Gamma-ray log correlation and stratigraphic architecture of the Cambro-Ordovician Alum Shale Formation on Bornholm, Denmark: Evidence for differential syndepositional isostasy

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The Cambro–Ordovician Alum Shale Formation on Bornholm, Denmark, is in total 26.7 to ≥ 34.9 m thick in nine boreholes, but may be up to ~39 m thick. The well sections are correlated using gamma-ray logs supplemented in some boreholes with resistivity and sonic logs. The gamma radiation of the 'hot' Alum Shale Formation primarily reflects the uranium content, which is moderately high in the Miaolingian (≈ middle Cambrian) and Tremadocian (Lower Ordovician), and very high in the Furongian (≈ upper Cambrian). The log pattern is calibrated with the detailed biozonation established in the Gislövshammar-1 and -2 wells in south-eastern Skåne, Sweden. Except for the *Eccaparadoxides oelandicus* Superzone, all superzones known from the Alum Shale in Scandinavia are also developed on Bornholm, but not all zones.

On Bornholm, the Miaolingian interval is 7.2–11.9 m thick, the Furongian is 16.4–22.8 m thick and the Tremadocian is 2.5–4.0 m thick. The Miaolingian strata exhibit no systematic thickness variations across southern Bornholm, whereas the Furongian *Parabolina*, *Peltura* and *Acerocarina* Superzones and, less pronounced, the Tremadocian, show increased condensation towards the south-east. In comparison with Skåne, the Alum Shale Formation is overall strongly condensed on Bornholm, but different stratigraphic levels show variable developments. The Miaolingian *Paradoxides paradoxissimus* Superzone is thus extremely condensed and incomplete, whereas the *Paradoxides forchhammeri* Superzone has almost the same thickness as in Skåne, and locally is even thicker. The Furongian *Olenus* and *Parabolina* Superzones are slightly thinner than in Skåne while the *Protopeltura*, *Peltura* and *Acerocarina* Superzones are half as thick or less. The Tremadocian is also much thinner on Bornholm. The Furongian *Olenus scanicus–O. rotundatus* and *Parabolina brevispina* Zones seem to be developed on Bornholm, and a thin '*Leptoplastus neglectus*' Zone is also possibly present. The '*Parabolina megalops*' Zone in the upper part of the *Peltura* Superzone appears to be absent. It is impossible to distinguish the individual thin zones in the lower part of the *Acerocarina* Superzone using wireline logs. A thin veneer of the Lower Ordovician Tøyen Formation, hitherto considered absent on Bornholm, is described from the Billegrav-2 core. It may also be present in the uncored Sømarken-3 and -4 wells. The Middle Ordovician Komstad Limestone Formation thins from c. 4.0–4.7 m in the Læså area to 0.1– c. 2.5 m in the Øleå area.

The general decrease in thickness of Cambro–Ordovician strata from Skåne to Bornholm and also within Bornholm from the Læså to the Øleå area is inferred to reflect isostatic uplift of the southern margin of Baltica commencing with the terminal 'early' Cambrian Hawke Bay Event and lasting until the Late Ordovician. In detail, several uplift and subsidence phases can be discerned. The isostatic adjustments are surmised to reflect stress changes related to ongoing plate tectonic processes in the adjacent closing Tornquist Sea.

Keywords: Cambrian, Ordovician, Alum Shale Formation, wireline log correlation, uranium, biostratigraphy, isostasy, Scandinavia, Bornholm.

