DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2015/64

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1. Introduction

This report presents an update of the regional geological knowledge of the Alum Shale Formation on Zealand, Denmark, based on newly released well data from three exploration wells that drilled the Lower Palaeozoic shale succession from the Upper Silurian to the top of the Lower Cambrian in Sweden (Pool et al. 2012; Erickson 2012).

The aim of the report is to present updated thickness estimates for the Alum Shale Formation on Zealand and to identity the main geological events that controlled its distribution. To the extent that data have permitted it the organic rich Ordovician and Silurian shales are included in the analysis.

The Alum Shale Formation consists of dark organic rich mudstone with abundant disseminated pyrite. It was deposited from the Mid Cambrian to the Early Ordovician (Tremadocian). The depositional area extended more than 800.000 km^2 across the western and southern margins of Baltica (Figure 1). Throughout this area the Alum Shale lithology was remarkably similar. The lithostratigraphy is fairly simple and subdivision is mostly based on event beds (Nielsen & Schovsbo 2006). The geological knowledge of the Alum Shale stems mostly from biostratigraphical studies of which most dates back several decades and many were based on outcrops in streams and quarries. In recent years, however, data from drill-cores and wire-line logs have been available, which has added significantly new knowledge on the stratigraphical development of the Alum Shale and its lithological variation.

Based on wire-line data and core descriptions a log-stratigraphical frame-work for the Alum Shale Formation and the Lower Ordovician to Lower Silurian shales has recently been presented (Schovsbo et al. 2015a,b). The log-stratigraphy enables correlation of un-cored wells where no biostratigraphical data exist. In this report the new log-stratigraphy is used to evaluate the dispositional architecture of the Alum Shale along correlation profiles that extend across Zealand, Scania and the southern Baltic Sea. Based on this new evidence the geological model for the Alum Shale Formation is updated and thickness scenarios for the Alum Shale Formation and the Ordovician to Silurian TOC-containing shales on Zealand are presented.

The lithostratigraphy and palaeogeography presented here is based on the concepts developed by Nielsen & Schovsbo (2006, 2011, 2013, 2015). The log-stratigraphy presented here is based on concepts developed in Schovsbo et al. (2015a,b).

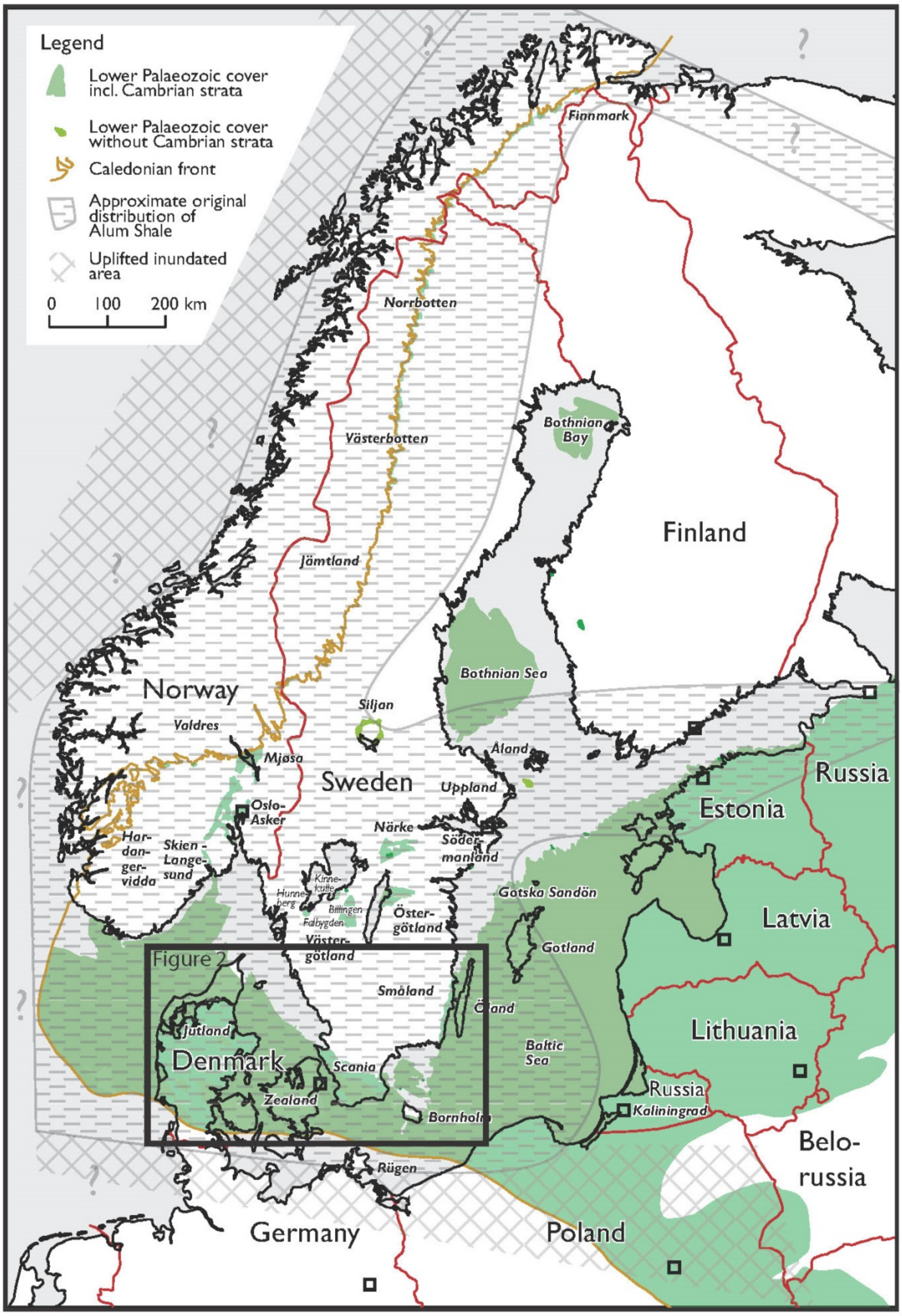

Figure 1. Distribution of Lower Palaeozoic strata with indication of the Alum Shale paleo-basin of the Alum Shale. The figure is based on Nielsen & Schovsbo (2011). The outlined area marks the study area for this report.

2. Updated litho- and log-stratigraphy for the Alum Shale

An updated lithostratigraphy for the Alum Shale Formation in southern Scandinavia is presented in Figure 2. In preparing this report the chart (Figure 2) has been expanded to also include Zealand (Slagelse-1) and Kattegat (Terne-1). In the Alum Shale Formation three new members with low organic content are recognised, namely the Middle Cambrian Terne Member, the Lower Ordovician Albjära Member, and the Lower Ordovician Brattefors Member (Figure 2). The facies types represented by the Albära and the Brattefors members have previously been included under the older term “Ceratopyge beds”. The Terne Member has not been recognised previously.

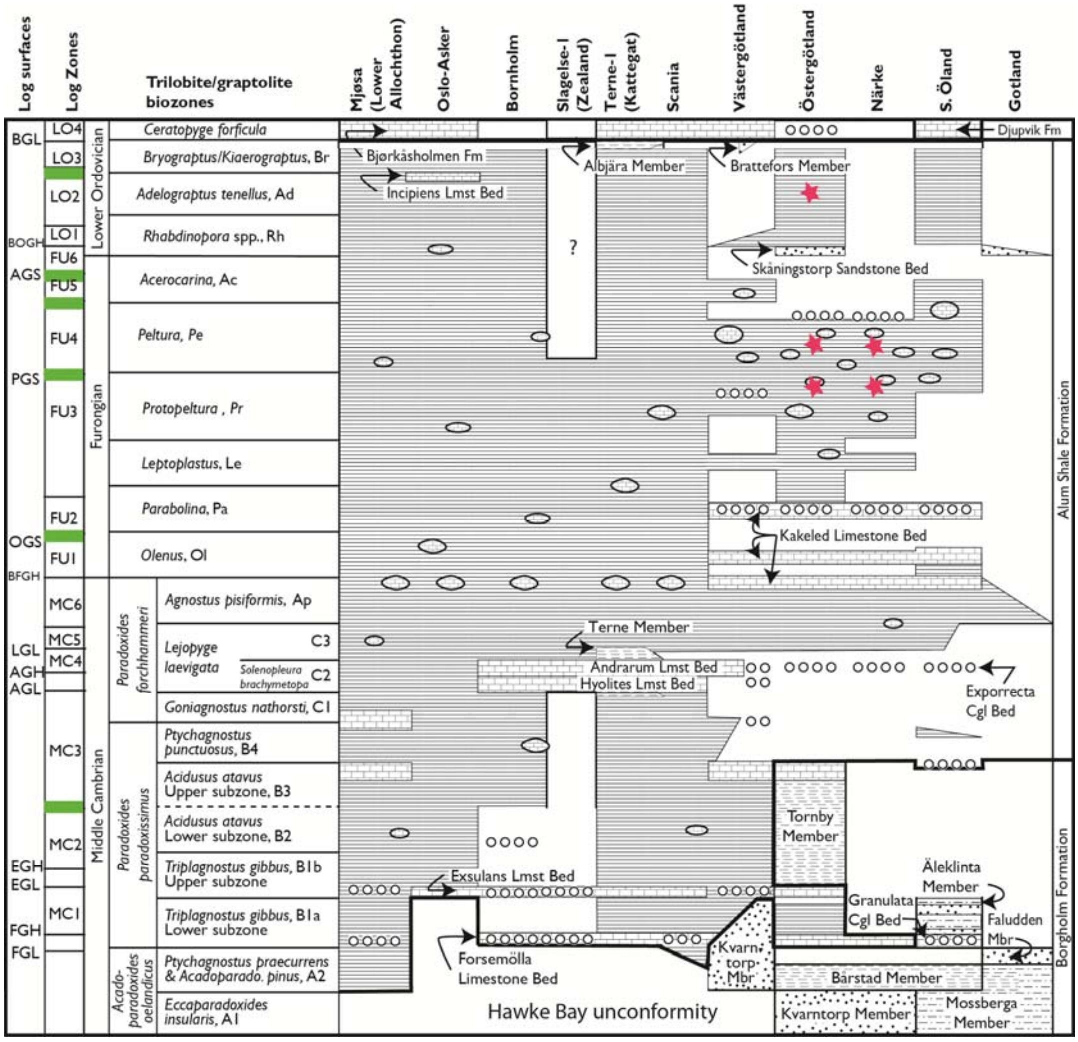

Figure 2. An updated lithostratigraphy of the Alum Shale Formation in Scandinavia with log units and surface pick acronyms. For localities see Figure 1. Modified and updated from Nielsen & Schovsbo (2006). Log zones of Schovsbo et al. (2015a) are included. Characteristic log surfaces are named and their acronyms are shown to the left. They include: FGL: Forsemölla Gamma low; FGH: Forsemölla Gamma high; EGL: Exsulans Gamma low. Red stars indicate stratigraphical positions of kolm nodules (cf. Schovsbo 2002).

The updated lithostratigraphic chart includes 18 log units. The log units were defined by Schovsbo et al. (2015a) based on wire-line log patterns, notably the gamma ray log in combination with the resistivity log or the sonic log. The log zonation is consistent with the biostratigraphical subdivision although the precise boundaries between the log zones and the biozones do not necessarily coincide. To ease identification of the most characteristic log zones some log zone boundaries have been named and an acronym is proposed for selected log surfaces (Figure 2).

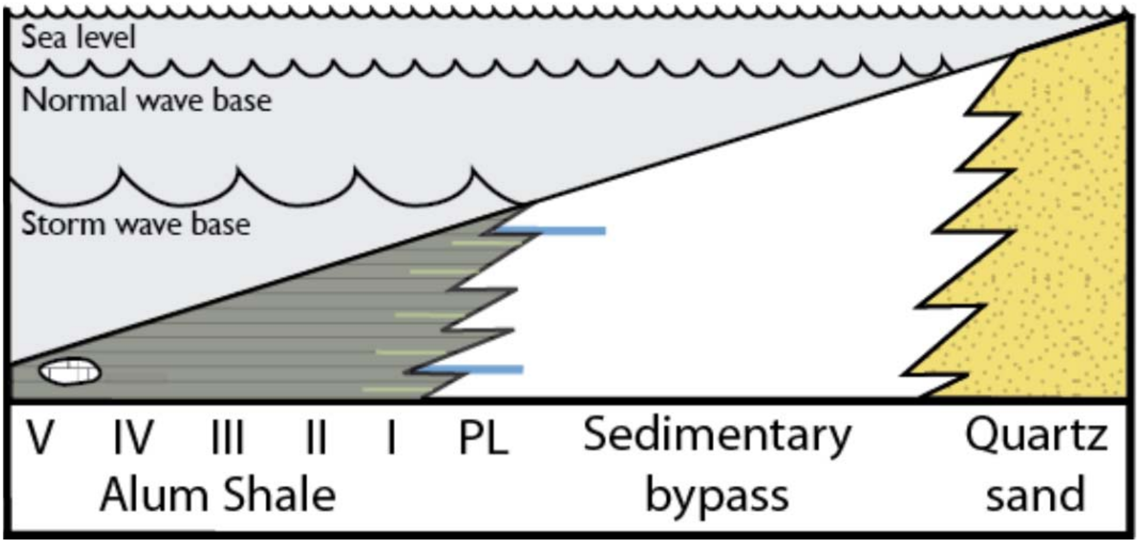

Figure 3. Simplified facies model for the Alum Shale. The number (I to V) refers to facies types described in the text. Blue horizontal lines indicate the zones where primary limestone such as the Forsemölla, Exsulans and Andrarum beds occur.

Lithological description of the Alum Shale Formation

The Alum Shale Formation consists of dark organic rich mudstone with abundant disseminated pyrite and was deposited from the Mid Cambrian to the Early Ordovician (Tremadocian) i.e. over a period of nearly 30 million years. In Denmark and Scania the formation contains a low proportion of diagenetic carbonate beds and was termed the 'outer shelf type' by Schovsbo (2002). Alum Shale with high proportions of carbonate including primary carbonates, carbonate conglomerates and diagenetic carbonate concretions are located in the south-central parts of Sweden and on Öland and was termed 'inner shelf type' by Schovsbo (2002). The Forsemölla, Exsulans and Andrarum limestone beds are all <1 m thick and occur in the lower part of the formation (Figure 2). These marker beds are primary bio-clastic limestones, and represent periods with elevated oxygen levels at the sea-floor that allowed for colonisation of diverse benthic faunas (Schovsbo 2001 and Nielsen & Schovsbo 2006). Such marker beds represent important stratigraphical horizons that are particularly easy to recognise on gamma ray logs due to their low GR response (Figure 2).

The Alum Shale is capped by the Bjørkåsholmen Fm that is a 1.5 m thick cold water bio-clastic carbonate unit that contains variable amounts of clay, phosphorite and glauconite.

Within the Alum Shale five facies types, labelled I to V, have been recognized (see also Figure 3). Facies type I is interpreted to represent the shallowest and best oxygenated facies and facies type V is interpreted to represent the deepest and most oxygen depleted facies. Type V is further subdivided into a highly pyritic facies type and a barite-containing facies type. Below is a brief description of the facies types with reference to the occurrence in the Albjära-1 core (Figure 4).

Core photo 1. Core photo of the core-boxes 26-28 from the Albjära-1 well showing a part of the Middle Cambrian. The black Alum Shale in box 28 and left part of Box 27 is black high TOC rich Alum Shale of facies type IV. The Andrarum Lmst is present in the right part of box 27 and in the left part of box 26. The Alum Shale above the Andrarum (right part of box 26) is organic clean and assigned to the new Terne Member. Photo: Niels Schovsbo.

