DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2011/113

Geochemical and stratigraphical evaluation of the Lower Paleozoic shales on Bornholm

The Skelbro and Billlegrav wells on Bornholm

Niels H. Schovsbo

CONFIDENTIAL
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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF CLIMATE AND ENERGY

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1. Introduction

The purpose of this report is to outline the work done so far on the Skelbro-1 and Billegrav-1 wells in a log-stratigraphical framework, which allows comparison with the new fully cored Skelbro-2 and Billegrav-2 wells (Figure 1). The review deals with lithology, stratigraphy, TOC content, maturity and the burial history of Bornholm. A detailed log-based correlation between the four wells facilitates a direct comparison of measured properties between the wells.

The Skelbro-1 and Billegrav-1 wells were drilled in 1984 on Bornholm. The scientific wells were drilled by GEUS and represented the first cored sequence of the Lower Palaeozoic from Bornholm. The cores have been extensively studied, including sedimentology (Pedersen 1989), stratigraphy (Pedersen & Klitten 1990, Koren & Bjerreskov 1997), geochemistry (Buchardt et al. 1986), maturity (Buchardt & Lewan 1990) and fluid inclusions (Jensenius 1987).

In order to obtain fresh core material for the GASH project and to conduct new stratigraphical studies of the Lower Palaeozoic the Skelbro-2 and Billegrav-2 wells were drilled in August 2010 as part of a new drilling campaign (Schovsbo et al. 2011).

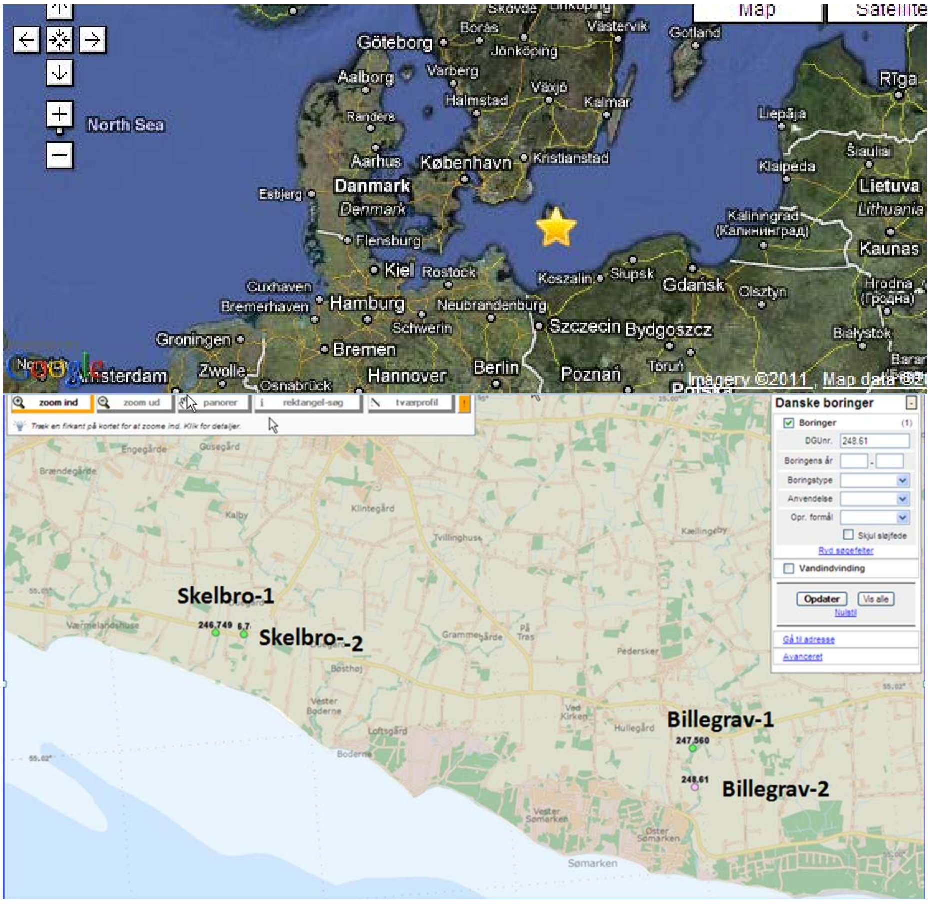

Figure 1. Map showing location of the Skelbro-1 (246.749), Billegrav-1 (247.560), Skelbro-2 (246.817) and Billegrav-2 (248.61) wells on southern Bornholm, Denmark. The Skelbro wells were drilled approximately 8 Km west of the Billegrav wells.

2. Well summary Skelbro-1

DGU well number:	246.749
Common well Name:	Skelbro-1
Location:	Drilled in the abandoned Komstad Limestone quarry
UTM zone	33
Drill Position, UTM:	492250, 6099614
Terrain elevation, m:	35 DNN
TD:	43.2 m drillers depth below top of the Komstad Limestone in the quarry
Formation at TD:	Læså Fm, Norretorp Mbr
Drilling type:	Diamond coring
Core diameter:	2.5 cm
Core barrel length:	1.5 m
Recovery:	From below 0 m: 100%
Drilling fluids:	Fresh water with no additives
Casing:	None
Drilling company:	GEUS
Drilling date:	May 1984
Logging:	Technical University of Denmark (DTU). The GR log was the only log type obtained in the hole. The log trace was obtained in analogue form and no digital version of the log exists
Purpose:	Scientific
Location of cores:	Institute of Geography and Geology, University of Copenhagen (Gunver K. Pedersen).
Summary:	The Skelbro-1 well cored the Komstad Limestone from 0 to 3.9 m (Fig. 2). The Alum Shale Formation is 33.4 m thick and includes the Middle Cambrian Andrarum and Exsulans limestone beds that both serve as important regional marker beds (Nielsen & Schovsbo 2006). The base of the Alum Shale was reached at 37.2 m and the well was terminated at 43.2 m in the Norretorp Member of the Læså Fm after penetrating the Rispebjerg Mbr (3.2 m thick).

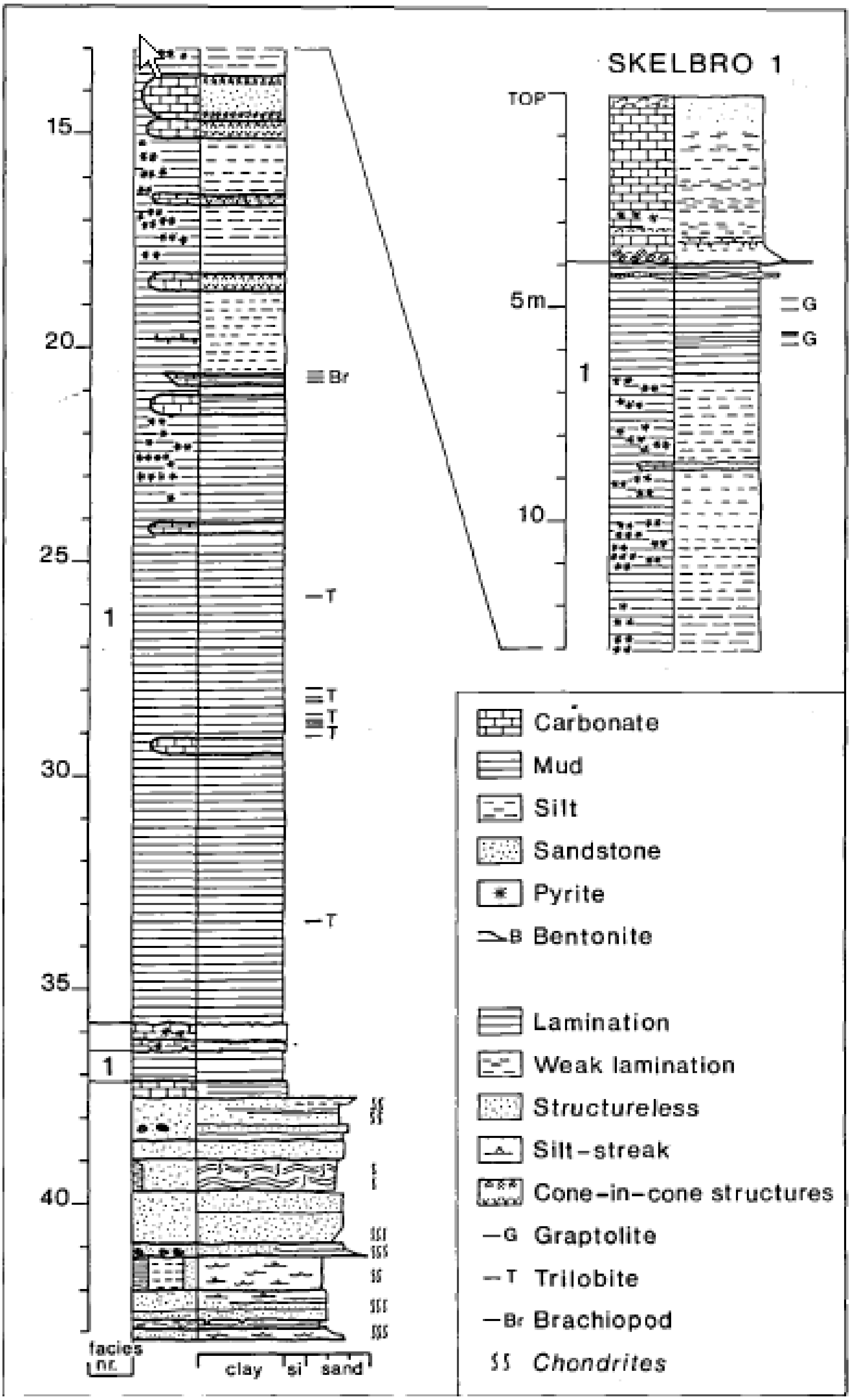

Figure 2. Sedimentological log of the Skelbro-1 well. The well cored 33.4 m of Alum Shale. From Pedersen (1989).

2.1. Logstratigraphical units in Skelbro-1

Pedersen & Klitten (1990) discerned 6 units (A-F) and 16 subunits based on the GR log pattern in the Billegrav-1 and Skelbro-1 wells (Figure 12).

Below follows a brief description of the units in Skelbro-1. The description is based on Pedersen (1989), Pedersen & Klitten (1990) and Nielsen & Schovsbo (2006). The biostratigraphy is inferred from Nielsen & Schovsbo (2006) and Schovsbo (2002).

Unit A: Rispebjerg Member and top of Norretorp Member, Læså Fm
Rispebjerg Member (3.7 m in Skelbro-1): Light grey medium to coarse grained quartz sandstone. The top part is impregnated with phosphorite.
The Norretorp Member is c. 100 m thick (Nielsen & Schovsbo 2006) and only the very top of the unit is penetrated by the Skelbro-1 well. The upper part of the member is composed of fine silty sandstone partly heterolitic. The unit is extensively bioturbated.
TOC: No sample (0% TOC assumed).
Age: Early Cambrian. *Schmidtiellus mickwitzi* trilobite Zone.

Unit B: Alum Shale Formation (33 m in Skelbro-1)
The unit is characterized by gamma- readings much higher than all other units. The Alum Shale consists of black organic rich mudstone with beds and nodules of limestone. Barite and pyrite occur both as disseminated crystals and as nodules.

<u>Unit B1: Exsulans Limestone and Lower Alum Shale (0.8 m in Skelbro-1)</u>
The unit top is characterised by low gamma values indicative of the base of the Andrarum Limestone. The B1 unit represent the Exsulans Limestone (0.2 m) and Alum Shale (0.6 m). The Exsulans Limestone is a primary bio-clastic carbonate bed.
TOC: 4% (one sample).
Age: Mid Cambrian (*P. paradoxissimus* to *P. forchhammeri* superzones).

<u>Unit B2: Andrarum Limestone and Mid Cambrian to basal Furongian Alum Shale (9.4 m in Skelbro-1)</u>
The log unit is bounded upwards by a sharp increase in gamma ray readings and the unit represents an interval in the Alum Shale characterised by intermediate gamma values. The unit contains in the Skelbro-1 well a diagenetic carbonate concretion (with low gamma readings) located about 3 m from the top of the unit. The concretion contains abundant olenid trilobites and represents the basal part of the Furongian. Concretions of similar age are also known from Scania (southern Sweden) and the concretion is informally termed the '*Olenus* stinkstone'.
TOC: 5–8% (12 samples).
Age: Mid Cambrian (*P. forchhammeri*) to the lowermost Furongian (lower *Olenus* Zone).

<u>Unit B3: Furongian Alum Shale (18 m in Skelbro-1)</u>
An interval characterised by very high gamma values. Top of the interval is placed at the start of a stepwise decrease in GR values. The high fluctuation in GR values in some intervals in the unit reflects the presence of diagenetic carbonate nodules and beds. A very distinct spike in the gamma values occurs in the middle of the unit. A similar spike can be observed in numerous logged water wells on Bornholm and in logged wells in Scania. The high GR readings occur in a shale level that represents the Furongian *Peltura* Zones.
TOC: 8–14% (19 samples).
Age: Furongian (upper *Olenus* Zone – *Acerocare* Zone).

Unit B4: Ordovician Alum Shale (5 m in Skelbro-1)
An interval characterised by intermediate GR values. The interval is bound upwards by a very sharp drop in GR values reflecting the Komstad Limestone.
TOC: 4–9% (5 samples).
Age: Furongian (*Acerocare*) – Early Ordovician (Tremadocian).

Unit C: Early Mid Ordovician Komstad Limestone (0–3.9 m)
An interval characterised by very low GR readings reflecting the Komstad Limestone. The unit is a cold water carbonate that contains variable amounts of clay, phosphorite and glauconite.
TOC: 0% (no samples TOC assumed).
Age: Mid Ordovician (Dapingian).

2.2. Mineralogy in Skelbro-1

The clay mineralogy and bulk mineralogy were measured in 5 samples with a sample frequency of about one sample pr. 5 m of core. The clay mineralogy was identified by X-ray on oriented mounts on chemical pre-treated samples and the bulk mineralogy was calculated from the XRD-peak heights in random oriented mounts.

Pedersen (1989) indicated that the clay mineralogy and the bulk mineralogy varied systematically with stratigraphy (Figure 14). In the Alum Shale the dominant clay mineral is illite. Kaolinite and chlorite minerals do not occur in the Alum Shale. In the Ordovician and Silurian shales illite occurs together with kaolinite and chlorite (Figure 14).

Unit B: Alum Shale bulk mineralogy
The bulk mineralogy studies indicate that the Alum Shale contains about 50-65% quarts, 5-15% feldspar and 10-15% mica. The pyrite content is about 11% whereof most is finely disseminated. Macroscopic pyrite varies in amount and mode of occurrence from very thin (0.3-1 mm) streaks to nodules 0.5-1 cm in diameter. Barite crystals may also occur especially in the Furongian part of the succession.

Too few samples were analysed to enable a description of the bulk mineralogical variation within the log units. Judging from the samples it appears that the B3 unit is slight more clay-rich relative to quarts in comparison with the other units. B4 appear most quartz rich. K-feldspar is only present in the B1-B2 units.

2.3. Major and trace elements

Major and trace elements were measured in 13 samples from Skelbro-1. Measurements were determined on XRF apparatus at GEUS (major elements) and the Geological Institute, University of Copenhagen (trace elements). The analysis is presented in Appendix B. The major element analysis of the Alum Shale indicates that the SiO_2/Al_2O_3 ratio is about 3.5 (Figure 3). Only one sample from unit B4 exhibits a very high SiO_2 content relative to Al_2O_3.

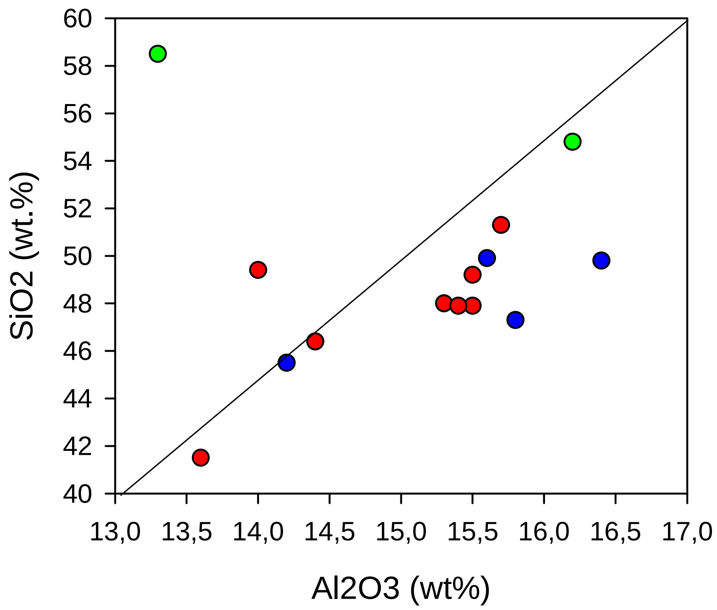

Figure 3. Al_2O_3 versus SiO_2 for Alum Shale samples in Skelbro-1. Fill colour of circles indicate the log unit: blue, unit B2; red, unit B3; green, unit B4. The two parameters are positively correlated as indicate by the black line. Geochemical data are presented in Appendix B.