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The Scandinavian Alum Shale Formation was deposited from the 'mid' Cambrian (Miaolingian) to the Early Ordovician in the offshore deeper parts of a widespread epicontinental sea that covered western Baltica (Fig. 1). The formation comprises blackish, finely laminated, organic- and pyrite-rich mudstone, deposited under dys- and anoxic, maybe occasionally even euxinic conditions (Schovsbo 2000, 2001; Nielsen & Schovsbo 2007, 2015; Hints *et al*. 2014; Egenhoff *et al*. 2015). The mud was deposited extremely slowly; compacted accumulation rates were mostly only 1–2 mm/1000 years on average with a maximum of 4–5 mm/1000 years in southern Scandinavia (e.g. Lindström 1971; Schovsbo 2003). On Bornholm the average Furongian ('late' Cambrian) accumulation rate was ≤ 2.0 mm/1000 years but only *c*. 1 mm/1000 years for the Alum Shale Formation as a whole (compacted values). The low depositional rates in combination with the prevailing low-oxygen conditions near the seafloor (and euxinia within the sediment) caused a strong enrichment of many trace elements in the shale, including Mo, V and U (Armands 1972; Andersson *et al*. 1985; Buchardt *et al*. 1997; Schovsbo 2001, 2002a). The high uranium content gives the 'hot' Alum Shale Formation a unique gamma-ray log pattern in wells (Pedersen & Klitten 1990; Schovsbo *et al*. 2011, 2015a,b, 2018; Ericsson 2012).

No detailed sea-level reconstructions have been published for the Alum Shale interval. During sea-level lowstands the storm wave base was lowered, causing erosion of the inboard parts of the unit (Nielsen & Schovsbo 2015), which created numerous regional hiati in the mid-shelf succession (see Martinsson 1974, fig 5). At the same time the offshore successions in Skåne and the Oslo area became expanded due to outboard transport of reworked Alum Shale mud. By combining these data, a rough interpretation of general sea-level changes can be pieced together, which forms the basis