Type I: A silt streaked laminated shale with thin silt bands, < 2 cm thick. No carbonate concretions occur. Some irregularly shaped pyrite concretions up to a couple of cm thick may occur. The TOC content is low to moderately high. In the Albjära-1 well the interval c. 136.8-top of formation (upper part of the Tremadocian) is characterized as type I facies. The same facies is locally seen in the Middle Cambrian of eastern Scania. The Albjära Member is composed of this facies type; it shows an increasing abundance of silt bands upwards.

Type II: Shale where bands of blackish shale alternate with bands of dark grey shale; individual shale bands are from 1-5 cm thick. No limestone concretions occur. Low TOC content and macroscopic pyrite content is moderate hig; low content of dissiminated pyrite is seen on macroscopic inspection. This facies type occurs below and above the Andrarum Lmst up to about 209-210 m in the Albjära-1 core (upper boundary is gradual over a metre). This stratigraphic interval is much more expanded in the Terne-1 well. Facies type II (more blackish than greyish), constituting the Terne Member, occurs down to 0.75 m below the Andrarum Lmst in the Albjära-1 core.

Type III: Blackish laminated mudstone with numerous very small rounded limestone nodules, 0.5-1 cm in diameter. No visible dissiminated pyrite, macroscopic pyrite nodules rare; no large stinkstone concretions. Comparatively low TOC content. The facies is present below the Exsulans Lmst Bed and in the Albjära-1 core also a short interval in the Tremadocian between 136.8-138.7 m.

Type IV: Relatively homogenous, laminated Alum Shale; macroscopic pyrite rare and low content of dissiminated pyrite. Carbonate concretions may occur but are not common. The TOC content is moderately high. This facies characterizes the Middle Cambrian interval between the Exsulans and Andrarum limestone beds except immediately below the Andrarum Limestone. In the Albjära core, facies type IV also characterizes the uppermost part of the Furongian and the basal Tremadocian, interval c. 150-142.2 m.

Type V-a: Blackish, laminated, usually highly pyritic (dissiminated) shale with occasional stinkstone nodules (more common than in the other Alum Shale facies). Comparatively large pyrite nodules occur (up to some 5 cm in diameter), but dissiminated pyrite dominates. The facies is characterised by high TOC content. In the Albjära-1 well this facies type characterizes core interval 206.6-c. 150 m (base of *A. pisiformis* Zone - most of the Furongian). In particular the interval 162.6-171.5 m but also 176.9-179.8 are very rich in dissiminated pyrite (subtype V-b). Dissiminated pyrite less common between c. 197-202.2 m. Interval 210-206.6 m transitional between subtypes IV and V.

Type V-b: As for type V-a but very rich in dissiminated pyrite.

Type V-c: Laminated Alum Shale containing barite, occurring as whitish nodules, often rhomb-shaped, up to c. 1 cm in diameter, concentrated in distinct horizons. TOC content is moderately high. No large limestone concretions are seen in this facies in the Albjära-1 core. Barite and pseudomorphs after barite is common at several levels in the Furongian Alum Shale of Bornholm and eastern Scania but for unknown reasons rare in the Albjära-1 core. Within the Albjära-1 core, facies type V-c characterizes the interval 142.2-138.70 m (Tremadocian). Barite is particularly common in the interval 140.2-139.5 m and rare/sporadic above this level, where pyrite in bands (dissiminated) is common.

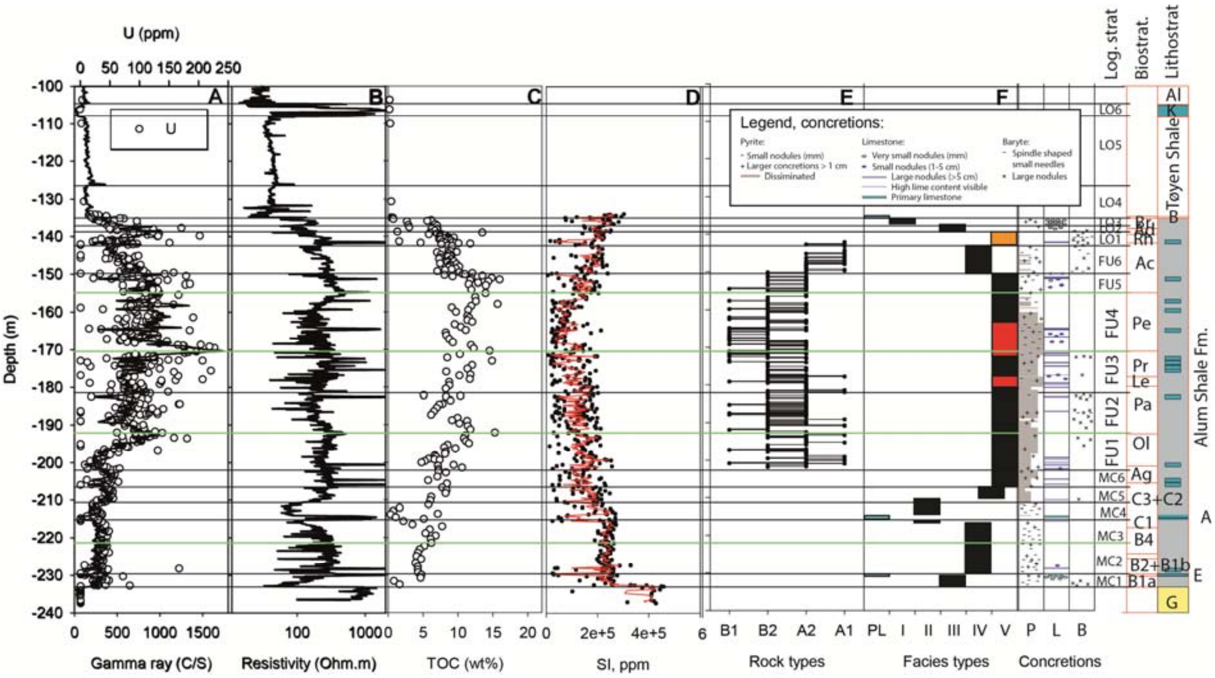

Figure 4. The Albjära-1 well showing A) gamma log, B) resistivity log, C) TOC content, D) Si content, E) PCA defined rock types , F) facies types and concretions type and distribution. The log stratigraphical units (MC1-MC6, FU1-FU6 and LO1-LO6) are also shown.

<u>The Terne Member</u>

The Mid Cambrian Terne Member (new) has been recognised in the fully cored Albjära-1 bore hole where it is 5 m thick and from log correlation it is interpreted to be 18 m thick in the un-cored Terne-1 well. The unit may also be present in the Lövestad A3-1 well in Scania judging from the log signature. The member is bounded downwards by the Andrarum Limestone Bed. The unit consist of grey to dark green mudstone of facies type II. Up to 1 cm thick dark Alum Shale intercalations occur in the unit. The upper boundary to the Alum Shale of type IV is gradual.

The member is recognised on wire-line logs by its low gamma ray response combined with its TOC lean shale sonic velocities (medium values) and formation resistivity (medium to high values) signature. This combination separates it from the underling Andrarum Limestone that has low gamma ray readings and high sonic interval time and resistivity values. The Terne Member is readily distinguished from typical Alum Shale that are characterised by high gamma ray readings and low sonic velocities and a high formation resistivity.

The unit formed during a sea-level low stand characterised by oxygenation of the sea-floor environment causing reduced accumulation of TOC in the mud. Depositional rates were probably higher than average for the formation due to winnowing of more proximal sites. The presence of intercalations with black Alum Shale of type III in the Terne Member resembles the interfingering of black Alum Shale facies types with more organic lean mud seen in the Tornby Member of the Borgholm Formation (c.f. Nielsen & Schovsbo 2006).

The Albjära Member

The Ordovician Albjära Member (new) is recognised in the Albjära-1 core and is interpreted also to be present in the Terne-1 well. In the Albjära-1 well it is 1.3 m thick and log correlation suggests that it is 5 m in the Terne-1 well. The unit consists of grey-dark green low TOC rich shale with abundant silt streaks. The unit shows a gradual transition to dark black Alum Shale. The unit is interpreted to represent increases oxygen content at the sea-floor and reduced accumulation of TOC in the mud leading up to the Bjørkåsholmen Fm that cap the Alum Shale Formation. The Albjära Member has previously been assigned to the Ceratopyge shale that was included in the Alum Shale Formation by Nielsen & Schovsbo (2006). The occurrence of this transitional bed is rarely preserved due to the erosion associated with the so called Ceratopyge Regressive Event that typical give an erosive nature of the top of the Alum Shale.

The Albjära Member consists of facies type I as described above.

The Albjära Member is characterised by low gamma ray and intermediate sonic velocity and formation resistivity compared to that of the typical Alum Shale Formation. In the Albjära-1 well the gamma ray log shows a gradual decline in readings throughout the Lower Ordovician. This reflects the gradual transition of the facies types seen in the core (Figure 4). In the Terne-1 well the topmost part of the formation is characterised by a very gradual decrease in the Gr response accompanied with gradual increase in sonic interval times reflecting a lower TOC content in the shale. This pattern is interpreted to indicate the presence of the Albjära Member. The member is capped by the Bjørkåsholmen Fm that is a thin bioclastic carbonate bed.

The Brattefors Member

The Brattefors Member (new) is a sandy to silty mudstone rich in glauconite. It is preserved locally in small collapse structures in Västergötland (Figure 2). The unit has previously been included in the Ceratopyge beds. The Member is capped by the Bjørkåsholmen Fm that is a thin bioclastic carbonate bed.

Log stratigraphy

The log stratigraphical subdivision of the Alum Shale is presented in Figure 2 and an example of the subdivision of the Alum Shale in the Albjära-1 well is presented in Figure 4. The Middle Cambrian shale is divided into eight units viz. three limestone zones representing the Forsemölla, Exsulans and Andrarum Lmst beds, respectfully, and six shaly units (MC1-MC6). The MC4 unit includes only the Terne Member (Figure 2).

The Furongian is divided into six units (FU1 to FU6). The most characteristic log signatures are the gamma ray responses across the boundaries between FU1 and FU2, termed the OGS (*Olenus* Gamma Spike), and between FU3 and FU4, termed the PGS (*Peltura* Gamma Spike) (see Figure 2).

The Lower Ordovician is divided into three log units (LO1-LO3). The Albjära Member occurs in the topmost parts of the LO3 log unit.

3. Geological results from the Shell wells in Scania

As part of an exploration program for shale gas in the Alum Shale the company Royal Dutch Shell plc. (Shell) drilled three wells in Scania (Figure 5). According to Pool et al. (2012) the Alum Shale did not contain any producible hydrocarbons in any of the wells and in May 2012 Shell relinquished the licence areas (Colonus Trough and Höllviken Graben) back to the Swedish authorities. According to Swedish law the data are released to the general public three years after a licence has been relinquished and thus the data obtained in the wells has recently been available for the geological analysis presented here.

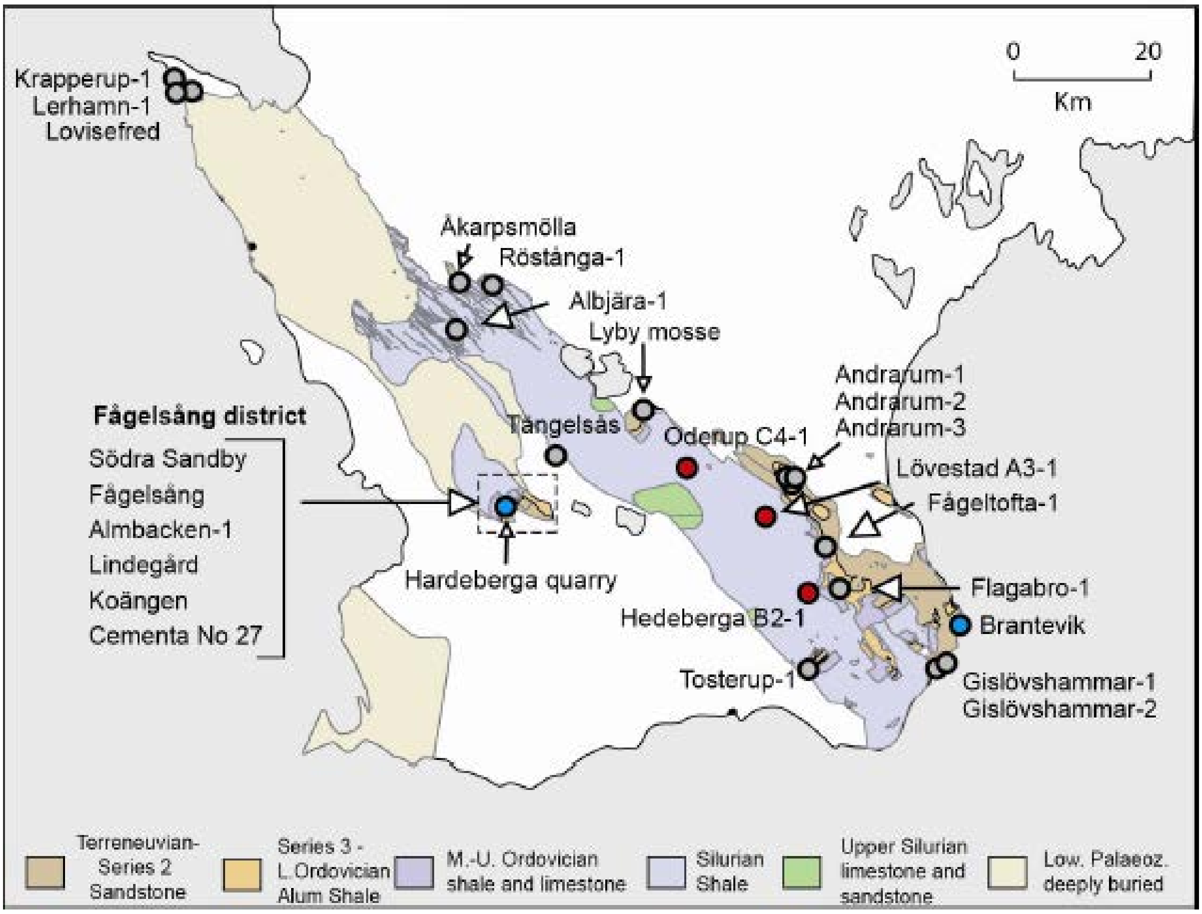

Figure 5. A geological map of southern Sweden (Scania) with drill location of selected wells. The wells drilled by Shell in 2009-2011 as part of their shale gas campaign are marked with red circle and includes: Oderup C4-1, Lövestad A3-1 and Hedeberga B2-1. Terreneuvian-Series 2 corresponds to the term Lower Cambrian used here; Series 3 corresponds to the Middle Cambrian. Map from Eriksson (2012).