The organic carbon and uranium content are very closely associated in the Alum Shale (Figure 4). This suggests that organic richness might be calculated from the gamma ray log once proper calibrations have been calculated. Schovsbo (2002) showed that the U/TOC varied with stratigraphy. The ratio is about 6 in the Middle Cambrian and Lower Ordovician whereas the ratio increases in the Furongian part of the shale.

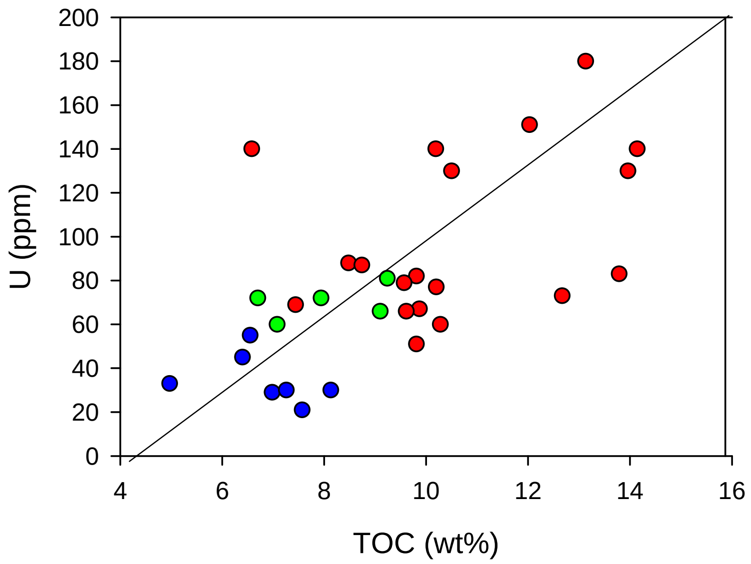

Figure 4. TOC content versus uranium concentrations in Alum Shale samples from Skelbro-1. Fill colour of circles indicate the log unit: blue, unit B2; red, unit B3; green, unit B4. The two parameters are positively correlated as indicate by the black line. Geochemical data is presented in Appendix A and B.

3. Well summary Billegrav-1

DGU well number:	247.560
Common well Name:	Billegrav-1
Location:	Drilled in the Øle Å valley
UTM zone	33
Drill Position, UTM:	499994, 6097068
Terrain elevation, m:	15 DNN
TD:	60.6 m drillers depth below terrain
Formation at TD:	Dicellograptus Shale, Upper Ordovician
Drilling type:	Diamond coring
Core diameter:	2.54 cm
Core barrel length:	1.5 m
Recovery:	From below 2 m: 100%
Drilling fluids:	Fresh water with no additives
Casing:	None
Drilling company:	GEUS
Drilling date:	May 1984
Logging:	Technical University of Denmark (DTU). The GR log was the only log type obtained in the hole. The log trace was obtained in analogue form and no digital version of the log exists.
Purpose:	Scientific
Location of cores:	Institute of Geography and Geology, University of Copenhagen (Gunver K. Pedersen) of the Ordovician section and the Geological Museum, University of Copenhagen (Arne Thorshøj Nielsen) of the Silurian section.
Summary:	The Billegrav-1 well cored Silurian Rastrites Shale from 2 m below the ground level down to 29.2 m. The Rastrites Shale comprises light to dark grey mudstone except for a distinct grey mud to siltstone unit containing carbonate cemented sandy beds (Fig. 3). The Upper Ordovician includes the Lindegård Formation (previously referred as the Tretaspis Shale or Tommarp and Jerrestad mudstones), comprising grey mud- and siltstones, and the dark organic-rich Dicellograptus Shale (Fig. 3). The Dicellograptus Shale was not penetrated when the well was stopped at 60.6 m. The shale contains numerous bentonites in its lowermost part including a 1 m thick K-bentonite bed (Kinnekulle Bentonite) which represents the most significant volcanic eruption in the entire early Palaeozoic (Bergström et al. 1995).

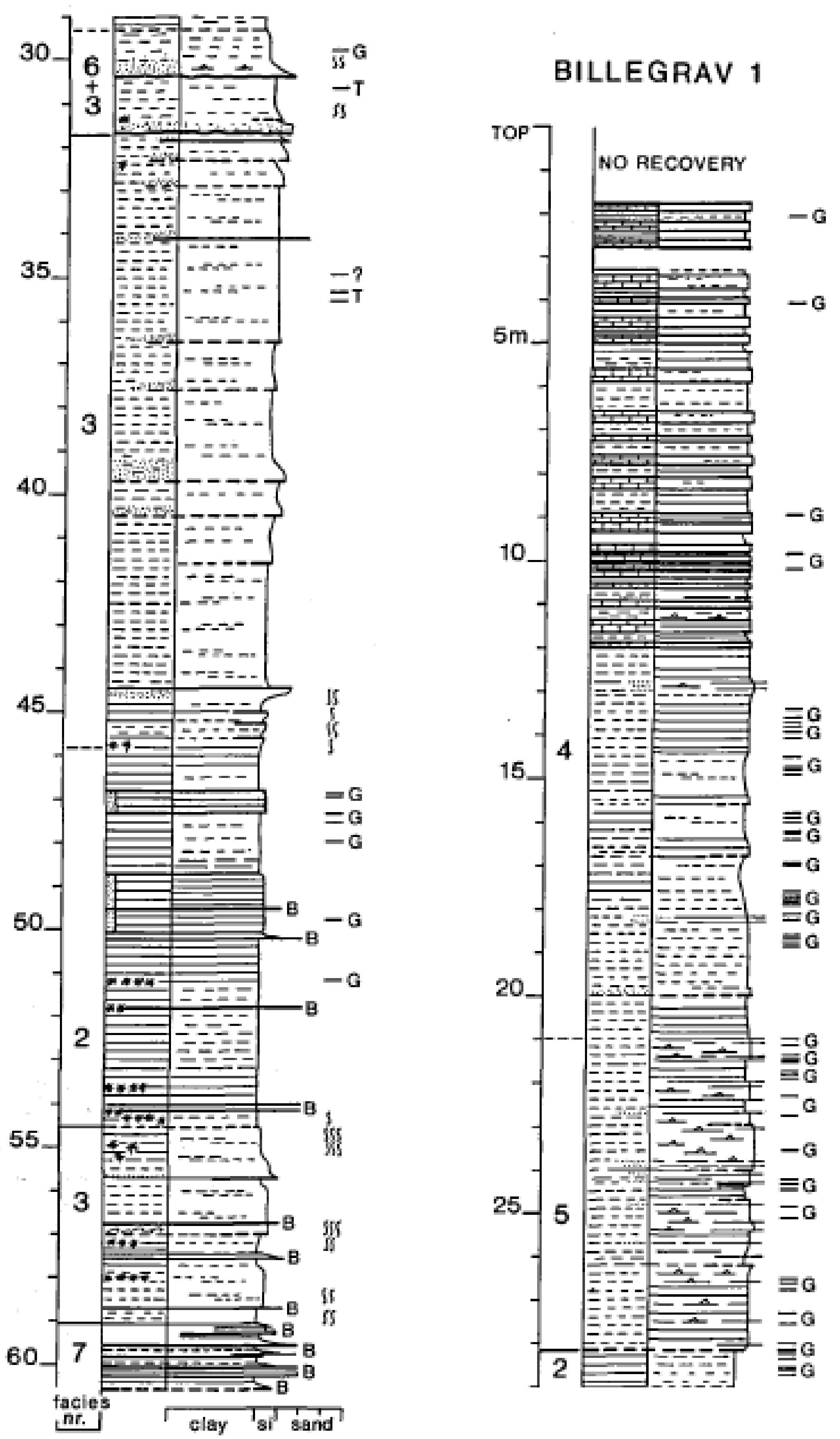

Figure 5. Sedimentological log of the Billegrav-1 well. For legend see Figure 2. From Pedersen (1989).

3.1. Logstratigraphical units

A brief description of the units in Billegrav-2 based on Pedersen (1989), Pedersen & Klitten (1990) is provided below. The biostratigraphy is inferred from Bjerreskov (1975), Koren & Bjerreskov (1997), Stouge & Nielsen (2003) and Nielsen & Schovsbo (2006).

Unit D: Dicellograptus Shale (> 7 m in Billegrav-1)
The unit is represented by grey to dark grey mudstone. It contains numerous bentonite beds in its lower part. The unit was not penetrated by Billegrav-1.

<u>Unit D1: “Lower” Dicellograptus Shale (> 2 m in Billegrav-1)</u>
The unit is characterized by high GR readings. The unit is composed by grey mudstone with abundant bentonite beds. The bentonites are easily recognized due to their high GR readings. The unit is bounded upwards by a local minimum in the GR values.
TOC: 0.5% (one sample).
Age: Late Ordovician (Caradoc), roughly corresponding to the *Dicellograptus foliaceus* Zone.

<u>Unit D2: “Middle” Dicellograptus Shale (5 m in Billegrav-1)</u>
The unit is characterized by high GR readings, and is composed of grey mudstone with few bentonite beds. The trace fossil *Chondrites* occurs frequently. The unit is bounded upward by a marked increase in GR values.
TOC: 0.1–1% (7 samples).
Age: Late Ordovician (Caradoc), roughly corresponding to the lower part of the *Dicranograptus clingani* Zone.

<u>Unit D3: “Upper Dicellograptus Shale” (9 m in Billegrav-1)</u>
The unit is characterized by high GR readings and is upward bound by an interval with very low GR values. The unit is composed by dark graptolitic mudstone with a few bentonite beds.
TOC: 0.1–5% (8 samples).
Age: Late Ordovician (Caradoc- Ashgill) roughly corresponding to the upper part of the *Dicranograptus clingani* Zone and the *Pleurograptus linearis* Zone.

Unit E: Lindegård Formation (25 m in Billegrav-1)
The unit is characterized by moderate high GR readings, and is composed by green-grey mud and siltstones that usually are bioturbated. Sandstone beds and thin conglomeratic horizons occur.

<u>E1: “Lower” Lindegård Fm (6 m in Billegrav-1)</u>
The unit is characterized by low GR reading. The top is marked by an interval of distinctive low GR values. The unit comprise grey mudstone intensely bioturbated in its top and base.
TOC: 0.1–0.4% (7 samples).
Age: Late Ordovician (Ashgill), *Tretaspis granulata* Zone.

<u>E2: ”Middle” Lindegård Fm (5 m in Billegrav-1)</u>
The unit is characterized by higher GR reading that the units above and below. The upper boundary is located at a low GR interval. The unit are composed of grey green siltstone.
TOC: 0.1–0.2% (5 samples)
Age: Late Ordovician (Ashgill), likely roughly corresponding to the *Staurocephalus clavifrons* Zone.

E3: “Upper” Lindegård Fm (5 m in Billegrav-1)
The unit is characterized by very low GR readings. It is composed by silty mudstone with occasional sandstones, partially conglomeratic. The sandstone beds are carbonate cemented with up to 25% carbonate.
TOC: 0.1–0.2% (4 samples).
Age: Late Ordovician (Hirnantian), likely roughly corresponding to the *Dalmanitina mucronata* Zone.

Unit F: Rastrites Shale (> 27 m in Billegrav-1)
The formation is characterized by low to medium high GR readings. The total thickness of the Rastrites Shale is estimated at 80 m in the Øle Å area (Bjerreskov 1975). Only the lower 29 m were penetrated by the Billegrav-1 well. The unit is composed by silty mudstones, occasionally with current generated sedimentary structures, and grey siltstone which contains calcite cemented sandy beds in some intervals. Dark grey to black intervals occur.

F1: Rastrites Shale (23–29.2 m)
The base of the unit is characterized by a very marked increase in GR reading. This base consists of approximately 1.5 m thick dark graptolitic mudstone with some silt beds. From here the GR values decreases and the top of the unit is placed at a local minimum in GR values.
TOC: 0.4–3% (7 samples).
Age: Late Ordovician (Hirnantian) to Early Silurian (Llandovery). *G. persculptus* to *A. ascensus graptolite* zones.

F2: Rastrites Shale (11 m in Billegrav-1)
The unit is characterized by intermediate high GR values. The top of the unit is defined at a plateau in GR values just below a low GR interval. The unit is characterized by grey siltstone with silty mudstone beds.
TOC: 0.5–1% (12 samples).
Age: Early Silurian (*M. acuminatus* - *vesiculosus* graptolite zones).

F3: Rastrites Shale (10 m in Billegrav-1)
The unit is characterized by low and variable GR values. The top of the unit is defined at a GR minimum just prior to a low GR interval. The unit consist of grey siltstone with abundant calcite cemented sandy beds. The interval has a cyclic appearance on the log that is caused by alternating cemented sandy beds (low GR values) with silty mudstone (high GR values).
TOC: 0.5–0.8% (10 samples).
Age: Early Silurian (*vesiculosus* graptolite Zone).

3.2. Mineralogy

The clay mineralogy and bulk mineralogy were measured in seven samples (Figure 14). The clay mineralogy was identified by X-ray on oriented mounts on chemical pre-treated samples and the bulk mineralogy was calculated from the XRD-peak heights in random oriented mounts.

Unit D: Dicellograptus Shale bulk mineralogy
Three Dicellograptus Shale samples were measured. They are all very quarts dominated and the lowermost sample in unit D1 almost consists exclusively of quarts. In the most TOC rich unit (D3) 70% quarts, 10% mica and 10% feldspar were measured.

Unit E: Lindegård Fm bulk mineralogy
Only one sample were analysed for bulk mineralogy. It was fairly clay rich with >30% mica and 50% quarts. The upper unit (E3) had about 25% carbonate content (cement).

Unit F: Rastrites Shale bulk mineralogy
Two samples, one from F2 and one from F3, were measured for bulk mineralogy. The sample from the F2 unit had about 20% mica and about 60% quarts and low carbonate content. The F3 sample contained about 10% clay and 50% quarts. The carbonate value was 25% reflecting carbonate cement. High carbonate content was observed in all samples from this unit.

4. Well summary Skelbro-2

DGU well number:	246.817
Common well Name:	Skelbro-2
Location:	Drilled next to the abandoned Duegård Komstad Limestone quarry - 200 m east of the Skelbro-1 drill location.
UTM zone	33
Drill Position, UTM:	492534, 6099356
Terrain elevation, m:	39.3 DNN
TD:	42.9 m drillers depth below ground level
Formation at TD:	Læså Fm, Rispebjerg Mbr
Drilling type:	Diamond coring
Core diameter:	5.5 cm
Core barrel length:	3 m
Recovery:	From below 4.5 m: 100%
Drilling fluids:	Fresh water with no additives
Casing:	Steel casing in the quaternary sediments only (0-4.5m).
Drilling company:	Fakse Kalk A/S, Hovedgade 13, 4654 Fakse Ladeplads.
Drilling date:	11-12th August 2010
Logging:	GEUS
Purpose:	Scientific studies during the GASH project
Location of cores:	At GFZ in Potsdam for the duration period of the GASH project else GEUS in Copenhagen.
Summary:	The Skelbro-2 cored a 4 m thick mid Ordovician Komstad Limestone at this location. The top of Alum shale was encountered at 8.5m below terrain and a total of 33.5 m of Alum Shale was drilled. The formation includes the Middle Cambrian Andrarum and Exsulans limestone beds that both serve as important regional marker beds. The well was terminated in the Lower Cambrian Rispebjerg Member of the Læså Fm at 42.9 m. The well record a nearly identical succession compared to the Skelbro-1 core, described by Pedersen (1989).

