DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2012/80

Integrated report for the Billegrav-2 well (DGU 248.61)

Report prepared to E.ON Ruhrgas E&P GmbH

Niels H. Schovsbo

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

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Table of Contents

1. Introduction to the Billegrav-2 well study

Potential shalegas shales are characterised by elevated TOC content (>2%), net thicknesses >30 m (within a 100 m interval) and thermal maturities within the gas generative stage (Ro >1.3%). In Denmark shales that meet these criteria occur only in the Lower Palaeozoic and include the Alum, Dicellograptus and Rastrites shales (Schovsbo et al. 2011).

Knowledge of the Lower Palaeozoic shales in sub-surface Denmark are, however, limited to a few wells since only the Terne-1 (offshore Kattegat) and the Slagelse-1 (Zealand) deep wells penetrate the shales. The Lower Palaeozoic shales are, however, accessible at shallow depth on the Danish island of Bornholm (Figure 1) and shallow drilling of the Billegrav-2 well was made here with the aim to provide fresh sample material for studies of the important aspects of a shalegas evaluation namely the TOC distribution, porosity, mineralogy and physical properties of the shales.

This report is prepared to E.On Ruhrgas E&P GmbH and summarises the main results of the studies made on the Billegrav-2 well. The studies are detailed in the five completion reports: 'Results of down hole logs and core scanning' (Schovsbo 2011a), 'Review of the Billegrav-1 and Skelbro-1 wells' (Schovsbo 2011b), 'Results of core plug analysis' (Schovsbo 2012), 'Cambrian to basal Ordovician lithostratigraphy in southern Scandinavia' (Nielsen & Schovsbo 2012) and 'Fracture description and mineralogical analysis' (Jakobsen & Schovsbo 2012) and the report 'Pumping test of the Billegrav 2 well (248.61) Bornholm' (Klitten et al. 2010) prepared to E.On Ruhrgas.

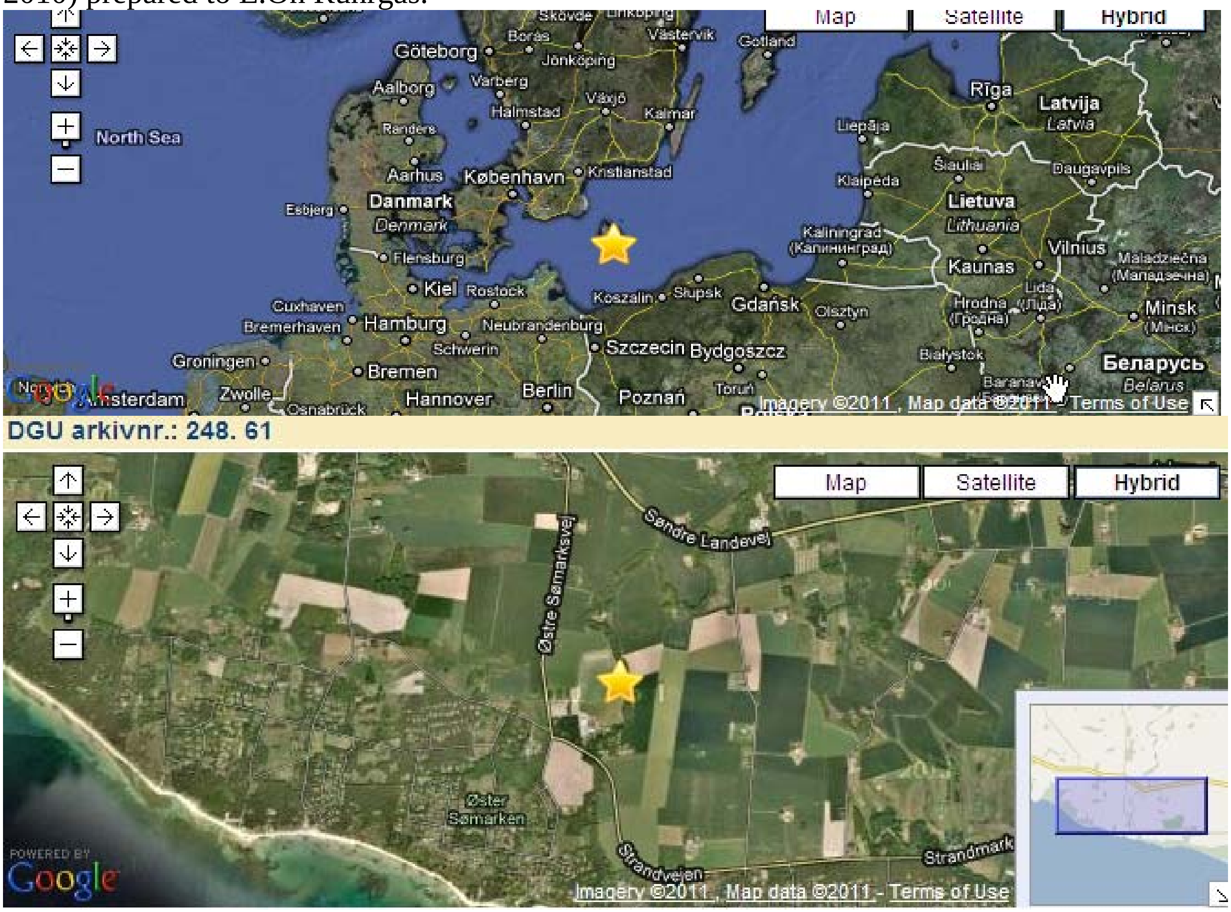

Figure 1. Location of the Billegrav-2 well, southern Bornholm, Denmark.

Overview of the logging and analytical program for the Billegrav-2 well
A comprehensive logging and core work program was made in the bore hole and on the cores (Table 1 and 2). A total of 12 log types were obtained and up to 212 samples were analysed. In addition core descriptions of the lithology, stratigraphy and fracture distribution were made.

Due to a hole failure at 92 m no sonic log was obtained in the deeper part of the hole. The sonic log obtained in the Skelbro-2 well was instead used to characterise the Alum Shale (Figure 5). The Skelbro-2 well was drilled approximately 8 km east of the Billegrav-2 well (Schovsbo et al. 2011).

Table 1. Logs obtained in the drill hole or measured on the core.

Name	**Unit**	**Description**
Gamma ray	API	Formation gamma ray response
Induction	mS/m	Formation induction
Resistivity	Ohm-m	Formation resistivity
Sonic	Km/s	Sonic velocity
Caliper	Mm	Diameter of borehole
Fluid temperature	degree C	Fluid temperature. No pumping
Fluid temperature	degree C	Fluid temperature during pumping
Fluid property	µS/cm	Fluid conductivity. No pumping
Fluid property	µS/cm	Fluid conductivity during pumping
Flow rate	Rpm	Flow log. No pumping
Flow rate	Rpm	Flow log during pumping
Flow rate	%	Flow log during pumping
Core GR	Cps	Core gamma ray response
K	%	K concentrations
U	Ppm	U concentrations
Th	%	Th concentrations
Density	g/cm3	Measured bulk density
Density selected	g/cm3	Selected bulk densities based on filtering
Core index	%	0: full preserved core, 100: no core/rubble based on a 7 cm running average measurement
Fracture density log	fractures pr m	Fracture occurrence in the core

Table 2. Analytical and core work program for the Billegrav-2 well.

Analysis	Samples/measurements
Acoustic velocity measurements	42
Unconfined compression test	11
Brazil tests	10
Hg-injection measurements	10
He-porosity measurements	38
Surface area (BET)	30
TOC content	212
Carbonate and pyrite content	212
Mineralogy, XRD	60
Fracture description	full core
Lithology description	full core
Stratigraphical description	full core

2. Stratigraphical summary

The Billegrav-2 well drilled 126 m Lower Palaeozoic shales and was terminated in the Lower Cambrian Sandstone (Figure 2).

The Silurian Rastrites Shale was cored from 4.5 m below the ground level down to 60.5 m. The Rastrites Shale comprises light to dark mudstone except for a distinct grey limy mudstone with carbonate cemented beds between 31.2 and 46.0 m (Figure 2). The Upper Ordovician includes the Lindegård Formation, comprising grey mud- and siltstones, and the dark organic-rich Dicellograptus Shale (Figure 2). The base of the Dicellograptus Shale is at 95 m. The shale contains in its lowermost part numerous bentonites including a 1 m thick K-bentonite bed that represents the most significant volcanic eruption that occurred in the entire early Palaeozoic.