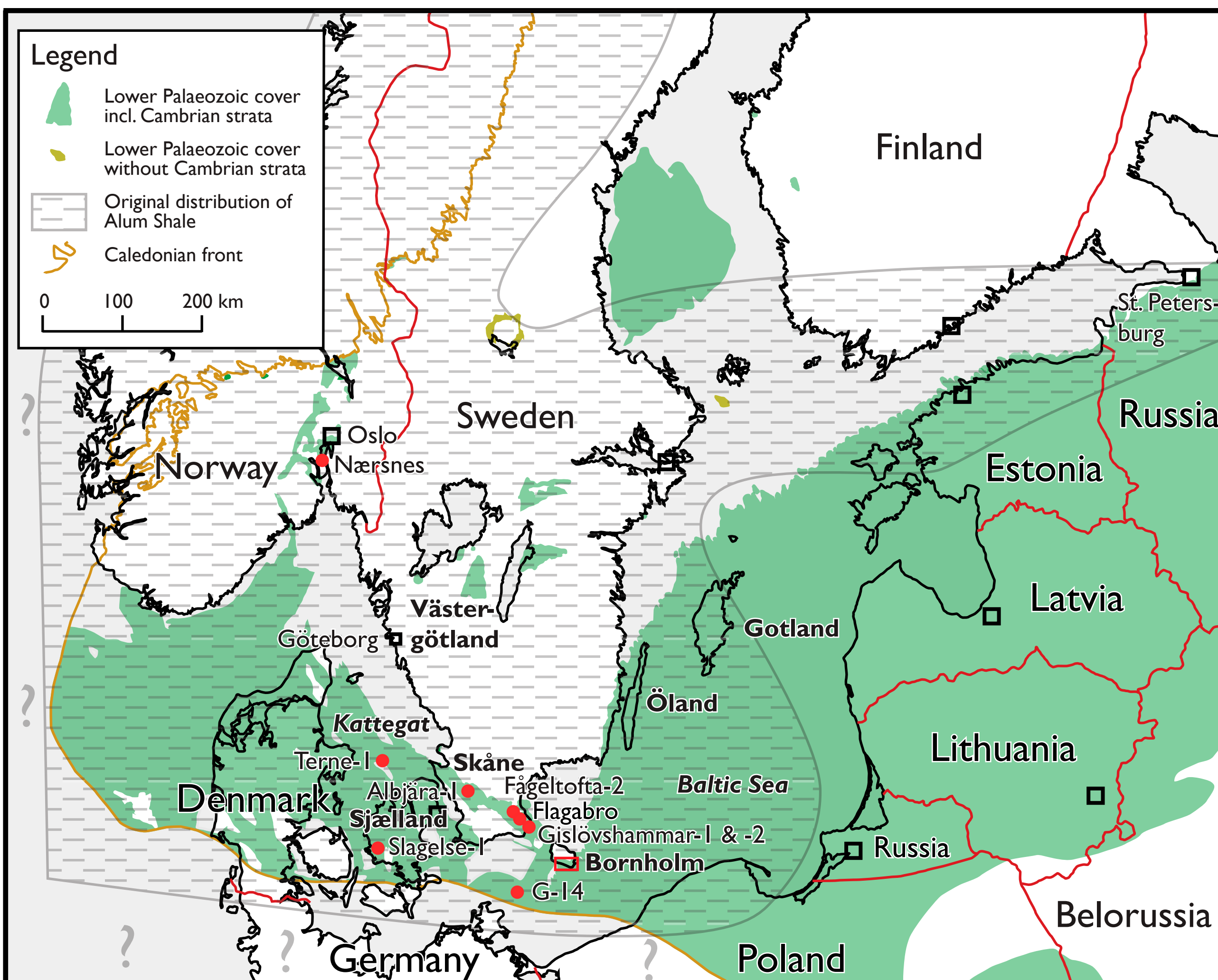


Fig. 1. Location map showing localities and areas referred to in this study. A detailed map of southern Bornholm (red quadrangle) is shown in Fig. 2. The approximate original distribution of the Alum Shale Formation in southern Scandinavia is also shown.

for references to sea-level changes made in this paper.

Despite the prevailing low-oxygen conditions during deposition, the Cambrian Alum Shale contains a low-diverse, but highly abundant trilobite fauna adapted to cope with the harsh living conditions on the seafloor (e.g. Henningsmoen 1957; Clarkson & Taylor 1995; Schovsbo 2000, 2001; Lauridsen & Nielsen 2005; Clarkson 2011). Agnostoids and various 'normal' trilobites known from better ventilated facies are common in the Miaolingian interval, while the Furongian is strongly dominated by olenid trilobites (e.g. Westergård 1922, 1946, 1947, 1948, 1950, 1953; Henningsmoen 1957; Terfelt 2006; Høyberget & Bruton 2012). The Tremadocian (Lower Ordovician) Alum Shale contains common graptolites and phosphatic brachiopods (e.g. Tjernvik 1958), whereas trilobites are mostly rare or absent, which is probably a taphonomic artefact caused by dissolution (Schovsbo 2001). Sparse trilobites have, however, been described from Skåne and the Oslo area (Moberg 1898, Henningsmoen 1957, Bruton *et al*. 1988, Terfelt *et al*. 2014). The abundant fauna in the Alum Shale Formation has facilitated definition of a high-resolution bio- and chronostratigraphy comprising three Miaolingian superzones with seven zones, six Furongian superzones with 22 zones and up to nine Tremadocian zones (see summary of stratigraphy below).

The present study focusses on the Alum Shale Formation of Bornholm, which has for long been known from discontinuous outcrops in the Læså and Øleå stream sections (Fig. 2) (Grönwall 1902, 1916; Poulsen 1922, 1923; Hansen 1945; Berg-Madsen 1985a,b, 1986). The Alum Shale is also intermittently exposed in the Risebæk stream (Fig. 2), but these outcrops have never been studied in any degree of detail.

The Alum Shale Formation of Bornholm has been penetrated in its entirety by eight wells, both cored and uncored (Pedersen 1989; Pedersen & Klitten 1990; Schovsbo *et al*. 2011, 2015b; this study). Seven of these wells plus a well missing only the Ordovician part of the formation are correlated in this study using gamma-ray logs supplemented in some wells with resistivity and sonic logs (for location of the wells, see Fig. 2). The primary aim of this paper is to calibrate the log patterns with the established biozonation via comparison with the intensively studied, fully cored Gislövshammar-1 and Gislövshammar-2 wells in south-eastern Skåne, Sweden.

