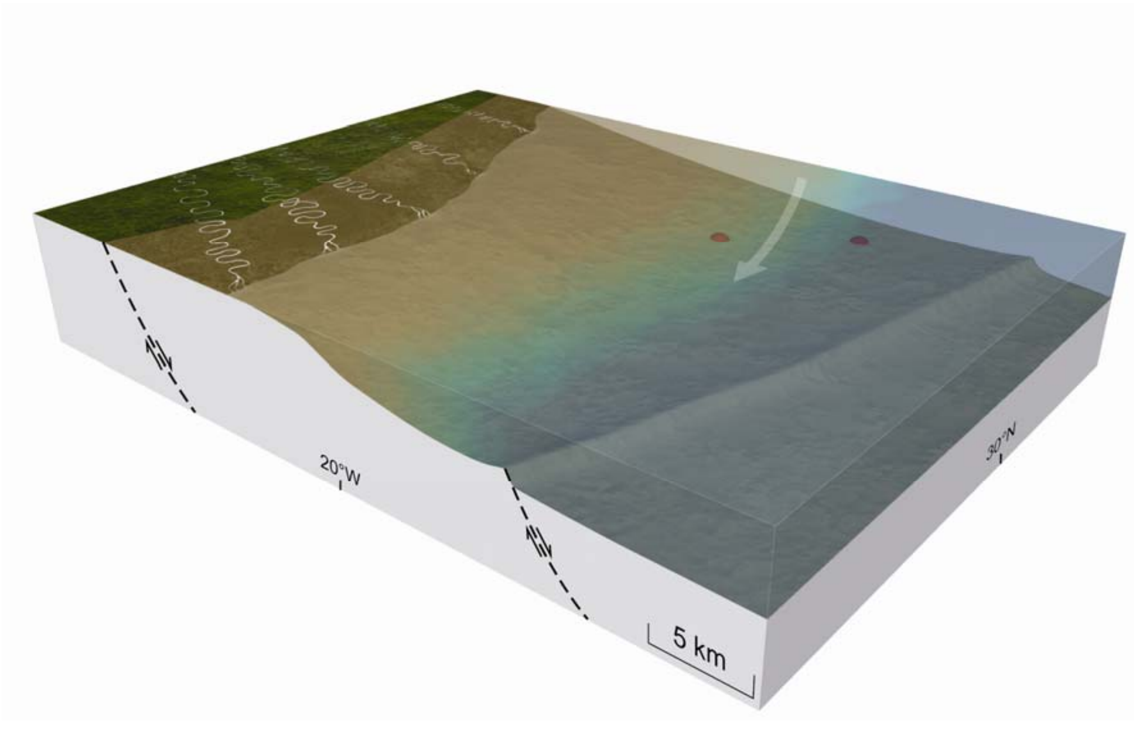


Figure 3. A simplified palaeogeographic/depositional model illustrating the Kimmeridgian depositional setting in Wollaston Forland. The arrow indicates the main sediment transport direction, red dots indicate borehole positions. The faults shown from left to right are the Dombjerg and Hühnerbjerg faults. See text for further explanation.

A requirement for long-distance alongshore sediment dispersal is turbid coastal waters that keep mud in a resuspended state, and prevent sea-bed consolidation (see Aplin and Macquaker, 2011 for a synthesis of mud-accumulation). The mud plumes are commonly forced to move alongshore by coastal winds and Coreolis forces during the fair-weather conditions whereas during storms, obliquely offshore-directed sediment transport by the means of wave-enhanced gravity flows (Macquaker et al., 2010) may prevail. The mud accumulation is commonly concentrated on the mid-shelf, where a coast-parallel mud-belt may develop (e.g., Po-River Coast, Adriatic Sea; Aplin and MacQuaker, 2011 and references therein).

Palaeocurrent measurements from ripple foresets and sole marks from the Kimmeridgian interval suggest S-SE-directed flow (Surlyk and Clemmensen, 1983; Appendix 6.3) pointing to general alongshore oriented sediment transport also in the Bernbjerg Fm. In addition to the above mentioned controls, this pattern was also influenced by larger scale palaeo-oceanographic circulation and possibly by the incipient relay ramp related topography in the Late Jurassic of the NE Greenland. The wave-influenced gravity flow deposits documented from modern muddy shelfs are well developed in the Kimmeridgian interval in the Rødryggen-1 core. Overall, distribution of mud may have been similar to the modern mid-shelf mud-belts.

It is believed that above mentioned features coupled with enhanced primary productivity induced by high nutrient content were the main controls shaping the Kimmeridgian source rock development. The high marine and terrestrial organic matter content, shallow wave-base, as well as sea bottom irregularities caused by the early rifting bolstered sea-bottom dysoxia, which together with moderate depositional rates (stacked thin event laminae) led to preservation of high TOC, which is typical for the Kimmeridgian interval (Section 3).

2.2 Lower Volgian

The Lower Volgian interval records the onset of increasing fault activity and basin segmentation in the studied cores. Facies successions in the two cores can no longer be correlated, and depositional rates show marked lateral variability (condensation vs. stratigraphic expansion). A zone of maximum regression took place during this interval (Fig. 2).

The Elegans-Wheatlyensis zones represent a progradational to aggradational phase, which leads to decreasing source quality especially in the Rødryggen-1 core. The interval is characterized by increasing silt-content, which may partly reflect changes in the source areas (uplifting block-shoulders). This change in depositional conditions may explain the marked change in diasteranes/(steranes+diasteranes) ratio in the both cores within this interval. Even though the water depth remained relatively shallow until the Wheatlyensis Zone (above storm wave base during late progradational phases), the source rock quality starts to improve already around 100 m (Elegans Zone) in the Brorson Halvø-1 core (Section 3). This is interpreted to reflect intensified uplift along the Hühnerbjerg fault and partial change in source area to east (see below).

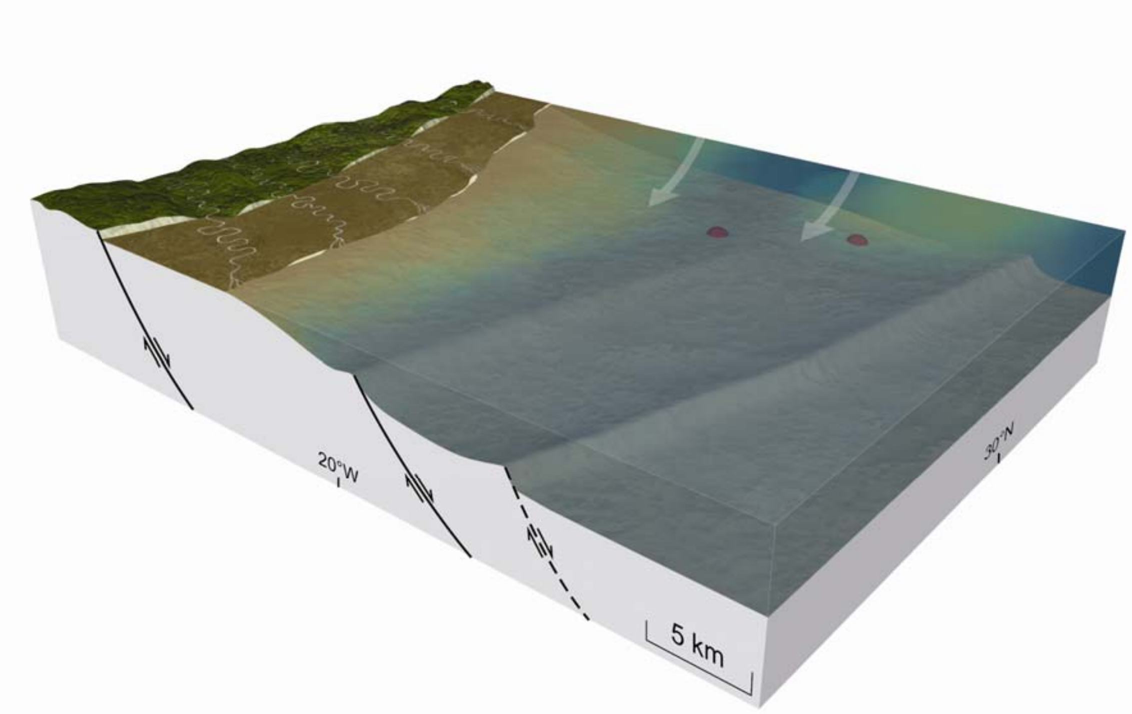


Figure 4. A simplified palaeogeographical/depositional model illustrating the Early Volgian depositional setting in Wollaston Forland. The arrows indicate main palaeoflow orientation, red dots indicate borehole positions. The faults shown from left to right are the Dombjerg, Permpas and Hühnerbjerg faults. See text for further explanation.

The sediment successions show marked differences in thickness. The Elegans Zone presents an expanded stratigraphy in the Brorson Halvø-1 in comparison to the Rødryggen-1. Rødryggen-1 contains a ~2 m-thick ankerite- and dolomite-cemented interval, which may point to prolonged condensation and sediment starvation. The corresponding interval in Brorson Halvø-1 includes common small-scale slumps (folded bedding) and normally graded beds interpreted as mud turbidites. A slump fold axis measurement from a probable Lower Volgian interval (Appendix 6.3) near the Brorson Halvø drill site suggests an E-NE dipping slope.

A possible palaeogeographic/depositional scenario that would explain the data is illustrated in Figure 4. This involves fault activity along the Permpas fault, which turns into a flexure towards the north coast of Wollaston Forland (Surlyk, 1978), potentially generating a relay ramp system. Minor uplift in the Rødryggen-1 area would have led to sediment starvation, concentration of microfossils and stratigraphic condensation. The Brorson Halvø-1 is situated on the down-thrown side of the fault and received sediments as slumps and mud-turbidites from the west, northwest and possibly east.

An alternative explanation could be that the condensed section in the Rødryggen-1 core contains an erosional unconformity, which is not sedimentologically visible and below the resolution of the dinoflagellate stratigraphy (intra Elegans Zone). This is considered unlikely since the differential development in two cores begins already below the condensed section.