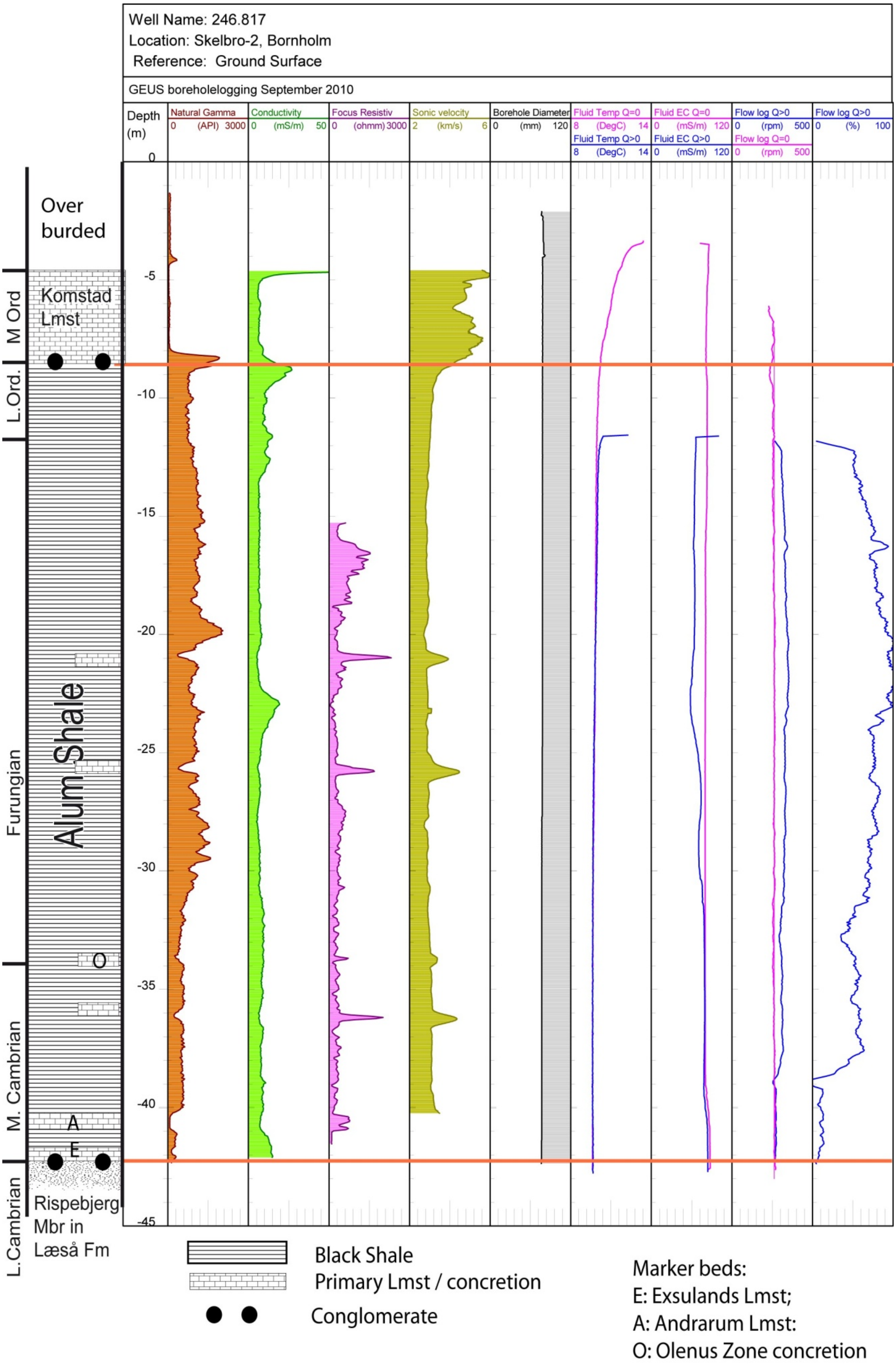

Figure 6. Sedimentological log of the Skelbro-2 well and logs obtained in the Skelbro-2 hole.

4.1. Down hole logs

The Skelbro-2 hole was logged in September 2010 by Kurt Klitten, Per Jensen and Hans Jørgen Lorentzen all from GEUS. Due to technical problems no sonic log was obtained. In November 2010 a second run with the sonic tool was made with success. Flow logs, water temperature and water conductivity was measured both with no flow in the well and with. Flow was established in the well with pumps.

The following logs were obtained in the hole:

Table 1. Down hole logs obtained in Skelbro-2

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	Borehole Diameter
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

4.2. Spectral core gamma and density scanning

The core sections were scanned with a spectral gamma and bulk density scanner at GEUS Core Laboratory. The natural gamma radiation is recorded within an energy window of 0.5 - 3.0 MeV, using Tl activated NaI scintillation detectors, connected to a multichannel analyzer.

The core sections were scanned sequentially with the core sections being fitted together to obtain scan of a continuous core. Scanning was performed with a speed of 1 cm/min with read-out of the collected gamma and density data every 60 seconds. The spectral gamma data have an intrinsically low signal-to-noise ratio. To improve the readability of the gamma log the spectral gamma data were smoothed with a boxcar filter with a bandwidth of 10 cm. This procedure removes little spatial information from the data as the gamma scanner has a depth resolution of approximately 17 cm. The bulk density data were not smoothed, because these data intrinsically have a high signal-to-noise ratio and a depth resolution of approximately 1 cm.

The results are presented in Figure 7.

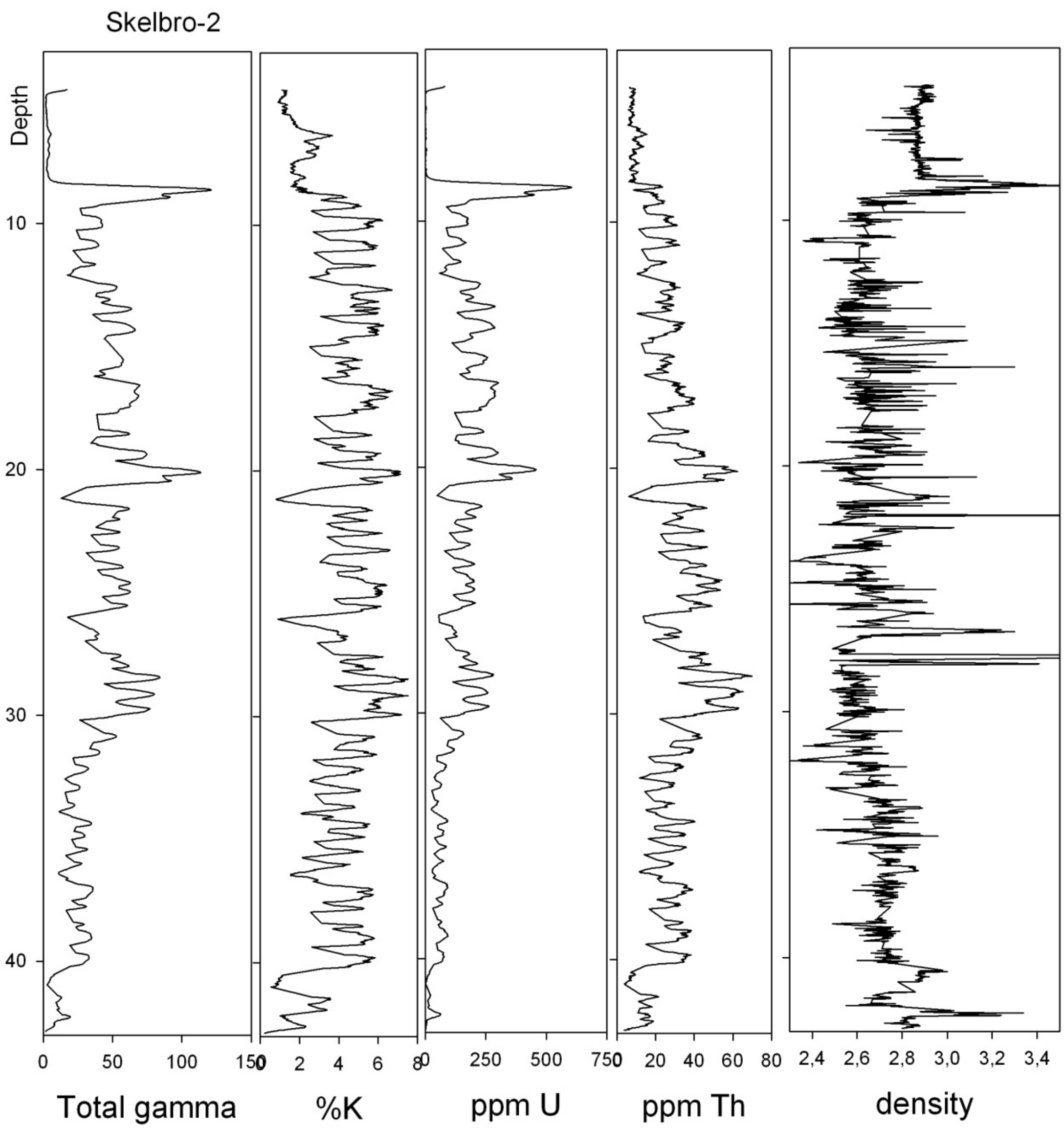

Figure 7. Spectral gamma logs and density scanning obtained by the core scanning at GEUS. The core was heavily sampled prior to scanning and thus the logs are characterised by many intervals with no data (compare with Figure 6).

4.3. Logstratigraphical units in Skelbro-2

Below follows a brief description of the log units in Skelbro-2. The description of the units in Skelbro-2 has been made with reference to the descriptions made by Pedersen (1989), Pedersen & Klitten (1990) and Nielsen & Schovsbo (2006) and to the work made on the Billegrav-2 well. The biostratigraphy is inferred from Nielsen & Schovsbo (2006) and Schovsbo (2002).

Unit A: Rispebjerg Member, Læså Fm 42.1- 42-9 (TD)
Rispebjerg Member (0.8 m in Skelbro-2): Light grey medium to coarse grained quartz sandstone. The top part is impregnated with phosphorite.
Age: Early Cambrian. *Schmidtiellus mickwitzi* trilobite Zone.

Unit B: Alum Shale Formation (33.5 m in Skelbro-2)
The unit is characterized by gamma- readings much higher than all other units. The Alum Shale consists of black organic rich mudstone with beds and nodules of limestone. Barite and pyrite occur both as disseminated crystals and as nodules.

<u>Unit B1: Exsulans Limestone and Lower Alum Shale (1.0 m in Skelbro-2)</u>
The unit top is marked by low gamma values indicative of Andrarum Limestone. The B1 unit represent the Exsulans Limestone (0.3 m) and Alum Shale (0.7 m). The Exsulans Limestone is a primary bio-clastic carbonate bed.
Age: Mid Cambrian (*P. paradoxissimus* to *P. forchhammeri* superzones).

<u>Unit B2: Andrarum Limestone and Mid Cambrian to basal Furongian Alum Shale (10 m in Skelbro-2)</u>
The log unit is bounded upwards by a sharp increase in gamma ray readings and the unit represents an interval in the Alum Shale characterised by intermediate gamma values.
Age: Mid Cambrian (*P. forchhammeri*) to the lowermost Furongian (lower *Olenus* Zone).

<u>Unit B3: Furongian Alum Shale (19 m in Skelbro-2)</u>
An interval characterised by very high gamma values. Top of the interval is placed at the start of a stepwise decrease in GR values. The high fluctuation in GR values in some intervals in the unit reflects the presence of diagenetic carbonate nodules and beds. A very distinct spike in the gamma values occurs in the middle of the unit. A similar spike can be observed in numerous logged water wells on Bornholm and in logged wells in Scania. The high GR readings occur in a shale level that represents the Furongian *Peltura* Zones.
Age: Furongian (upper *Olenus* Zone – *Acerocare* Zone)

<u>Unit B4: Ordovician Alum Shale (3 m in Skelbro-2)</u>
An interval characterised by intermediate GR values. The interval is bound upwards by a very sharp drop in GR values reflecting the Komstad Limestone.
Age: Early Ordovician (Tremadocian)

Unit C: Early Mid Ordovician Komstad Limestone (4.5–8.5 m)
An interval characterised by very low GR readings reflecting the Komstad Limestone: The unit is a cold water carbonate that contains variable amounts of clay, phosphorite and glauconite.
Age: Mid Ordovician (Dapingian)

5. Well summary Billegrav-2

DGU well number:	248.61
Common well Name:	Billegrav-2
Location:	Drilled in the Øle Å valley
Landowner:	Andreas Ipsen, Strandvejen 5, Pedersker, 3720 Åkirkeby
UTM zone	33
Drill Position, UTM:	499901, 6096171
Terrain elevation, m:	12.2 DNN
TD:	125.9 drillers depth below terrain
Formation at TD:	Læså Fm, Rispebjerg Sandstone Mbr.
Drilling type:	Diamond coring.
Core diameter:	5.5 cm
Core barrel length:	3 m
Recovery:	From below 2.5 m: 100%
Drilling fluids:	Fresh water from Øle Å. No additives.
Casing:	Steel casing in the quaternary sediments only (0-2.5m).
Drilling company:	Fakse Kalk A/S, Hovedgade 13, 4654 Fakse Ladeplads.
Drilling date:	14th -20th August 2010.
Logging:	13th -16th September by GEUS.
Purpose:	Stratigraphic and to establish the water flow properties.
Location of cores:	GEUS
Stratigraphy	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 mud to siltstone unit containing carbonate cemented sandy beds between 31.2 and 46.0 m. The Upper Ordovician includes the Lindegård Formation (previously referred to as the Tretaspis Shale or Tommarp and Jerrestad mudstones), comprising grey mud- and siltstones, and the dark organic-rich Dicellograptus Shale. 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 (Bergström & Nilsson 1974). 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 Alum Shale Formation is 27 m thick and includes the Middle Cambrian Andrarum and Exsulans limestone beds that are important regional marker beds. The base of the Alum Shale was reached at 122 m and the well was terminated at 125.9 m in the Rispebjerg Member.

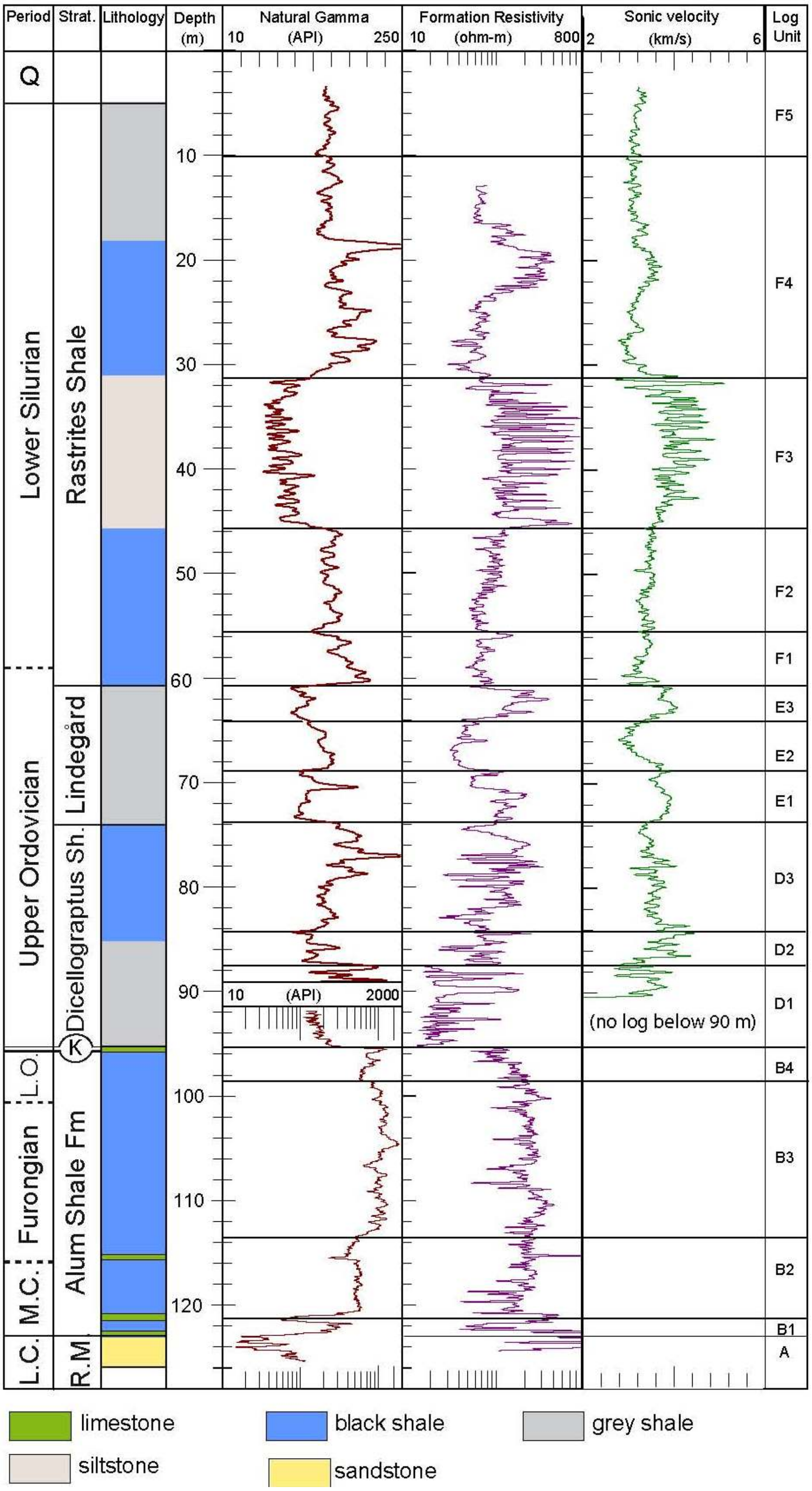

Figure 8. Lithologic and stratigraphic division of the Billegrav-2 well (from Schovsbo et al. 2011). Abbreviation: R.M.: Rispebjerg Mbr, K: Komstad Lmst, Q: Quaternary. Broken lines indicate uncertain chronostratigraphic boundaries. Log units are according to Pedersen & Klitten (1990).