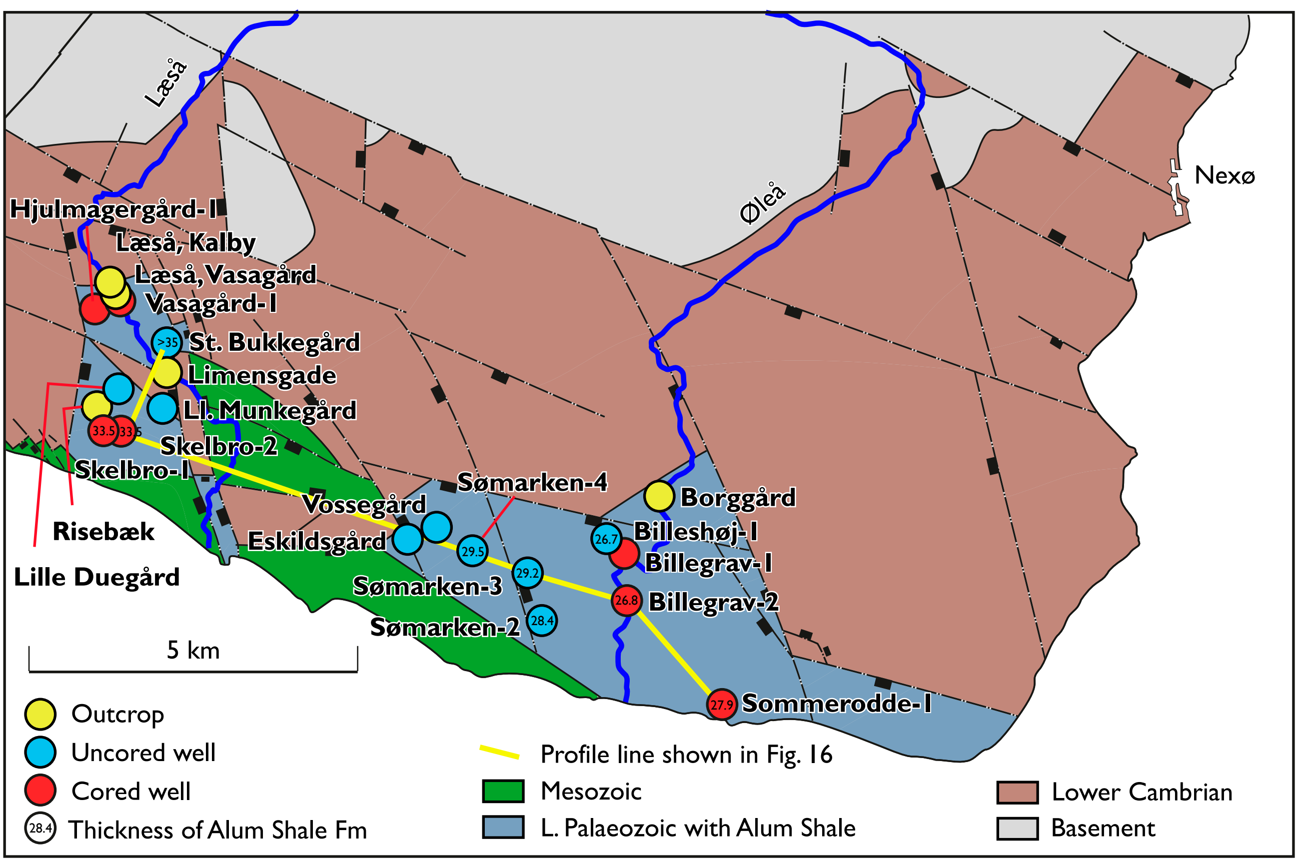


Fig. 2. Location map showing location of the wells and localities referred to in the text. The distribution of the Alum Shale Formation in fault blocks on southern Bornholm is also shown. Geological map modified from Graversen (2009). Thickness data are shown for wells penetrating the entire formation. In the St. Bukkegård well the Ordovician section is missing (see text).

On Bornholm, the Alum Shale Formation is unconformably overlain by the Middle Ordovician Komstad Limestone Formation (Nielsen 1995 and references therein), except in the Billegrav-2 well where a thin veneer of the Lower Ordovician Tøyen Formation is preserved (described below). It is also possible that a thin Tøyen Formation is present in the uncored Sømarken-3 and -4 wells. In south-eastern Skåne the ≤ 1 m thick Bjørkåsholmen Formation and the up to 19 m thick Tøyen Formation are in most places developed between the Alum Shale and the Komstad Limestone Formations.