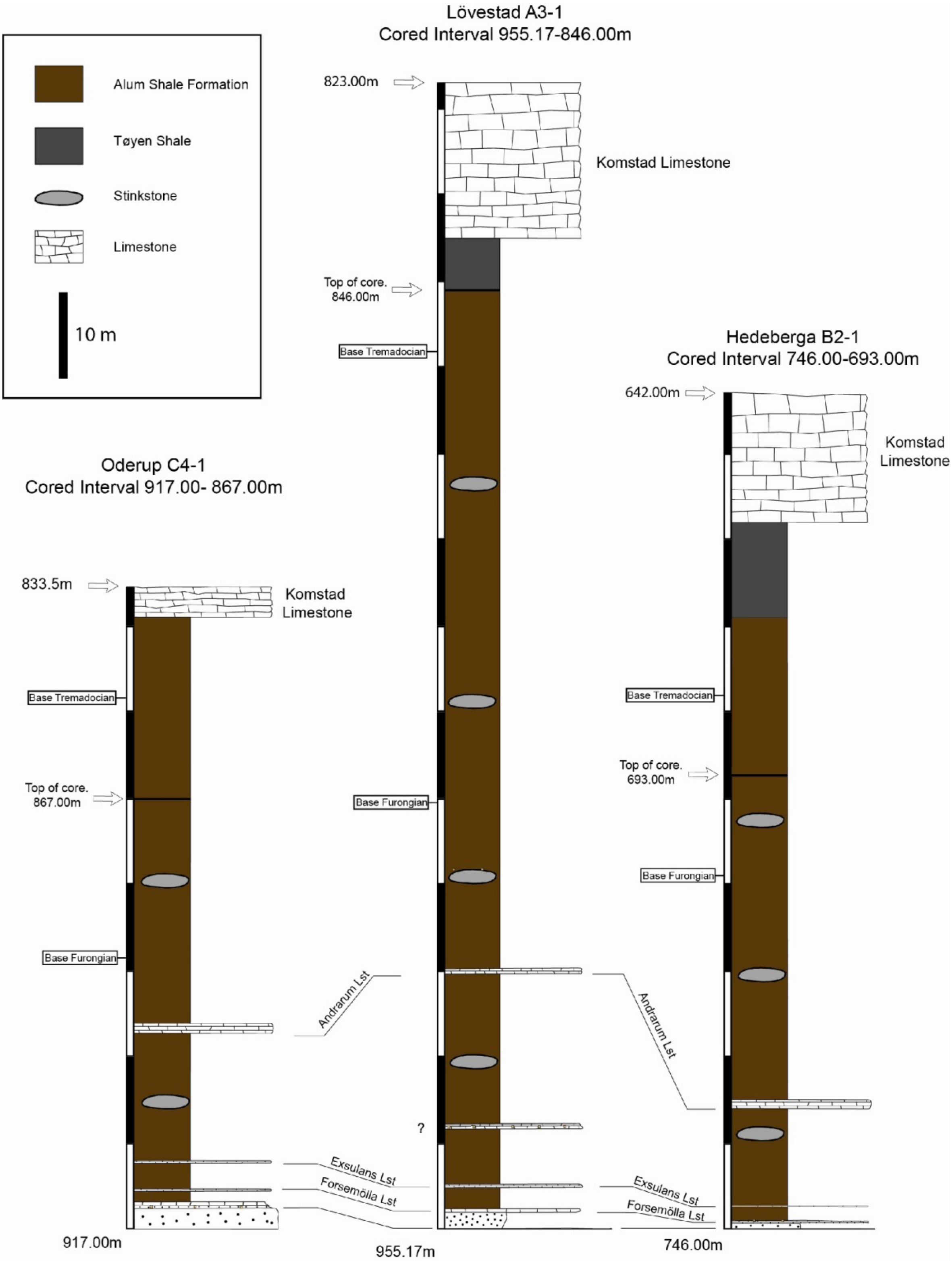

Figure 6. Overview of the Alum Shale Formation drilled in the Oderup C4-1, Lövestad A3-1 and Hedeberga B2-1 wells. In neither of the wells were the uppermost part of the Alum Shale Formation cored. The cores have not been available for inspection when this report was made. From Eriksson (2012).

Overview, gas shows and wire-line data types obtained in the wells

The data available for the geological evaluation of the wells released by the Swedish authorities includes well logs and final well reports. Below is provided a short overview of the log types and gas shows encountered when drilling the wells as it was presented in the final well reports. A full evaluation of geological findings apart from those apparent from the log correlation panels is outside of the scope of this report.

Hedeberga B2-1

The Alum Shale is 61 m thick and was drilled between 685-746 m. Logs were measured only in the 6¼ hole (reservoir section). Clay minerals were dominated by illite (40-48%), quartz range between 25-28% and TOC range between 1.5-12.8%.

Table 1. Logs obtained in the Hedeberga B2-1 well.

	Run	Log Description	Date	Interval (m BGL)
6 ¼'' Section	1	Natural gamma ray, Focused Resistivity (Century 9072)	05/06/2010	0-749
	2	Natural gamma ray, Sonic	05/06/2010	0-750.1
	3	Spectral Gamma Ray (Geovista)	05/06/2010	0-749.68

Table 2. Hydrocarbon breakdown and gas ratios for gas peaks at various depths in the Hedeberga B2-1 well.

Hydrocarbons Breakdown								Gas Ratios				
Depth	C1 ppm	C2 ppm	C3 ppm	iC4 ppm	nC4 ppm	iC5 ppm	nC5 ppm	C1/C2	Inverse Oil	Wetness	Balance	Character
625.6	13223	232	14	2	0	0	0	57	778	1.8	791	0.2
689.6	14354	766	10	2	0	0	0	18.7	1104	5.1	1163	0.3
700.6	6930	582	7	0	0	0	0	11	770	7.8	835	0.3
710.4	7851	588	7	0	0	0	0	13.4	872	7.1	938	0.3
717.8	8818	575	7	0	0	0	0	15.3	980	6.2	1044	0.3
724.7	9900	839	10	0	0	0	0	11.8	825	7.9	895	0.2
725.7	13989	1190	15	0	0	0	0	11.8	823	7.9	893	0.1
730.9	8721	914	11	0	0	1	0	9.6	670	9.6	741	0.2

<u>Lövestad A3-1</u>

The Alum Shale was 98.5 m thick and drilled between 851-949.5 m. Logs were measured both in the 8½ and the 6¼ section in this well, however, only the logs measured in the 6¼ section (reservoir section) were included in the data delivery. Clay minerals were dominated by illite (35-51%), quartz range between 22-31%, TOC range between 3.5-13.7%.

Table 3. Logs obtained in the Lövestad A3-1 well.

	Run	Log Description	Date	Interval (m BGL)
8 ½'' Section	1	Sonic (9310 century) and Gamma Ray	18/01/2010	0-845.1
	2	Dual Guard Resistivity + Gamma Ray	18/01/2010	0-845
	3	Acoustic Televiewer (azimuth and inclination data)	19/01/2010	0-847
6 ¼'' Section	1	Sonic (9310 century) and Gamma Ray	31/01/2010	829.91-957.75
	2	Neutron + deep guard resisitivity + gamma ray (9072 century)	31/01/2010	0-955.37
	3	Compensated Density (9139 century)	31/01/2010	826.85-955.26
	4	Borehole fluid temperature + resistivity + 3arm caliper	31/01/2010	0-954.7
	5	Spectral gamma ray	31/01/2010	0-956
	6	Sonic (Geovista) - failed at 630m	31/01/2010	-
	7	Acoustic Borehole Televiewer	31/01/2010	830-954.6

Table 4. Hydrocarbon breakdown and gas ratios for gas peaks at various depths in the Lövestad A3-1 well.

	Hydrocarbons Breakdown							Gas Ratios				
Depth	C1 ppm	C2 ppm	C3 ppm	iC4 ppm	nC4 ppm	iC5 ppm	nC5ppm	C1/C2	Inverser Oil Ind	Wetness	Balance	Character
649	9252	179	9	1	0	1	0	51.69	841	2.01	857	0.22
673	11280	214	9	1	0	1	0	52.71	1025	1.95	1044	0.22
757	23316	372	10	1	0	1	0	62.68	1943	1.62	1974	0.20
787	23745	494	12	1	0	1	0	48.07	1696	2.09	1731	0.17
796	28904	597	11	1	0	1	0	48.42	2223	2.07	2269	0.18
874	24846	967	10	0	0	0	0	25.69	2485	3.78	2375	0.09
917	22824	771	7	0	0	0	0	29.60	2922	3.30	3021	0.12

Oderup C4-1

The Alum Shale here is 76.3 m thick and was drilled between 836-912.3 m. Logs were obtained both in the 8½ and in the 6¼ section (reservoir section). Clay minerals were dominated by illite (52-51%), quartz range 25-33%, TOC range between 2.8-12.8%.

Table 5. Logs obtained in the Oderup C4-1 well.

	Run	Log Description	Date	Interval (m BGL)
8 ½'' Section	1	Natural Gamma Ray + Caliper + Mud temperature, Mud resisitivty	13/05/2010	0-865.5
	2	Geovista Full Waveform Sonic	13/05/2010	0-720
	2a	Century Sonic Tool	13/05/2010	0-874.22
	3	Neutron porosity + Guard Focused Resistivity	14/05/2010	0-863.96
	4	Spectral Gamma Ray + Magnetic Susceptibility	14/05/2010	0-867.2
	5	Formation Sidewall Density	14/05/2010	
	6	Acoustic Televiewer - 1	14/05/2010	0-250 (failure)
	7	Mud temperature, Mud resisitivty + Caliper + Natural Gamma Ray	14/05/2010	0-866.81
	8	Acoustic Televiewer - 2	14/05/2010	0-238
6 ¼'' Section	1	Natural Gamma ray + Caliper + Thermal conductivity	25/05/2010	0-926.08
	2	Resistivity + Natural Gamma Ray + Density	25/05/2010	0-929.28
	3	Sonic	25/05/2010	Failure
	4	Natural Gamma Ray + Thermal Conductivity	25/05/2010	0-928.83
	5	Neutron Porosity	25/05/2010	0-929.67
	6	Spectral Gamma Ray + Magnetic Susceptibility	25/05/2010	0-926.85
	7	Acoustic Televiewer	26/05/2010	0-927.75
	8	Century Sonic	26/05/2010	

Table 6. Hydrocarbon breakdown and gas ratios for gas peaks at various depths in the Oderup C4-1 well.

Hydrocarbons Breakdown								Gas Ratios				
Depth	C1 ppm	C2 ppm	C3 ppm	iC4 ppm	nC4 ppm	iC5 ppm	nC5 ppm	C1/C2	Inverse Oil	Wetness	Balance	Character
648	2471	170	35	8	6	2	0	14.5	48	8.2	52	0.45
796	4173	263	28	4	3	1	0	15.9	116	6.7	123	0.29
838	3681	176	10	2	1	0	0	20.9	283	4.9	296	0.3
843	6332	277	10	2	1	0	0	22.9	49	4.4	508	0.3
853	10585	439	12	2	1	1	0	24.1	66	4.1	689	0.3
860	10449	525	14	2	1	1	0	19.9	581	4.9	610	0.3
877	7481	514	7	1	0	0	0	14.6	935	6.5	999	0.1
880	9943	606	7	0	0	0	0	16.4	1400	5.8	1486	0
884	8095	461	4	0	0	0	0	17.6	1974	5.4	2087	0
887	8259	513	6	0	0	0	0	16.1	1354	5.9	1438	0

4. Log-stratigraphy in the Alum Shale

The Alum Shale Formation exhibits a large thickness variation in the Kattegat-Zealand-Scania area (Figure 7). Within this area the maximum thickness was recorded in the Terne-1 well (Kattegat, 180 m) and the minimum thickness in the Slagelse-1 well (Zealand, 30 m). To illustrate the geological processes related to the thickness variation, three well correlation profiles have been constructed (Figure 8). Profile 1 extends from the Terne-1 well across the Colonus Trough in Scania and to the Sommerodde-1 well, Bornholm. Profile 2 extends from the Slagelse-1 well across the Höllviken Graben in Scania and to the Fågeltofta-2 well in Scania. Profile 3 extends from the Slagelse-1 well, across the G-14 well, offshore Rügen in the Baltic Sea, and to the Yoldia-1 well, offshore in the Baltic Sea south of Öland (Figure 8).

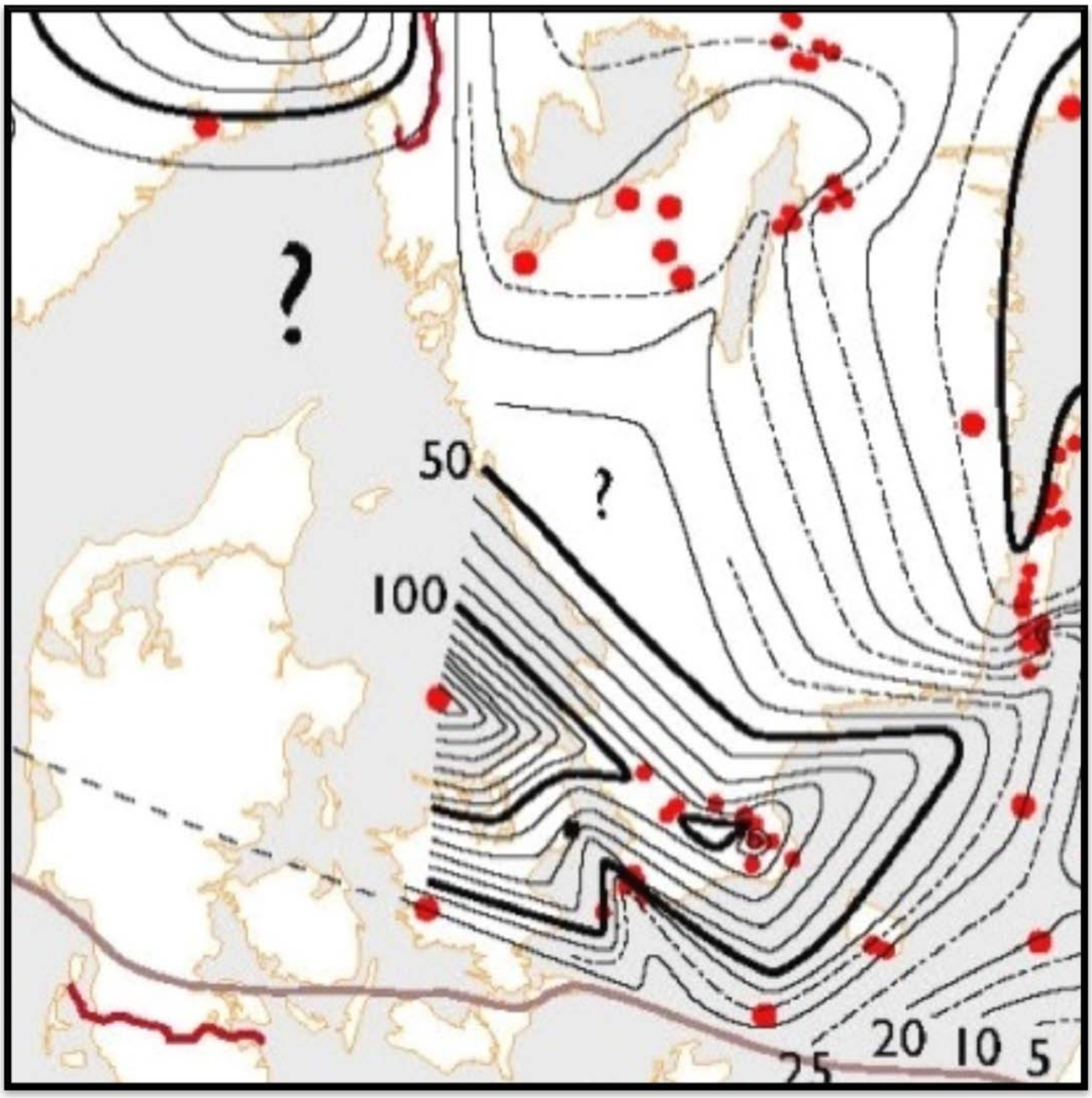

Figure 7. Isochore map of the Alum Shale Formation. Thickness in metres. Detail of map presented in Nielsen & Schovsbo (2013).