5.1. Downhole logs

The following logs were obtained in the Billegrav-2 hole:

Table 2. Down hole logs obtained in Billegrav-2

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	Borehole Diameter
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

In addition to this a spectral core scanning and density scanning was made on the Billegrav-2 core.

5.2. Log stratigraphy

The logstratigraphical units defined by Pedersen & Klitten (1990) have all been identified in the Billegrav-2 well (Schovsbo et al. 2011, Figure 8). At current time no detailed descriptions of the lithology in the Billegrav-2 core are available. In Table 3 the pick depths of the log units in the well are presented.

6. Litho- and biostratigraphical frame for the Lower Palaeozoic on Bornholm

On Bornholm the Middle Cambrian Alum Shale rests directly on the Lower Cambrian Læså Fm being separated by the pronounced regional unconformity termed the Hawke Bay event (Figure 9). The Hawke Bay event is a combined tectonic uplift of the plate margins and a sea level lowering that affected the sedimentation on a regional scale in Baltoscandia.

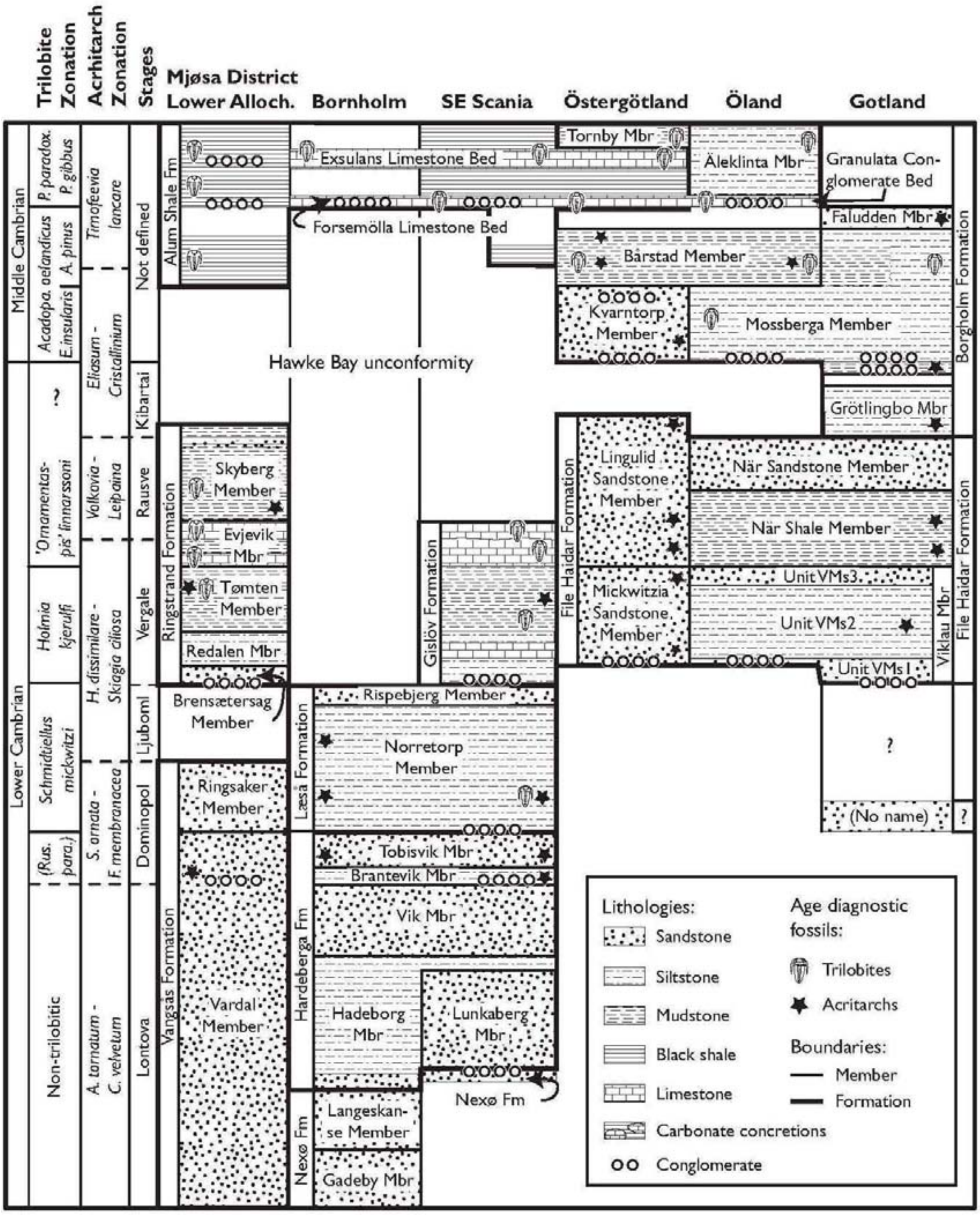

Figure 9. Lithostratigraphic scheme for the Lower and lower Middle Cambrian of southern Scandinavia. From Nielsen & Schovsbo (2006).

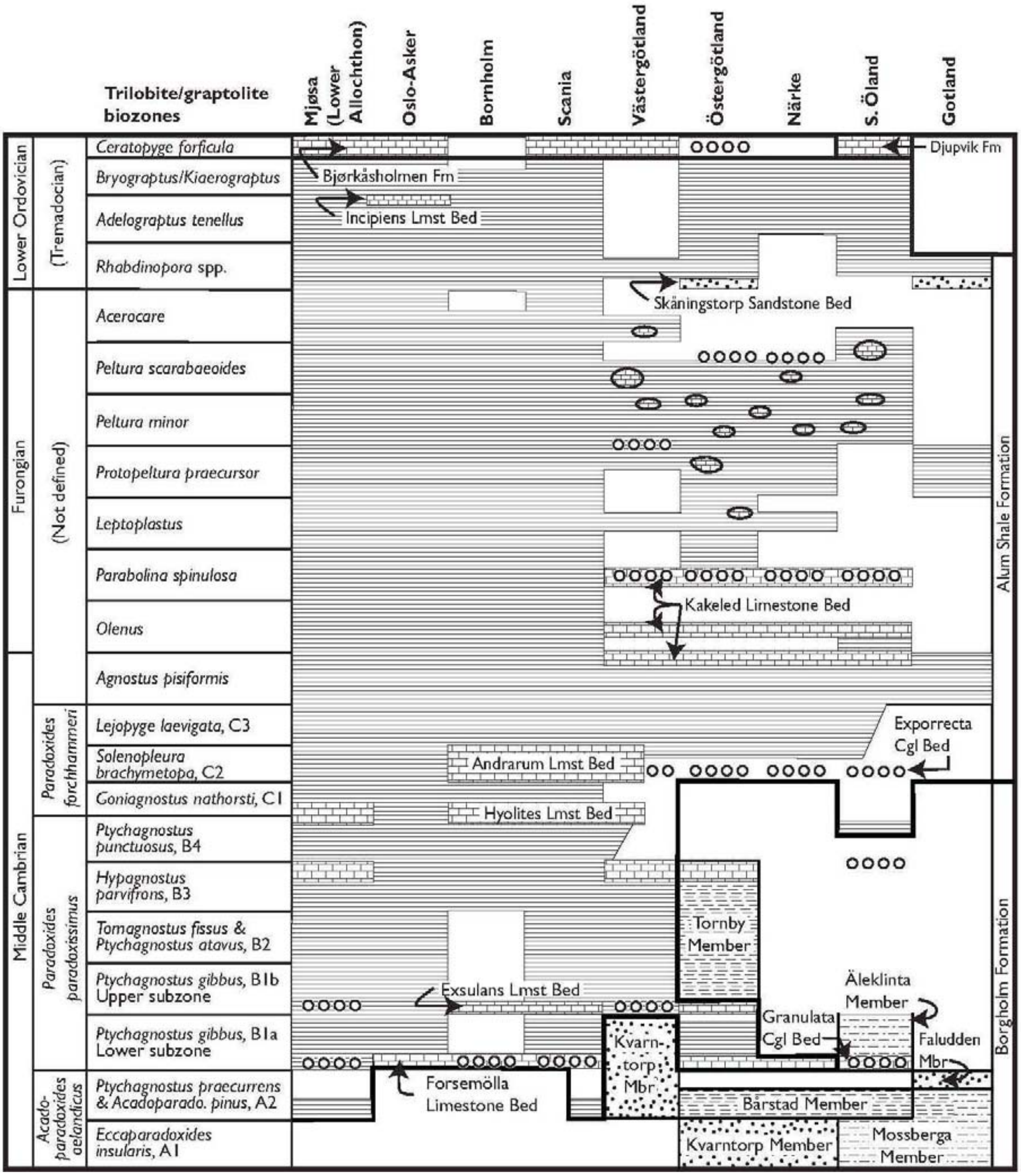

Figure 10. Lithostratigraphic scheme for the Middle Cambrian, Furongian and Lower Ordovician (Tremadocian) of southern Scandinavia. Avery sophisticated biostratigraphy has been established for the Middle Cambrian and Furongian based on agnostid and olenid trilobites. From Nielsen & Schovsbo (2006).

The lower part of the Alum Shale on Bornholm contains the thin Exsulans Limestone (c. 0.2 m thick) with a basal conglomerate equivalent to the Forsemölle Limestone Bed. The Exsulans Limestone is a primary bio-clastic limestone. Above the Exsulans follow a thin (up to 1.5 m thick) Alum Shale interval followed by the Andrarum Limestone, about 0.8 m thick (Figure 10). The Alum Shale sandwiched by these two beds represents the Middle Cambrian *P. paradoxissimus* Superzone.

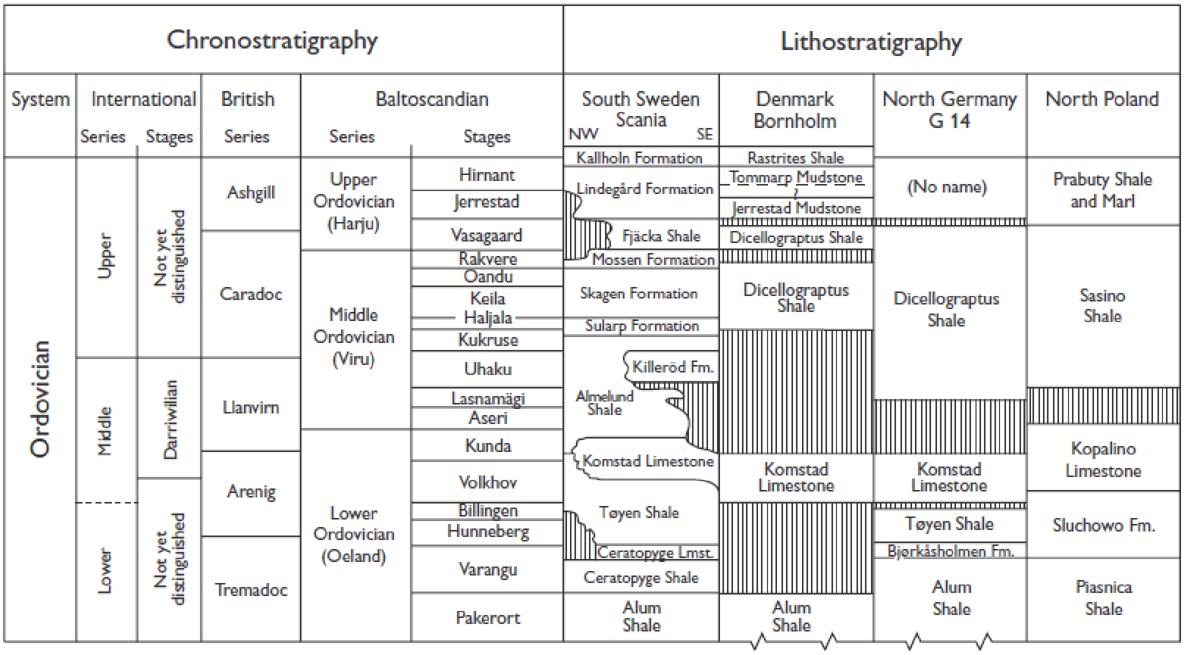

Figure 11. Stratigraphy of Scania, Bornholm, northern Germany (G14) and northern Poland with indications of main lithologies. From Stouge & Nielsen (2003).

The Alum Shale sequence above the Andrarum Limestone is overall fairly homogeneous and is composed of fine-grained mudstone with a low proportion of diagenetic carbonate beds. This type of Alum shale is also deposited in Scania and has been termed the 'outer shelf' type by Schovsbo (2002). Alum Shale with higher proportions of primary carbonates, conglomerates and diagenetic carbonate concretions is present in the south-central parts of Sweden and Öland (Figure 10) and is termed 'inner shelf' type (Schovsbo 2002).

The Alum Shale Fm is overlain directly by the Middle Ordovician (Arenig) Komstad Limestone on Bornholm (Figure 11). Compared to the stratigraphically more complete section in Scania the uppermost part of the Alum Shale (the Ceratopyge shale), the Bjørkåsholmen Fm and the Tøyen shale are missing on Bornholm. This unconformity likely reflects slight uplift/adjustment of the plate margins (Stouge & Nielsen 2003).

The Komstad Limestone is overlain directly by the Upper Ordovician Dicellograptus shale reflecting yet another gap in the succession corresponding to most of the Middle Ordovician and lowermost Upper Ordovician (Figure 11). Again this regional unconformity traceable from South Sweden to northern Poland may be related to both sea-level lowering and plate adjustment of the margins of Baltica (Stouge & Nielsen 2003).

In the uppermost parts of the Dicellograptus Shale on Bornholm unconformities of shorter duration, associated with conglomerates, reflect erosion related to sea-level fluctuations.

7. Correlation between wells

Pedersen & Klitten (1990) discerned 6 units (A-F) and 16 subunits based on the GR log pattern in the Billegrav-1 and Skelbro-1 wells (Figure 12). They demonstrated its local consistency via detailed log based correlation of water wells on Southern Bornholm. The log stratigraphical units defined in Skelbro-1 and Billgrav-1 have all been identified in the Skelbro-2 and Billegrav-2 well (Figure 13 and Table 3).