The Komstad Limestone is 0.1 m thick and represented only by its basal conglomerate. There is no conglomerate at the base of the overlying Dicellograptus Shale and a thin bentonite rests directly on the Komstad Limestone conglomerate. The Komstad limestone overlays a 0.1 m thick grey Tøyen Shale (Figure 2).

The Alum Shale Formation is 27 m thick and includes the Middle Cambrian Andrarum and Exsulans limestone beds that are important regional marker beds (Nielsen & Schovsbo 2006). The base of the Alum Shale was reached at 122 m and the well was terminated at 125.9 m in the Rispebjerg Member (Figure 2).

Local stratigraphical unites have been established by Pedersen and Klitten (1990) in the Billegrav-1 well and in local water wells. The units are based on gamma variation and has served as an effective mean of correlation between water wells (Pedersen & Klitten 1990). All gamma log defined units and shales identified in nearby water wells and in exposed sections can also be recognized in the Billegrav-2 well (A-F in Figure 3). Moreover, the resistivity and sonic logs provides important additional information. In the Rastrites Shale the resistivity tool is particular powerful to resolve the lithological variation since the carbonate cemented beds in the mid part (the F3 unit) stand out as high resistivity beds (Figure 3).

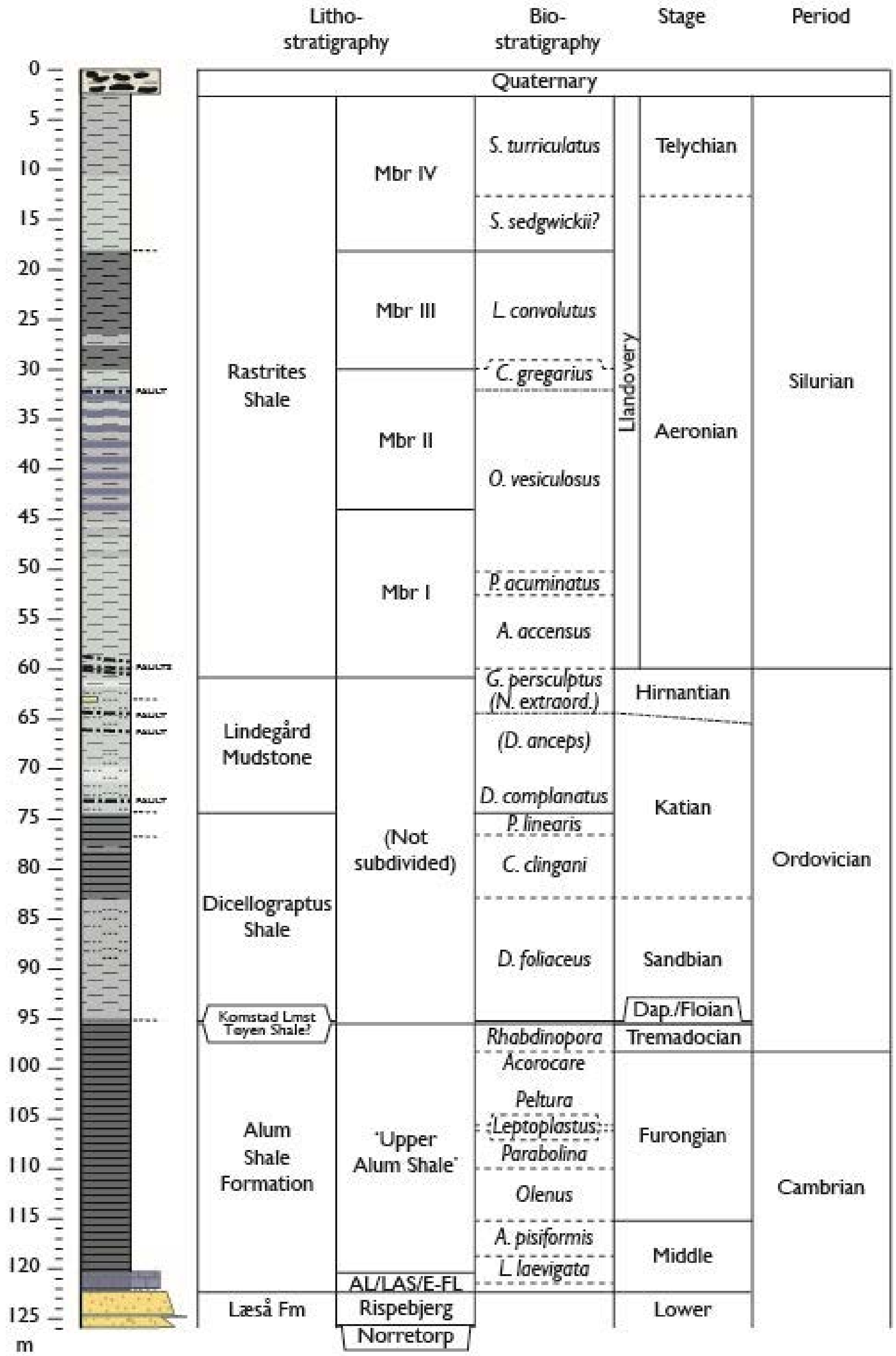

Figure 2. The encountered lithostratigraphic units in the Billegrav-2 well. A simplified log of the Billegrav-2 well is shown to the left. For legend see Figure 3.

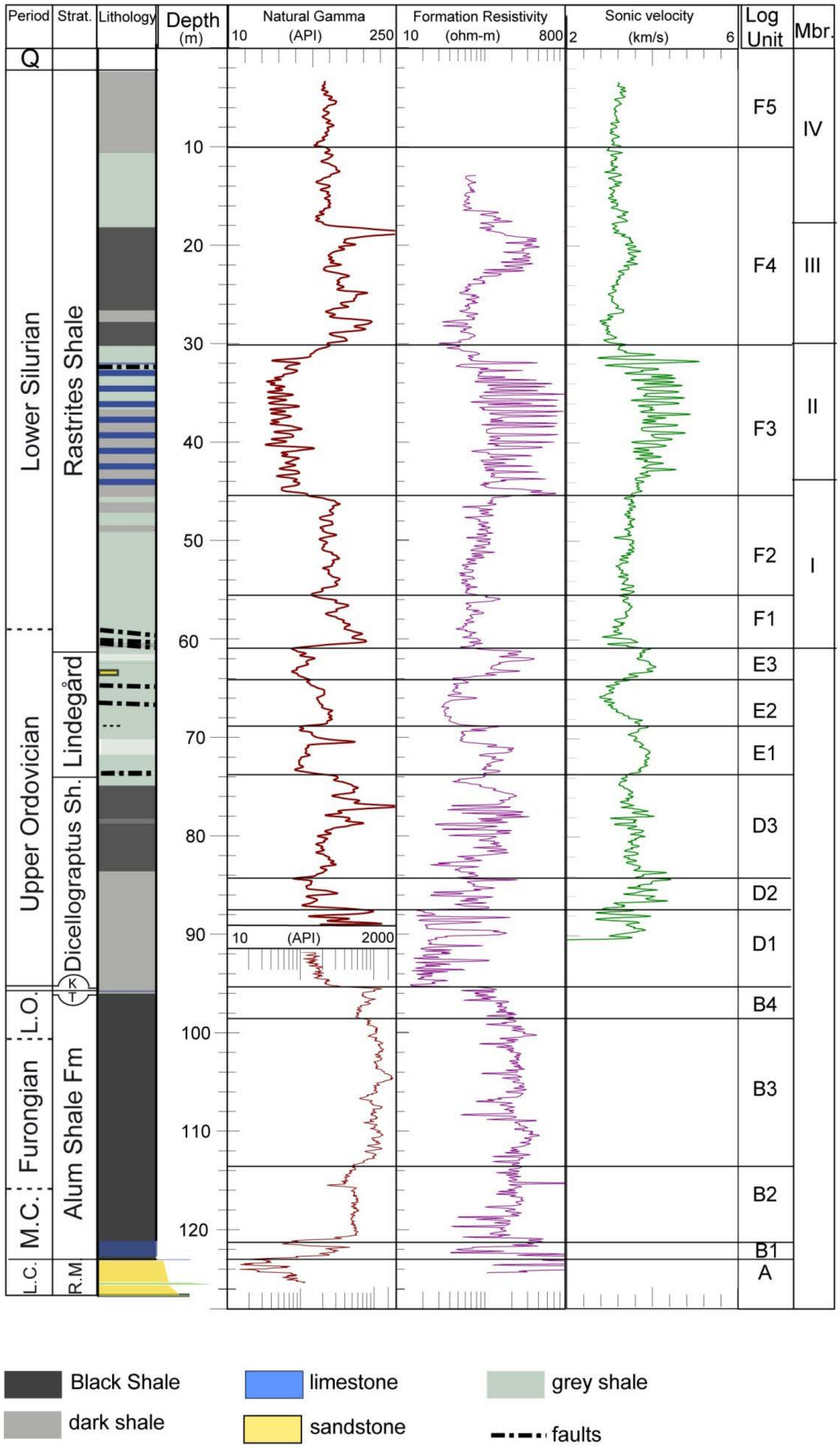

Figure 3. Gamma ray, formation resistivity and sonic velocity logs obtained in the Billegrav-2 bore hole.