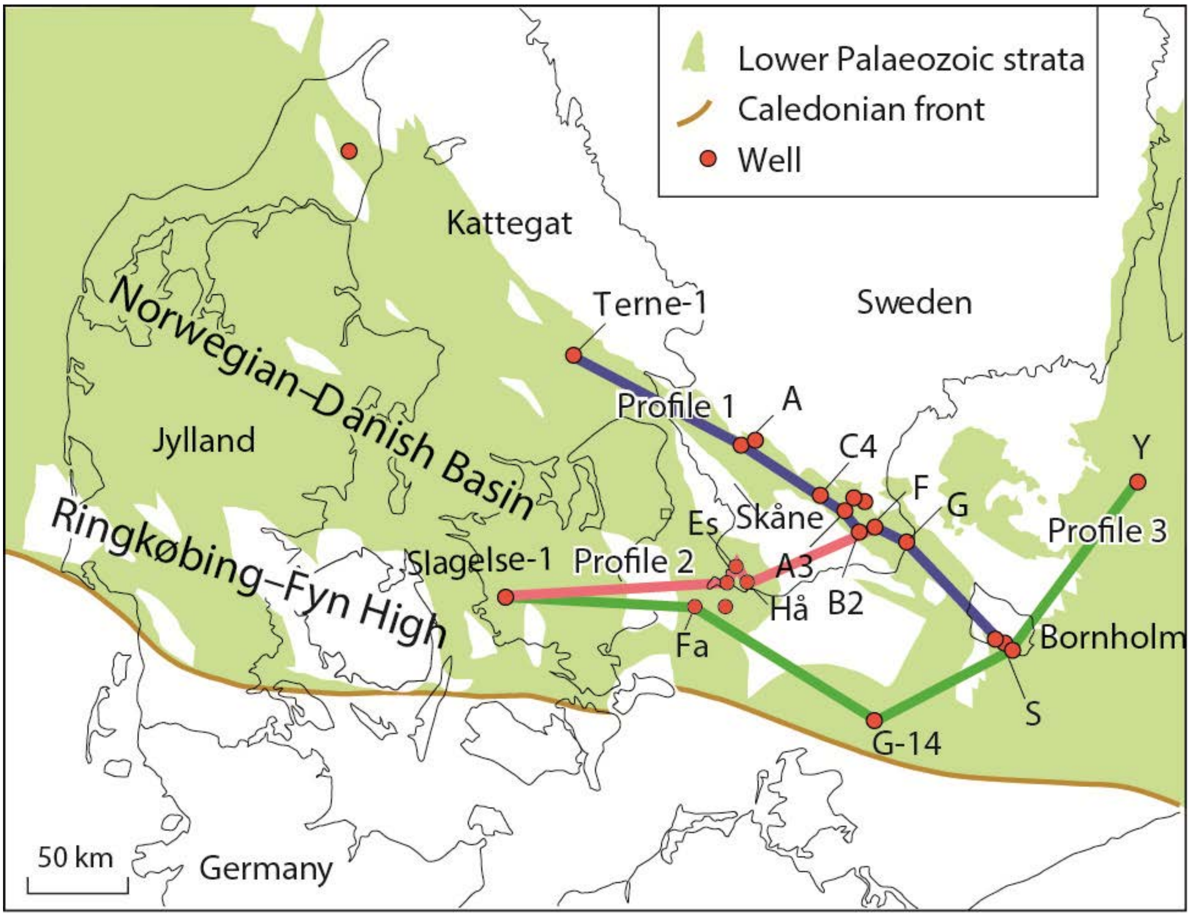

Figure 8. Locality map showing position of the three well correlation profiles (blue, red and green) and wells (red dots) used for the interpretation. Light green fill indicates the presence of Palaeozoic strata (from Nielsen & Schovsbo 2011). Abbreviations: A, Albjära-1; C4, Oderup C4-1; F, Fågeltofta-2; G, Gislövshammar-2; A3, Lövestad A3-1, B2, Hedeberga B2-1; Y, Yoldia-1; S, Sommerodde-1; Es, Eskilstorp-1; Ha, Hammerlöv-1; Hå, Håslöv-1; Fa, Falsterborev-1. Figure modified from Schovsbo et al. (2014).

Profile 1: Terne-1 across the Colonus Trough to Sommerodde-1

The orientation of the profile is parallel to the general orientation of the Tornquist Zone and of the Colonus Trough. The profile extends from the Terne-1 well in NW across wells in the Colonus Trough in Scania and to the Sommerodde-1 well on Bornholm, in SE (Figure 8). The profile thus extends from the basin centre to a basin margin position (Figure 7).

Profile 1 shows a general thinning of the Alum Shale Formation from the Terne-1 well and to the Sommerodde-1 well (Figure 9). Judging from the log response the thickness variation is caused mostly by condensation since the general log motif of the Alum Shale is preserved in all wells along the profile.

<u>Middle Cambrian</u>

In the Terne-1 well the Alum Shale Formation rests directly on the Lower Cambrian Hardeberga Fm. The Middle Cambrian is about 80 m thick whereas the Middle Cambrian in most of the Colonus Trough wells is up to about 30 m thick with a maximum of 40 m in the Lövestad A3-1 well. The main thickness difference reflects an expanded MC1-MC4 interval in the Terne-1 well compared to the same interval in Scania. In contrast to the MC1-MC4 interval the topmost Middle Cambrian (MC5 and MC6) is of almost equal thickness between the Terne-1 well and the wells in the Colonus Trough. Within the expanded MC1-MC4 interval the most expanded log zones in the Terne-1 well are the approximately 10 m thick MC1 zone and the about 20 m thick MC4 zone interpreted to be developed as the organic lean Terne Member.

<u>Furongian</u>

The Furongian part of the Alum Shale is 65 m thick in the Terne-1 well which is by and large similar to the thicknesses observed in the Colonus Trough wells as exemplified by the Albjära-1 well (Figure 9). The log correlation thus suggests that this part was deposited as a blanket of equal thickness throughout the area. Within the Colonus Trough the Furongian varies about 15 m in thickness between the Lövestad A3-1 and the Oderup C4-1 well. The thinner development in the Oderup C4-1 well seems to reflect condensation and no major erosive events have been inferred from the log correlation.

<u>Lower Ordovician</u>

The Ordovician part of the Alum Shale Formation is 35 m thick in the Terne-1 well and 8 m thick in the Albjära-1 well in the Colonus Trough. In the Fågeltofta-2 well this unit is up to 17 m thick. The log signature in the Terne-1 well shows generally decreasing gamma ray values and increasing interval velocities. This pattern is usually observed in in the other wells. The very gradual decrease in gamma ray to a level where there is little difference in natural radioactivity between the uppermost Alum Shale and the above lying Tøyen Shale suggest that the topmost c. 5 m in the Terne-1 well are developed as an organic lean types similar to the Albjära Member in Scania.

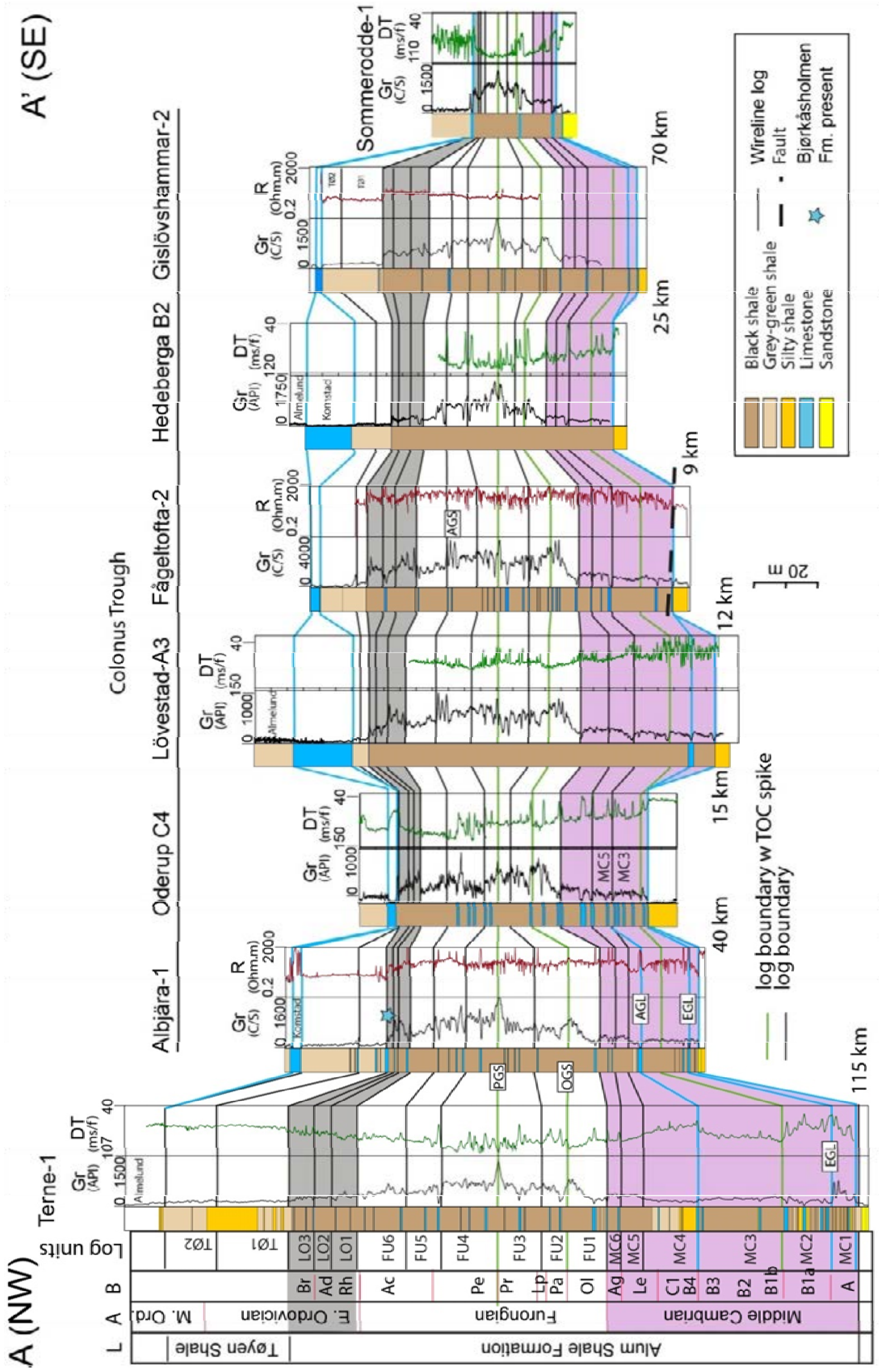

Figure 9: Well correlation profile 1 (AA') showing the Terne-1, Albjära-1, Oderup C4-1, Lövestad A3-1, Fågeltofta-2, Hedeberga B2-1, Gislövshammar-2 and Sommerodde-1 wells. The interval shown is from slightly above the top of the Komstad Lmst (or its correlated surface) to slightly below the top of the Lower Cambrian. The profile is flattened on the PGS surface. Grey colour: Middle Cambrian, pink colour: Lower Ordovician Alum Shale. Lithology is interpreted from the log responses and/or core descriptions. Abbreviations: Gr: gamma ray log, DT: sonic interval time log, R: resistivity log. L: lithostratigraphy, A: age, B: biostratigraphy (superzone/zone), OGS: *Olenus* Gr spike, PGS: *Peltura* Gr spike, AGL: Andrarum Lmst Gr Low, EGL: Exsulans Lmst Gr low, BFGL: Base Furongian Gr low or MCGS: Middle Cambrium Gr spike. Same vertical scale used for all wells. The scale for the Gr and DT are linear and logarithmic for the R.

Profile 2: Slagelse-1 across the Höllviken Graben to Fågeltofta-2

Profile 2 extends from the Slagelse-1 well, Zealand, across wells in the Höllviken Graben, SW Scania, to the Fågeltofta-2 well in the Colonus Trough in SE Scania (Figure 10). The profile thus represents a section almost perpendicular to the orientation of Profile 1 which ran subparallel to the Tornquist Zone and the Colonus Trough. The log quality of the wells are quite variable, but the log motif of the Alum Shale along the profile is still fairly recognisable and all log zones have been recognised apart for the LO1-LO3 (Figure 10). The correlation suggests that erosion rather than condensation are responsible for the thickness variation along the profile, which is in contrast to profile 1.

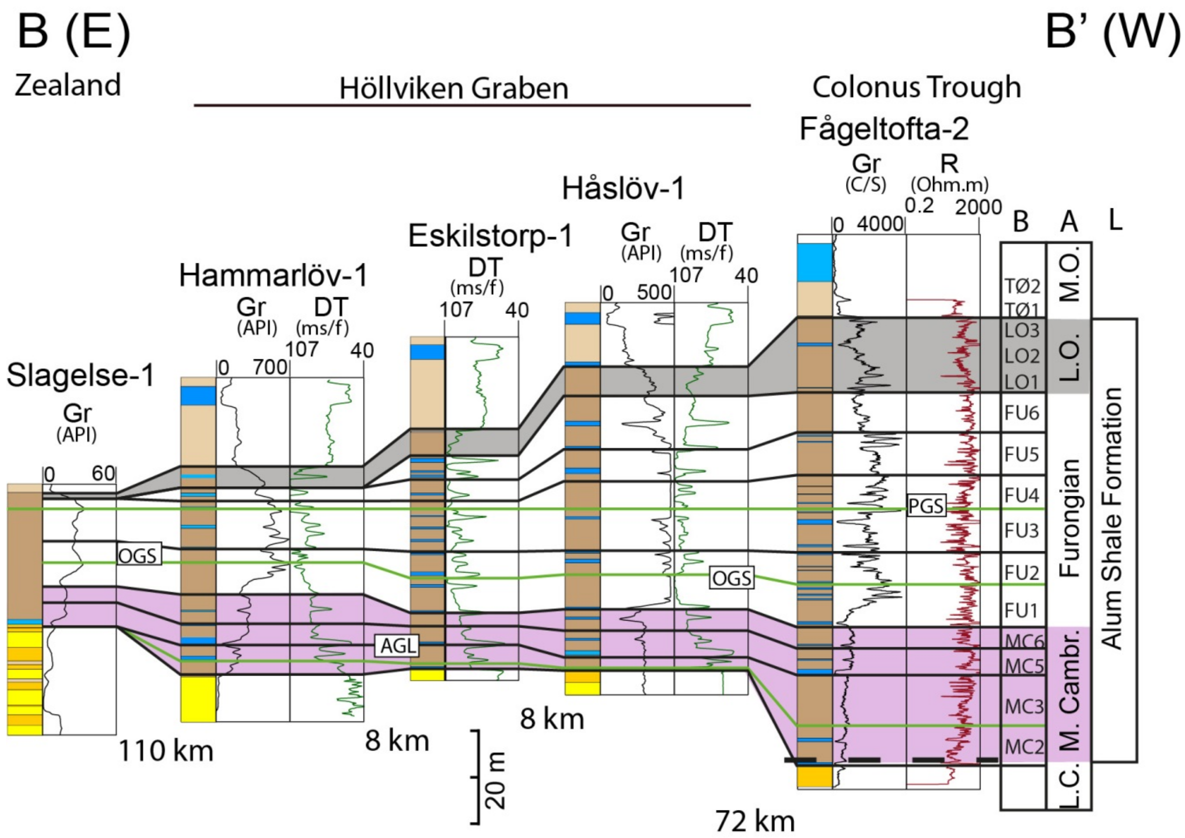

Figure 10. Well correlation profile 2. The interval shown in the well is from slightly above the top of the Komstad Lmst (or its correlated surface) to slightly below the top of the Lower Cambrian. The profile is flattened on the PGS surface. Legend and abbreviations as in Figure 9.

<u>Middle Cambrian</u>

The basal part of the Alum Shale Formation in the Slagelse-1 and in the Höllviken Graben wells seems stratigraphically incomplete compared to the Fågeltofta-2 well (Figure 10). The Andrarum Limestone Bed can easily be correlated along the profile suggesting that no MC1-MC4 shale is present in the Slagelse-1 well and that the youngest shale belongs to MC5. The reason for this is probably related to the late phase of the Hawke Bay uplift where subsidence was slightly variable in different areas (Nielsen & Schovsbo 2015). As seen also along profile 1 the thickness differences are minor from MC5 and onwards, suggesting that the area behaved in a similar manner in the late part of the Mid Cambrian.