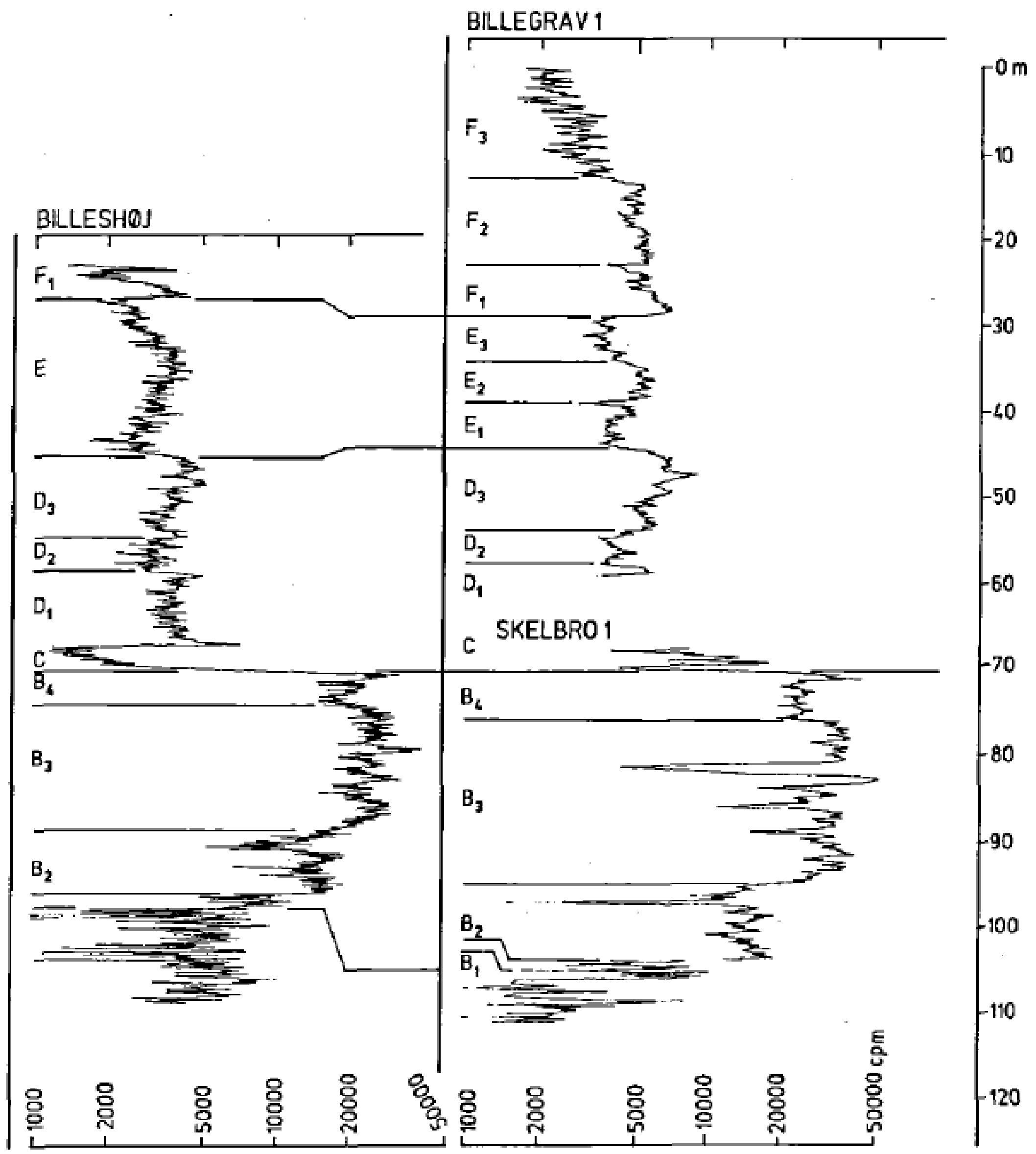

Figure 12. Example of correlation between the Billegrav-1 and Skelbro-1 wells and the uncored water well Billeshøj. The A-F refers to the log units. From Pedersen & Klitten (1990).

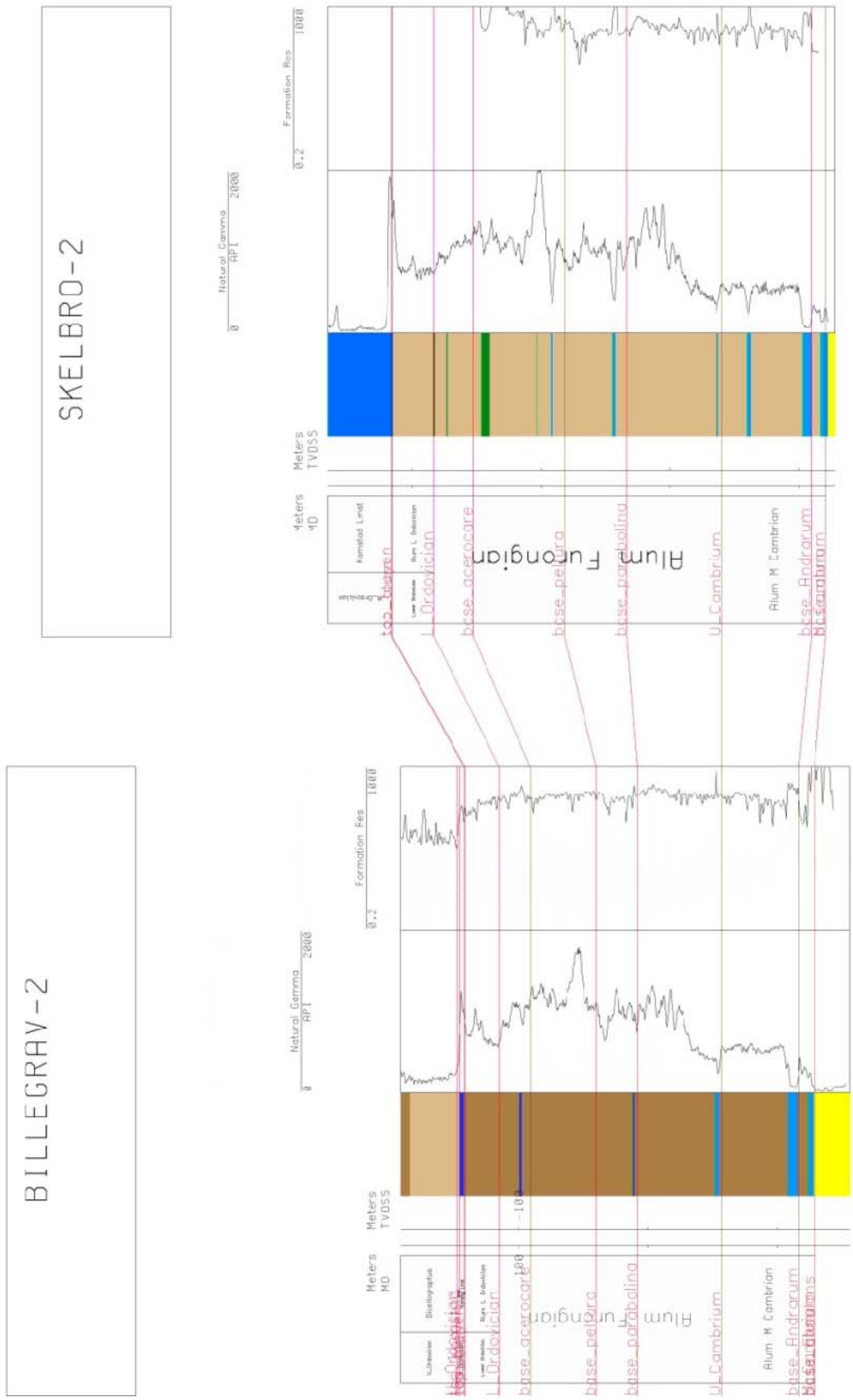

Figure 13. Correlation between Skelbro-2 and Billegrav-2. The profile has been ‘flattened’ on the base Furongian surface.

Table 3. Stratigraphic picks in the Skelbro-1 and -2 and Billegrav-1 and -2 wells.

Pick name	Billegrav-1	Skelbro-1	Billegrav-2	Skelbro-2
	m. below surface	m. below surface	m. log depth below casing	m. below surface
Base Rastrites Unit F5	not present		10.1	
Base Rastrites Unit F4	not present		31.5	
Base Rastrites Unit F3	12.0		45.7	
	23.0		55.7	
Top Lindegård/Base Rastrites	29.2		61.1	
	34.0		64.3	
	39.0		69.1	
Top Dicellograptus/Base Lindegård	45.0		73.8	
	54.0		84.5	
	59.0		87.6	
Top Komstad/Base Dicellograptus	61.0 (TD)		95.3	
Top Alum / Base Komstad		3.9	95.4	8.5
Lower Ordovician. Base B4 unit		8.8	98.5	11.7
Base *Acerocare* Zone			100.9	14.8
Base *Peltura* Zone			106.0	21.8
Base *Parabolina* Zone			109.2	26.6
Base B3 unit		27.1	113.5	31.0
Base Furongian (*Olenus* Zone)			115.7	34.0
Base Andrarum Lmst. Base B2 unit		36.4	121.3	41.0
Top Læså / Base Alum Fm. Base B1 unit		37.2	123.0	42.1
TD		43.2 (TD)	126.3 (TD)	42.9 (TD)

8. TOC variation

8.1. TOC content in Skelbro-1 and Billegrav-1

The TOC content was measured with an equidistance of 1 metre between the samples in the Skelbro-1 and Billegrav-1 cores (see Buchardt et al. 1986). TOC measurements were carried out by combustion of acid treated carbonate-free samples in a LECO-type oven.

The data is included in Appendix A and the TOC content for each unit is summarised in Table 4.

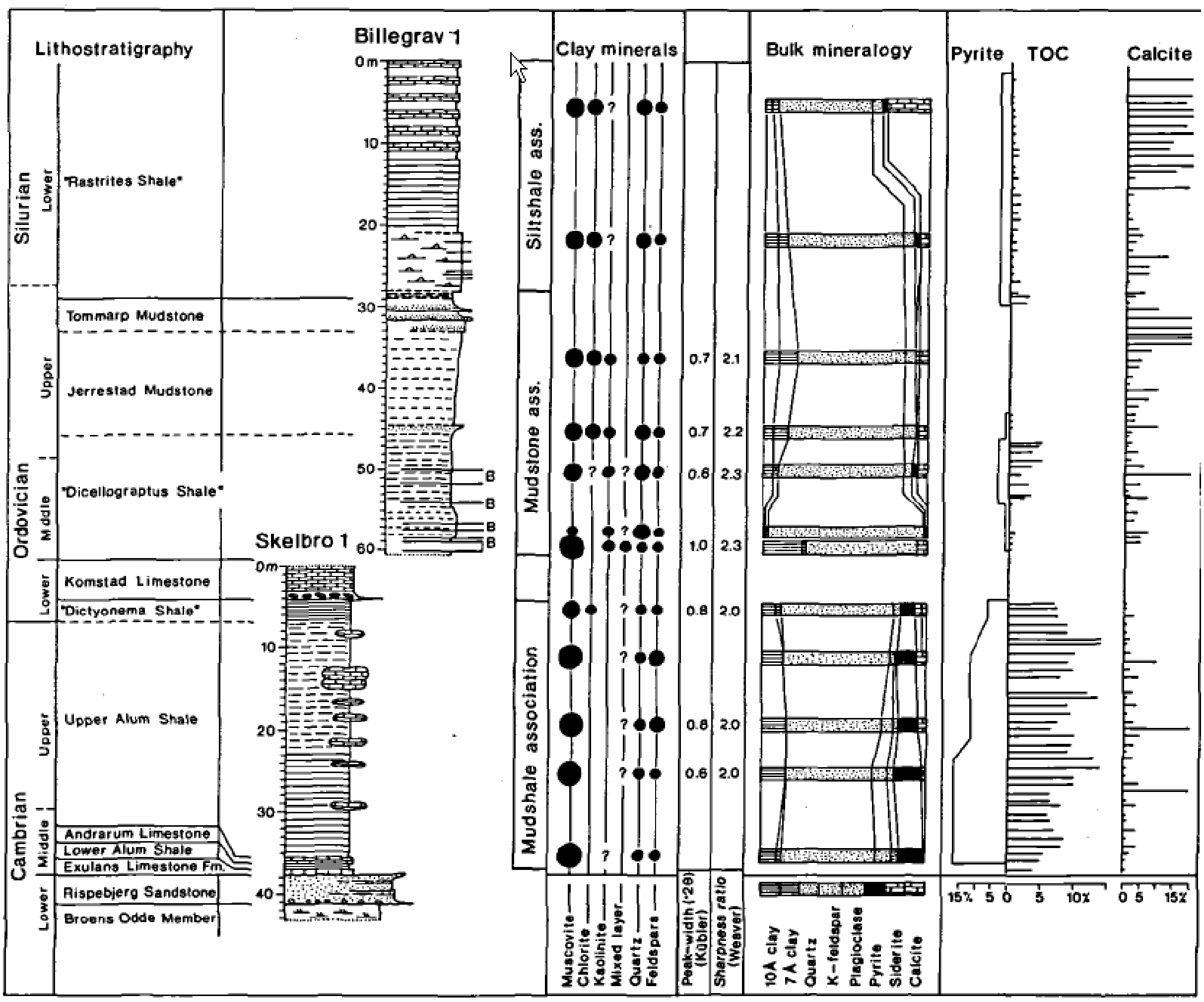

Figure 14. Mineralogy, TOC and carbonate content in the Skelbro-1 and Billegrav-1 wells (Pedersen, 1989). The clay minerals were identified using XRD and the size of the black dots is proportional to the height of the peaks in the diffractograms. The bulk mineralogy was calculated from XRD-peak height in random oriented mounts. The TOC data is included in Appendix A and the TOC content for each log unit is summarised in Table 4.

Table 4. TOC contents and main lithology of the units in the Skelbro-1 and Billegrav-1 wells. Bold indicate TOC enriched units (>1% TOC).

Formation	Main Lithology	TOC %	Log unit	Thickness, m
Rastrites Shale	Grey siltstone with calcite cemented beds	0.5-0.8	F3	+12
Rastrites Shale	Grey siltstone	0.5-1	F2	11
Rastrites Shale	**Dark mudstone with silt streaks**	**0.4-3**	**F1**	**6.2**
Lindegård	Grey mudstone	0.1-0.2	E3	4.8
Lindegård	Grey-green mudstone	0.1-0.2	E2	5
Lindegård	Sandstone –siltstone	0.1-0.4	E1	6
Dicellograptus	**Black mudstone**	**0.1-5**	**D3**	**9**
Dicellograptus	Grey mudstone	0.1-1	D2	5
Dicellograptus	Grey mudstone with bentonite beds	0.5	D1	+2
Komstad	Limestone	0	C	3.9
Alum Shale	**Black mudstone**	**4-8**	**B4**	**4,9**
Alum Shale	**Black mudstone**	**8-14**	**B3**	**18.3**
Alum Shale	**Andrarum Limestone + Black mudstone**	**5-8**	**B2**	**9.3**
Alum Shale	**Exsulans Limestone + Black mudstone**	**4**	**B1**	**0.8**

The highest TOC concentrations are seen in the Alum Shale (Table 4) notably in the 18 m thick B3 unit. In this unit TOC ranges between 8-14%. The unit represent the Furongian (upper *Olenus* Zone to *Acerocare* Zone).

The TOC content in the Skelbro-1 well is comparable to the concentrations measured in the Furongian part of the Alum Shale in Scania (Figure 15).

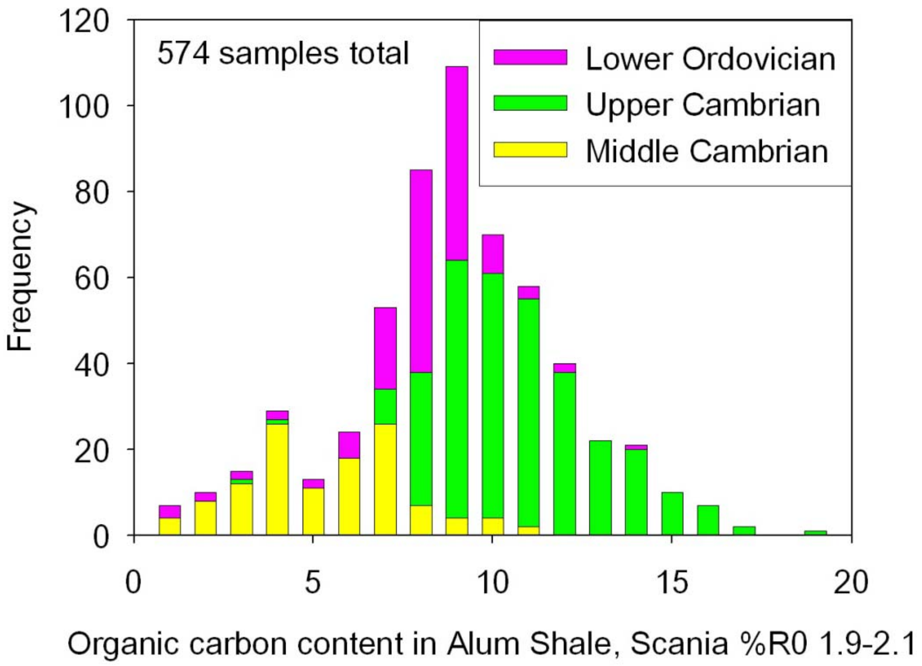

Figure 15. Distribution of TOC content in Alum Shale core sample from Scania divided into main stratigraphical units. Middle Cambrian Alum Shale have on average 4.9±2.2% TOC, Furongian (labelled ‘Upper Cambrian’) Alum Shale have on average 10.3±2.3% TOC and Lower Ordovician Alum Shale have on average 7.5±1.9% TOC.