3. Petrophysical characteristics

TOC estimation from gamma log

A relationship between core measured TOC concentrations and the U levels has been established and TOC values has been calculated from the core scanning U content (Figure 4). The calculated TOC values are in very good agreement with the measured TOC concentrations (Figure 4). Misfits between measured TOC and calculated TOC are seen, however, especially in the lower part of the organic rich D3 unit within the Dicellograptus Shale. Here high TOC values have been measured whereas only low TOC values have been calculated (Figure 4). In the upper part of the D3 unit there is a very good agreement between measured and calculated TOC concentrations.

In the F1 unit the opposite situation as seen in the D3 unit occur (Figure 4). In the F1 unit high TOC values have been measured only in the lowermost parts of the unit whereas the U concentrations are relative high throughout the whole F1 unit giving rise to overall high calculated TOC values. In the F4 unit of the Rastrites Shale there is a very good fit between measured and calculated TOC concentrations.

In the Alum Shale Formation there is a good match between calculated and measured TOC values (Figure 4). The calculated TOC content, however, tend to underestimate the TOC content compared to measured TOC concentrations in the Middle Cambrian and to overestimate the TOC content compared to the measured TOC content in the Furongian.

TOC content and sonic and density logs

Lower sonic velocities are generally seen in the TOC rich units compared to the sonic velocities in TOC lean units (Figure 5). A calibration between the sonic log and the TOC content has, however, not been made. The reason for this is that the sonic tool is also very influenced by the lithological variation and on the fracture intensity of the shale.

Also the density log is influenced by the presence of TOC in the shales (Figure 4). No attempts have been made to use the density log directly due to the presence of variable amounts of pyrite in the TOC rich parts of the formation which also influences the density of the organic carbon.

Porosity estimation from density log

The porosity has been calculated from the density log assuming a constant grain density of 2.9 g/cm^3 and a partial saturation by fresh water. The grain density used is about 0.2 g/cm^3 higher than the grain density estimated from core measurements. The fixed grain density was chosen to provide an overall fit with the measured He-porosities. A fixed grain density is probably incorrect due to the presence of variable amounts of light organic carbon. The calculated porosity log should therefore only be interpreted in a relative sense.

The core plug measured porosities range between 2-5% (Figure 4). The calculated porosities, however, show a much higher variability in the porosity and a strong relationship between porosity and lithology (Figure 4). The porosity log indicates relative high porosities in the TOC rich units i.e. the Alum Shale, the D3 and the F4 units (Figure 4). Part of this porosity might be related to the use of a fixed grain density in the well.

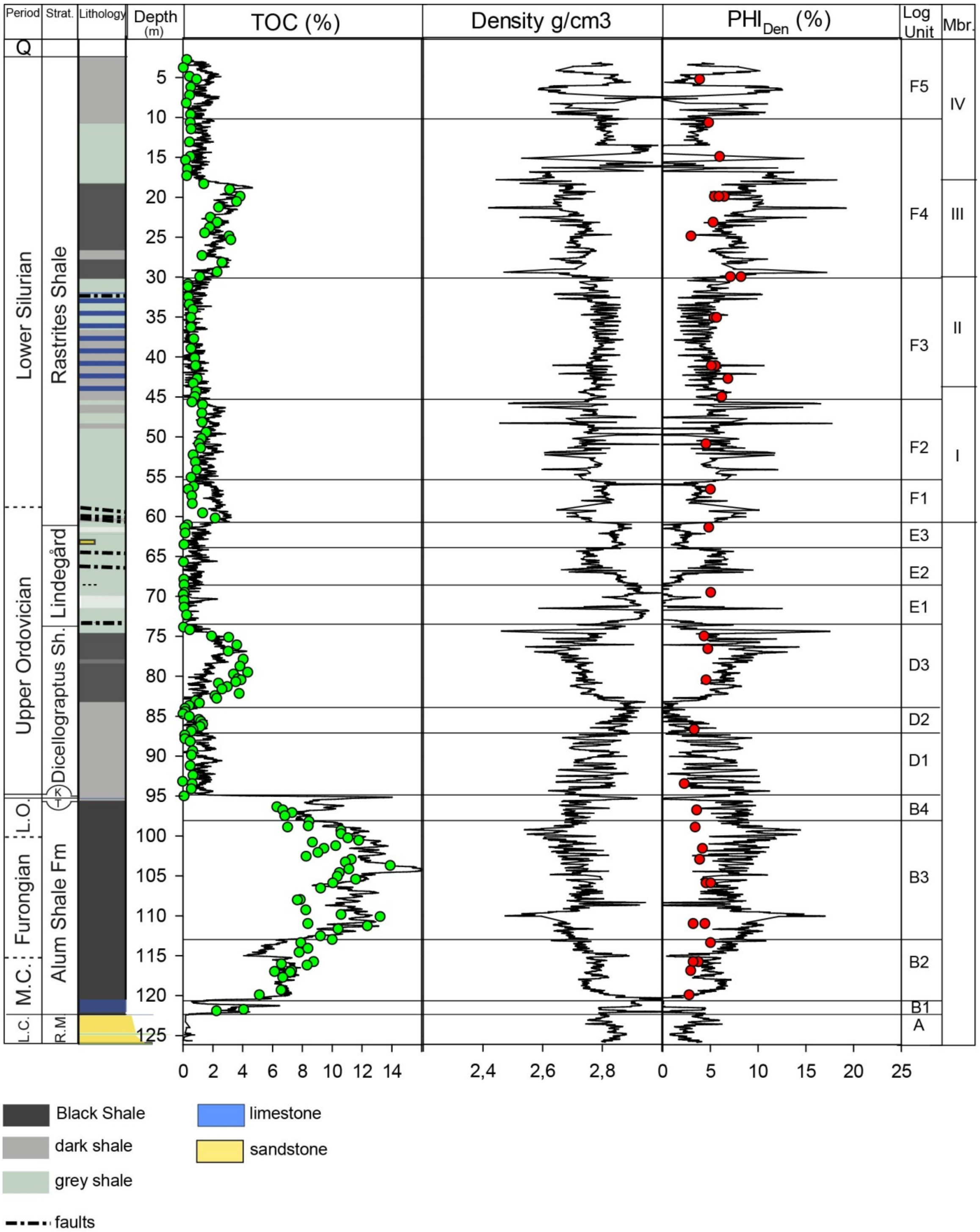

Figure 4. Left panel: TOC core measurements (green circles) and calculated TOC content ($TOC=0.72e^{(U-3)*0.59}$, black curve). Middle panel: Filtered core density log (running average of 11 cm). Right panel: He core porosities (red circles) and calculated porosity from core density log (assuming a grain density of 2.9 g/cm^3 and 50% saturation with a 1.0 g/cm^3 fluid, black curve).

Quartz variation and sonic response

The quartz content varies between 17-65% in the Billegrav-2 core (Figure 5). Relatively high quartz content are seen in the topmost part of the TOC rich units i.e. in the B4 unit of the Alum Shale, in the topmost part of the D3 unit in the Dicellograptus Shale and in the topmost part of the F4 unit in the Rastrites Shale. The increase in quartz content is interpreted to reflect high quartz influx during the high stand system tract.

The increase in quartz content in the TOC rich units impacts the sonic log response. In the B4 unit of the Alum Shale the sonic velocities increases despite general high TOC content (Figure 5). This increase in sonic velocities is attributed to the increase in quartz content.

The topmost TOC rich part of the D3 unit is characterised by high scatter in the sonic velocities (Figure 5). The samples with high quartz content appear to be from shales where high velocity beds occur (Figure 5). These beds possible reflect quartz rich intercalations in the shale.