Stratigraphy of the Alum Shale Formation

Lithostratigraphy

The Alum Shale Formation is 15–25 m thick across large parts of south central Sweden, increasing to 80–100 m in Skåne, southernmost Sweden, and it reaches a maximum thickness of almost 180 m in the Terne-1 well in Kattegat, offshore Denmark (Fig. 1; Michelsen & Nielsen 1991; Buchardt *et al*. 1997; Nielsen & Schovsbo 2007; Schovsbo *et al*. 2016). The formation peters out in the Baltic Sea east of mainland Sweden, but a tongue of Tremadocian Alum Shale extends into Estonia and the St. Petersburg area (Fig. 1). The Alum Shale Formation also thins southwards of Skåne towards Bornholm and into northern Poland, where it pinches out (Buchardt *et al*. 1997, fig. 7).

In Skåne, the Miaolingian Alum Shale Formation includes four thin bioclastic limestones, 0.1–0.8 m thick, that form easily recognisable marker beds, viz. the Forsemölla, Exsulans, Hyolithes and Andrarum Limestone Beds (Nielsen & Schovsbo 2007 and references therein). On Bornholm, the Forsemölla and Exsulans Limestones are amalgamated to form one thin bed (≤ 0.25 m thick) that unconformably overlies the lower Cambrian Rispebjerg Member of the Læså Formation and marks the lower boundary of the Alum Shale Formation. Higher up, the Hyolithes and Andrarum Limestone Beds are also amalgamated (in total ≤ 1 m thick). Lenticular bituminous limestone concretions, up to 1 m thick and 2.5 m in diameter and traditionally called anthraconite or orsten, occur scattered throughout the Alum Shale Formation, although some stratigraphic levels contain more common limestone than others. Early precipitation of calcite took place immediately below the seafloor, conceivably due to bacterial degradation of organic material that produced bicarbonate (Buchardt & Nielsen 1985). Bituminous limestone beds also formed by winnowing of trilobite carapaces from the muddy sediment, likely associated with storm reworking. The latter bituminous bioclastic limestone is common in the mid-shelf facies in south central Sweden, whereas the offshore facies in Skåne and Bornholm is primarily characterised by diagenetic limestone concretions. Anthraconitic limestone beds and lenses are comparatively uncommon in the Alum Shale Formation of Bornholm and overall constitute less than 5 % of the formational thickness.

On Bornholm, the Alum Shale Formation has traditionally been subdivided into the 'Lower Alum Shale', including the thin succession between the lower Cambrian Læså Formation and the amalgamated Hyolithes and Andrarum Limestone Beds, and the 'Upper Alum Shale', comprising the shale above the Andrarum Limestone (Johnstrup 1874; Berg-Madsen 1985a,b, 1986; Pedersen 1989). However, these informal member designations are no longer used. Historically, the shale has also been divided into the Paradoxides Shale or Series (Miaolingian up to and including the *Lejopyge laevigata* Zone), the Olenid Shale or Series (the Furongian + the *Agnostus pisiformis* Zone) and the Dictyograptus or Dictyonema Shale (comprising the Ordovician section of the Alum Shale Formation) (Grönwall 1916; C. Poulsen 1922, 1923; V. Poulsen 1966). These chronostratigraphic designations are also abandoned (Nielsen & Schovsbo 2007). The lithostratigraphic classification of the Forsemölla, Exsulans, Hyolithes and Andrarum Limestone Beds has varied through time (see Nielsen & Schovsbo 2007); they are here ranked as formal marker beds of the Alum Shale Formation. A bioclastic limestone in the *Acidusus atavus* Zone is informally referred to as the 'Atavus limestone bed'. It is developed as a distinct bed in Västergötland, south central Sweden (Fig. 1), but on Bornholm it occurs only as scattered pockets immediately on top of the Exsulans Limestone Bed (Weidner & Nielsen 2014).