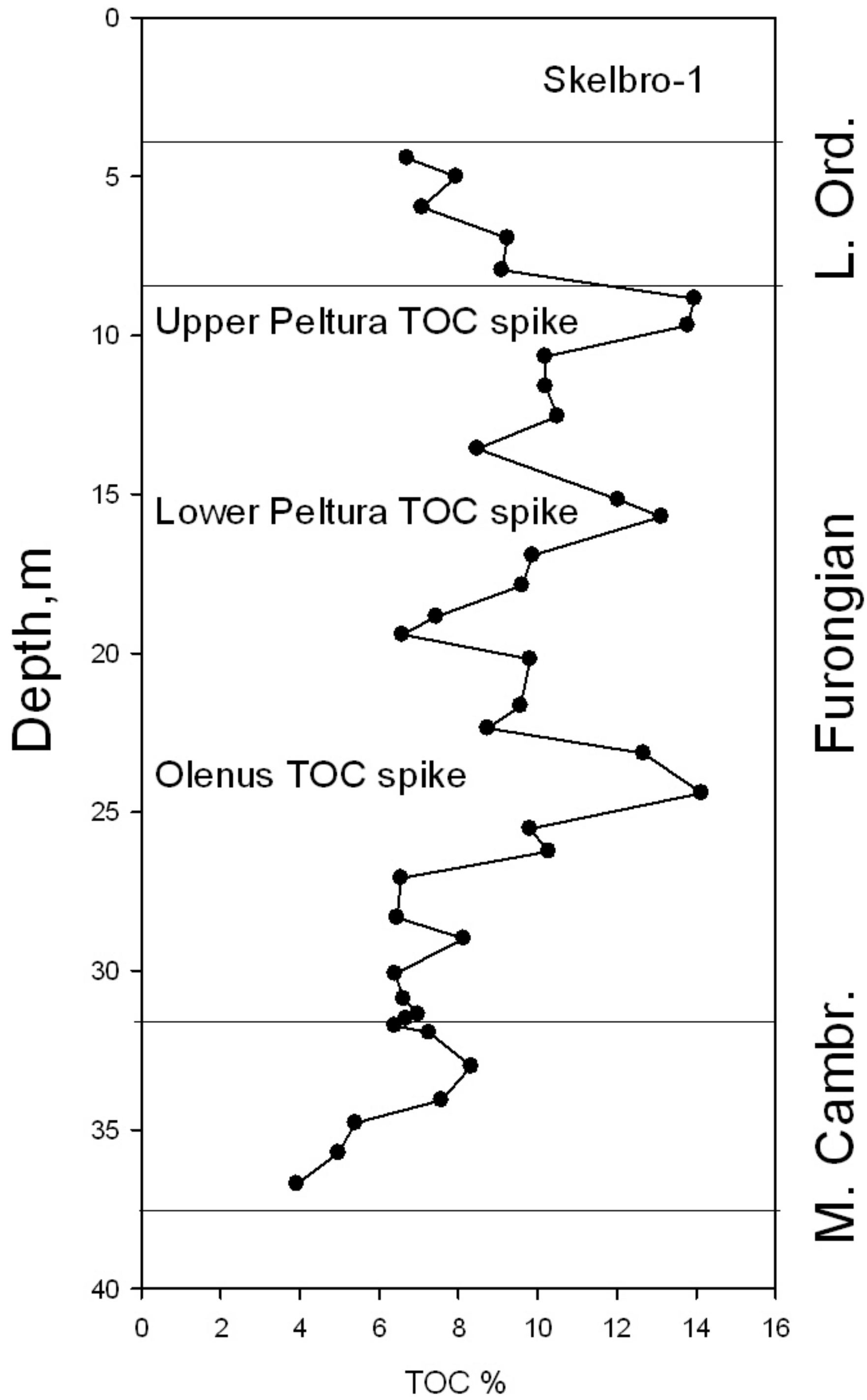

Figure 16. Detail of the TOC variation in the Alum Shale in the Skelbro-1 well. For additional information see Figure 14. In the Furongian part of the Alum Shale Formation three peaks in TOC content can be seen namely what is informally termed the *Olenus* spike, and the upper and lower *Peltura* spikes.

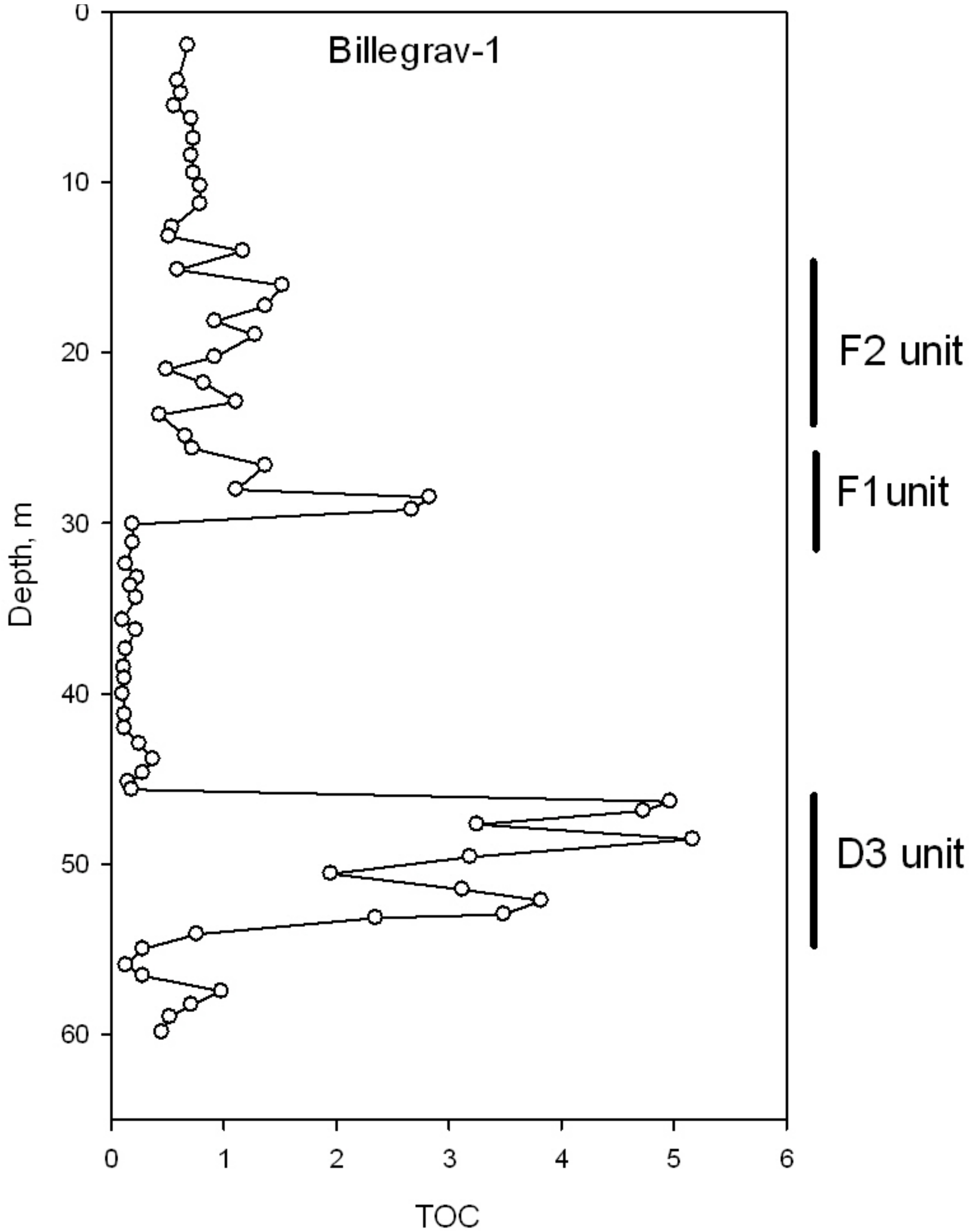

Figure 17. Detail of the TOC variation in the Ordovician and Silurian in the Billegrav-1 well. For additional information see Figure 14. TOC enriched units are the 9 m thick upper Dicellograptus unit D3 and the 5.5 m thick lower Rastrites F1 unit. Beside of this the c. 9 m thick Lower Silurian *M. convolutus* Zone, above the level penetrated by Billegrav-1, is also enriched in TOC (lower part of log unit F4 in Figure 8).

8.2. TOC profile in the Skelbro-2 well

45 TOC measurements have been made in the Skelbro-2 well by the GASH scientists (Figure 19C). The TOC variation seen in the Skelbro-2 well is very alike the variation in Skelbro-1 and the three levels with high TOC content i.e. the '*Olenus*' and the 'upper and lower *Peltura* spikes' identified in the Skelbro-1 (Figure 16) can also be identified in the Skelbro-2 well (Figure 19C).

In order to detail the description of the TOC variation a log based expression of the TOC content has been calculated (Figure 19). The modelling of the TOC content is based on the relationships between sonic velocity and gamma radiation (Figure 18). In the Alum Shale the TOC content and the sonic velocities exhibit a very strong inverse correlation. In the shale high TOC content is thus characterised by low interval times which is as expected for organic rich shale. The TOC calculated directly from the sonic log is termed TOC (sonic) and is shown in Figure 19A.

The TOC (sonic) reproduce the long term trend in the measured TOC values quite well. The *Olenus* and lower *Peltura* TOC spikes can also be recognised on the TOC (sonic) curve whereas the upper *Peltura* spike is not clearly expressed. A misfit between TOC (sonic) and measured TOC is evident in the interval from 31-34 m. Here the TOC (sonic) consistently model lower TOC values. This might suggest slight difference in the shale matrix occur in the formation.

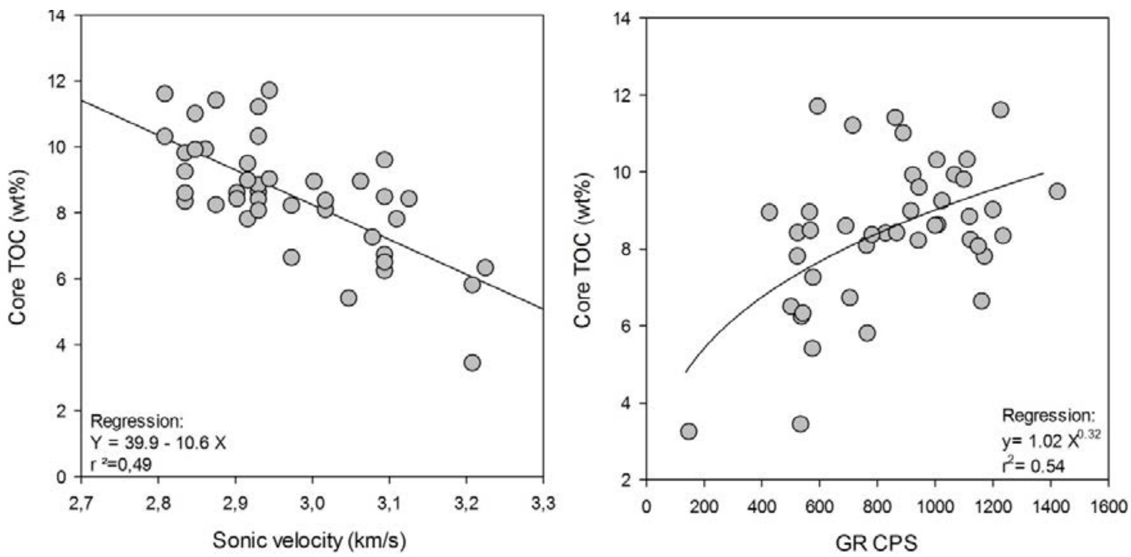

Figure 18. Data from the Skelbro-2 well: Relationship between TOC measured on core samples from the GASH scientist database (by October 2011) and down-hole log responses. The established correlations between TOC and sonic velocity (left) and between TOC and GR response (right) are used in the TOC modelling presented in Figure 19. Three samples have been identified as outliers and have been removed prior to calculation.

The GR response has also been used to calculate a TOC expression (Figure 19A). The calculation is based on the relationship between TOC content and Gr curve established and is termed TOC (Gr). The correlation reflects the strong co-enrichment of uranium with organic carbon during deposition of the shale as also illustrated from Figure 4.

The TOC (Gr) curve also depicts the long term trend in the measured TOC content (Figure 19A). The TOC spikes in the upper *Olenus* and in the lower *Peltura* Zone are also captured by the calculation. Too high TOC content is estimated in the topmost part of the formation whereas too low TOC content have been estimated in the interval 30-34 m. These discrepancies probably reflect a slight variability in the U/TOC content which is known to be related to the depositional environment (Schovsbo 2002).

A combined average TOC expression have been calculated (avgTOC in Figure 19B) from the TOC (sonic) and TOC (Gr) curves. Comparison between the avgTOC content and the measured TOC content shows a maximum offset of 2 wt% for the most part of the formation (Figure 18C). Larger differences between modelled avgTOC and measured TOC values are seen in the interval 31-36 m. The poorly modelled TOC might reflect difference in U/TOC ratio and variability in the shale matrix. This awaits further consideration.

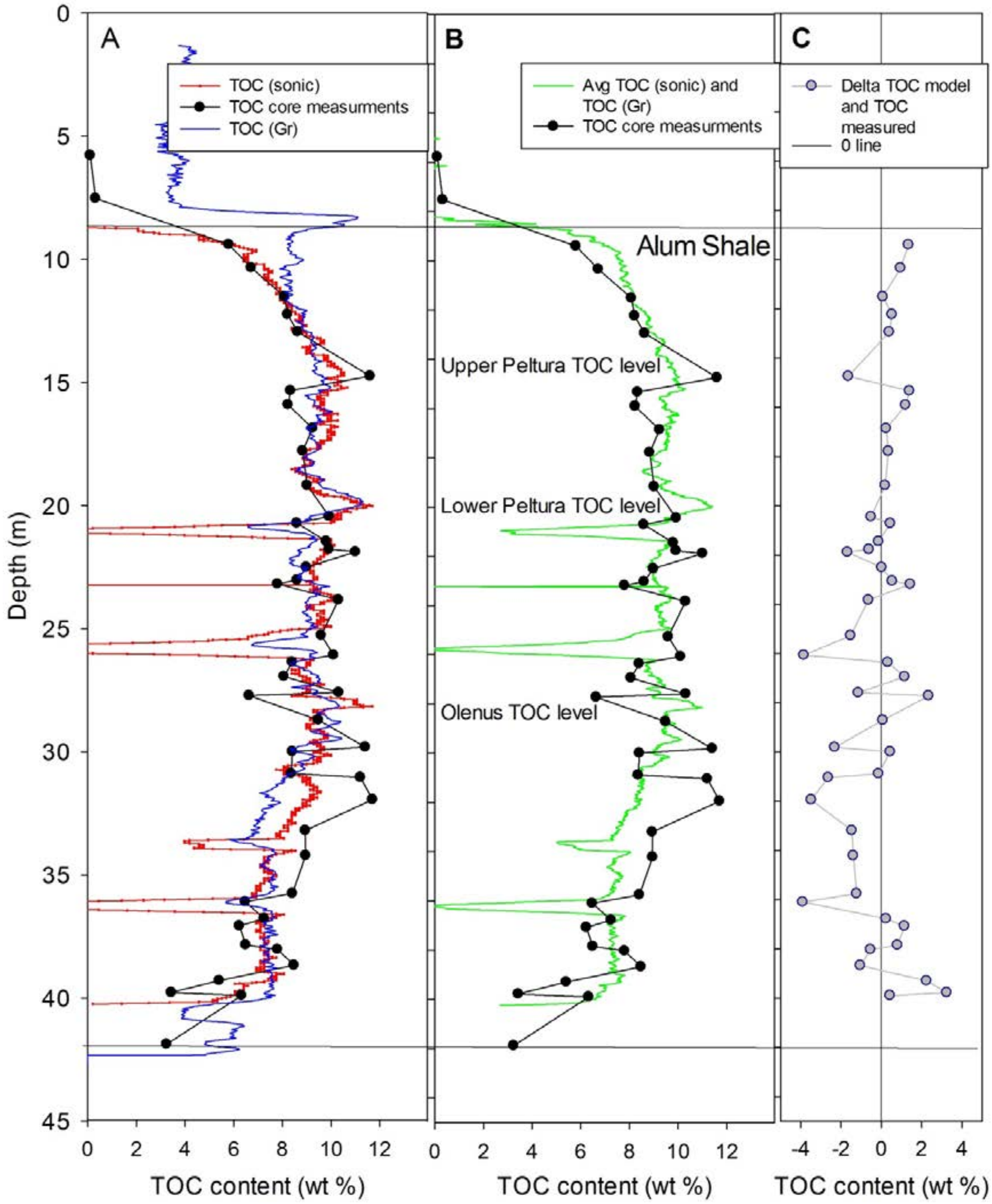

Figure 19. Data from the Skelbro-2 well: A) TOC calculated from the sonic log (red), Gr log (blue) and TOC measurements (black), B) Average of the TOC calculated from sonic and Gr curves (green curve) and TOC measurements (black symbols). C) Difference between avgTOC (green line in FIgure 19B) and TOC measurments. Calculating of the TOC content from the log reponse is based on the correlation lines established in Figure 18.