The top of the F4 unit is characterised by relatively high sonic velocities despite high TOC content whereas only the lower part of the F4 unit are characterised by both high TOC content and low sonic velocities.

Carbonate variation and sonic response

The Lindegård E3 unit and the Rastrites F3 unit are relative carbonate rich and has carbonate content >25% (Figure 5). In addition carbonate rich beds occur in the Alum Shale both as primary limestone beds in the Middle Cambrian (Andrarum, Forsemölla and Exsulans limestone beds) and as concretions especially in the Furongian part of the formation (Figure 5).

The sonic log is very sensible to the changes in the carbonate content and relatively high sonic velocities are seen in all carbonate rich units (Figure 5).

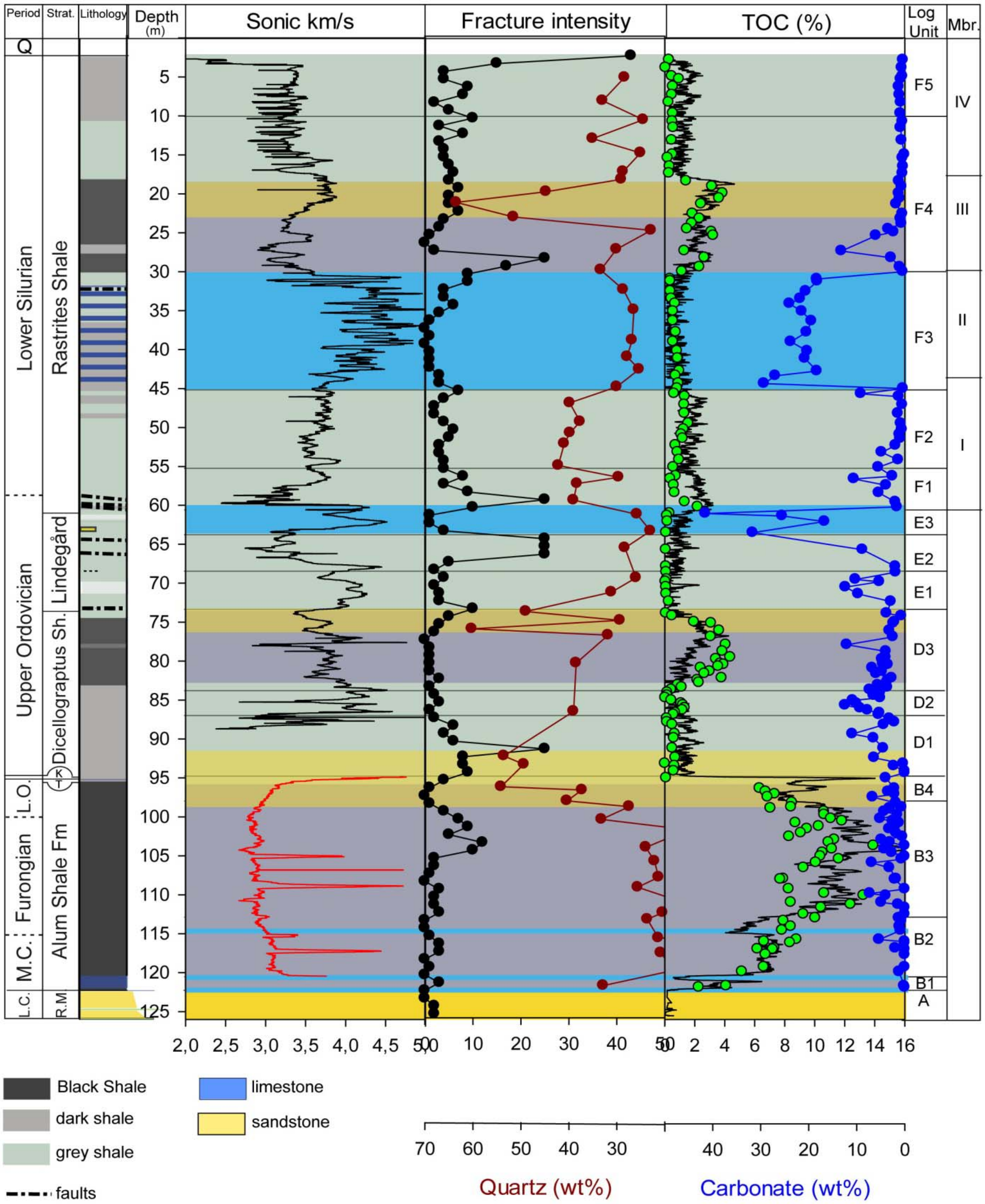

Figure 5. Left panel: Sonic log obtained in the Billegrav-2 well (black curve) and sonic log obtained in the nearby Skelbro-2 well (red curve). Middle panel: fracture intensity (black line), quartz content (red line). Right panel: TOC content (green line), calculated TOC (black curve), carbonate content (blue curve). Colour code for vertical: bars, yellow quartz content >40%; dark grey, TOC content >2 wt%; blue, carbonate content >20%; light grey, shale not characterised by elevated TOC, quartz and/or carbonate content. The sonic log obtained in the Skelbro-2 well has been fitted to the Billegrav-2 well by applying a depth shift of +88.2 m and a 0.8 compression factor for the depth scale.

4. Natural fracture network in Billegrav-2

Several faults and numerous fractures were observed in the core. The estimated fault throws are 7 m for the Lindegård Formation (notable in the E3 unit) and 1 m for the Rastrites Shale (in the F3 unit). No major faults occur in the Dicellograptus Shale or in the Alum Shale.

Several deformation phases have been identified and up to three generations of fracture formation have been distinguished.

Burial related fractures

Vertical to inclined fractures that may be cemented/headed with calcite cement. Pyrite fill may also occur. Healed factures occur predominantly in carbonate rich units suggesting a local source of the carbonate cement. Fractures filled with clay injected from bentonite layer occur predominantly in the D1 unit in the Dicellograptus Shale where bentonite beds occur frequently.

The fracturing and healing likely formed during deep burial in the Silurian.

Uplift and block faulting

A late phase of faulting/brecciating that cuts calcite cemented fractures. These fracture are associated with the major fault zones characterised by fracture intensities >15 fractures pr. m. The faulting and brecciating were likely generated during uplift and block faulting in the Mesozoic.

Glacial induced fractures

Horizontal to sub-horizontal fractures. The fractures occur frequently within the upper 20 m of the well. At greater depths these fractures do not occur. The fractures are interpreted to be formed by glacial induced shear stress and from loading-unloading induced stress by advances and retreats of glaciers