During the late Early Volgian (latest Wheatlyensis–Pectinatus zones) transgression occurred and/or wave-base was lowered due to gradational change in basin morphology towards N-S oriented fjord-like basins. The cores record a gradation into fossiliferous, oxygen restricted basinal (Rødryggen-1) and slope (Brorson Halvø-1) environments, representing a transitional phase into the Lindemans Bugt Formation. In both cores, the source rock becomes markedly more marine in this interval (e.g., TS, HI, C_{30}-steranes). The formation gradation is somewhat diachronous, starting earlier in the East, which is again interpreted to reflect the initial uplift along the Hühnerbjerg fault crest and redeposition of marine mudstones. The top most part of the Lower Volgian is missing from the Brorson Halvø-1 core due to the late Early Volgian – Middle Volgian intensified uplift of that fault crest.

2.3 Middle Volgian – Ryazanian

The data from the drill cores support the general tectonic scheme of Surlyk (1978), which suggested that the Middle Volgian–Ryazanian interval represented the rift climax phase in the Wollaston Forland area. The data point to the development of westward tilted fault block geometry, and detachment of the Permpas/Hühnerbjerg block(s) from the main coastline. Most of this interval is missing from Brorson Halvø-1, which is most likely due to the core's location near the rising block crest. Overall, the Middle Volgian – Ryazanian interval is characterized by a reduction in depositional rates (Ryazanian) and decreasing terrestrial input into the block. The fjord-like basin morphology may have favoured development of dysoxia-anoxia. No clear depositional cycles are recognized, and the interval reflects a generally deepening trend.

The early Middle Volgian (Primus–Communis Zones) is only present in the Rødryggen-1 core. The Primus Zone contains a condensed interval with high phosphate content (at 90 m), indicating an episode of sediment starvation. This is followed by a progradational phase, which is reflected by increasing silt and terrestrial organic matter content. The regression probably lasted until the Communis Zone, which was followed by an aggradational phase. An eustatic transgression and tectonic quiescence may have occurred during the Pseudoapertum-Liostracus Zones since the truncated, uplifted block crest in the Brorson Halvø-1 was covered with slope mudstones and the deposits reverted to fossiliferous basinal mudstones in the Rødryggen-1 core. The deepening trend went on until the late Middle Volgian in the Rødryggen-1 core, whereas a new major hiatus started at the Brorson Halvø-1 location.

Figure 5. A simplified palaeogeographical/depositional model illustrating the Middle Volgian – Ryazanian interval, red dots indicate borehole positions. The faults shown from left to right are the Dombjerg, Kuppel, Permpas and Hühnerbjerg faults. See text for explanation.

A simplified palaeogeographic/depositional model is presented in Figure 5. The model shows major uplift along the Dombjerg fault and the development of the coarse-grained fan deltas of the Rigi Member (Lindemans Bugt Fm) to the east of the fault (Surlyk, 1978; 2003). The fan delta related gravity flows did not reach the studied core locations, suggesting that they were blocked by the uplifted Kuppel fault crest, which defined the western margin of the Permpas/Hünerbjerg block(s). This interpretation is also supported by decreasing depositional rates, deepening, and decreasing terrestrial matter input in the preserved intervals in both cores. Probable source areas were the uplifted block crests of the Kuppel and Hühnerbjerg faults that were probably the main basin development controlling faults at that time.

In summary, the main controls shaping the Middle Volgian–Ryazanian source rock development are considered to have been the above mentioned basin segmentation, decreasing sediment input and shift in source areas, deepening, as well as dysoxia/anoxia-prone fjord-like geometry.

3. Petroleum Source Potential

3.1 Introduction

As mentioned in the foregoing, the Kimmeridgian–Ryazanian succession penetrated by the Rødryggen-1 core is complete in the sense that no hiati have been detected despite dense biostratigraphic sampling. In lithostratigraphic terms, this means that complete representations of the Lindemans Bugt Formation and the upper portion of the Bernbjerg Formation are present. Conversely, in the Brorson Halvø-1 core, prominent hiati have been detected. The upper portion of the Lower Volgian and the lower portion of the Middle Volgian successions are missing. In addition, the upper part of the Middle Volgian is missing along with the entire Lower Volgian and Lower Ryazanian successions. Thus the Lindemans Bugt Formation is severely truncated, leaving only a central part that corresponds to a less prolific part of the succession found in the Rødryggen-1 core, and the drilled part of the Bernbjerg Formation is also incomplete. This is important when attempting to compare the petroleum potential of the two successions and in the following, comparison will be based on age-equivalent portions of the two coreholes unless explicitly stated otherwise.

3.2 Present-day petroleum source potential

Geochemical logs, with correlative units indicated, showing TOC, S2 and Hydrogen Index for the two cores are shown in Figures 6–8. A close scrutiny of the data reveals that several log-motifs can be recognized in both datasets. Larger scale trends are particularly clear in the 10-sample moving average of Hydrogen Index data shown in Figure 9.

The Kimmeridgian succession in both cores is characterized by high levels of TOC, decreasing upwards, and moderate petroleum generation capacity (S2), corresponding to a gas- and oil-prone kerogen type intermediate between ideal types II and III. By comparison, the overlying Lower Volgian succession in both cores shows a continued decrease in TOC upwards through the lower part followed by stabilization of TOC, but unchanged or just slightly lower generation capacity (S2), leading to higher average Hydrogen Index, corresponding to a slightly more oil-prone kerogen type containing higher proportions of marine organic matter. The Middle Volgian is very similar to the Early Volgian. These variations have also been documented by petrographic, stable Carbon isotopic and biomarker data; see Hovikoski et al. (2010 and 2011) for details.

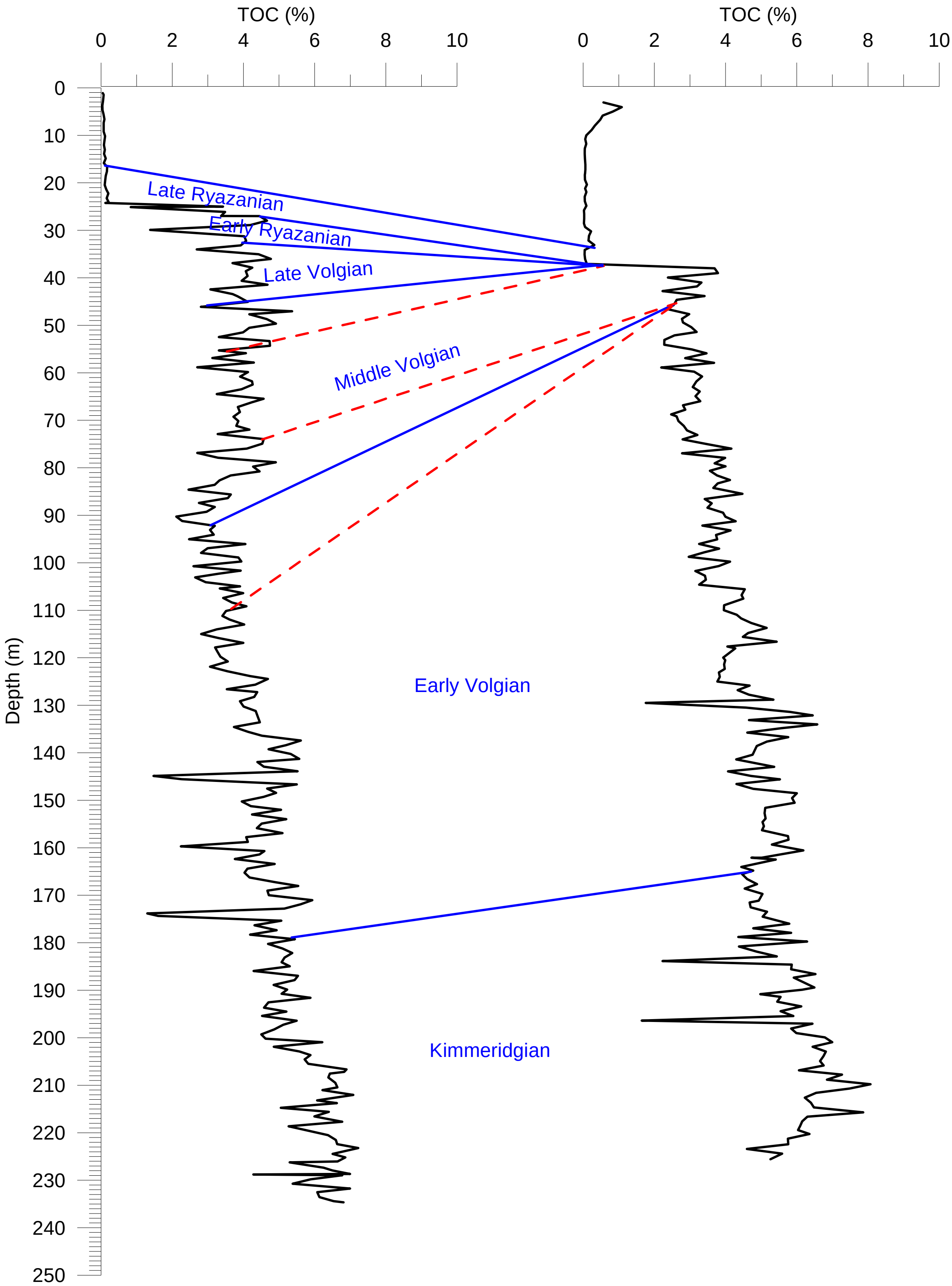


Figure 6. Total Organic Carbon (TOC) versus depth for the Rødryggen-1 (left) and Brorson Halvø-1 (right) coreholes.