Furongian

Profile 2 shows a uniform thickness of the Alum Shale from MC5 until the FU4 time (Figure 10). Younger strata are absent in the Slagelse-1 well and the thickness varies within the Höllviken Graben wells compared to the Fågeltofta-2 well. The log correlation of the uppermost Furongian suggests that most of the upper Furongian is missing or is strongly condensed in the Slagelse-1 Hammarlöv-1 and Eskilstorp-1 wells. The Håslöv-1 well exhibits nearly similar thickness as the Fågeltofta-2 well.

The wire-line log correlation presented here for the Håslöv-1 well is in accordance with the biostratigraphy published by Terfelt et al. (2005) on the partially cored *Peltura* interval.

The log pattern in the Slagelse-1 and Fågeltofta-2 wells suggests that the thickness of the interval MC5-FU3 is approximately the same between the wells. Substantial parts of the Furongian and the Lower Ordovician shales are seemingly missing in the Slagelse-1 well. The section that is not present in the Slagelse-1 well is approximately 30 m thick compared to what is seen in the Fågeltofta-2 well and it may be reasonable to suggest that the original depositional thickness of the Alum Shale in the Slagelse area could have been 60 m.

Lower Ordovician

The topmost part of the Alum Shale Formation in the Slagelse-1 well may be of Lower Ordovician age – but it is too thin for a log correlation to verify this. The log signature of the Lower Ordovician is recognised in the Hammarlöv-1 and Eskilstorp-1 wells (Figure 10).

Profile 3: Slagelse-1 across G-14 to Yoldia-1

Profile 3 follows a tract from the Slagelse-1 well to the G-14 well that is sub-parallel to profile 1 and a tractor from the G-14 well to the Yoldia-1 well that is sub-parallel to profile 2 (Figure 8).

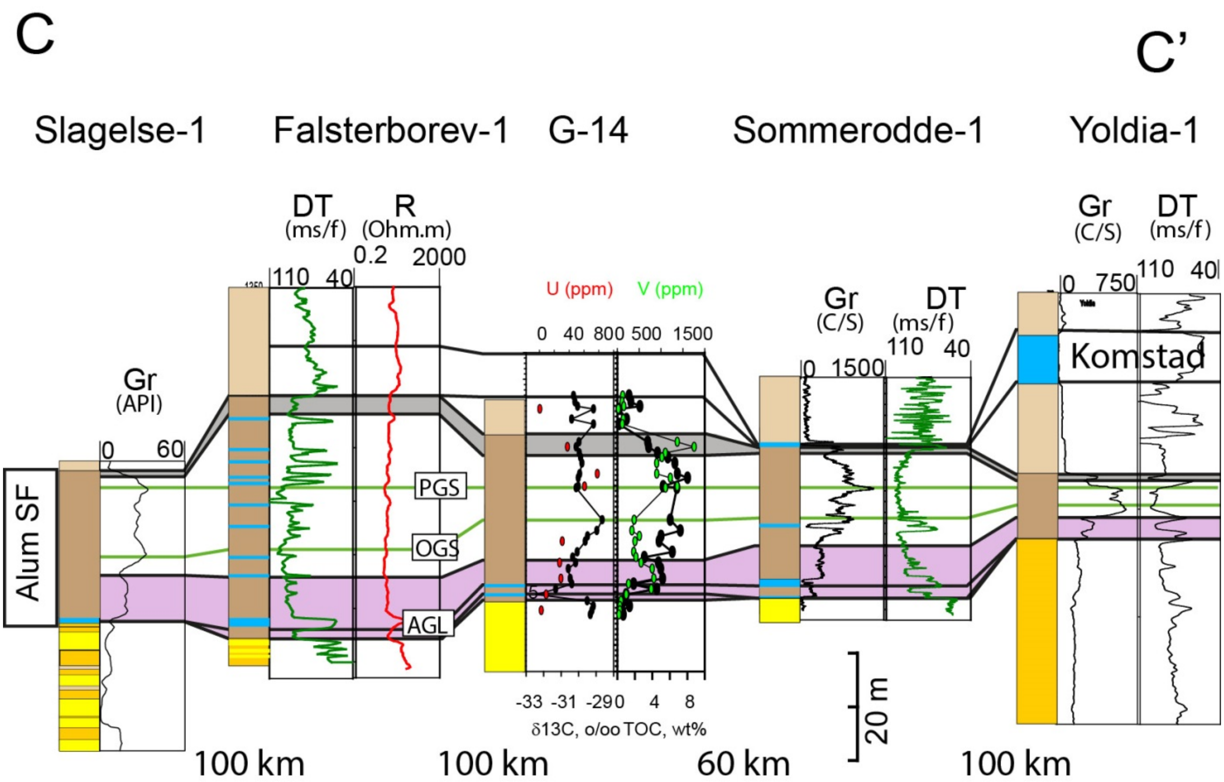

Figure 11. Well correlation profile 3 (CC'). The interval shown is from slightly above the top of the Komstad Lmst (or its correlated surface) to slightly below the top of the Lower Cambrian. The profile is flattened on the PGS surface. For legend see Figure 9. The Bjørkåsholmen Fm is present in the G-14 well.

The wells along profile 3 have a very variable log quality and only the most characteristic log patterns can be tracked (Figure 11). For the G-14 well no wire-line logs are available. Instead a chemostratigraphy developed from the vanadium, TOC content and carbon isotopes have been used in combination with information from Nielsen & Schovsbo (2015) regarding the basal part of the Alum Shale.

In profile 3 the Andrarum Limestone Bed can be traced in all wells together with the *Olenus* gamma spike (OGS) (Figure 11). The thickness of the Alum Shale Formation in all wells apart for the Falsterborev-1 well is quite similar, however, the internal stratigraphical development of the shale are quite different between the wells. In the Slagelse-1 well a rather thick incomplete Furongian section is present whereas in the Sommerodde-1 well a stratigraphically complete but highly condensed section is present.

5. Log-stratigraphy in the Ordovician – Silurian

A log-stratigraphical subdivision of the Middle Ordovician to the Lower Silurian (Wenlock) on Bornholm has been presented by Schovsbo et al. (2015b). The logstratigraphical scheme was originally developed by Pedersen & Klitten (1990) and subsequently refined by Schovsbo et al. (2011). It is based on the gamma ray log in combination with either the sonic log or the resistivity log (Figure 12).

Log stratigraphy in the Sommerodde-1 well

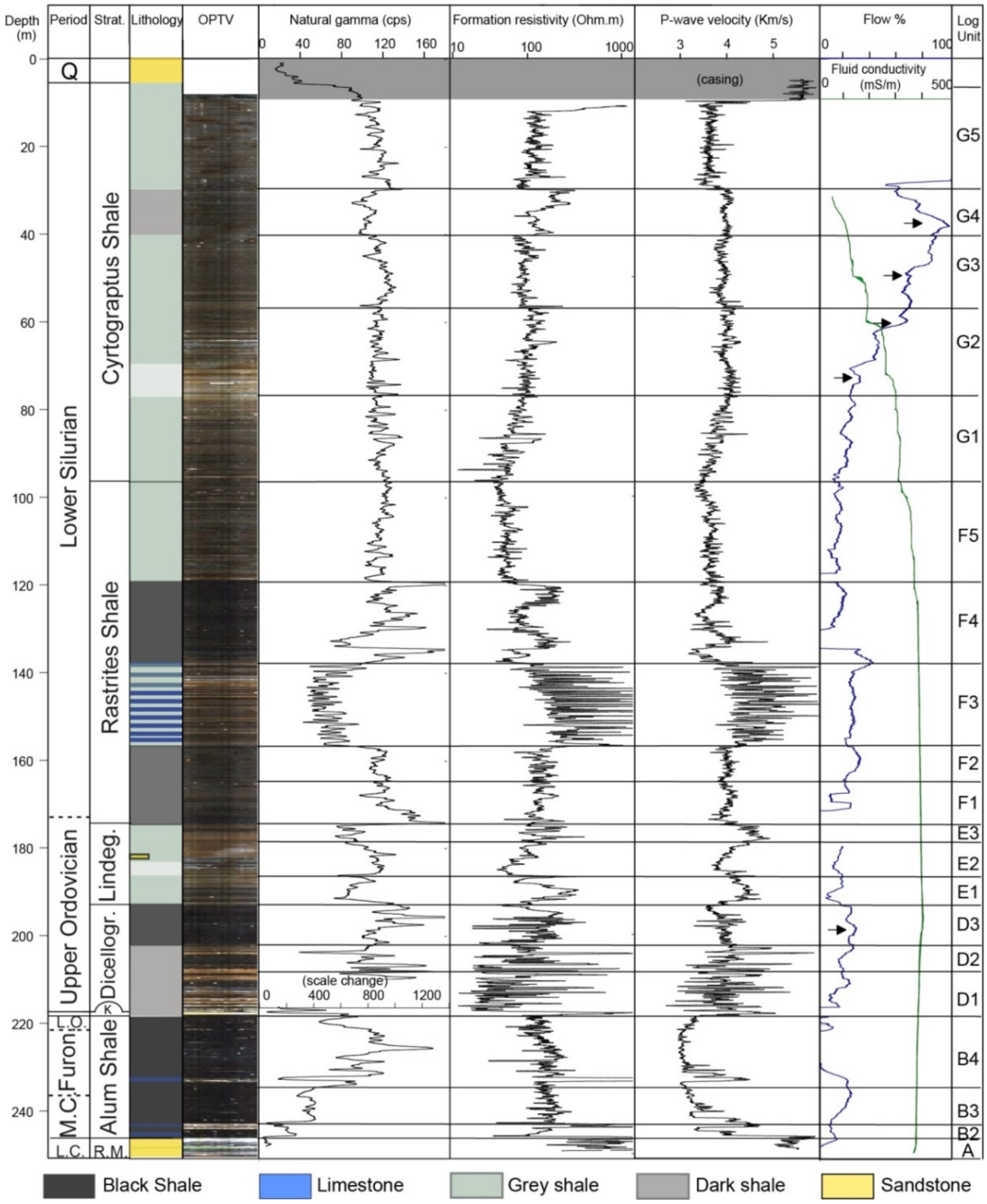

Figure 12. A log stratigraphical breakdown (A to G5) of the Sommerodde-1 well on Bornholm. From Schovsbo et al. (2015b).

Correlation between the Sommerodde-1 and the Oderup C4-1 wells

The wire-line log data from the wells drilled by Shell in Scania have been analysed in order to investigate if the logstratigraphical subdivision developed on Bornholm can be applied to Scania.

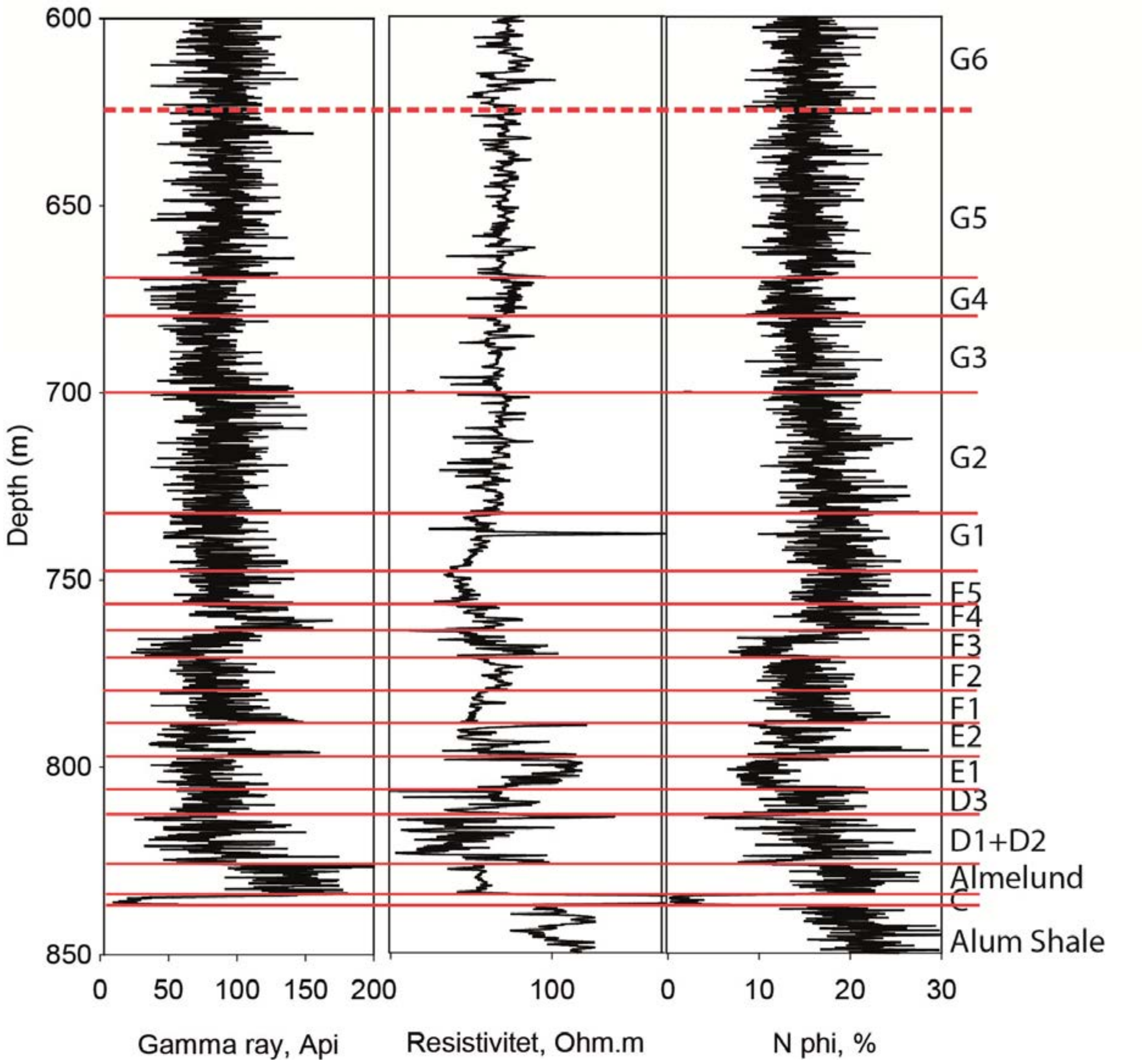

Figure 13. The stratigraphical breakdown of the Ordovician and Silurian section in the Oderup C4-1 well. The log units (D1 to G5) are defined in the Sommerodde-1 well (red solid lines). The top of the G5 unit and thus the base of the G6 unit (new) (red broken line), which is above the level penetrated by the Sommerodde-1 well, is tentative placed at a prominent break in the resistivity log at 625 m. The recognition of the log zones in the Oderup C4-1 well rely mostly on the resistivity log pattern rather than the Gr log since this log curve appears rather noisy.

In the Lövestad A3-1 and Hedeberga B2-1 wells only wire-line logs recorded in the casing were available for analysis whereas in the Oderup C4-1 well the open-hole log runs were available. In the Oderup C4-1 well all wire-line log zones defined on Bornholm could easily be identified (Figure 13) whereas in the Lövestad A3-1 and the Hedeberga C2-1 wells only a few log zones could be positively identified (Figure 14). In all three wells the quality of the gamma ray log appears to be rather poor. By applying a box filtering over a one m interval (moving average) the high amplitude variation was reduced in the Gr curves (Figure 14).