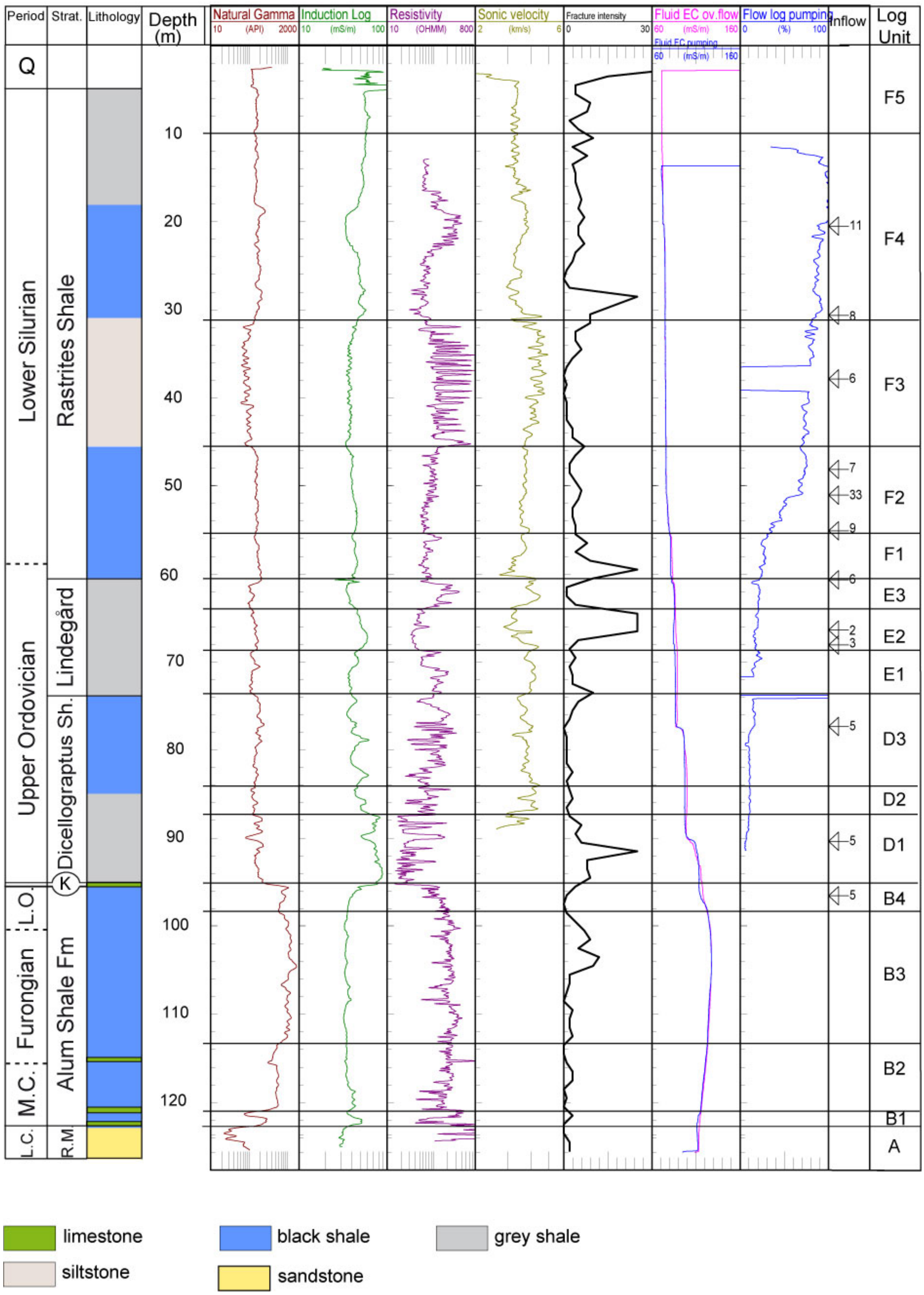

Figure 6. Down hole logs and water flow logs measured in the Billegrav-2 well. The fracture density log is shown in panel 5. Flow zones are shown with arrows to the right. Numbers indicate relative influx of water in the well.

Fracture distribution and water flow log

The water flow were investigated in the well and a total of 12 inflow zones were identified (Figure 6). The most important influx zone was in the F2 unit. Here 33% of the total flow in the well occurred through irregular fractures at a depth of 51 m.

Test pumping was made in order to quantify the water transmissivities in the well and the following transmissivities were found:

$T_{0\text{-}33m} = 1.29 \times 10^{-3} \times 0.19 = 0.24 \times 10^{-3} (m^2/min)$ – the F4 and F5 units in the Rastrites Shale

$T_{33\text{-}48m} = 1.29 \times 10^{-3} \times 0.06 = 0.08 \times 10^{-3} (m^2/min)$ – the F3 unit in the Rastrites Shale

$T_{48\text{-}59m} = 1.29 \times 10^{-3} \times 0.49 = 0.63 \times 10^{-3} (m^2/min)$ – the F1 and F2 units in the Rastrites Shale

$T_{59\text{-}90m} = 1.29 \times 10^{-3} \times 0.16 = 0.21 \times 10^{-3} (m^2/min)$ – the E1-E3 and D2-D3 units in the Lindegård and Dicellograptus shales

$T_{90\text{-}128m} = 1.29 \times 10^{-3} \times 0.10 = 0.13 \times 10^{-3} (m^2/min)$ – the D1 and B1-B4 units in the Dicellograptus and Alum shales

Largest transmissivities were found in the upper part of the well in the units with abundant horizontal to sub-horizontal glacial induced fractures. These appear thus to be hydraulic active. There was no flow associated with the larger faults possibly reflecting healing of these by smearing of clay on the fracture planes.

The carbonate rich E3 and F3 units appear to act as bafflers with respect to water flow. The reason for this is that these units have an overall low fracture occurrence and because the fractures that occur tend to be carbonate cemented/healed.

The Alum Shale and the underlying Rispebjerg Sandstone do not show any water bearing zones, and therefore have low transmissivity.

The high water influx in the F2 unit appear thus to reflect the combination of the presence of hydraulic active glacial induced fractures below a baffling zone (F3 unit) characterised by calcite healed fractures.

5. Summary: Shale gas prospective areas in Denmark

Potential shalegas shales occur in the Palaeozoic sequence in Denmark. These shales are preserved in most of sub-surface Denmark (Figure 7). The maturities of the shales range from thermally immature in central Sweden and Estonia to oil prone off-shore in the Baltic Sea and to gas prone in southern Sweden, Poland and sub-surface Denmark (Figure 9). Maturation occurred during the Late Silurian to Early Devonian in response to deep burial during the Caledonian orogeny. Erosion, uplift, and block faulting occurred during the Early Devonian (Figure 11).

The most organic rich shale in the Palaeozoic is the Alum Shale witch have on averages 9% TOC and range in thickness between 30-160 m (Figures 8 and 10). The porosities of the Alum Shale range between 2-5% (He injection) and a significant part of the pore system is within the micro-pore size range which gives a rather high storage capacity for sorbed methane (Pool et al. 2012). The quartz content in the Alum Shale range between 9–54% and the formation has an overall brittle fracture behaviour which will allow the formation to be stimulated by fracturing.

Additional shalegas potential occur in the Upper Ordovician and Lower Silurian shales. These units are, however, thinner (4-12 m), and has less TOC content (1-4%) than the Alum Shale. The lateral extensions of these shales are the main target for shalegas exploration in Poland.

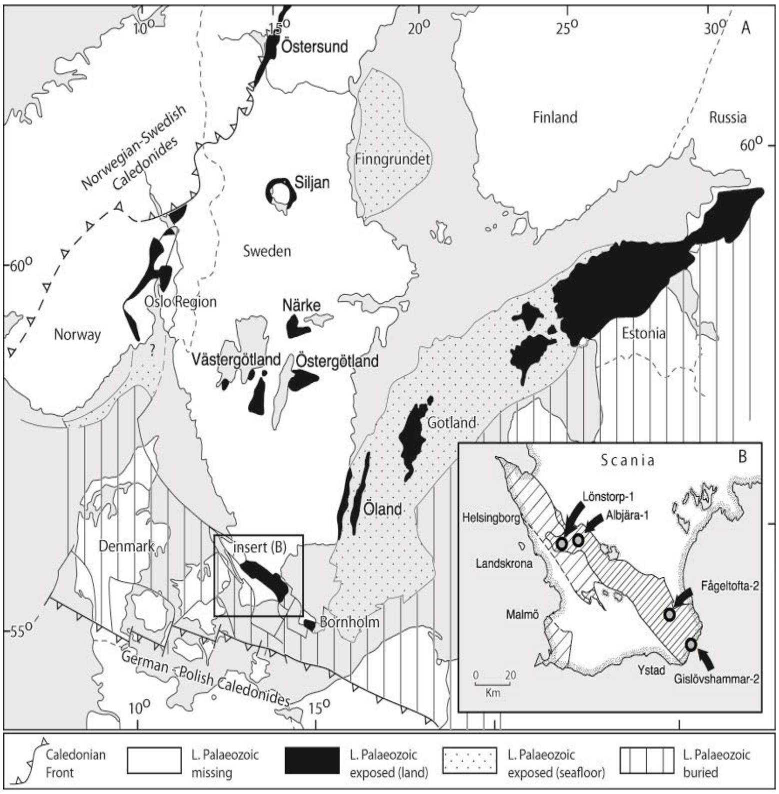

Figure 7. Distribution of Lower Palaeozoic strata.