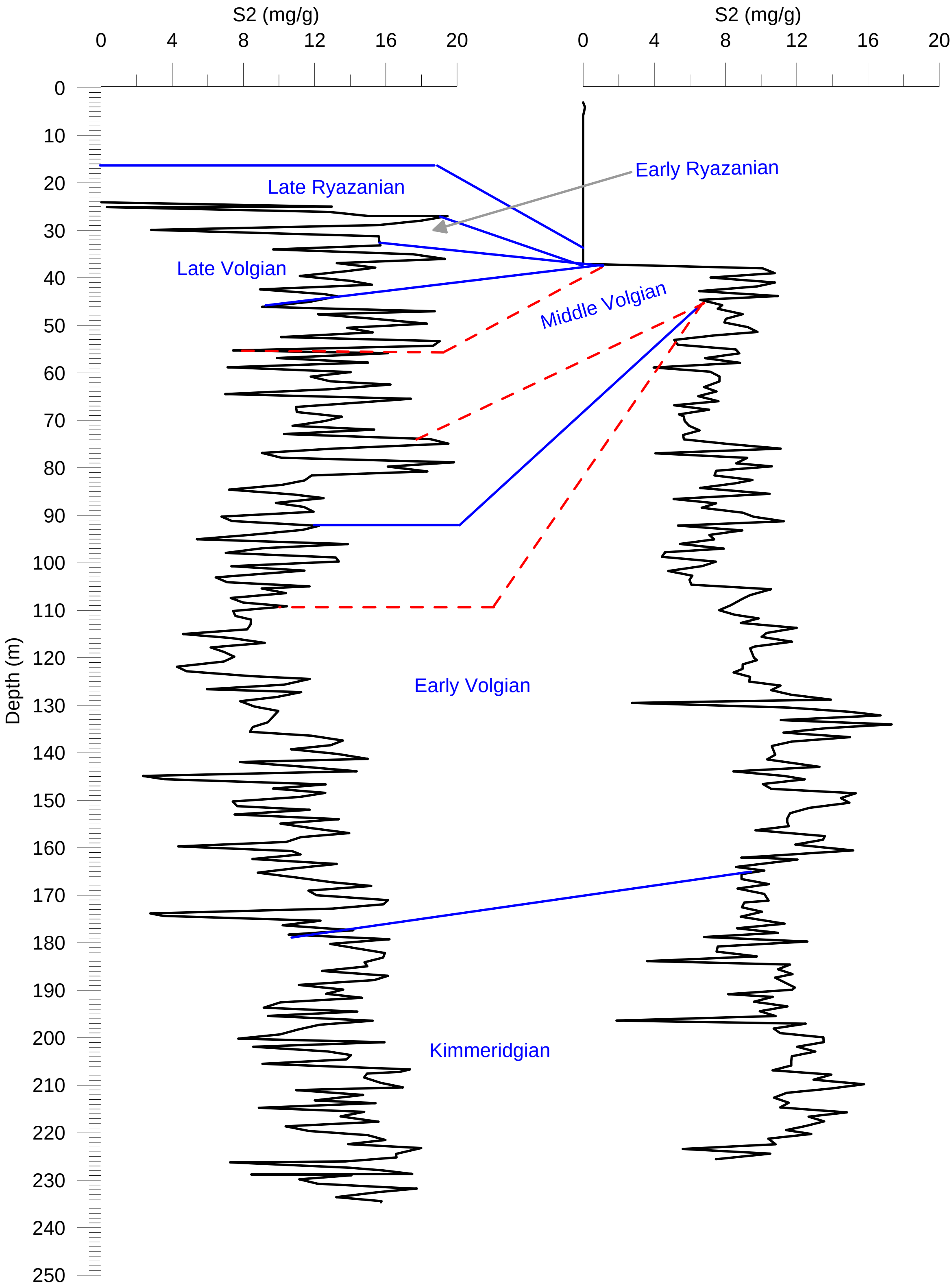


Figure 7. Petroleum potential (S2) versus depth for the Rødryggen-1 (left) and Brorson-1 Halvø (right) coreholes.

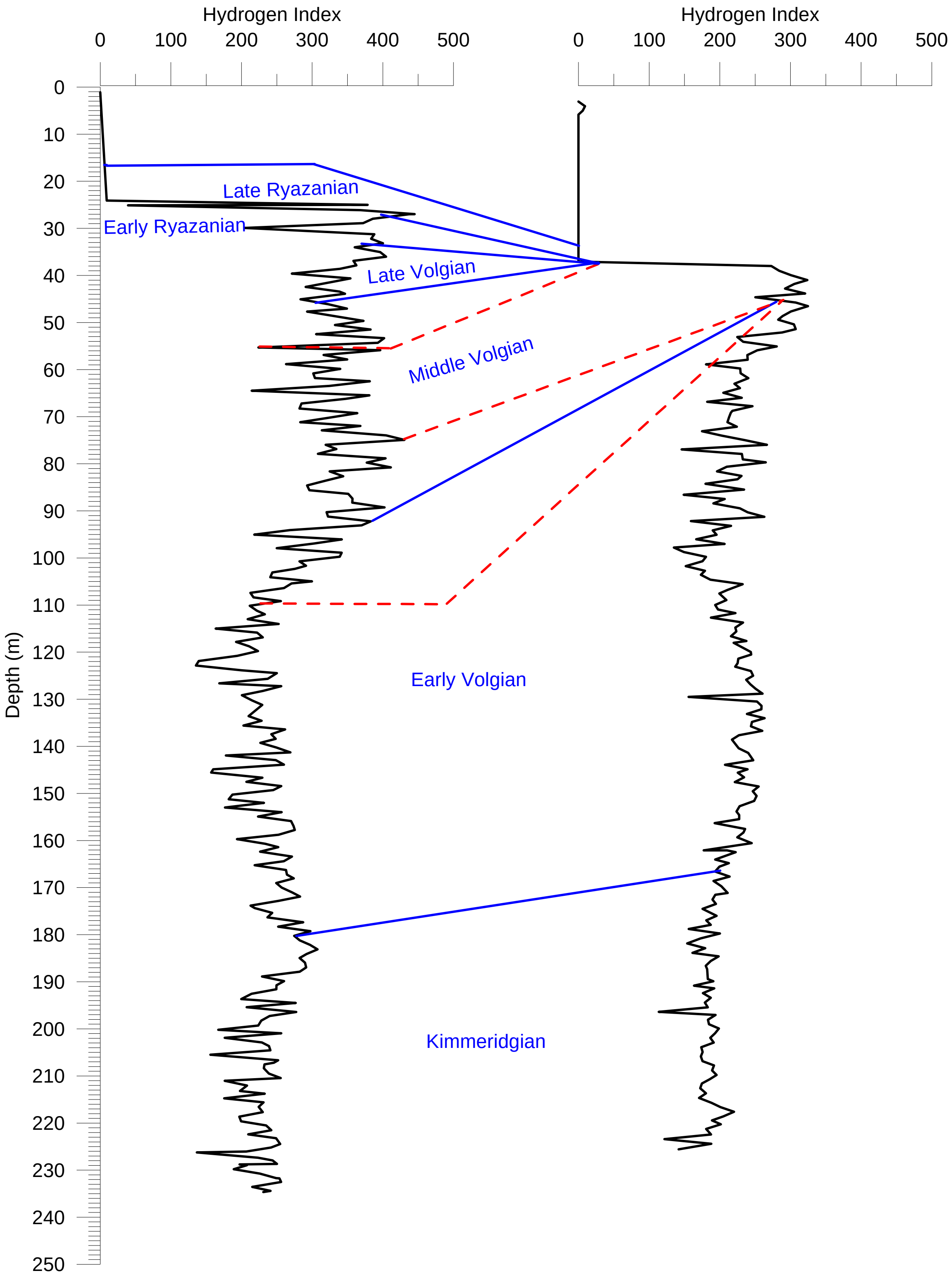


Figure 8. Hydrogen Index versus depth for the Rødryggen-1 (left) and Brorson Halvø-1 (right) coreholes.