9. Maturity and burial history of Bornholm

Thermal maturity of the Alum Shale at Bornholm has been studied by Buchardt & Nielsen (1985), Buchardt et al. (1986, 1997, 1998), Buchardt & Lewan (1990) and Jensenius (1987). Thermal maturity parameters include stable isotopes, vitrinite reflectance, Rock Eval, atomic H/C and O/C ratios and fluid inclusions. Burial modelling of the Alum Shale in the Bornholm area has been published by Vejbæk et al. (1994) and a regional maturity map for the Alum Shale was presented by Buchardt et al. (1997, 1998).

9.1. Vitrinite Reflectance

The Alum Shale was deposited prior to the evolution of vascular land plants and thus the shale does not contain terrestrial derived vitrinite particles. Nevertheless the unit contains vitrinite like particles supposedly of marine origin. According to Buchardt & Lewan (1990) these particles behaves in a similar manner as true vitrinite. Consequently reflectance of vitrinite like particle has been widely used as a thermal marker in the shale. For detailed discussion of the origin and geochemical similarities between Alum Shale vitrinite and true vitrinite, see Buchardt & Lewan (1990).

Table 5. Summary of vitrinite reflectance data from the Skelbro-1 and Billegrav-1 wells.

Formation	Log Unit	Sample number	Depth. m	%Ro	STD %Ro	%Rmax	STD Rmax	%Rmin	STD Rmin	N
Alum Shale	B4	SKK 56	6.0			2.75	0.09	1.93	0.08	35
Alum Shale	B4	SKK 55	6.9	2.51	0.44					70
Alum Shale	B4	SKK 54	7.9	2.37						
Alum Shale	B3	SKK 52	9.7			2.66	0.12	1.98	0.06	27
Alum Shale	B3	SKK 48	13.6			2.91	0.08	1.96	0.08	22
Alum Shale	B3	SKK 45	16.9			2.94	0.1	2.09	0.08	29
Alum Shale	B3	SKK 44	17.9	2.14	0.42					70
Alum Shale	B3	SKK 41	20.2			2.88	0.08	2.15	0.09	21
Alum Shale	B3	SKK 38	23.2			2.92	0.09	1.99	0.09	33
Alum Shale	B3	SKK 35	26.2			2.89	0.14	2.09	0.11	22
Alum Shale	B2	SKK 34	27.1	2.31	0.41					70
Alum Shale	B2	SKK 31	30.1			2.77	0.15	2.04	0.09	21
Alum Shale	B2	SKK 25	35.7	2.36	0.27	2.84				52
Alum Shale	B1	SKK 24	38.2			2.88	0.13	1.71	0.15	38
Dicellograptus	E2	SKS 07	46.9	2.14	0.12					42
Rastrites	D2	SKS 27	28.5	2.50	0.38					45

Vitrinite reflectance measurements have been carried out on 14 samples from Skelbro-1 and 2 samples from Billegrav-1 (Table 5). All vitrinite reflectance analyses were measured at GEUS in the period 1980-1990. Measurements were conducted on polished slides of powdered whole rock (1-2 mm). Measurements were performed with non-polarized light at a wavelength of 546 nm through an immersion oil (n=1.52). The average of different vitrinite-like macerales in each slide is referred to as the mean reflectance and the abbreviation % Ro is used. In some cases measurements of oriented macerales was made. For these samples highest and lowest reflectance values was measured for the macerales and reported as Rmax and Rmin reflectance value. Rmax-Rmin measurements on samples were published by Buchardt et al. (1986). However it should be noted that in this publication Rmax values was reported erroneously as % Ro-values.

For the Alum Shale in Skelbro-1 the average Ro is 2.34% based on five measurements. For Billegrav-1 the average Ro is 2.32% Ro based on two samples.

9.2. Rock Eval and atomic H/C ratio

Rock Eval data from the Skelbro-1 well was published by Buchardt et al. (1986). The data was analyzed at GEUS on whole rock powder samples using a Delsi Rock Eval instrument. Results include extractable organic matter S1, pyrolysis yield S2 and temperature of maximal pyrolysis yields (Tmax). Calculated indices include the HI that represents the pyrolysis yield normalized to the TOC content.

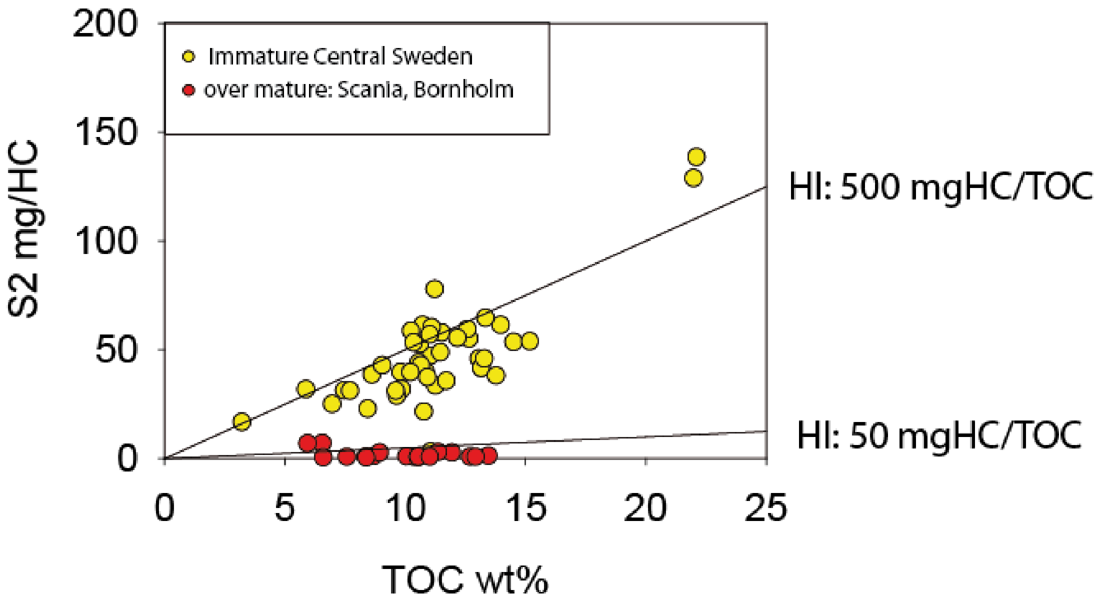

Figure 20. Comparison between Rock Eval S2 yields of immature (%Ro<0.5) and mature (%Ro>2) Alum Shale samples. Immature Alum Shale samples have pyrolysis yield between 400-600 mg HC/g TOC. At higher maturation the pyrolysis yield decreases to less than 50 mg HC/ g TOC. The S2 yield of the Bornholm samples are less than 10 mg HC/g TOC.

The pyrolysis yields of the S1, S2 and S3 are very low and thus the Rock Eval data from Skelbro-1 all indicates a very high thermal alteration (Table 6, Figure 20). Due to low yields no Tmax-value could be defined based on the S2 shape.

For comparison immature Alum Shale samples have S2 yield in the range of 15-145 mg HC / g rock and HI index of about 400-600 mg HC/ g TOC (Figure 20).

No Rock Eval analysis was made for samples from the Billegrav-1 well.

The atomic ratio was measured in 3 samples from Skelbro-1 (Table 6). The ratio ranges from 0.41 to 0.44, which is in agreement with the high maturation rank indicated by the vitrinite and Rock Eval data (Buchardt & Lewan 1990).

Table 6. Summary of Rock Eval and atomic H/C and O/C measurements from the Skelbro-1 well. The Tmax was not defined due to low S2 yields.

Formation	Log Unit	Sample number	atomic H/C	atomic O/C	TOC wt. %	S1. mg HC/g sample	S2. mg HC/g sample	S3. mg CO2/g sample	HI. mg HC/g TOC	OI. mg CO2/ g TOC
Alum Shale	B4	SKK 56			7.6	0.05	0.31	0.21	4	3
Alum Shale	B4	SKK 55	0.44	0.04						
Alum Shale	B4	SKK 54			9.0					
Alum Shale	B3	SKK 52			11.1	0.03	0.24	0.05	2	0
Alum Shale	B3	SKK 48			10.6	0.03	0.41	0.02	4	0
Alum Shale	B3	SKK 45			13.0	0.05	0.30	0.00	2	0
Alum Shale	B3	SKK 44	0.42	0.04	9.6					
Alum Shale	B3	SKK 41			8.4	0.04	0.11	0.33	1	4
Alum Shale	B3	SKK 38			12.7	0.05	0.27	0.42	2	3
Alum Shale	B3	SKK 35			10.6	0.04	0.14	0.19	1	2
Alum Shale	B2	SKK 34	0.41	0.04	6.6					
Alum Shale	B2	SKK 31			6.6	0.04	0.01	0.19	0	3
Alum Shale	B2	SKK 25	0.46	0.06	5.0					

9.3. Fluid inclusion studies

Jensenius (1987) analyzed three samples from the Skelbro-1 well for fluid inclusions and one sample from Billegrav-1. The samples from the Skelbro-1 well were picked at 40.1 m (Rispebjerg Mbr), 3.3 m and 2.8 m (Komstad Limestone). A sample from 5.7 m in the Billegrav-1 (vein in Silurian shale) was also analysed. Additional 4 outcrop samples were analyzed from Bornholm. Jensenius observed both aqueous and hydrocarbon inclusions in the samples.

Hydrocarbon and gaseous inclusions occurred in calcite veins cutting the Komstad Limestone. The inclusion fluoresced green-yellow during UV fluorescence microscopy. He found that that the hydrocarbons were slightly more enriched with higher hydrocarbons than usually in a wet gas.

Clathrate (gas hydrates) formation was observed in a few aqueous liquid-vapour inclusions in quartz veins from the Hardeberga sandstone. The analysis strongly indicated the presence of trace methane levels in the inclusions. Petrographic studies by Møller & Friis (1999) on analyses of outcrop samples of Hardeberga sandstone on Bornholm contained pyro-bitumen. Møller & Friis (1999) together with Jensenius assumed that the Alum Shale have sourced the hydrocarbons on Bornholm.

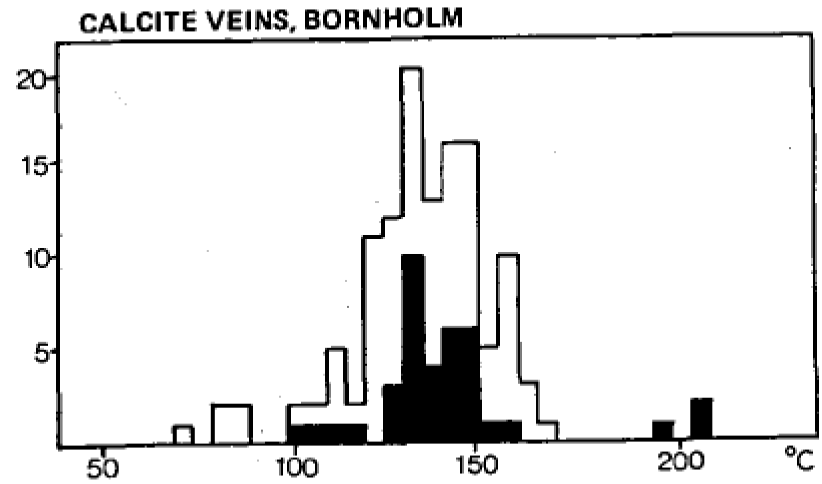

Figure 21. Homogenization temperatures for aqueous inclusions in calcite veins from Bornholm. All veins belong to the same 136 °C group of inclusions. From Jensenius (1987)

Studies of homogenization temperatures in the fluid inclusions indicate that the calcite veins at Bornholm belonged to a 136 °C group (Figure 21). A few quartz veins belonged to a 82 °C group. Jensenius (19879 also observed that the salinity of the inclusions decreases with increasing homogenization temperature, possible reflecting dilution of the saline formation water with clay bound water released during smetite to illite transformation.

9.4. Burial History

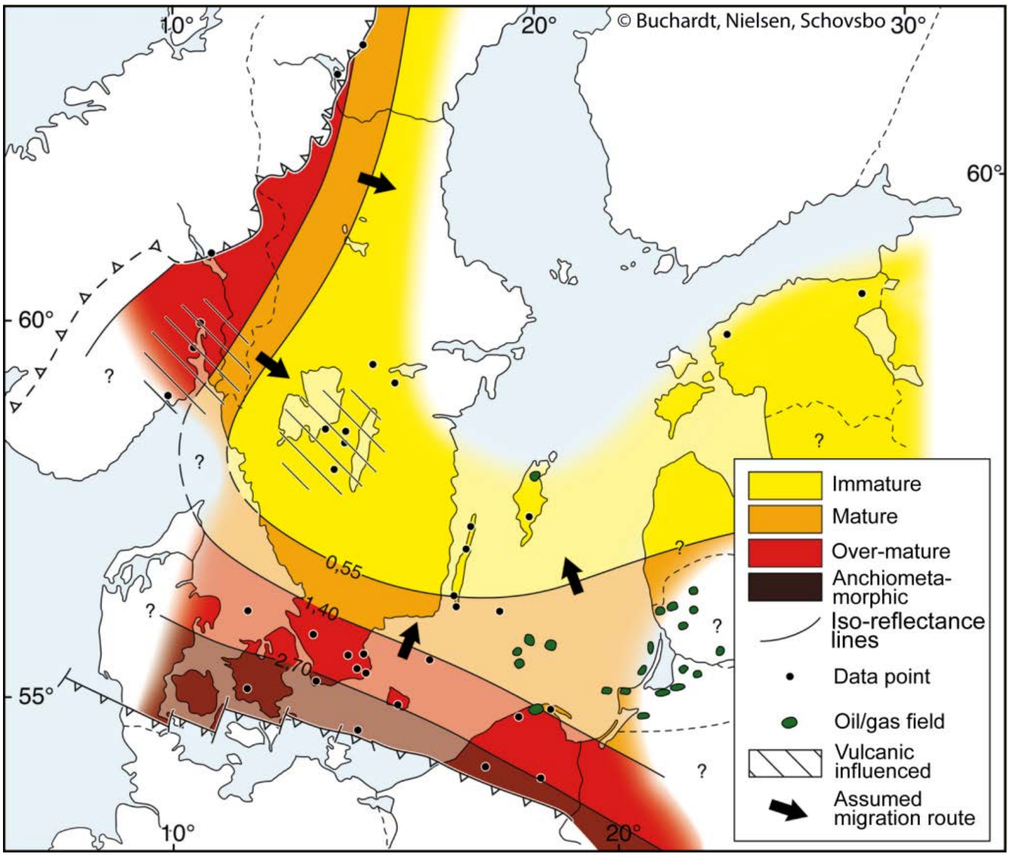

Figure 22. Maturity map of the Alum Shale formation based on vitrinite reflectance data. From Buchardt et al. (1997).