Regional bio- and chronostratigraphy

Trilobites are common in the Cambrian part of the Alum Shale Formation in Scandinavia, and a detailed zonation has been established (Fig. 3). The Tremadocian zonation is based on graptolites. This paper focusses on correlation of superzones but individual zones are also addressed where possible.

Miaolingian

The Miaolingian (new term, see Yuanlong *et al*. submitted) comprises the traditional 'Middle' Cambrian plus the *Agnostus pisiformis* Zone. It is highly trilobitic in Scandinavia and a robust zonation was outlined by

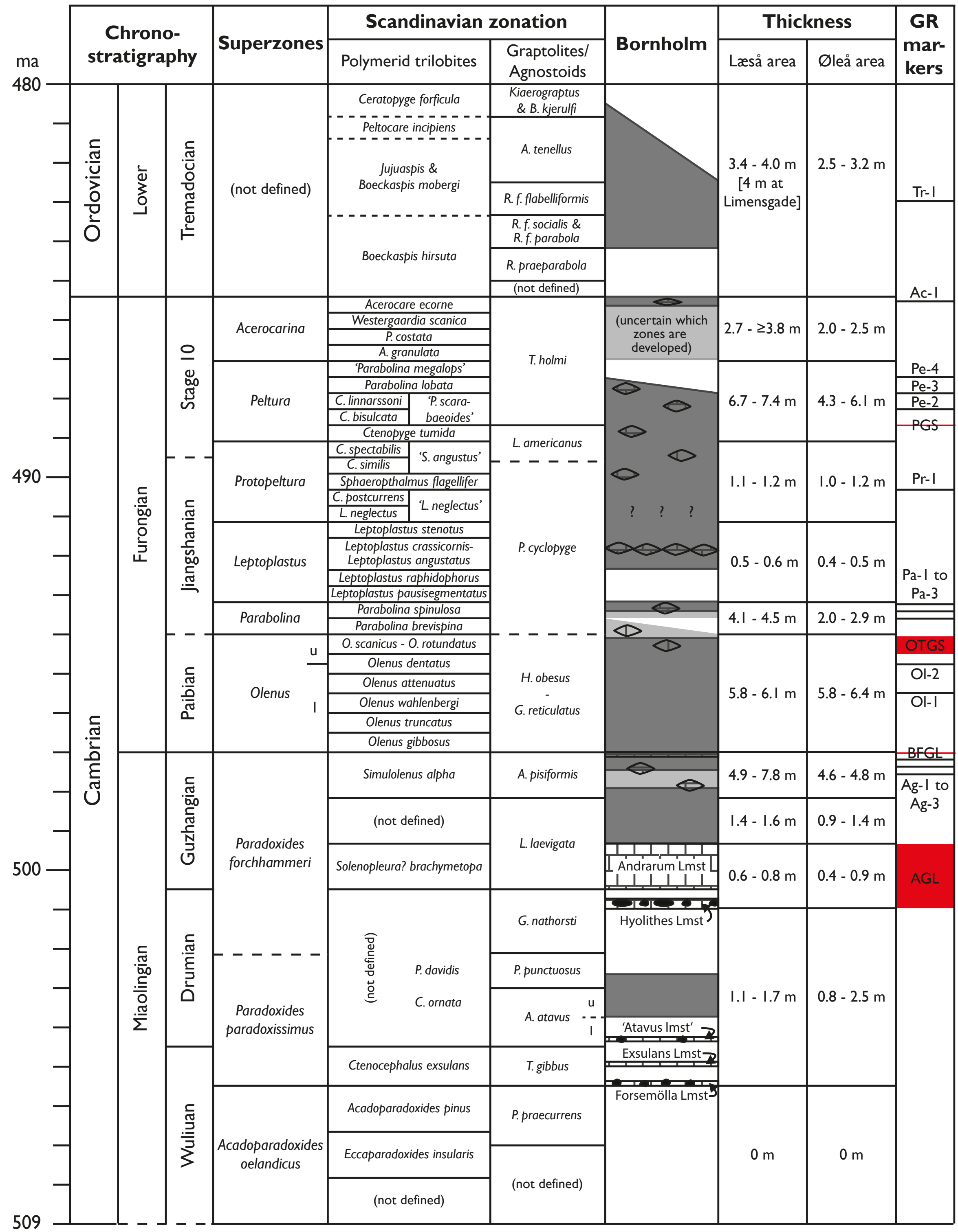


Fig. 3. Biozonation of the Miaolingian to Tremadocian Alum Shale Formation in Scandinavia and on Bornholm. Based on data from Grönwall (1902), Poulsen (1923), von Jansson (1979), Nikolaisen & Henningsmoen (1985), Bruton *et al.* (1988), Axheimer *et al.* (2006), Terfelt *et al.* (2008), Ahlberg & Terfelt (2012), Høyberget & Bruton (2012), Weidner & Nielsen (2013, 2014), Nielsen *et al.* (2014), B.W. Rasmussen *et al.* (2015, 2016, 2017), and this study. The zones listed in inverted commas are used in the sense of Westergård (1944, 1947). This simpler zonation is more workable for the Skåne–Bornholm Alum Shale succession than the elaborate zonation outlined by Henningsmoen (1957). The tentative time scale is adopted from Peng *et al.* (2012). Light grey shading in the Bornholm column indicates unexposed intervals known only from drillings. Correlation with GR (gamma ray) markers is shown in the right-hand column; regional markers defined by Schovsbo *et al.* (2018) are red. The exact correlation of the Ol-1 and Pe-2 markers in relation to the biozonal boundaries is uncertain. Abbreviations: l: lower, u: upper. For remarks on this informal subdivision of the *Olenus* Superzone, see text.

Westergård (1946); for a recent update, see Weidner & Nielsen (2014). Three superzones are now recognised (Fig. 3). Traditionally, the *A. pisiformis* Zone has been assigned to the 'Upper Cambrian' (e.g. Westergård 1922; Henningsmoen 1957), but as the first appearance datum (henceforth FAD) of *Glyptagnostus reticulatus* defines the base of the Furongian Series (Peng *et al*. 2004), the underlying *A. pisiformis* Zone is, accordingly, assigned to the Miaolingian (Fig. 3). Nielsen *et al*. (2014) proposed including the *A. pisiformis* Zone in the *Paradoxides forchhammeri* Superzone.