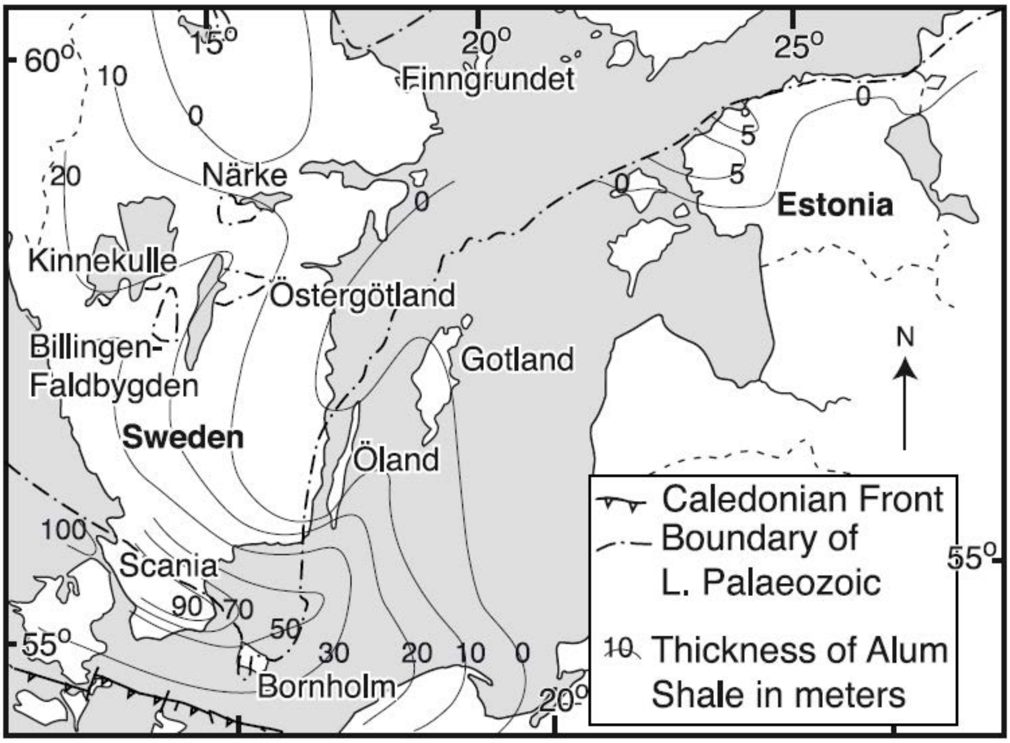

Figure 8. Thickness of the Alum Shale Formation.

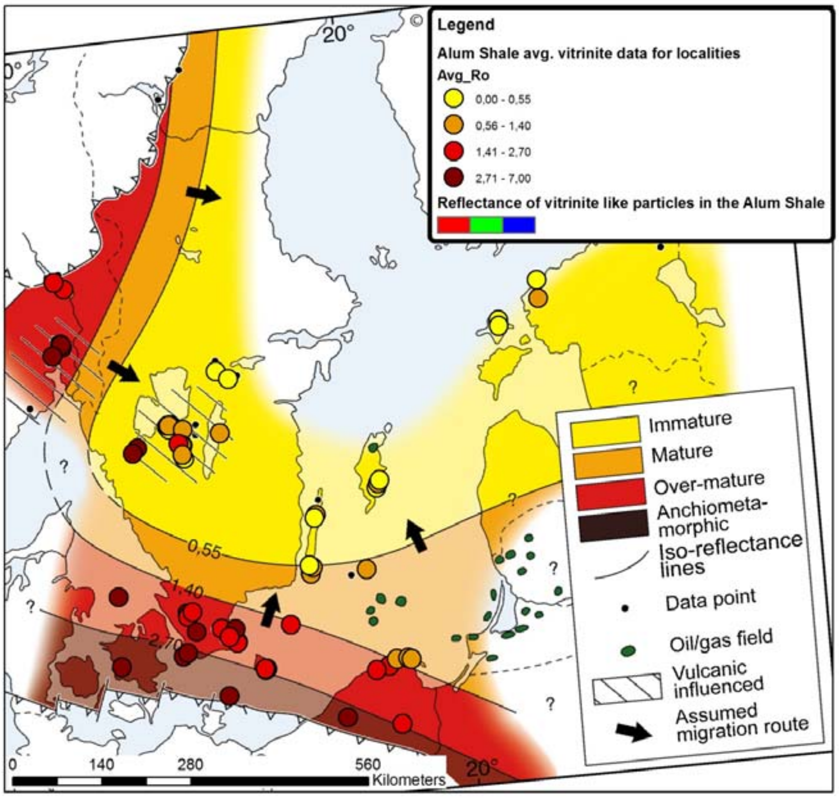

Figure 9. Reflectance of vitrinite-like particles in the Alum Shale. Note that the large range in maturity in Central Sweden is caused by heating of the shale by sills and dikes.

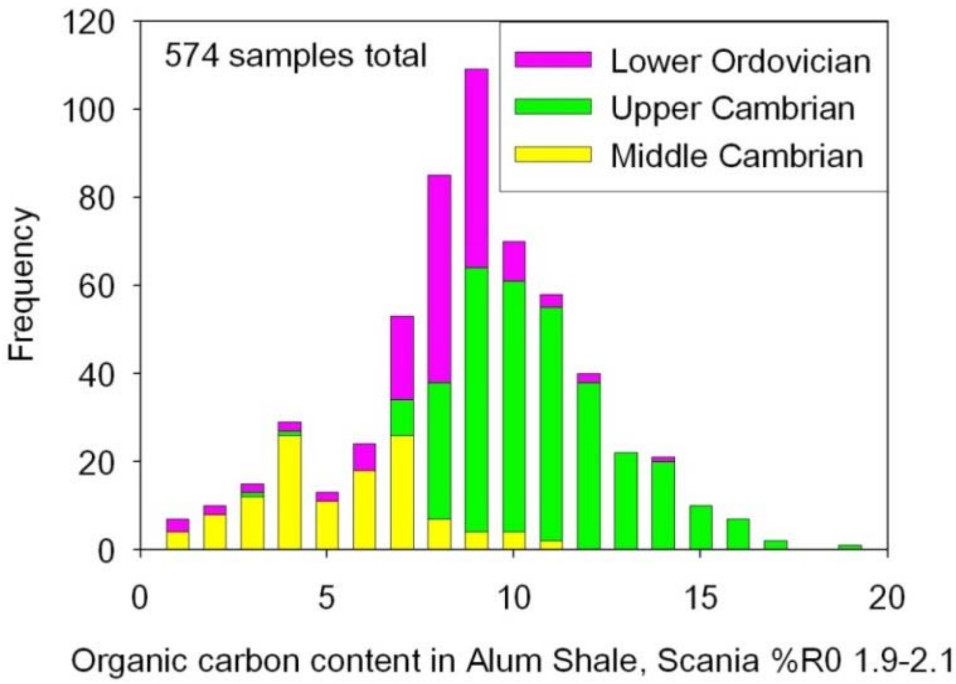

Figure 10. Stratigraphical distribution of TOC content in thermally mature Alum Shale. Middle Cambrian Alum Shale has on average 4.9±2.2% TOC, Furongian Alum Shale has on average 10.3±2.3% TOC and Lower Ordovician Alum Shale has on average 7.5±1.9% TOC.

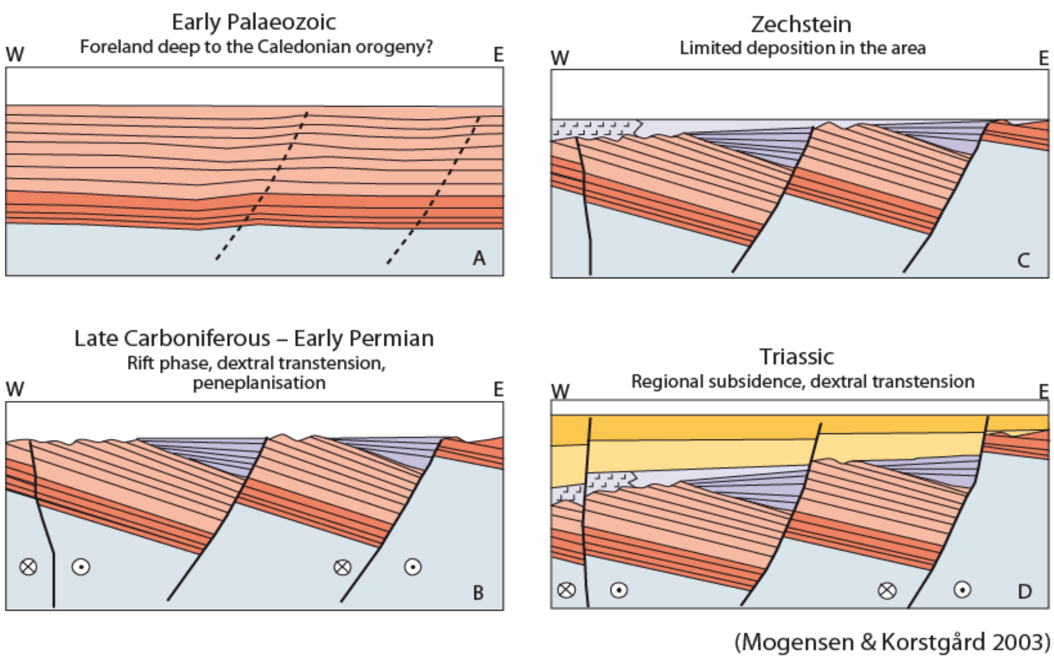

Figure 11. Geological development during the Palaeozoic in the Norwegian-Danish Basin. From Mogensen & Korstgård (2003).