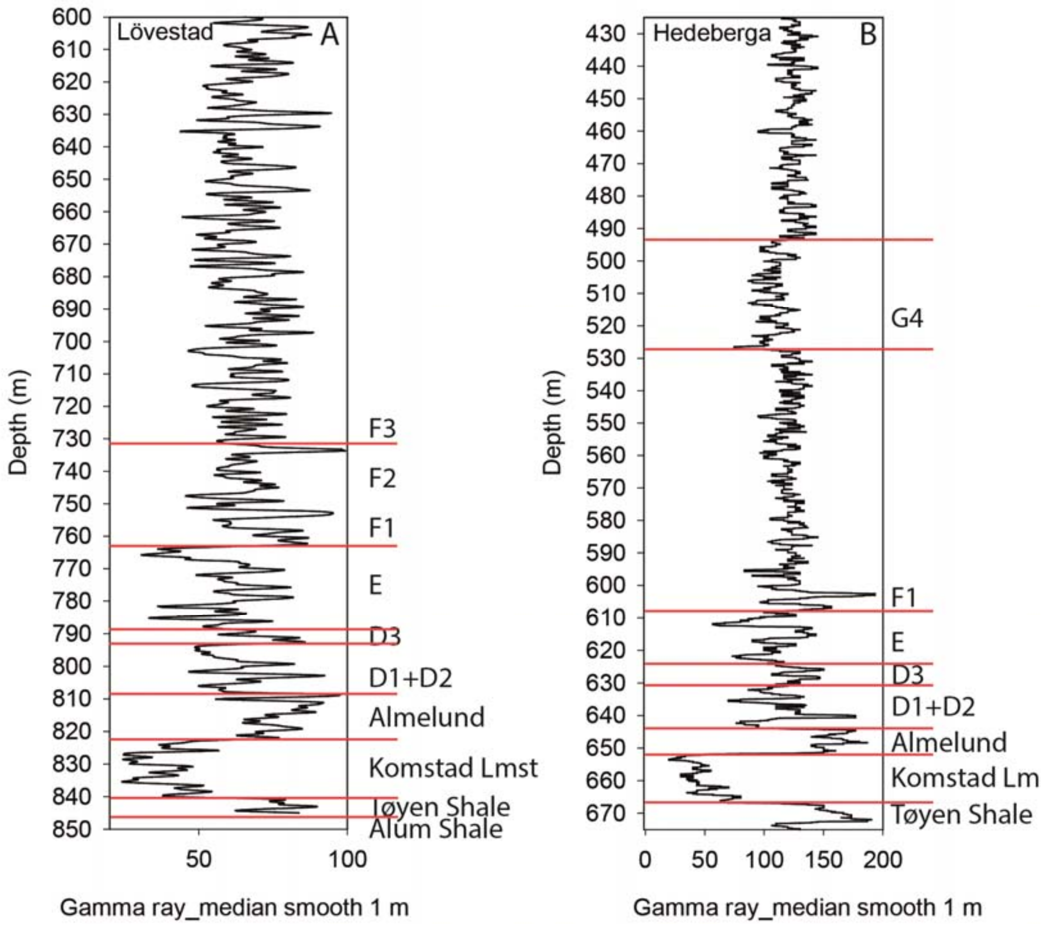

Figure 14. A log stratigraphical breakdown of the Ordovician and Silurian section in the A) Lövestad A3-1 and B) Hedeberga B2-1 wells. Well logs measured in the section above the Alum Shale were recorded in the casing and hence are of poor quality.

The D3 unit, which is the most organic rich shale interval in the Upper Ordovician (Figure 21) is about 8 m thick in the Oderup C4-1 well, 5 m in the Lövestad A3-1 well and 7 m in the Hedeberga B2-1 well (Figure 13 and 14). Regardless of the low quality of the GR log, the lack of a strong Gr spike in all wells introduces an uncertainty on the TOC content. The Lower Silurian TOC rich units are located within the F1+F2 and the F4 units. The units in Scania are about 5 m each and not associated with a high and pronounced gamma ray log response which might indicate a lower TOC values that observed on Bornholm in these units.

Mud log descriptions

The log interpretation of the TOC rich units were compared to the mud log descriptions for the same intervals in the respective wells. In the Oderup C4-1 well the shale is described mostly as a dark grey to medium dark grey shale. Only an interval around 790 m is described as black corresponding to the F1 log zone. In the Lövestad A3-1 well an interval corresponding to the D3 unit is described as black whereas cuttings from all F units are described as dark grey shale. The section in the Hedeberga B2-1 well is described as dark grey shale within the D3 to F4 section.

The agreement between the log interpretation and the descriptions suggests that the Silurian "hot shales" are thin and with a low TOC content in Scania. With respect to Zealand this places a very high risk on the TOC content of these stratigraphical intervals.

6. TOC content and thickness estimates for the Alum Shale on Zealand

The total organic carbon content versus stratigraphy of the Alum Shale
The TOC content in the Alum Shale is known to vary systematically with the stratigraphy and thus the ability to predict the stratigraphical development in an area is important for estimation of the potential shale gas resources (Schovsbo et al. 2014).

The most organic rich interval is the Furongian which holds on average about twice as much TOC as the Middle Cambrian and about a quarter more than the average content in the Lower Ordovician Alum Shale (Table 7 and Figure 15).

The average TOC content in the entire formation is about 9% in both immature and dry gas mature Alum Shale (Table 7). In the Terne-1 well, which has highest thermal maturities (post-mature) in the Danish area, the average TOC content is 6% (Table 7). The fact that immature and dry gas mature Alum Shale has similar TOC content is quite surprising taking into account the expected impact on the TOC content related to hydrocarbon expulsion. However, the formation is very in-homogeneously developed between the areas and includes organic lean units such as the MC4 and LO3 in Scania and Kattegat and organic lean Alum Shale that interfingers with the Borgholm Fm in south-central Sweden (Figure 2). Primary differences in the TOC content thus may exist that makes the comparison of the formation average TOC invalid. This is also seen in the relative high standard deviation of the mean for the entire formation (Table 7).

Comparing a more homogeneous interval such as the Furongian a higher average TOC content in immature areas is observed compared to the average values in Scania which again are slightly higher than the average TOC content in the Terne-1 well (Table 7). The difference between the areas may reflect expulsion of generated hydrocarbons since the primary difference in the depositional environment is minimal within the Furongian.

Similar systematic is also seen for the Lower Ordovician part of the Formation and to a lesser extend for the Middle Cambrian part of the formation (Table 7).

Table 7. Average TOC content in the Alum Shale with respect to thermal maturity (% reflectance). Data presented in Figure 15.

	Immature <0.6 %Ro gr			Gas mature 1.9-2.1 %Ro gr			Post mature 3.6 %Ro gr		
Stratigraphy	**N**	**Std.**	**TOC, %**	**N**	**Std.**	**TOC, %**	**N**	**Std.**	**TOC, %**
Entire Alum Shale Fm	322	4.4	9.6	792	3.4	9.0	60	2.6	6.4
Lower Ordovician	50	2.5	10.8	142	1.9	7.4	10	1.2	4.1
Furongian	102	2.7	13.9	475	2.7	10.8	20	1.9	9.0
Middle Cambrian	160	3.0	6.3	175	2.4	5.3	30	1.5	5.2

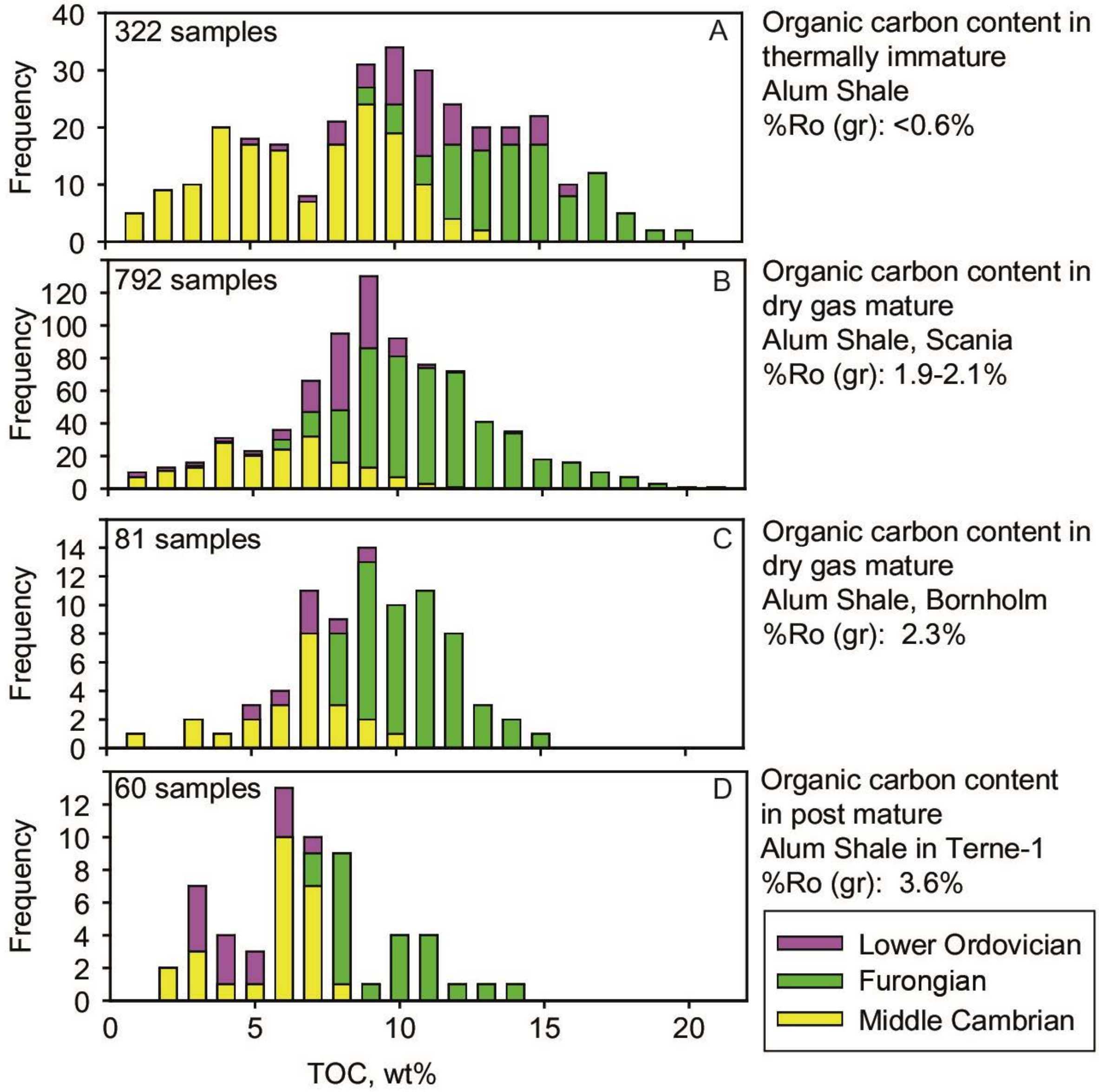

Figure 15. Distribution of the TOC content in the stratigraphical units of different maturity ranges. The immature Alum Shale is from Västergötland, Östergötland and Öland (GEUS archive data). The thermal maturation of the areas are expressed as graptolite reflectance (%Ro(gr)).

Thickness models for the Alum shale

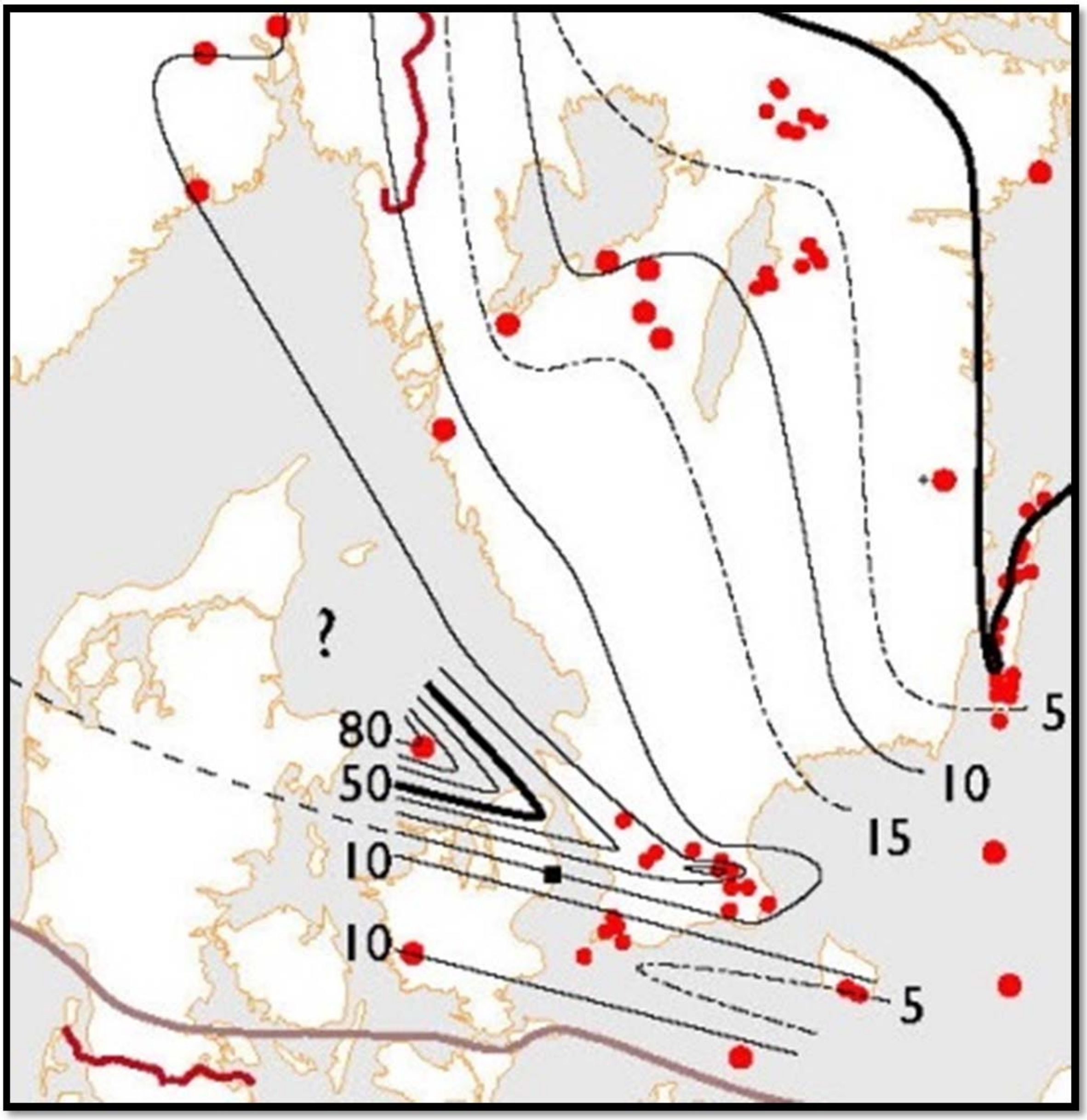

Figure 16. Isochore map of the Middle Cambrian part of the Alum Shale Formation. From Nielsen & Schovsbo (2013).

The thickness distribution of the Middle Cambrian, which is the least organic rich with 5% average TOC in Scania (Table 7) is shown in Figure 16. The lower part (MC1-MC4) has a wedge-like distribution with the greatest interval thickness attained in the Kattegat areas (Figure 9 and 16). The upper part (MC5-MC6) has a more blanket like distribution. The thickness variation reflects the differential subsidence pattern in the aftermath following the Lower-Middle Cambrian Hawke Bay uplift (Figure 19).

Based on a countered thickness map (Figure 16) the thickness on Zealand is expected to range between 20-70 m (P90-P10) with a mean of 30 m (P50) of the Middle Cambrian Alum Shale. Expanded sections as seen in Kattegat comprise primarily comparatively organic lean shale and a thick Middle Cambrian section on Zealand may expectedly show rather low average TOC content.