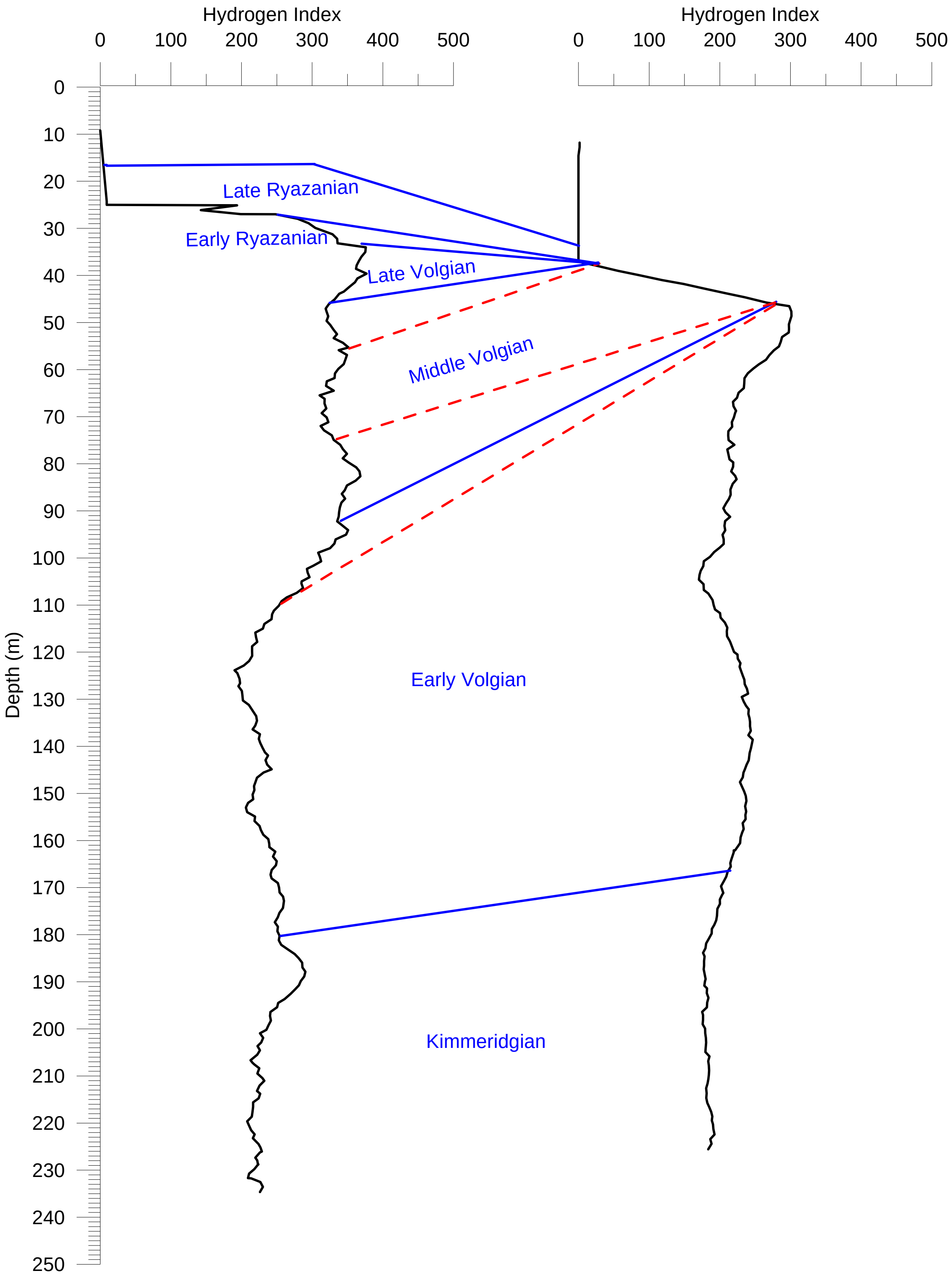
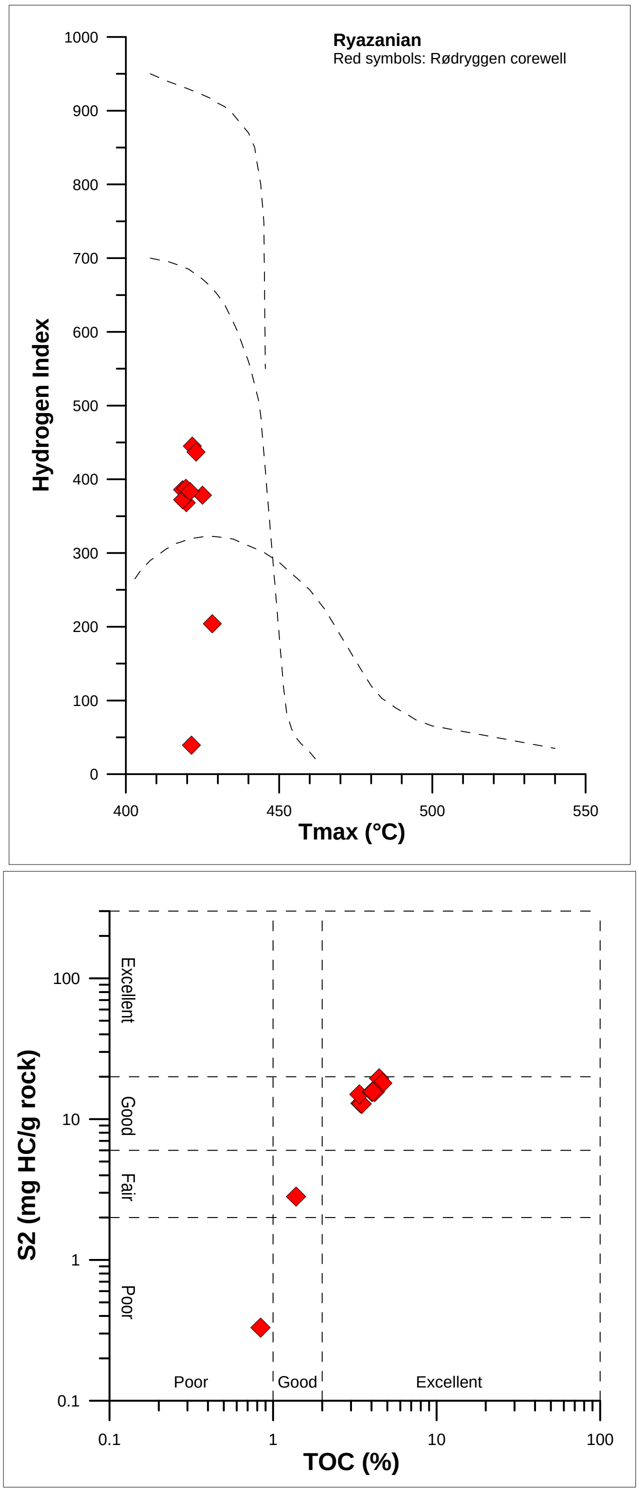


Figure 9. 10 sample moving average of Hydrogen Index versus depth for the Rødryggen-1 (left) and Brorson Halvø-1 (right) coreholes.

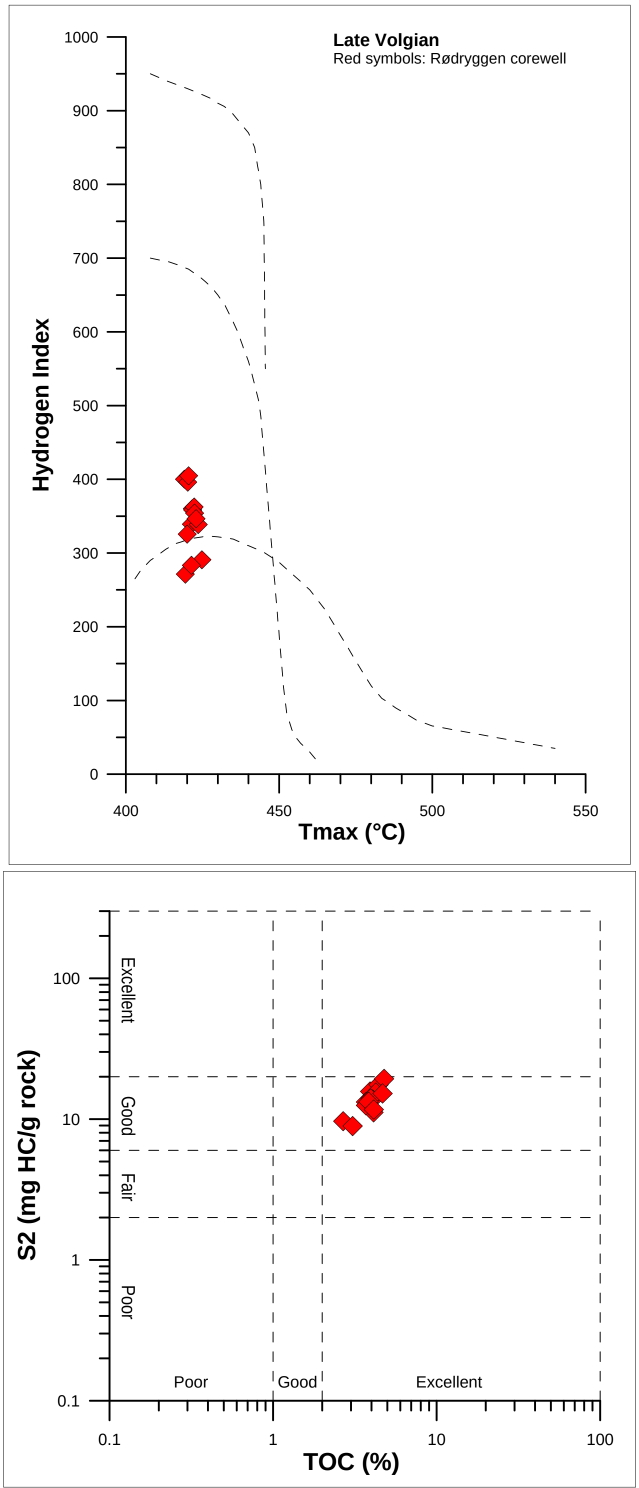
Significant differences in the level of thermal maturity exist between the two coreholes. Both sections show clear (- and enigmatic!) increases in the level of thermal maturity with depth, but from different initial values. The Rødryggen-1 corehole succession is as a whole thermally immature to marginally mature, showing values of T_{max} generally less than 430°C and Production Index below 0.1, whereas the succession penetrated by the Brorson Halvø-1 corehole is oil window mature, showing values of T_{max} generally above 440°C and Production Index between 0.1 and 0.2. Both the levels of maturity and the increasing trends are corroborated by several independent datasets – see Hovikoski et al. (2010 and 2011) for details.

Figures 10-14 show standard plots of Tmax vs. Hydrogen Index and TOC versus S2 for the source rock successions according to age, Ryazanian (Rødryggen-1 corehole only), the Late Volgian (Rødryggen-1 corehole only), the Middle Volgian, the Early Volgian, and the Kimmeridgian. It is evident that the Ryazanian and Late Volgian successions represented by the Rødryggen-1 core only on average constitute more oil-prone petroleum source rocks than the older successions present in both cores, but the difference is not conspicuous. However, with respect to the Kimmeridgian–Middle Volgian parts of the succession, the similarity in petroleum source rock characteristics of the correlative units is striking; the differences seem to be caused more or less exclusively by the disparity in thermal maturity. This is illustrated in Figure 15, where the Kimmeridgian through the Middle Volgian units seem to follow maturation paths intermediate between ideal kerogen types II and III.



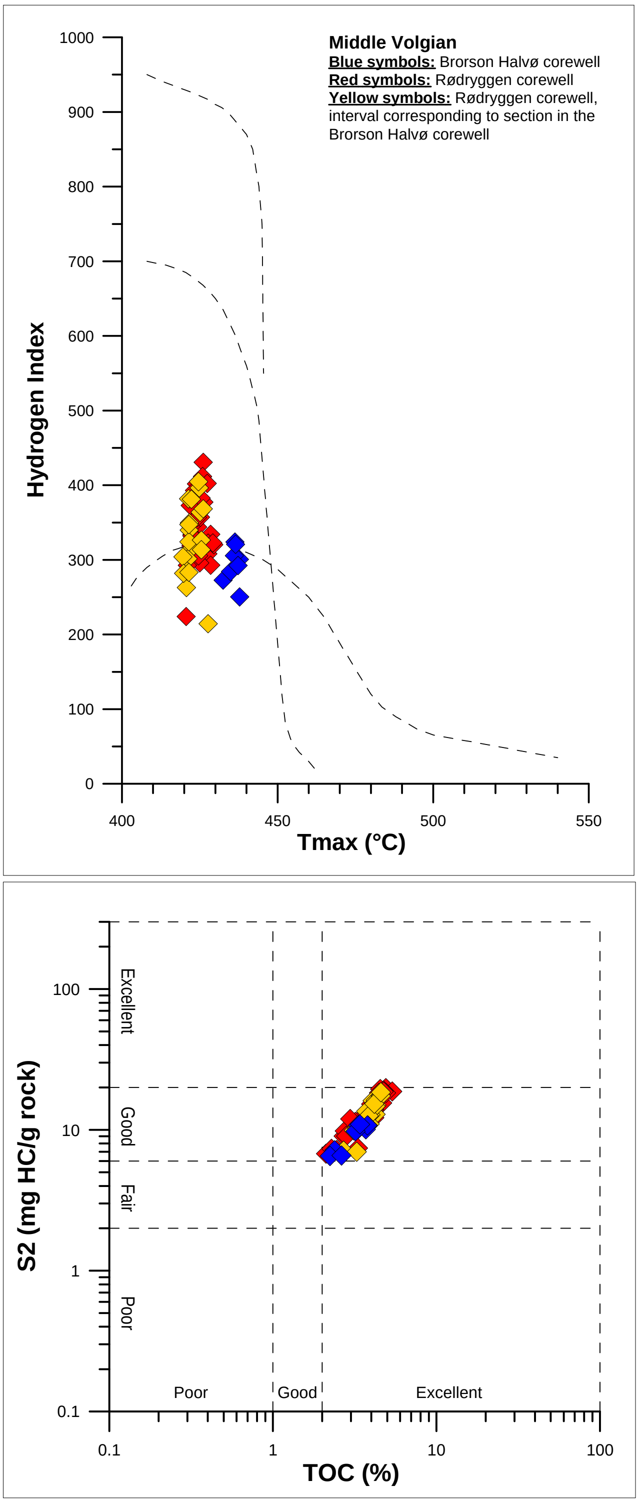
Ryazanian
Red symbols: Rødryggen corewell

Figure 10.