The burial history of the Bornholm area is very complex and involves several subsidence and uplift histories. It is generally assumed that the present day maturation pattern of the Lower Palaeozoic in the Bornholm area reflects deep Caledonian burial and subsequent maturation. This part of the thermal maturation burial history in the Bornholm area has been discussed by Jensenius (1987), Buchardt & Lewan (1990), Vejbæk et al. (1994) and Buchardt et al. (1997).

According to Buchardt et al. (1997) the Caledonian burial commenced in Late Silurian time where rapid subsidence led to deposition of at least 3 km of sediments. The increase in subsidence reflected the development of foreland basin in front on the German-Polish Caledonides. Based on oxygen isotope systematic of carbonate on Bornholm Buchardt & Nielsen (1985) concluded that Bornholm was heated to above 90^{o}C during this deep burial. They assumed about 4 km of burial in the Bornholm-Scania area.

Vejbæk et al. (1994) conducted a series of burial and maturation modelling of the basins surrounding Bornholm. According to their model maturation to oil and gas stage was reached in Late Silurian time and peak burial occurred in the Early Devonian. About 3 km of Palaeozoic sediments was inferred to be present from seismic mapping around Bornholm.

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Appendix A: Analysis of TOC in Skelbro-1 and Billegrav-1

TOC data Billegrav-1

Age	Stage	Zone	Formation	Log Unit	Sample	Depth	TOC
						m	wt.%
Silurian	Llandovery	vesiculosus	Rastrites	F3	SKS 54	1.98	0.68
Silurian	Llandovery	vesiculosus	Rastrites	F3	SKS 53	4.06	0.59
Silurian	Llandovery	vesiculosus	Rastrites	F3	SKS 52	4.8	0.62
Silurian	Llandovery	vesiculosus	Rastrites	F3	SKS 51	5.54	0.56
Silurian	Llandovery	vesiculosus	Rastrites	F3	SKS 50	6.28	0.71
Silurian	Llandovery	vesiculosus	Rastrites	F3	SKS 49	7.45	0.73
Silurian	Llandovery	vesiculosus	Rastrites	F3	SKS 48	8.45	0.71
Silurian	Llandovery	vesiculosus	Rastrites	F3	SKS 47	9.45	0.73
Silurian	Llandovery	vesiculosus	Rastrites	F3	SKS 46	10.23	0.79
Silurian	Llandovery	vesiculosus	Rastrites	F3	SKS 45	11.29	0.79
Silurian	Llandovery	vesiculosus	Rastrites	F2	SKS 44	12.65	0.54
Silurian	Llandovery	vesiculosus	Rastrites	F2	SKS 43	13.18	0.51
Silurian	Llandovery	vesiculosus	Rastrites	F2	SKS 42	14.04	1.17
Silurian	Llandovery	vesiculosus	Rastrites	F2	SKS 41	15.14	0.59
Silurian	Llandovery	vesiculosus	Rastrites	F2	SKS 40	16.05	1.52
Silurian	Llandovery	vesiculosus	Rastrites	F2	SKS 39	17.27	1.37
Silurian	Llandovery	vesiculosus	Rastrites	F2	SKS 38	18.16	0.92
Silurian	Llandovery	vesiculosus	Rastrites	F2	SKS 37	18.96	1.28
Silurian	Llandovery	acuminatus	Rastrites	F2	SKS 36	20.26	0.92
Silurian	Llandovery	acuminatus	Rastrites	F2	SKS 35	20.98	0.49
Silurian	Llandovery	acuminatus	Rastrites	F2	SKS 34	21.78	0.82
Silurian	Llandovery	ascensus	Rastrites	F2	SKS 33	22.88	1.11
Silurian	Llandovery	ascensus	Rastrites	F1	SKS 32	23.65	0.43
Silurian	Llandovery	ascensus	Rastrites	F1	SKS 31	24.9	0.66
Silurian	Llandovery	ascensus	Rastrites	F1	SKS 30	25.62	0.72
Silurian	Llandovery	ascensus	Rastrites	F1	SKS 29	26.63	1.37
Ordovician	Ashgill	persulptus	Rastrites	F1	SKS 28	28.03	1.11
Ordovician	Ashgill	persulptus	Rastrites	F1	SKS 27	28.48	2.83
Ordovician	Ashgill	persulptus	Rastrites	F1	SKS 26	29.2	2.67
Ordovician	Ashgill	extraordinarious	Lindegård Fm	E3	SKS 25	30.06	0.19
Ordovician	Ashgill	extraordinarious	Lindegård Fm	E3	SKS 24	31.15	0.19
Ordovician	Ashgill	extraordinarious	Lindegård Fm	E3	SKS 23	32.4	0.13
Ordovician	Ashgill	extraordinarious	Lindegård Fm	E3	SKS 22	33.2	0.23
Ordovician	Ashgill	extraordinarious	Lindegård Fm	E3	SKS 21	33.67	0.17
Ordovician	Ashgill	extraordinarious	Lindegård Fm	E2	SKS 20	34.37	0.22
Ordovician	Ashgill	extraordinarious	Lindegård Fm	E2	SKS 19	35.67	0.1

TOC data Billegrav-1 (continued)

Age	Stage	Zone	Formation	Log Unit	Sample	Depth	TOC
						m	wt.%
Ordovician	Ashgill	complanatus+ anceps	Lindegård Fm	E2	SKS 18	36.27	0.22
Ordovician	Ashgill	complanatus+ anceps	Lindegård Fm	E2	SKS 17	37.38	0.13
Ordovician	Ashgill	complanatus+ anceps	Lindegård Fm	E2	SKS 16	38.44	0.11
Ordovician	Ashgill	complanatus+ anceps	Lindegård Fm	E1	SKS 15	39.1	0.12
Ordovician	Ashgill	complanatus+ anceps	Lindegård Fm	E1	SKS 14	40.01	0.1
Ordovician	Ashgill	complanatus+ anceps	Lindegård Fm	E1	SKS 13	41.22	0.12
Ordovician	Ashgill	complanatus+ anceps	Lindegård Fm	E1	SKS 12	42.02	0.12
Ordovician	Ashgill	complanatus+ anceps	Lindegård Fm	E1	SKS 11	42.94	0.25
Ordovician	Ashgill	complanatus+ anceps	Lindegård Fm	E1	SKS 10	43.84	0.37
Ordovician	Ashgill	complanatus+ anceps	Lindegård Fm	E1	SKS 55	44.63	0.28
Ordovician	Ashgill	linearis	Dicellograptus	D3	SKS 9	45.17	0.15
Ordovician	Ashgill	linearis	Dicellograptus	D3	SKS 8	45.62	0.18
Ordovician	Caradoc	linearis	Dicellograptus	D3	SKS 56	46.32	4.97
Ordovician	Caradoc	linearis	Dicellograptus	D3	SKS 7	46.86	4.73
Ordovician	Caradoc	linearis	Dicellograptus	D3	SKS 6	47.66	3.25
Ordovician	Caradoc	linearis	Dicellograptus	D3	SKS 5	48.53	5.17
Ordovician	Caradoc	linearis	Dicellograptus	D3	SKO 25	49.58	3.19
Ordovician	Caradoc	linearis	Dicellograptus	D3	SKO 24	50.57	1.95
Ordovician	Caradoc	clingani	Dicellograptus	D3	SKO 23	51.48	3.12
Ordovician	Caradoc	clingani	Dicellograptus	D3	SKO 29	52.14	3.82
Ordovician	Caradoc	clingani	Dicellograptus	D3	SKO 22	52.95	3.49
Ordovician	Caradoc	clingani	Dicellograptus	D3	SKO 21	53.16	2.35
Ordovician	Caradoc	clingani	Dicellograptus	D2	SKO 20	54.1	0.76
Ordovician	Caradoc	foliaceus	Dicellograptus	D2	SKO 27	54.97	0.28
Ordovician	Caradoc	foliaceus	Dicellograptus	D2	SKO 19	55.92	0.13
Ordovician	Caradoc	foliaceus	Dicellograptus	D2	SKO 18	56.55	0.28
Ordovician	Caradoc	foliaceus	Dicellograptus	D2	SKO 17	57.45	0.98
Ordovician	Caradoc	foliaceus	Dicellograptus	D2	SKO 16	58.24	0.71
Ordovician	Caradoc	foliaceus	Dicellograptus	D2	SKO 15	58.96	0.52
Ordovician	Caradoc	foliaceus	Dicellograptus	D1	SKO 14	59.85	0.45

TOC data Skelbro-1

Age	Zone	Formation	Log Unit	Sample	Depth	TOC
					m	wt.%
Lower Ordovician	D2	Alum Shale	B4	SKO 13	4.42	6.7
Lower Ordovician	D1	Alum Shale	B4	SKO 12	5.00	7.94
Lower Ordovician	D1	Alum Shale	B4	SKK 56	5.96	7.08
Lower Ordovician	D1	Alum Shale	B4	SKK 55	6.94	9.24
Furongian (U Cambrian)	*Acerocare*	Alum Shale	B4	SKK 54	7.94	9.1
Furongian (U Cambrian)	*Peltura*	Alum Shale	B3	SKK 53	8.84	13.96
Furongian (U Cambrian)	*Peltura*	Alum Shale	B3	SKK 52	9.68	13.79
Furongian (U Cambrian)	*Peltura*	Alum Shale	B3	SKK 51	10.66	10.19
Furongian (U Cambrian)	*Peltura*	Alum Shale	B3	SKK 50	11.60	10.2
Furongian (U Cambrian)	*Peltura*	Alum Shale	B3	SKK 49	12.54	10.5
Furongian (U Cambrian)	*Peltura*	Alum Shale	B3	SKK 48	13.56	8.48
Furongian (U Cambrian)	*Peltura*	Alum Shale	B3	SKK 47	15.16	12.03
Furongian (U Cambrian)	*Peltura*	Alum Shale	B3	SKK 46	15.70	13.13
Furongian (U Cambrian)	*Leptoplastus*	Alum Shale	B3	SKK 45	16.92	9.87
Furongian (U Cambrian)	*Leptoplastus*	Alum Shale	B3	SKK 44	17.86	9.61
Furongian (U Cambrian)	*Parabolina spinulosa*	Alum Shale	B3	SKK 43	18.85	7.44
Furongian (U Cambrian)	*Parabolina spinulosa*	Alum Shale	B3	SKK 42	19.41	6.58
Furongian (U Cambrian)	*Parabolina spinulosa*	Alum Shale	B3	SKK 41	20.19	9.81
Furongian (U Cambrian)	*Parabolina spinulosa*	Alum Shale	B3	SKK 40	21.66	9.57
Furongian (U Cambrian)	*Olenus* (Upper)	Alum Shale	B3	SKK 39	22.36	8.74
Furongian (U Cambrian)	*Olenus* (Upper)	Alum Shale	B3	SKK 38	23.15	12.67
Furongian (U Cambrian)	*Olenus* (Upper)	Alum Shale	B3	SKK 37	24.40	14.14
Furongian (U Cambrian)	*Olenus* (Upper)	Alum Shale	B3	SKK 36	25.53	9.81
Furongian (U Cambrian)	*Olenus* (Upper)	Alum Shale	B3	SKK 35	26.24	10.28
Furongian (U Cambrian)	*Olenus* (Lower)	Alum Shale	B2	SKK 34	27.08	6.55
Furongian (U Cambrian)	*Olenus* (Lower)	Alum Shale	B2	SKK 33	28.32	6.45
Furongian (U Cambrian)	*Olenus* (Lower)	Alum Shale	B2	SKK 32	28.98	8.13
Furongian (U Cambrian)	*Olenus* (Lower)	Alum Shale	B2	SKK 31	30.09	6.4
Furongian (U Cambrian)	*Olenus* (Lower)	Alum Shale	B2	SKK 30	30.88	6.61
Middle Cambrian	*A pisiformis*	Alum Shale	B2	SKK 57	31.37	6.98
Middle Cambrian	*A pisiformis*	Alum Shale	B2	SKK 58	31.50	6.67
Middle Cambrian	*A pisiformis*	Alum Shale	B2	SKK 59	31.72	6.39
Middle Cambrian	*A pisiformis*	Alum Shale	B2	SKK 29	31.94	7.26
Middle Cambrian	*A pisiformis*	Alum Shale	B2	SKK 28	33.00	8.33
Middle Cambrian	*A pisiformis*	Alum Shale	B2	SKK 27	34.06	7.57
Middle Cambrian	*Lejopyge*	Alum Shale	B2	SKK 26	34.78	5.4
Middle Cambrian	*Lejopyge*	Alum Shale	B2	SKK 25	35.72	4.97
Middle Cambrian	*P. paradoxides*	Alum Shale	B1	SKK 24	36.70	3.92

Appendix B: Major and trace element data in Skelbro-1

Log Unit	sample	Depth	CO2	SiO2	Al2O3	CaO	MgO	Na2O	K2O	Fe2O3	P2O5	Mn2O3	TiO2	Sum
		m	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%
B4	SKO 13	4.42	1.7	58.5	13.3	3	1.8	0	3.7	5.3	0.5	0.06	0.75	97.51
B4	SKK 55	6.94	0.5	54.8	16.2	0.9	1.7	0.1	4.8	5	0.1	0.04	0.89	96.87
B3	SKK 53	8.84	0.87	49.4	14	1.5	1.2	0.1	4.7	6.1	0.2	0.05	0.75	97.13
B3	SKK 51	10.66	0.5	51.3	15.7	1	1.2	0	5	6.1	0.2	0.04	0.84	96.67
B3	SKK 49	12.54	2.1	46.4	14.4	3.1	1	0	4.5	9.7	0.2	0.11	0.78	99.99
B3	SKK 46	15.70	0.1	48	15.3	0.4	1.1	0	5	8	0.2	0.02	0.81	98.36
B3	SKK 44	17.86	0.1	47.9	15.5	0.4	1.1	0	5	8.9	0.2	0.02	0.86	96.79
B3	SKK 42	19.41	0.9	47.9	15.4	1.5	1.1	0.1	4.8	8	0.2	0.05	0.84	93.77
B3	SKK 39	22.36	0.05	49.2	15.5	0.3	1.2	0	5.1	8.3	0.1	0.03	0.83	95.75
B3	SKK 37	24.40	0.3	41.5	13.6	0.8	1	0.1	4.4	13.5	0.2	0.03	0.78	101.05
B2	SKK 34	27.08	0.3	45.5	14.2	0.7	1.1	0.1	4.7	11.6	0.1	0.03	0.81	94.89
B2	SKK 31	30.09	0.27	49.9	15.6	0.6	1.5	0.2	4.9	10.6	0.1	0.04	0.9	98.71
B2	SKK 29	31.94	0.94	47.3	15.8	1.4	1.7	0.1	5	10.5	0.1	0.06	0.87	98.33
B2	SKK 25	35.72	0.1	49.8	16.4	0.3	1.7	0.2	5.5	11	0.1	0.03	0.91	98.41

Log Unit	sample	Depth	Ba	Cr	Nb	Rb	Sr	Th	U	Y	Zr
		m	ppm	ppm	Ppm	ppm	ppm	ppm	ppm	ppm	ppm
B4	SKO 13	4.42	450	200	30	190	40	14	72	20	130
B4	SKK 55	6.94	680	300	20	240	40	16	81	30	160
B3	SKK 53	8.84	840	200	20	220	50	10	130	50	130
B3	SKK 51	10.66	790	200	20	230	40	16	140	30	150
B3	SKK 49	12.54	1100	200	30	200	30	8	130	30	130
B3	SKK 46	15.70	770	200	20	240	30	12	180	40	160
B3	SKK 44	17.86	7440	200	20	240	80	14	66	30	150
B3	SKK 42	19.41	850	200	20	230	20	16	140	60	150
B3	SKK 39	22.36	880	200	40	250	20	14	87	40	160
B3	SKK 37	24.40	720	200	20	200	30	8	140	50	140
B2	SKK 34	27.08	820	200	30	240	30	10	55	30	150
B2	SKK 31	30.09	820	200	30	230	30	12	45	40	170
B2	SKK 29	31.94	840	100	20	250	50	10	30	10	170
B2	SKK 25	35.72	710	200	30	280	40	8	33	40	180