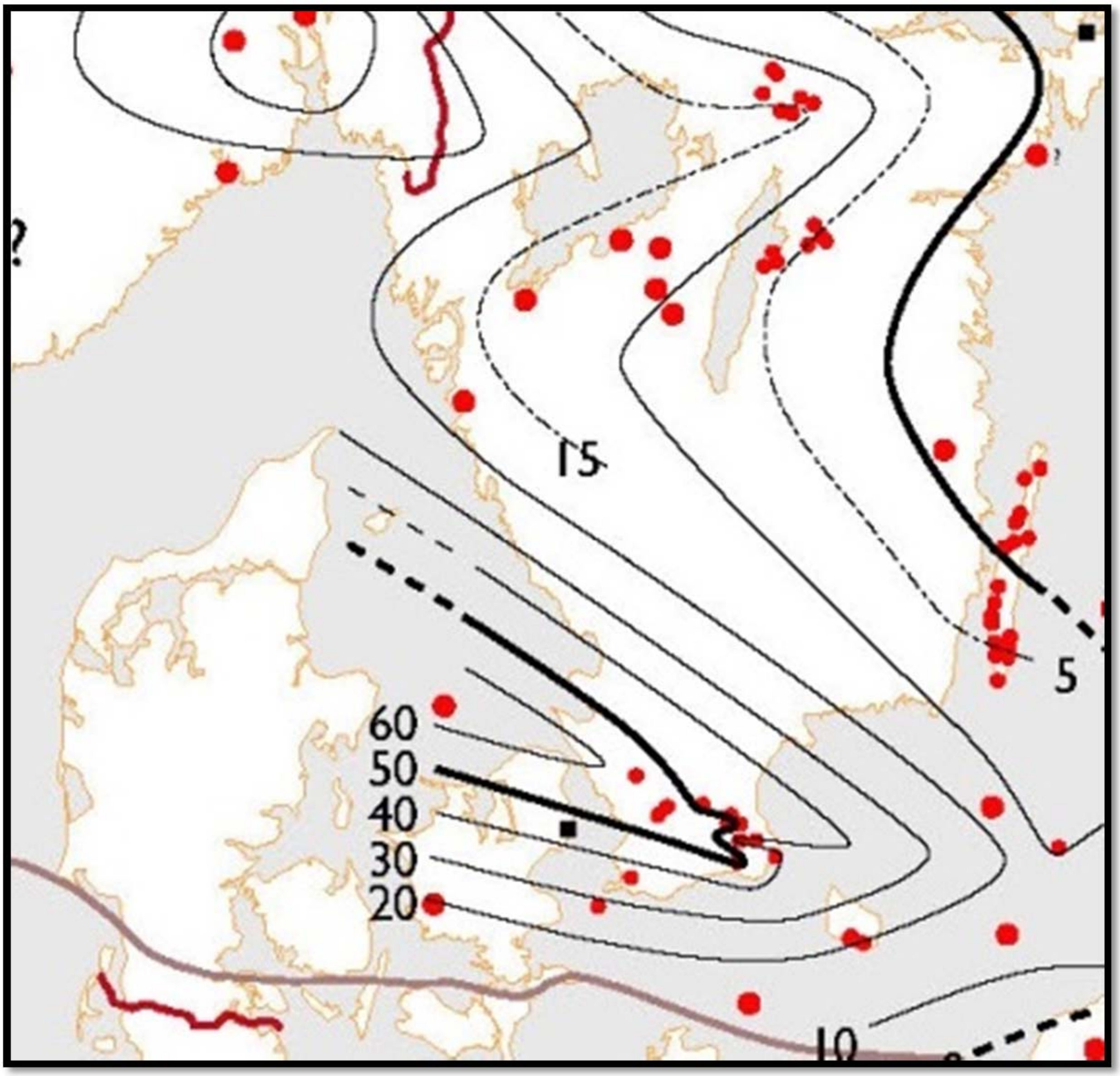

Figure 17. Isochore map of the Furongian part of the Alum Shale Formation. From Nielsen & Schovsbo (2013).

The Furongian holds the highest average TOC content of the Alum Shale Formation (Table 7) and this unit will have a much larger impact on the volume of the shale gas resource. Figure 17 present the contoured isochore map of the Furongian part of the formation. The contouring shows that throughout most parts of Zealand we expect a thickness of the Furongian <30 m. The reduced thickness is likely related to late Furongian uplift (Figure 20) causing non-deposition and even some erosion that reduced the interval thickness in the Slagelse-1, Falsterborev-1 and the Höllviken wells (Figures 9, 10 and 11). Relatively thick Furongian shales are expected to occur in the north-eastern part of Zealand where thicknesses similar to those in the Colonus Trough and the Terne-1 well are expected to occur.

In probabilistic terms we expect that the Furongian will range between 20-50 m (P90-P10) with a mean of 40 m (P50) on Zealand.

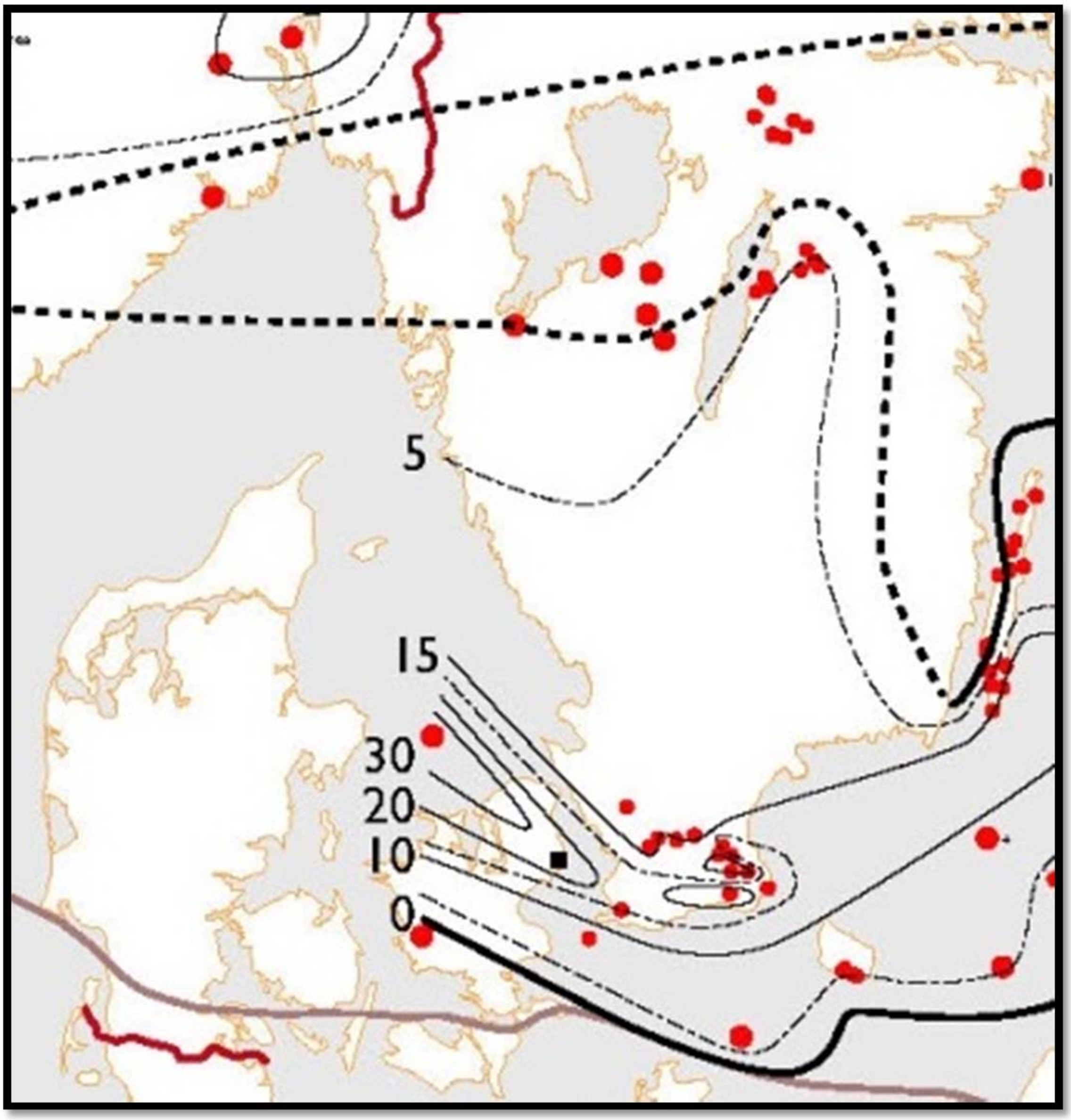

Figure 18. Isochore map of the Lower Ordovician part of the Alum Shale Formation. From Nielsen & Schovsbo (2013).

The thickness distribution of the Lower Ordovician Alum Shale shows an undulating pattern much controlled by local conditions (transient isostatic uplift in some areas) and is shown in Figure 18. The average TOC content is 7% of this stratigraphical interval (Table 7).

The thickness of the Lower Ordovician part of the Alum Shale is controlled by uplift and subsidence in the early to mid Tremadocian (Lower Ordovician, Figure 20) and the thickness distribution on Zealand is expected to range between 0-20 m (P90-P10) with a mean of 10 m (P50) based on the contoured map (Figure 18).

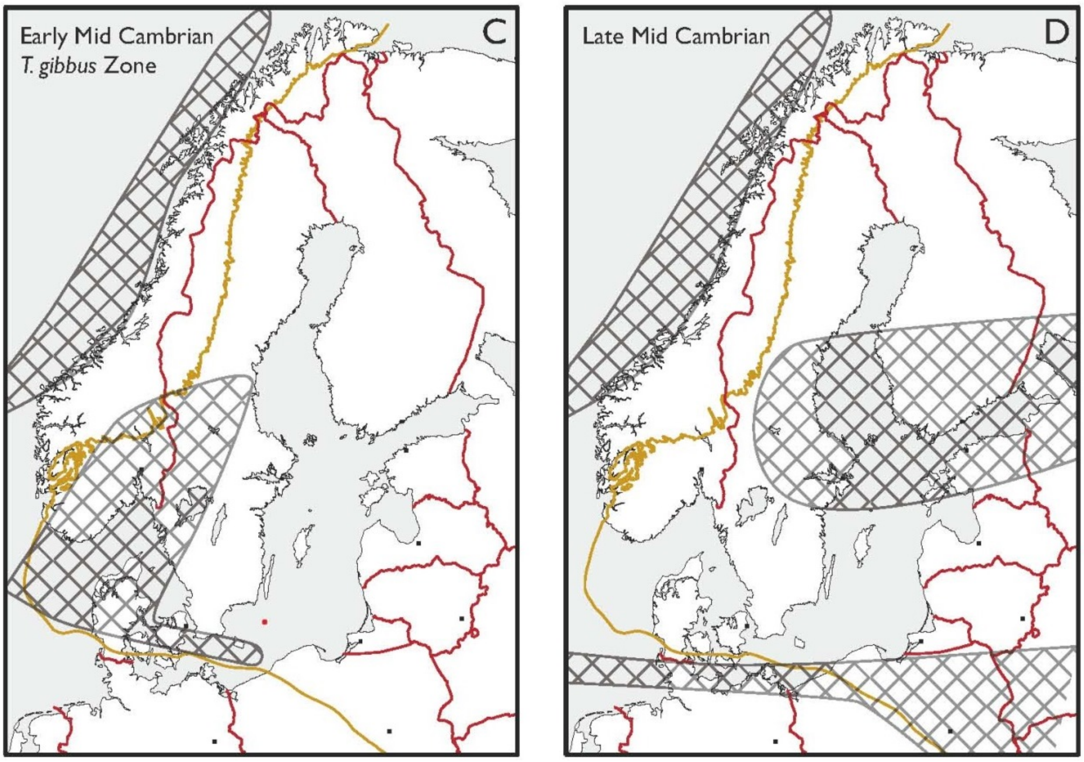

Figure 19. Map showing uplifted areas in the Middle Cambrian. From Nielsen & Schovsbo (2013).

The areas that were affected by the late Early Cambrian to early Mid Cambrian uplift termed the Hawke Bay uplift are shown in Figure 19, (Nielsen & Schovsbo 2015). The extent of the uplift is expected to have longest duration towards the margins of Baltica. The duration of the uplift will directly impact the interval thickness of the Middle Cambrian Alum Shales and thus most of Zealand is expected to have a relative thin Middle Cambrian Alum Shale as is expected to be the case for most parts of the subsurface of Denmark.

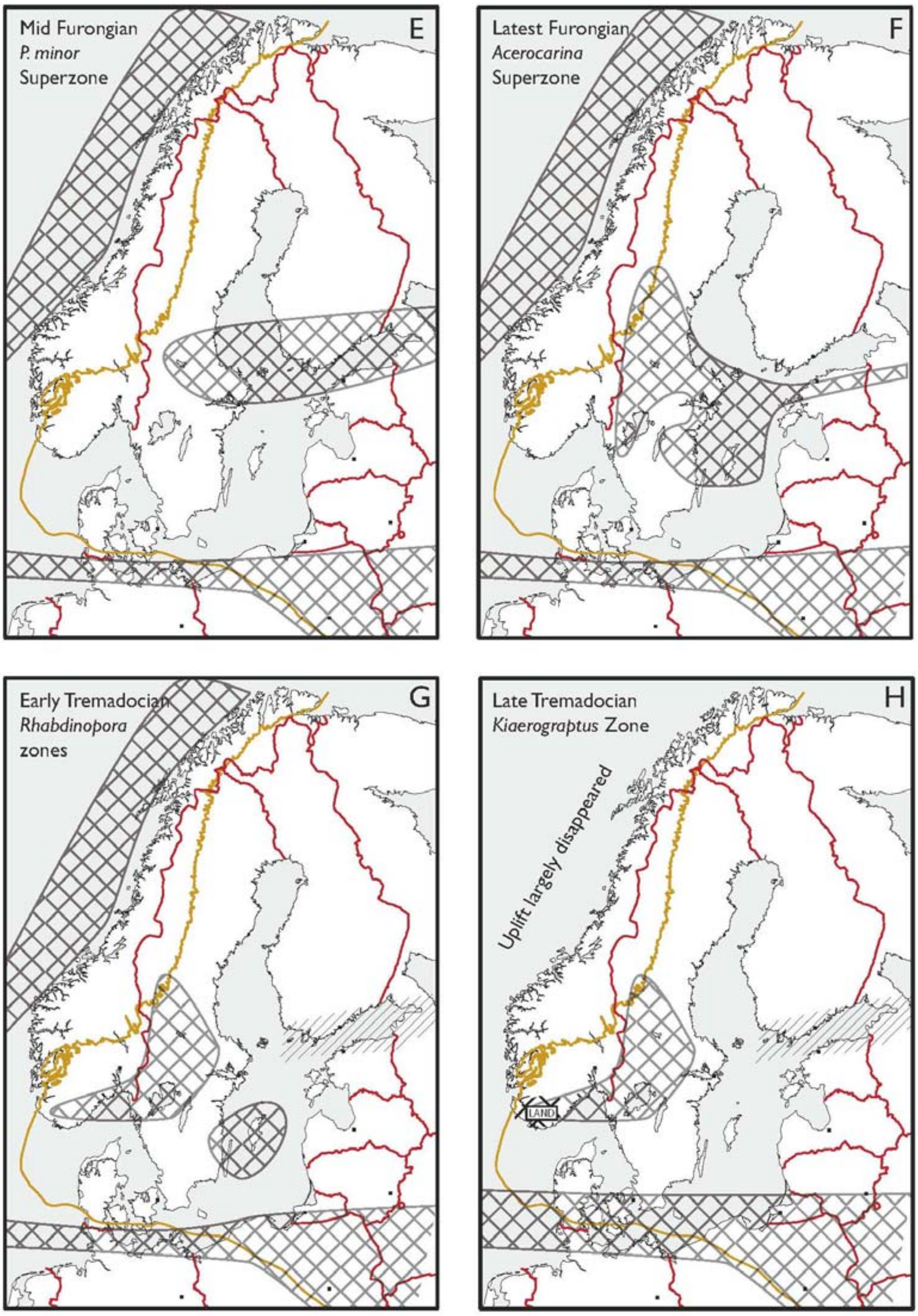

Figure 20. Map showing uplifted areas in the Furongian to Late Tremadocian. From Nielsen Schovsbo (2013). Oblique hatching indicates subsidence.