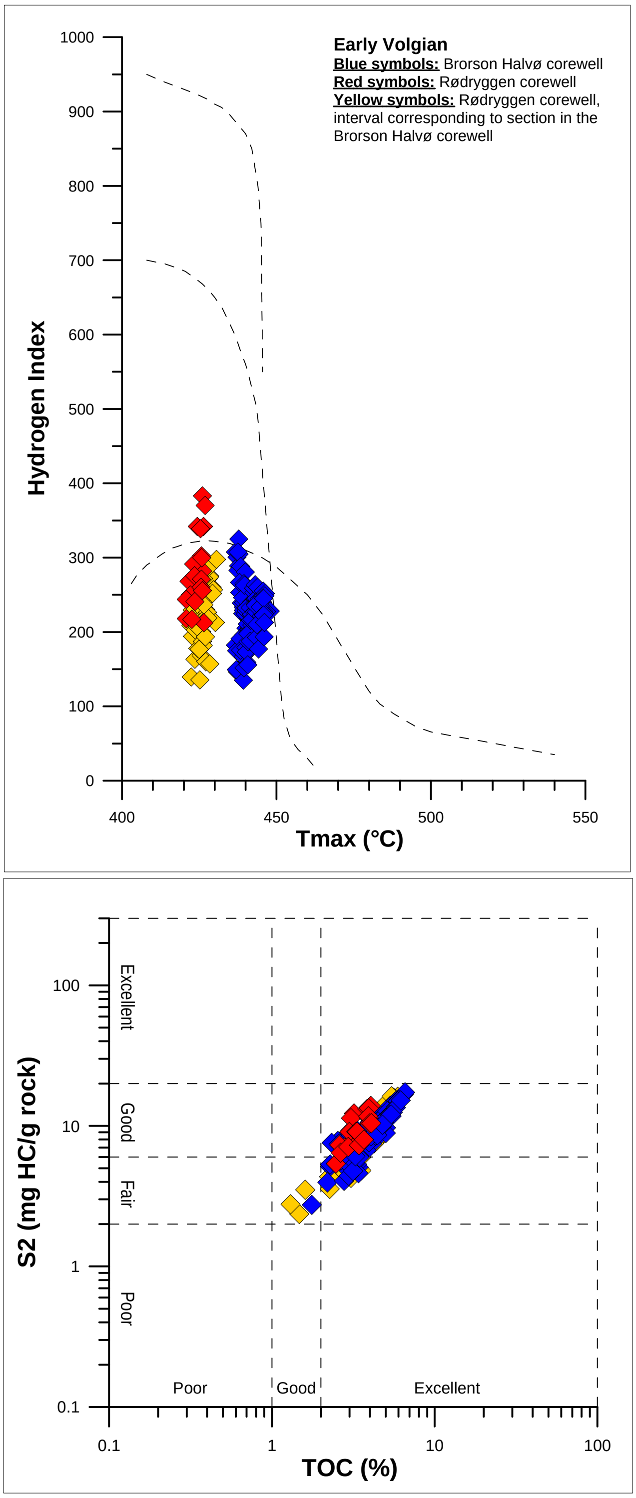
Late Volgian
Red symbols: Rødryggen corewell

Figure 11.



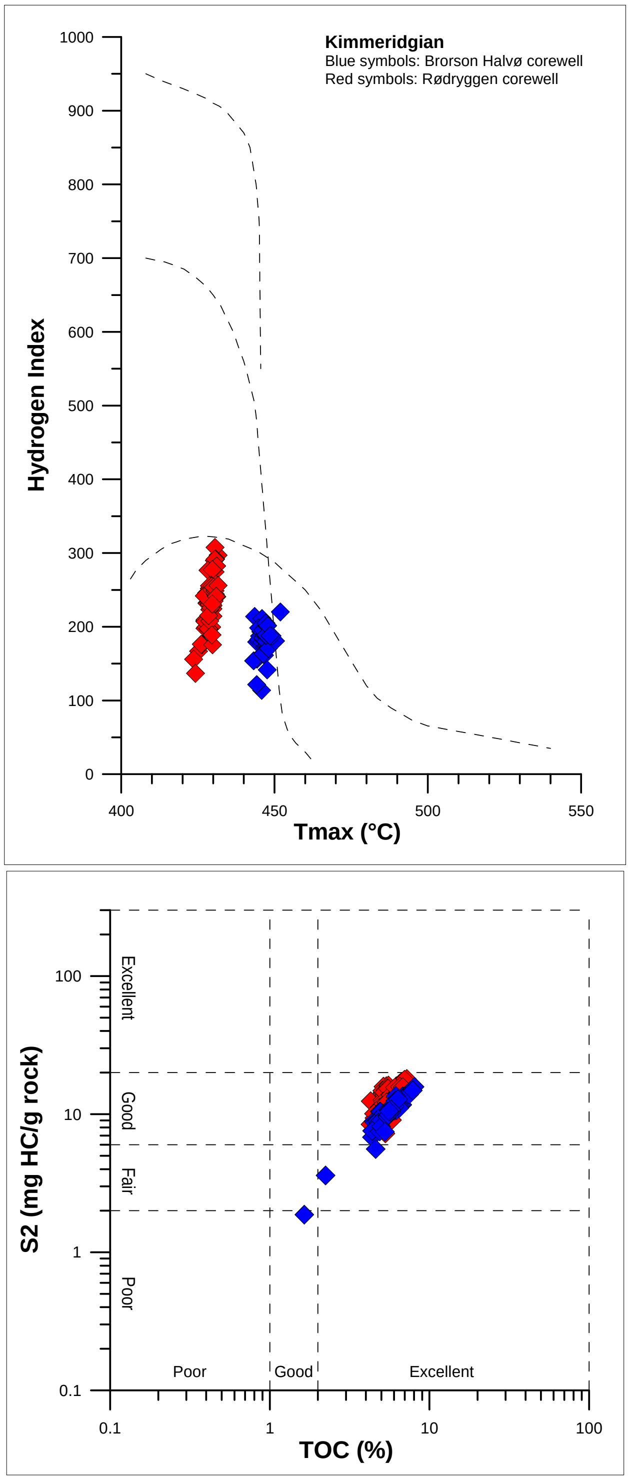
Middle Volgian
Blue symbols: Brorson Halvø corewell
Red symbols: Rødryggen corewell
Yellow symbols: Rødryggen corewell, interval corresponding to section in the Brorson Halvø corewell

Figure 12.



Early Volgian
Blue symbols: Brorson Halvø corewell
Red symbols: Rødryggen corewell
Yellow symbols: Rødryggen corewell, interval corresponding to section in the Brorson Halvø corewell

Figure 13.



Kimmeridgian
Blue symbols: Brorson Halvø corewell
Red symbols: Rødryggen corewell

Figure 14.

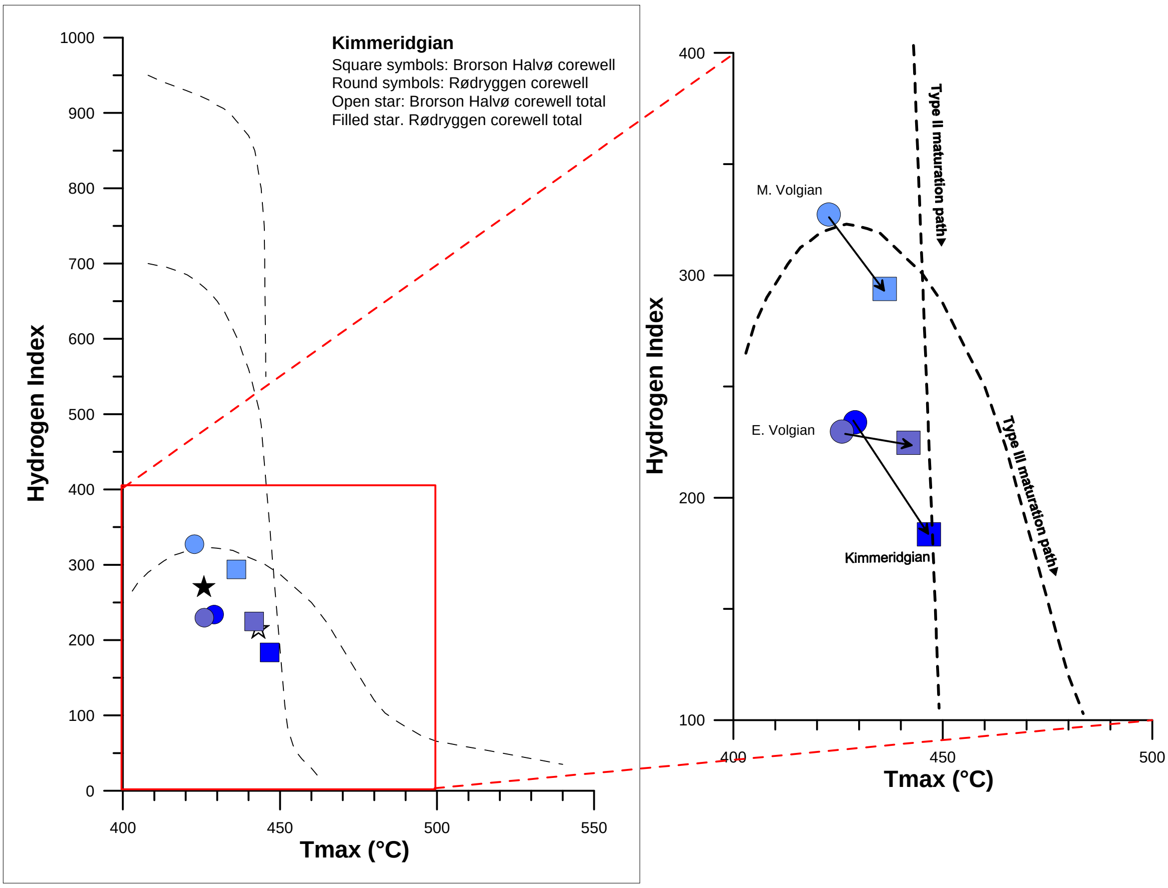


Figure 15. Average characteristics of the Kimmeridgian, Early Volgian and Middle Volgian correlative sequences in the Rødryggen-1 and Brorson Halvø-1 cores. Arrows on enlarged part indicate maturation trends – pointing to mixed type II/III kerogen