Risk elements in an Alum Shale shalegas play

Exploration for shalegas in the Alum Shale was initiated by Shell in 2008 in Scania, southern Sweden, where the company between 2008 and 2011 drilled 3 wells and acquired 80 km of 2D seismic lines (Pool et al. 2012). According to Pool et al. (2012) the company found an excellent Alum Shale reservoir in terms of TOC, porosity, maturation, gas sorption capacity. The Alum Shale had, however, high water saturation (80%) and no commercial gas could be produced. Consequently the company released the area in 2011.

According to Pool et al. (2012) the main critical component in the Alum Shale shalegas play is the risk of gas retention in the shales. The reason for this is that maturation of the Alum Shale occurred in a foreland basin developed in the Silurian where the shales experienced burial depth of at least 4 km in the Scania-Bornholm area and possible >6 km within the Sorgenfrie-Tornquist Zone in Kattegat (Figure 12).

The deep burial was followed by extensive uplift in Devonian. The uplift was in the size order of several km. Accordingly, the shales were most likely de-pressurised in the Upper Palaeozoic to a depth that corresponds to the present day thickness on the Palaeozoic interval (Figure 14). Renewed burial of the Alum Shale occurred in the Mesozoic time but since the Alum Shale was newer re-buried to same depths as in the Palaeozoic then gas generation was not re-activated. Hence the possibility of a de-pressurized reservoir where free gas has migrated out and the sorbed gas level has re-equilibrated to an Upper Palaeozoic shallow burial depth is high (Pool et al. 2012).

Numerous dikes intruded in Permian due to prevailing extensional tectonic regime (Mogensen and Korstgård 2003). At this time the Oslo Graben magmatic province developed and in Kattegat, central Sweden, Scania and on Bornholm numerous dolerite dike and sills intruded in the Palaeozoic strata. Pool et al. (2012) argued that the magmatic activity likely both increase the temperature of the reservoir and created hydrothermal convection cells that may also has driven down the gas saturation and thus increased the water saturation.

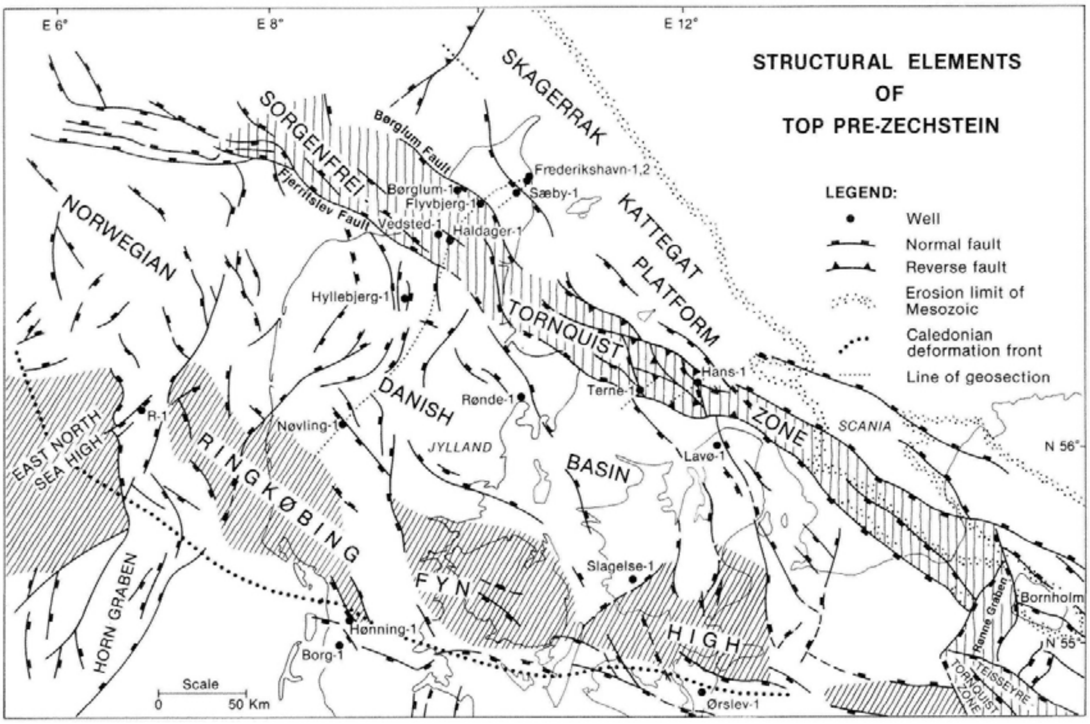

Figure 12. Structural elements at the top pre-Zechstein. From Michelsen & Nielsen (1991).

Prospective areas in Denmark for shale gas

Maps showing the depth to the Alum Shale and the thickness of the Palaeozoic strata have recently been published by Lassen & Thybo (2012). Based on these maps (Figures 13 and 14) and the main risk elements discussed by Pool et al. (2012) the prospective areas for shale gas in Denmark have been identified (Figure 14).

To outline the prospective areas a depth interval of 1-6 km to the base of the Alum Shale has been used. The thickness of the Palaeozoic sequence as shown in Figure 14 is taken as an indication of the minimum burial depth during the post Caledonian (Devonian) and hence to the depth level to which the shales de-pressurised to. The base of the Alum Shale that Shell drilled in Scania was about 1 km (Pool et al. 2012) and thus a buried depth shallower than 1.5 km is regarded to have no potential.

Applying the above mentioned cut-offs then the prospective areas are limited to essentially two areas in Denmark that has a thickness of Palaeozoic strata of at least 1.5 km and a current buried depth of less than 6 km (Figure 14). Both areas are currently held under licence for shalegas exploration.

Area 1: Northern Jutland

This area is bound northward by the Sæby/Frederikshavn fault and southwards by the Børglum fault (Figure 12). The area represents a tilted fault block as depicted in Figure 11. The thickness of the Lower Palaeozoic in the block is up to 4 km (Figure 14, Lassen & Thybo 2012). The depth of the base of the Alum Shale range between 2-6 km and the thickness of the Alum Shale is expected to range between 80-160 m. Maturity is expected to range between 2-4% Vr.

The prospective area is 600 km^2 and based on the methodology outlined by U.S. Energy Information Administration (2011) the technical recoverable gas amounts to 0.9 Tcf (Table 3).

Area 2: Northern Zealand

This area is fault bound; to the east by the ‘Öresund fault’ and to the west by the ‘Roskilde fault’ (Figure 13). The thickness of the Lower Palaeozoic is up to 4 km (Figure 14) and the depth of the base of the Alum Shale range between 2-6 Km. The thickness of the Alum Shale is expected to range between 80-100 m and the thermal maturity to range between 2-3% Vr.

The prospective area is about 400 km^2 calculated as the area where the Palaeozoic is more than 1.5 km thick (Figure 14). Based on the methodology outlined by U.S. Energy Agency the technical recoverable gas amounts to 0.6 Tcf (Table 3).

Table 3. Resource assessment in Denmark following the of US Energy Administration method. The result of the U.S. Energy Information Administration (2011) estimate is shown in the table.