Areas most severely influenced by uplift in the Furongian and the Early Ordovician were located close to the plate margins. The uplift is interpreted to reflect stress change related to plate movements. The effects of the uplift likely decrease northwards on Zealand and will have the least impact in the northern part of the island where the thickness, accordingly, is expected to be highest.

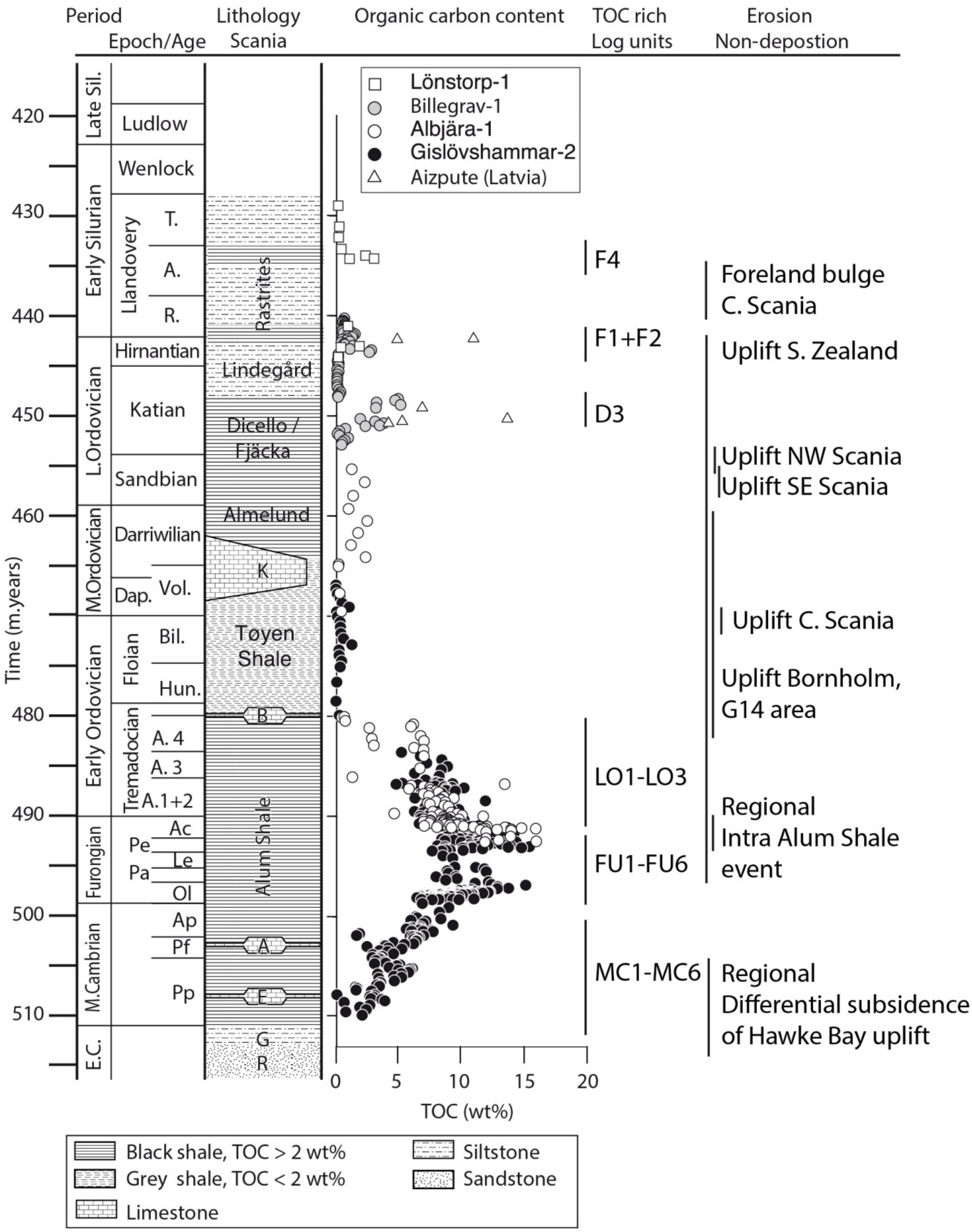

Figure 21. An overview of erosive events and distribution of organic rich intervals (shown as log stratigraphical units) in the Lower Palaeozoic shales. Modified from Schovsbo (2003).

A summary of uplift events in the Alum Shale is presented in stratigraphical order in Figure 21.

7. Thickness estimates for the Ordovician and Silurian TOC-rich shales on Zealand

On Bornholm the Ordovician and Silurian D3, F1+F2, and F4 units are TOC-rich (Figure 21). The units are 45 m thick in total (9, 18 and 18 m respectfully) and occur in a 82 m thick interval (Figure 12). The ratio between organic rich shale to organic lean shale (the reservoir net/gross ratio) is thus 55%. Compared to Scania (Oderup C4-1) the D3, F1+F2, and F4 units are 32 m thick in total (8, 18 and 6 m thick respectfully, Figure 22) and occur in a 57 m thick interval. The net/gross ratio in Scania is thus near equal to that observed on Bornholm (56% compared to 55%).

In the Slagelse-1 well the TOC-rich Ordovician and Silurian shales are not present since the area was uplifted (Figure 21). The risk that the shales are not present on Zealand is thus high.

The relative low thickness of individual shales in Scania combined with the high risk that the TOC content in Scania is lower than on Bornholm makes is difficult to envision that these units holds a large shale technical gas resource if present on Zealand.

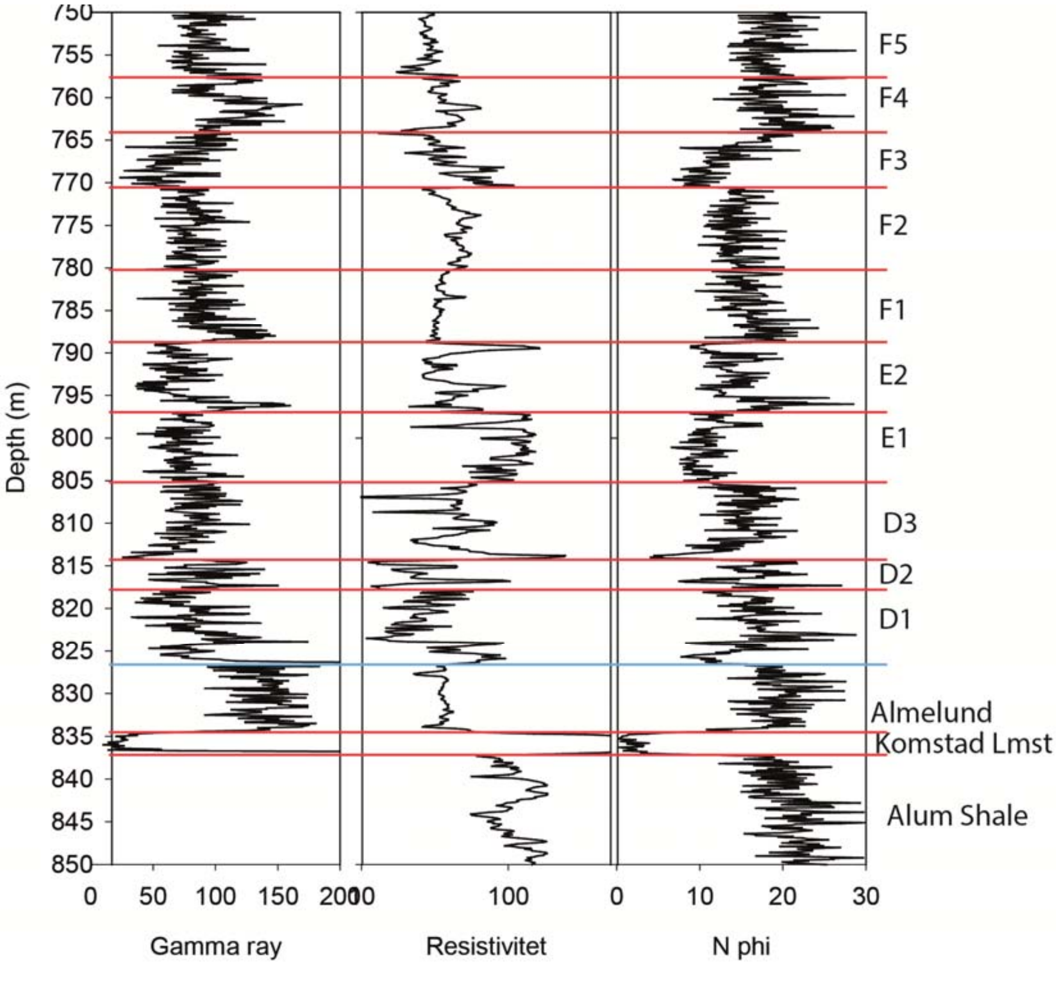

Figure 22. Detail of the log stratigraphical breakdown of the Oderup C4-1 well.

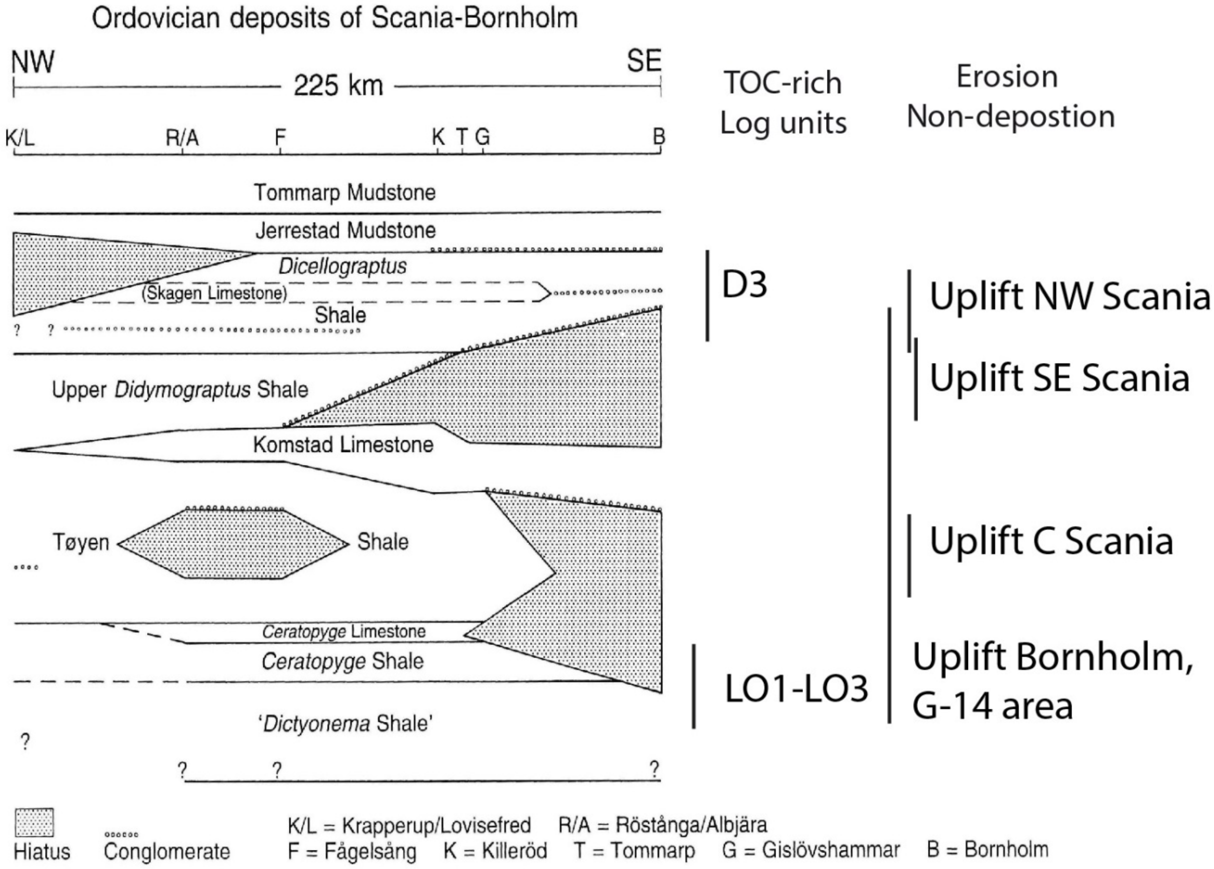

Figure 23. Overview of erosive events in the Ordovician of Scania and Bornholm. Modified from Nielsen (1995).

8. Conclusions

The total thickness of the Alum Shale Formation on Zealand is expected to range between 30-100 m (P90-P10) with an mean of 80 m (P50).

Furongian
The distribution of the Furongian part of the Alum Shale, which is the most organic rich with 11% average TOC content in Scania, is expected to have exhibited a blanket like even thickness across Zealand similar to the thickness of about 50-60 m, i.e. as preserved in the Colonus Trough. The main control on the preserved thickness is Late Furongian and early-to mid Tremadocian (E. Ordovician) uplift that has significantly reduced the thickness of the Furongian interval in the Slagelse area and in the Höllviken Graben to about 20 m. The extent of this uplift in northern Zealand is difficult to evaluate. Based on contoured thickness maps the Furongian part of the Alum Shale is expected to range between 20-40 m (P90-P10) with a mean of 40 m (P50) on Zealand. We expect that the greatest thicknesses will occur in the northernmost parts of Zealand only.

Middle Cambrian
The Middle Cambrian, which is the least organic rich part of the Alum Shale with 5% average TOC, shows a wedge-like distribution of the lower part (MC1-MC4) with the greatest thickness attained in the Kattegat area. The upper part of the Middle Cambrian (MC5-MC6) has a more blanket like distribution. The uneven thickness is mostly controlled by differential subsidence patterns following the Lower-Middle Cambrian Hawke Bay uplift. Based on contoured thickness maps the thickness on Zealand is expected to range between 20-70 m (P90-P10) with an average of 30 m (P50). Expanded sections as seen in the Kattegat area are characterised by organic lean shale sequences and thus a thick Middle Cambrian section on Zealand may be expected to show a lower average TOC content than expected.

Lower Ordovician
The Lower Ordovician Alum Shale shows an uneven distribution pattern much controlled by local conditions. The average TOC content is 7%. The thickness of the unit is controlled by uplift events in the early to Mid Tremadocian and the thickness distribution on Zealand is expected to range between 0-20 m (P90-P10) with an average of 10 m (P50).

Ordovician to Silurian shales
Secondary targets of organic rich shales (TOC 2-5%) are present in the Upper Ordovician (D3 log unit) and in the Lower Silurian (F1+F2 and F4 log units). On Bornholm the combined thickness of these units are 45 m with a net/gross of 55% for the interval from the base of D3 to the top of F4. In Scania these shales are up to 32 m thick showing a net/gross of 56%. In the Slagelse-1 well these units are absent or developed as TOC lean shales.

The distribution of these units are controlled by late Ordovician uplift and position of the emerging Caledonian foreland bulge in the Early to Late Silurian which both caused erosion but also rapid subsidence and deposition of TOC lean sediments in the foreland basin behind the bulge. Based hereon we expect that these units on Zealand will range in total thickness from 0 to 30 m (P90-P10) with a mean of 10 m (P50). We expect that the net/gross of this interval will range between 0-50% (P90-P10) and, accordingly, it is unlikely that these units will contribute to a significant shale gas resource.

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