3.3 Reconstruction of original petroleum source potential and the Source Potential Index (SPI)

Several schemes for recalculation of original petroleum generative potential exist, for instance: Cooles et al. (1986); Schmoker (1994), Dahl et al. (2004); Peters et al. (2005). Peters et al. (2005) describe a relatively simple and straight-forward procedure for assessment of original petroleum generation potential which was probably developed originally by George E. Claypool and coworkers at Mobil E&P. The method has been extensively documented by Peters et al. (2005); including the derivation of the formulae used for calculation, so only a brief summary of the essentials is given here. The method is excellently suited for spreadsheet use.

Based on actual Rock-Eval screening pyrolysis data, the method will calculate original TOC, total petroleum potential (*i.e.* S1+S2), petroleum generated, fractional conversion and expulsion efficiency for a series of assumed initial Hydrogen Index scenarios (for instance from 200 to 900 in increments of 100 or 50). Initial PI is assumed to be equal to 0.02 in all cases, and based on evaluation of returned values calculated from the input data, which in this case will be average values of TOC, S1+S2, HI and PI (all labeled with superscript "o" for "original", e.g. "TOC^o") for the units investigated, a "reasonable" initial HI scenario can be identified. In doing so, it should be kept in mind that the "fractional conversion" must always be greater than measured PI because of loss due to migration and sample handling (gaseous and low-boiling hydrocarbons).

Simple average values of the Rock-Eval data for the defined units can be used here because the samples were collected equidistantly. This eliminates the need for calculation of the depth interval represented by each individual sample – *i.e*. "sample weight".
For comparison of the two successions after recalculation/estimation of their original (*i.e.* pre-maturation) potentials, the "Source Potential Index" (SPI) of Demaison and Huizinga is useful (Demaison and Huizinga 1991, 1994). The SPI may be defined as:

"The maximum quantity of hydrocarbons that can be generated within a column of source rock under one square meter of surface area"

The SPI conveniently combines source rock richness and thickness into one single parameter, and is calculated as:

$$SPI = h*(average\ S1+S2)*\varrho / 1000$$

Where H is the thickness of the source rock unit, (average S1+S2) is the average generation potential derived from Rock-Eval pyrolysis throughout the source rock unit (in kg hydrocarbons / ton rock) and ϱ is the rock density – which for practical purposes is generally assumed to be equal to 2.5 t/m^3. The SPI is useful for comparison of different basins and for mapping of spatial variations in a source rock unit

Table 1 shows original petroleum generative capacities and SPI for the various units in the Rødryggen-1 and Brorson Halvø-1 coreholes. Calculation of original values for the individual units is shown in Appendix 6.2.

Accepting the uncertainties inherent to such recalculations – essentially they represent an "educated guess", it is clear that differences in original petroleum potential of the correlative units penetrated by the two coreholes are indeed minor. The Kimmeridgian succession is similar in both coreholes, both with respect to richness and generative potential, and accordingly the Hydrogen Index. The Kimmeridgian succession in both coreholes thus represents rich gas/oil-prone source rocks containing mixed type II/III kerogen. The Lower Volgian succession in the Brorson Halvø-1 core shows slightly higher generative potential than the correlative succession of Rødryggen-1 core, whereas the richness is similar. Hence, on average the original Hydrogen Index of the Lower Volgian succession in the Brorson Halvø-1 core is slightly higher than that of the Rødryggen-1 core, despite truncation of the upper part which in the latter is more prolific than the lower part. This difference is also evident in Figures 8 and 9, where the lower part of the Early Volgian in the Brorson Halvø shows an increase in Hydrogen Index, relative to the underlying Kimmeridgian, whereas the Rødryggen-1 corehole succession shows a decrease. Hence, it appears that during the Early Volgian the proportion of marine oil-prone organic matter contributed to the sediments was greater at the Brorson Halvø-1 location than at the Rødryggen-1 location. However, the kerogen type remains gas/oil-prone and fairly similar to the underlying Kimmerigian succession. With respect to kerogen type, the Middle Volgian successions are again very similar in the two coreholes, but the kerogen type has grown increasingly oil-prone, characterized by an initial Hydrogen Index of 350. Despite similar kerogen type, the Rødryggen-1 succession is somewhat richer (higher TOC and generative potential) than the correlative succession in the Brorson Halvø-1 corehole. The trend towards increasingly oil-prone kerogen continues into the late Volgian and the Ryazanian successions of the Rødryggen-1 core, whereas these intervals are absent from the Brorson Halvø-1 succession. Hence, when calculating the original potential for the total source rock successions in the two coreholes, the Rødryggen-1 comes out slightly more prolific than the Brorson Halvø-1 succession.

Calculation of the “Source Potential Index” (SPI) for the succession reflects the differences in thickness and the absence of the more prolific late Volgian and Ryazanian intervals from the Brorson Halvø-1 succession. Hence the total drilled source rock succession of the Rødryggen-1 corehole yields SPI=7.2 T/m^2 whereas the Brorson Halvø-1 succession yields SPI=5.5 T/m^2. However if only the correlative intervals of the Rødryggen-1 succession are concerned, SPI=4.4 T/m^2 results. Furthermore, if the differences in thickness of the correlative successions are taken into account, 139 m in the Rødryggen-1 corehole versus 188 m in the Brorson Halvø-1 corehole, the successions are again very similar in character.

The successions studied here represent only a fraction of the total Upper Jurassic – Lower Cretaceous source rock succession in Northeast Greenland – Surlyk (1977) estimates a thickness of the Bernbjerg Formation alone of up to 600 m, and in addition to this succession comes the overlying, highly prolific Upper Volgian – Ryazanian Lindemans Bugt Formation shales. Thus, the calculated SPI of 7.2 T/m^2 for the Rødryggen-1 succession represents only a fraction of the total source rock thickness in the region.

Demaison and Huizinga (1991) calculates SPI=15 for the Kimmeridge Clay Formation in the British part of the North Sea and the present data suggest that the Upper Jurassic – Lower Cretaceous source rock succession in Northeast Greenland will on average possess at least similar potential.

	Estimated original average values:					
	Rødryggen corehole			***Brorson Halvø corehole***		
	TOC	Total Potential	Hydrogen index	TOC	Total Potential	Hydrogen index
Ryazanian*	3,6	15	400	-	-	-
Late Volgian	4,2	17	400	-	-	-
Middle Volgian	4,0	14,0	350	3,3	11,5	350
Early Volgian	4,3	10,8	250	4,4	13,1	300
Kimmeridgian	5,9	14,8	250	6,1	15,3	250
Total section**	4,6	13,8	300	4,7	11,8	250

Total drilled SR-section	210m	Total drilled SR-section	188m
Correlative SR-section	139m		
SPI, drilled SR section	***7,2 T/m^2***		
SPI, correlative Section	***4,4 T/m^2***	SPI, drilled SR section	***5,5 T/m^2***

* Ryazanian part of Lindemans Bugt Fm. i.e. overlying Ryazanian part of non-SR Albrechts Bugt Mb. Excluded

** Rødryggen corehole: including stratigraphic intervals missing from the Brorson Halvø-1 core section

Table 1. Note: Middle and Early Volgian sections: correlative sections, calculations concern only that part of the intervals present in the Rødryggen-1 corehole that corresponds to the intervals preserved in the Brorson Halvø-1 corehole. Total Organic Carbon (TOC) in wt-%, total potential (S1+S2) in kg hydrocarbons/ton rock.

4. Conclusions

The Rødryggen-1 and the Brorson Halvø-1 cores documented the presence of prolific Kimmeridgian–Ryazanian source rock in an evolving half-graben system in the Wollaston Forland area. The source rock interval spanned two formations, namely the Kimmeridgian – Lower Volgian Bernbjerg and the Middle Volgian – Upper Ryazanian Lindemans Bugt Formations.

The data show that the Kimmeridgian palaeoenvironmental development is similar in both cores, suggesting possibly an eustatic control and more or less a single basin. The interval bears the strongest deltaic-influence in the studied cores. The upper part of the Kimmeridgian records a prominent eustatic transgression and a zone of Maximum Flooding.

The Lower Volgian interval records the onset of increasing fault activity and basin segmentation. Facies successions can no longer be correlated, and depositional rates show marked lateral variability (condensation vs. stratigraphic expansion). A zone of maximum regression took place during this interval. During the late Early Volgian, block rotation further intensified, and the deposits started to grade into the Lindemans Bugt Formation. The top of lower Volgian is missing from the Brorson Halvø-1 core due to the uplift of footwall crest.