	Prospective area	Resource pr unit*	Total resource	Risked GIP (20%)	Technical recoverable (25% recovery)
	km^2	Bcf/km^2	Bcf	Bcf	Tcf
Northern Jutland (area 1)	600	30	17838	3568	0.9
Northern Zealand (area 2)	400	30	11892	2378	0.6
Sum Denmark	**1000**		**29730**	**5946**	**1.4**
Denmark Total*	15496	30	460701	92226	23

*US Energy Administration

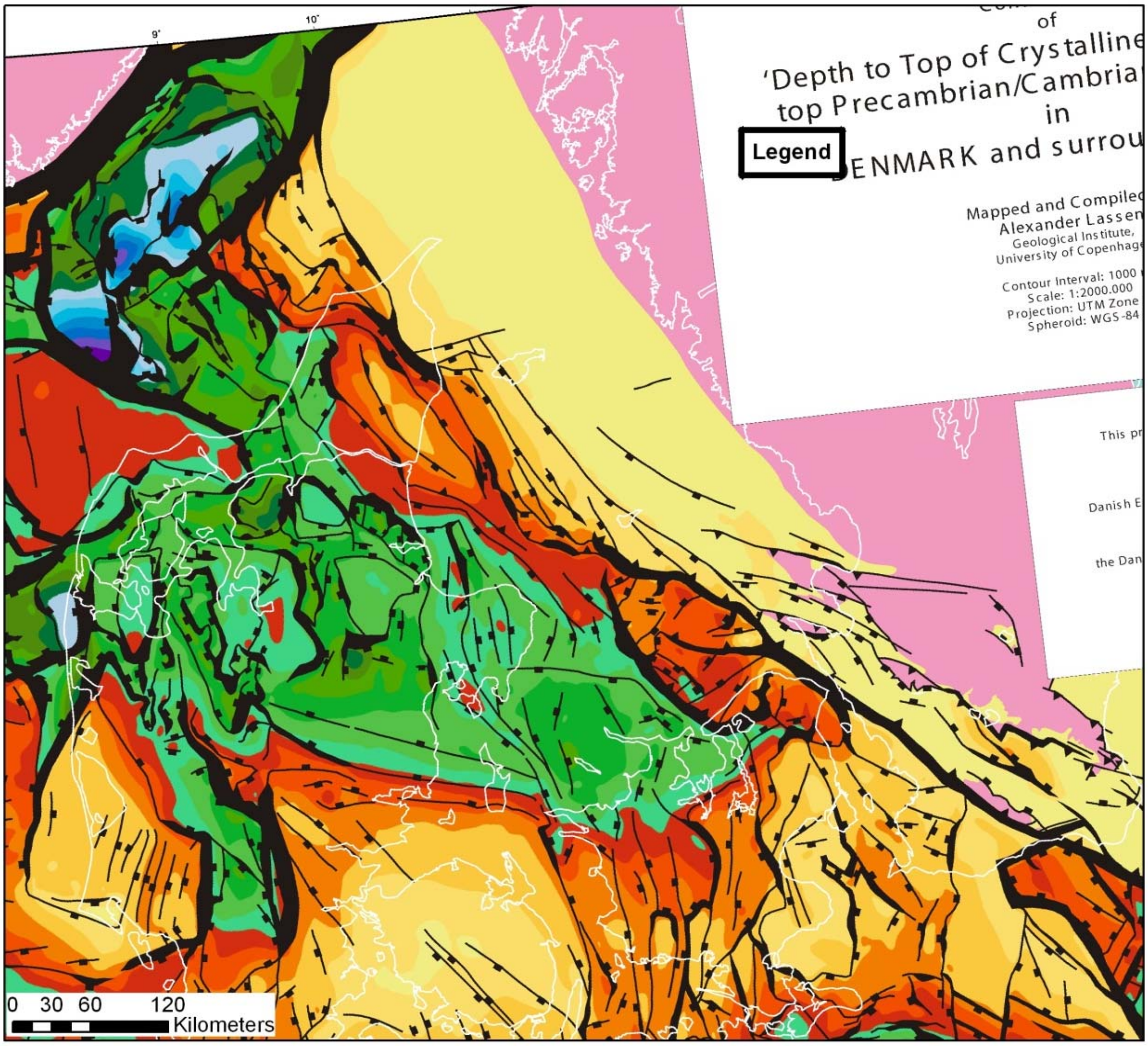

Figure 13. Depth to base of the Alum Shale (from Lassen & Thybo 2012). Legend: yellow, 0-1 km; orange, 3-4 km; green, 6-7 km. Prospective areas is interpreted to be within the yellow-red (1-6 km) depth interval (see Figure 14).

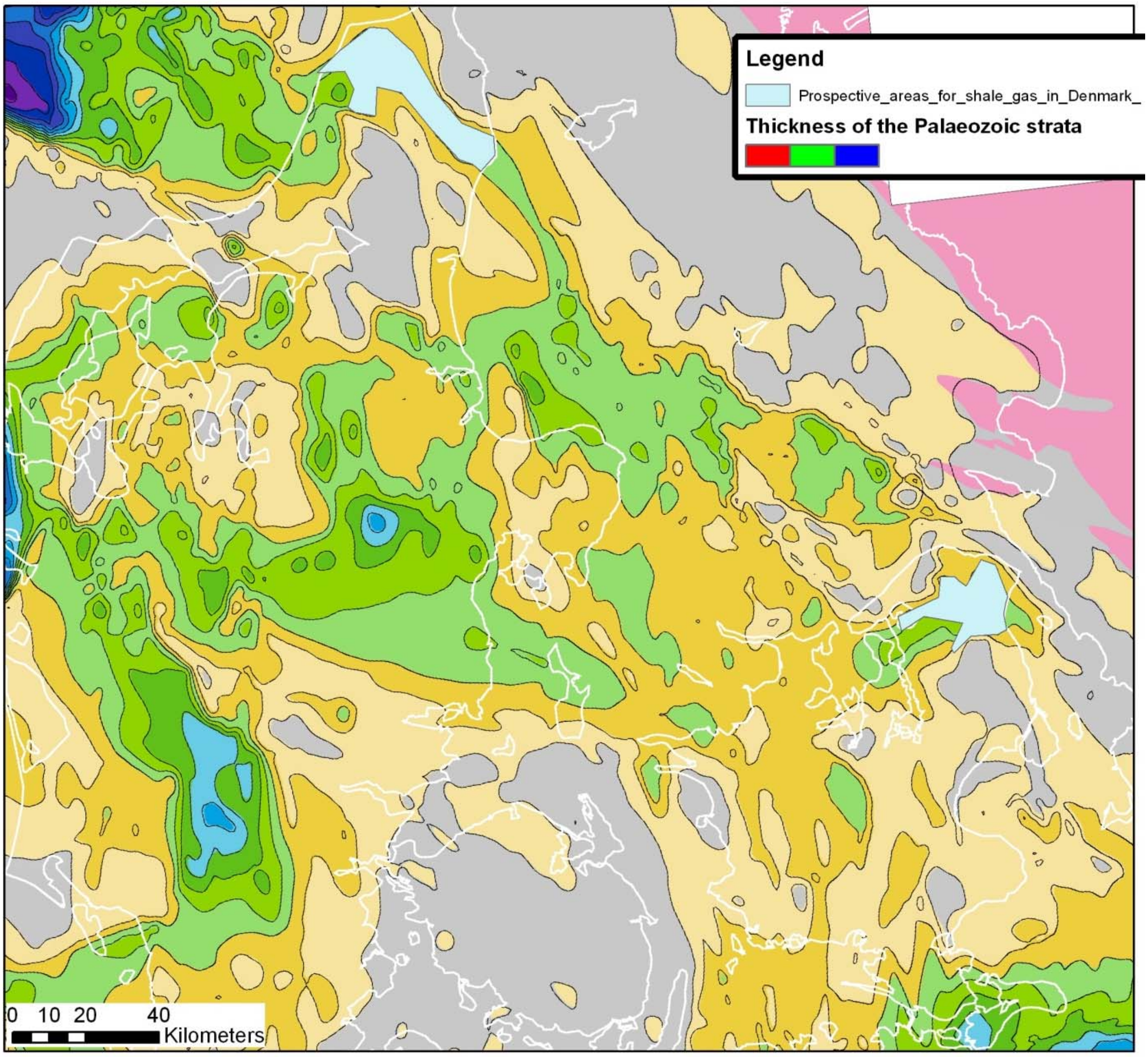

Figure 14. Thickness of the Palaeozoic strata (from Lassen & Thybo 2012). Thickness legend: light yellow, 0-1 km; dark yellow, 1-2 km; light green, 2-3 km; dark green, 3-4 km. Prospective areas are outlined in light blue. The area is expected to be within an area where the Palaeozoic strata are at least 1.5 km thick.

6. References

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7. Data included on CD

Attached to this report is a CD that contains the following documentation:

1. In folder *Appendix:*

   Excel file with calculated TOC concentrations and porosity

2. In folder *Gismodel* an ArcGis project with shape file of prospective areas for shale gas and other relevant maps for evaluating the prospectively
3. In folder *Literature*. Cited open source literature.
4. In folder *Tables* excel file with Tables presented in this report
5. A pdf of the report 'Integrated report on the Billegrav-2 (DGU 248.61) well.pdf'