The Middle Volgian – Ryazanian interval represented the rift climax phase in Wollaston Forland area. The interval is generally characterized by deepening, reduction in depositional rates (Ryazanian) and decreasing terrestrial input into the block. The data point also to the development of westward tilted fault block geometry, and detachment of the Permpas/Hühnerbjerg block(s) from the main coastline (cf. Surlyk, 1978). Most of the interval is missing from the Brorson Halvø-1, which is most likely due to the core's location near the uplifting block crest. The missing intervals include the Late Volgian and Ryazanian portions, which form the most prolific part of the source rock succession in the Rødryggen-1 corewell. In addition, significant parts of the Middle Volgian are missing.

Source rock data show that the Kimmeridgian succession in both cores is characterized by high levels of TOC and moderate petroleum generation capacity (S2), corresponding to a gas- and oil-prone kerogen type intermediate between ideal types II and III. The overlying Lower Volgian succession in both cores shows a decrease in TOC upwards through the lower part followed by stabilization of TOC, but unchanged or just slightly lower generation capacity (S2), leading to higher average Hydrogen Index, corresponding to a slightly more oil-prone kerogen type containing higher proportions of marine organic matter. The Middle Volgian is very similar to the Early Volgian.

There are major differences in the level of thermal maturity between the Rødryggen-1 and Broroson Halvø-1 locations.

Calculation of the original petroleum potential of the source rock successions shows that the correlative successions in the two cores are very similar with respect to petroleum source potential characteristics.

Calculation of the “Source Potential Index” (SPI) for the Rødryggen-1 corehole succession, using original source potential values, yields 7.2 Tonnes of petroleum per m^2 source rock area. Since the succession only comprises a fraction of the total Upper Jurassic – Lower Cretaceous petroleum source rock succession known from the region, a total SPI of 15 T/m2 or more is realistic, similar to the published SPI of the Kimmeridge Clay Formation in the British North Sea sector.

.

5. References

Aplin, A., & Macquaker, J., 2011: Mudstone diversity: Origin and implications for source, seal, and reservoir properties in petroleum systems. AAPG Bulletin, **95**, 2031–2059.

Cooles, G. P., Mackenzie A. S., & Quigley, T. M., 1986: Calculation of petroleum masses generated and expelled from source rocks. Organic Geochemistry, **10**, 235-245

Dahl, B., Bojesen-Koefoed, J. A., Holm, A., Justwan, H., Rasmussen, E., & Thomsen, E., 2004: A new approach to interpreting Rock-Eval S2 and TOC data for kerogen quality assessment. Organic Geochemistry, **35**, 1461–1477

Demaison, G., & Huizinga, B., 1991: Genetic classification of petroleum systems. AAPG Bulletin, **75**, 1626–1643

Demaison, G., & Huizinga, B., 1994: Genetic classification of petroleum systems using three factors: charge, migration and entrapment. AAPG Memoir 60, 73–89

Hovikoski, J., Alsen, P., Bojesen-Koefoed, J.A., Boserup, J., Kjøller, C., Nytoft, H.P., Olivarius, M., Olsen, D., Petersen, H.I., Piasecki, S., Sheldon E., & Vosgerau, H., 2010: Rødryggen-1 Core Well, GGU 517101, Wollaston Forland, Northeast Greenland – Final Well Report, Danmarks og Grønlands Geologiske Undersøgelse Rapport 2010/100, Confidential, 252 pp, 6 Appendices, 1 CD.

Hovikoski, J., Alsen, P., Bojesen-Koefoed, J.A., Boserup, J., Fries, K., Green, P., Japsen, P., Johannessen, P., Kazerouni, A.M., Kjøller, C., Lindgreen, H., Morigi, C., Nytoft, H.P., Nøhr-Hansen, H., Pauly, S., Petersen, H.I., Piasecki, S., & Springer, N., 2011: Brorson Halvø-1 Core Well, GGU 517103, Wollaston Forland, Northeast Greenland – Final Well Report, Danmarks og Grønlands Geologiske Undersøgelse Rapport 2011/128, Confidential, 248 pp, 10 Appendices, 1 CD.

Macquaker, J., Bentley, S., & Bochas, K., 2010: Wave-enhanced sediment-gravity flows and mud dispersal across continental shelves: Reappraising sediment transport processes operating in ancient mudstone successions. Geology, **38**, 947–950.

Schmocker, J., 1994: Volumetric calculation of hydrocarbons generated. AAPG Memoir **60**, 323–326

Surlyk, F., 1977: Stratigraphy, tectonics and palaeogeography of the Jurassic sediments of the areas north of Kong Oscars Fjord, East Greenland. Grønlands Geologiske Undersøgelse Bulletin, **123**, 56pp + enclosure

Surlyk, F., 1978: Submarine fan sedimentation along fault scarps on tilted fault blocks (Jurassic–Cretaceous boundary, East Greenland). Grønlands Geologiske Undersøgelse Bulletin, **128**, 108 pp.

Surlyk, F., 1990: A Jurassic sea-level curve for East Greenland. Palaeogeogr, Palaeoclimatol., Palaeoecol., **78**, 71–85.

Surlyk, F., 2003: The Jurassic of East Greenland: a sedimentary record of thermal subsidence, onset and culmination of rifting. In: Ineson, J.R. & Surlyk, F. (eds): The Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin, **1**, 659–722

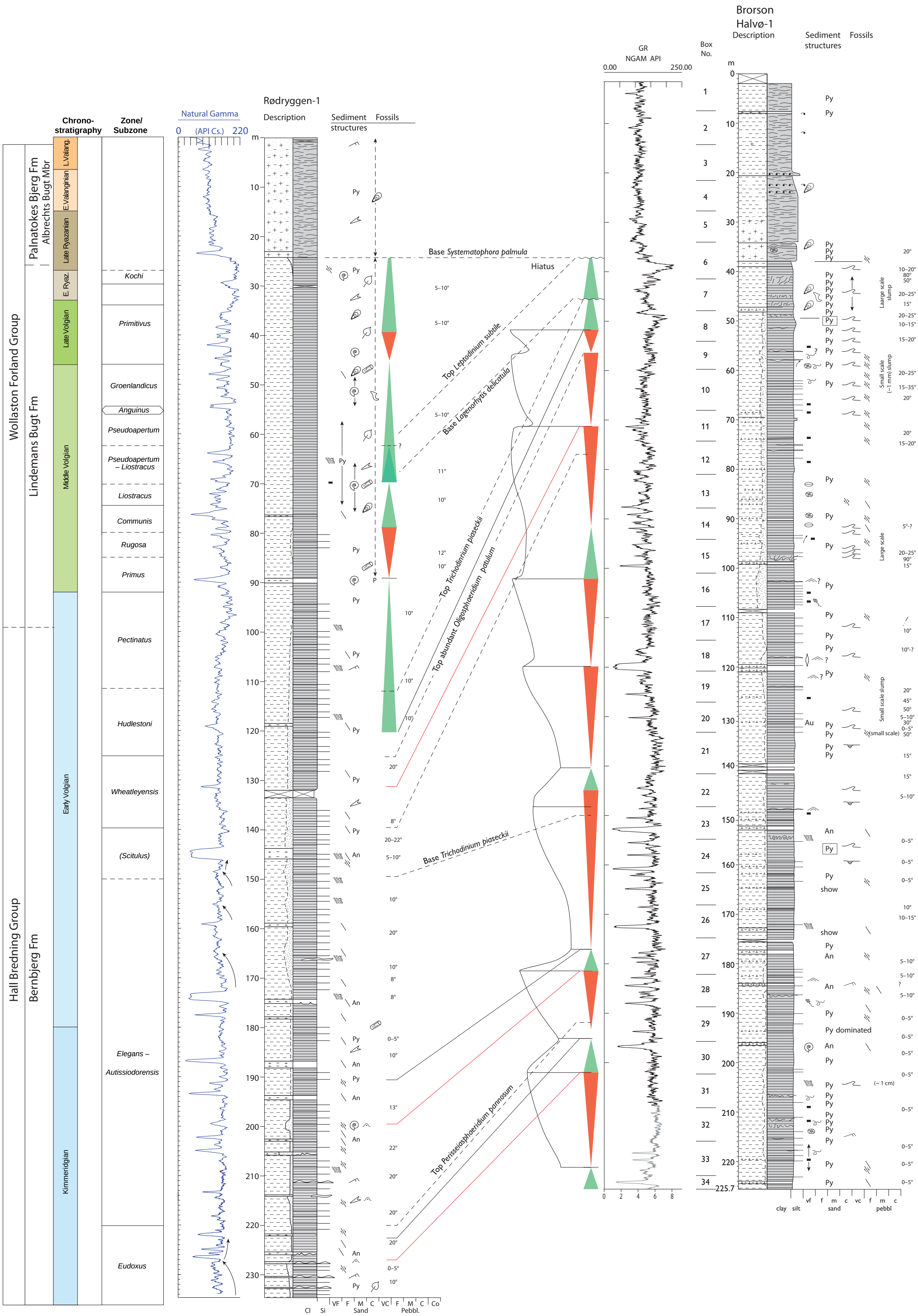
Surlyk, F., & Clemmensen, L.B., 1983: Rift propagation and eustacy as controlling factors during Jurassic inshore and shelf sedimentation in northern East Greenland. Sedimentary Geology, **34**, 119–143.

Peters; K.E., Clifford, C.C., & Moldowan, J.M., 2005: The Biomarker Guide, 2nd ed. Cambridge University Press, Cambridge, UK

6. APPENDIX

6.1 Correlation cross-section

Figure 6.1 (next page). Cross-section showing the correlation between the Rødryggen-1 and the Brorson Halvø-1 cores. Key biostratigraphic horizons are indicated by dashed lines. Red lines show turn around points from progradation to retrogradation, whereas black lines indicate changes from retrogradation to progradation. The inferred T/R cycles can be only correlated in the Kimmeridgian section. R-1–Rødryggen-1, B.H-1–Brorson Halvø-1.



GØ04_02M_303_JHOV

6.2 Calculation of original petroleum generative potential

Calculation of original petroleum generative potential for established stratigraphic intervals in the Rødryggen-1 and Brorson Halvø-1 coreholes using the method of Peters et al. (2005)

Input data are average vales of TOC, S1, S2, HI, and PI for each established unit (labeled with an "*" to indicate measured data).

Red frame indicate accepted recalculated values.

Rødryggen-1 corehole, Ryazanian:

Input parameters	
TOC*	3,39
S1*	0,46
S2*	12,82
HI*	340
PI*	0,03

Assumed		Calculated results				
HIº	PIº	Fractional conversion	TOCº (wt-%)	S1º+S2º (mg/g)	$S1_{expelled}$ (mg/g)	Expulsion Efficiency
900	0,02	0,87	9,03	81	71	0,99
800	0,02	0,80	6,96	56	45	0,99
700	0,02	0,72	5,66	40	28	0,99
600	0,02	0,60	4,77	29	17	0,98
500	0,02	0,45	4,18	21	10	0,96
450	0,02	0,35	3,91	18	6	0,94
400	0,02	0,21	3,63	15	3	0,88
350	0,02	0,04	3,43	12	0	0,45
300	0,02	-0,19	3,24	10	-2	1,24
250	0,02	-0,50	3,08	8	-4	1,11
200	0,02	-0,98	2,93	6	-6	1,07

Fractional conversion = $(G_0-G_x)/G_0$, G= generation capacity, initial (G_0) and at time = x (G_x)

$S1_{expelled}$ = expelled HC calculated on the basis of loss in TOC

Expulsion efficiency = $Petroleum_{expelled}$ / $Petroleum_{generated}$

Rødryggen-1 corehole, Late Volgian:

Input parameters	
TOC*	3,95
S1*	0,50
S2*	13,68
HI*	345
PI*	0,04

Assumed		Calculated results				
HIº	PIº	Fractional conversion	TOCº (wt-%)	S1º+S2º (mg/g)	$S1_{expelled}$ (mg/g)	Expulsion Efficiency
900	0,02	0,87	10,35	93	81	0,99
800	0,02	0,80	8,01	64	51	0,99
700	0,02	0,71	6,53	46	33	0,99
600	0,02	0,60	5,52	33	20	0,98
500	0,02	0,44	4,84	24	11	0,96
450	0,02	0,34	4,52	20	7	0,93
400	0,02	0,19	4,21	17	3	0,86
350	0,02	0,02	3,97	14	0	0,11
300	0,02	-0,21	3,76	11	-2	1,23
250	0,02	-0,53	3,57	9	-5	1,11
200	0,02	-1,02	3,40	7	-7	1,07

Fractional conversion = $(G_0-G_x)/G_0$, G= generation capacity, initial (G_0) and at time = x (G_x)

$S1_{expelled}$ = expelled HC calculated on the basis of loss in TOC

Expulsion efficiency = $Petroleum_{expelled}$ / $Petroleum_{generated}$

Rødryggen-1 corehole, Middle Volgian, section corresponding to the Middle Volgian section preserved in the Brorson Halvø-1 corehole:

Input parameters	
TOC*	3,89
S1*	0,67
S2*	12,90
HI*	327
PI*	0,05

Assumed		Calculated results				
HI°	PI°	Fractional conversion	TOC° (wt-%)	S1°+S2° (mg/g)	$S1_{expelled}$ (mg/g)	Expulsion Efficiency
900	0,02	0,87	10,40	94	82	0,99
800	0,02	0,81	8,05	64	52	0,99
700	0,02	0,73	6,57	46	34	0,98
600	0,02	0,62	5,54	33	21	0,97
500	0,02	0,48	4,87	24	12	0,95
450	0,02	0,38	4,55	20	8	0,92
400	0,02	0,25	4,23	17	4	0,86
350	0,02	0,09	3,99	14	1	0,57
300	0,02	-0,13	3,78	11	-1	1,56
250	0,02	-0,43	3,59	9	-4	1,18
200	0,02	-0,88	3,42	7	-6	1,11

Fractional conversion = $(G_0-G_x)/G_0$, G= generation capacity, initial (G_0) and at time = x (G_x)

$S1_{expelled}$ = expelled HC calculated on the basis of loss in TOC

Expulsion efficiency = $Petroleum_{expelled}$ / $Petroleum_{generated}$

Rødryggen-1 corehole, Early Volgian, section corresponding to Early Volgian section preserved in the Brorson Halvø-1 corehole:

Input parameters	
TOC*	4,22
S1*	0,72
S2*	9,91
HI*	230
PI*	0,07

Assumed		Calculated results				
HIº	PIº	Fractional conversion	TOCº (wt-%)	S1º+S2º (mg/g)	$S1_{expelled}$ (mg/g)	Expulsion Efficiency
900	0,02	0,92	12,25	110	102	0,99
800	0,02	0,88	9,54	76	67	0,99
700	0,02	0,83	7,81	55	45	0,99
600	0,02	0,76	6,61	40	30	0,98
500	0,02	0,67	5,81	29	20	0,97
450	0,02	0,61	5,44	24	15	0,96
400	0,02	0,53	5,06	20	11	0,94
350	0,02	0,42	4,78	17	7	0,91
300	0,02	0,29	4,53	14	4	0,83
250	0,02	0,10	4,30	11	1	0,46
200	0,02	-0,18	4,10	8	-2	1,52

Fractional conversion = $(G_0-G_x)/G_0$, G= generation capacity, initial (G_0) and at time = x (G_x)

$S1_{expelled}$ = expelled HC calculated on the basis of loss in TOC

Expulsion efficiency = $Petroleum_{expelled}$ / $Petroleum_{generated}$

Rødryggen-1 corehole, Kimmeridgian:

Input parameters	
TOC*	5,84
S1*	1,09
S2*	13,66
HI*	234
PI*	0,07

Assumed		Calculated results				
HI°	PI°	Fractional conversion	TOC° (wt-%)	S1°+S2° (mg/g)	$S1_{expelled}$ (mg/g)	Expulsion Efficiency
900	0,02	0,92	16,27	146	135	0,99
800	0,02	0,88	12,83	103	90	0,99
700	0,02	0,83	10,59	74	61	0,98
600	0,02	0,76	9,01	54	41	0,98
500	0,02	0,67	7,95	40	27	0,96
450	0,02	0,60	7,45	34	21	0,95
400	0,02	0,52	6,95	28	14	0,93
350	0,02	0,41	6,57	23	9	0,89
300	0,02	0,27	6,23	19	5	0,80
250	0,02	0,08	5,93	15	1	0,26
200	0,02	-0,21	5,65	11	-2	1,51

Fractional conversion = $(G_0-G_x)/G_0$, G= generation capacity, initial (G_0) and at time = x (G_x)

$S1_{expelled}$ = expelled HC calculated on the basis of loss in TOC

Expulsion efficiency = $Petroleum_{expelled}$ / $Petroleum_{generated}$

Brorson Halvø-1 corehole, Middle Volgian:

Input parameters	
TOC*	3,08
S1*	1,19
S2*	9,07
HI*	294
PI*	0,12

Assumed		**Calculated results**				
HIº	PIº	Fractional conversion	TOCº (wt-%)	S1º+S2º (mg/g)	$S1_{expelled}$ (mg/g)	Expulsion Efficiency
900	0,02	0,89	8,66	78	70	0,98
800	0,02	0,84	6,67	53	45	0,97
700	0,02	0,77	5,42	38	29	0,96
600	0,02	0,68	4,57	27	19	0,94
500	0,02	0,55	4,00	20	11	0,90
450	0,02	0,47	3,74	17	8	0,85
400	0,02	0,35	3,47	14	5	0,77
350	0,02	0,21	3,28	11	2	0,55
300	0,02	0,03	3,10	9	0	-1,75
250	0,02	-0,23	2,94	7	-2	1,78
200	0,02	-0,62	2,80	6	-3	1,36

Fractional conversion = $(G_0-G_x)/G_0$, G= generation capacity, initial (G_0) and at time = x (G_x)

$S1_{expelled}$ = expelled HC calculated on the basis of loss in TOC

Expulsion efficiency = $Petroleum_{expelled}$ / $Petroleum_{generated}$

Brorson Halvø-1 corehole, Early Volgian:

Input parameters	
TOC*	4,05
S1*	1,60
S2*	9,15
HI*	225
PI*	0,15

Assumed		Calculated results				
HIº	PIº	Fractional conversion	TOCº (wt-%)	S1º+S2º (mg/g)	$S1_{expelled}$ (mg/g)	Expulsion Efficiency
900	0,02	0,92	11,86	107	99	0,99
800	0,02	0,88	9,22	74	65	0,98
700	0,02	0,84	7,55	53	44	0,97
600	0,02	0,77	6,39	38	29	0,95
500	0,02	0,68	5,61	28	20	0,92
450	0,02	0,62	5,25	24	15	0,90
400	0,02	0,54	4,88	20	11	0,86
350	0,02	0,44	4,61	16	7	0,79
300	0,02	0,31	4,37	13	4	0,64
250	0,02	0,12	4,15	10	1	-0,04
200	0,02	-0,15	3,95	8	-1	2,51

Fractional conversion = $(G_0-G_x)/G_0$, G= generation capacity, initial (G_0) and at time = x (G_x)

$S1_{expelled}$ = expelled HC calculated on the basis of loss in TOC

Expulsion efficiency = $Petroleum_{expelled}$ / $Petroleum_{generated}$

Brorson Halvø-1 corehole, Kimmeridgian:

Input parameters	
TOC*	5,75
S1*	2,24
S2*	10,65
HI*	184
PI*	0,18

Assumed		Calculated results				
HI°	PI°	Fractional conversion	TOC° (wt-%)	S1°+S2° (mg/g)	$S1_{expelled}$ (mg/g)	Expulsion Efficiency
900	0,02	0,94	16,73	151	142	0,99
800	0,02	0,91	13,21	106	96	0,98
700	0,02	0,87	10,91	76	67	0,97
600	0,02	0,82	9,30	56	46	0,95
500	0,02	0,75	8,21	41	32	0,93
450	0,02	0,70	7,69	35	25	0,91
400	0,02	0,64	7,17	29	18	0,88
350	0,02	0,56	6,79	24	13	0,84
300	0,02	0,46	6,44	19	9	0,76
250	0,02	0,31	6,12	15	5	0,56
200	0,02	0,10	5,84	12	1	-0,66

Fractional conversion = $(G_0\text{-}G_x)/G_0$, G= generation capacity, initial (G_0) and at time = x (G_x)

$S1_{expelled}$ = expelled HC calculated on the basis of loss in TOC

Expulsion efficiency = $Petroleum_{expelled}$ / $Petroleum_{generated}$

6.3 Sedimentological log from Brorson Halvø area