The Miaolingian on Bornholm represents the *Paradoxides paradoxissimus* and *P. forchhammeri* Superzones. The lower part below the Andrarum Limestone Bed is highly condensed and stratigraphically incomplete.

Furongian

A distinct faunal change marks the base of the Furongian, with sudden appearance of olenid trilobites, and shortly afterwards agnostoids become rare. A detailed Furongian zonation for Scandinavia was outlined by Westergård (1947). Ten years later Henningsmoen (1957) emended this scheme and introduced an exceptionally detailed zonation, where the 'upper' Cambrian above the *A. pisiformis* Zone was subdivided into seven zones holding 31 subzones. Terfelt *et al*. (2008) elevated these subzones to zonal rank and abandoned the longer ranging zones. However, Weidner & Nielsen (2013) and Nielsen *et al*. (2014) proposed with minor amendments to resurrect the old zones as superzones and this approach is followed here. A simplification of the Furongian stratigraphy is planned (Nielsen & Høyberget unpublished), but here we provisionally use some of Westergård's (1947) original zones (referred to using inverted commas, Fig. 3) as they are more readily recognisable in Skåne and Bornholm than the zones defined by Henningsmoen (1957). In this study we also informally refer to the fossil-rich lower part of the *Olenus* Superzone simply as the 'lower part', and to the upper fossil-poor interval as the 'upper part'. The boundary is drawn at the last appearance datum of *Olenus dentatus*.

Lower Ordovician (Tremadocian)

In Scandinavia, the FAD of the graptolite *Rhabdinopora* (= *Dictyonema* or *Dictyograptus* in older literature) has traditionally been taken to indicate the base of the Ordovician. This level is almost certainly located marginally above the formal base of the Ordovician as defined by the FAD of the conodont *Iapetognathus fluctivagus*, but that taxon does not occur in Scandinavia (for remarks on the global boundary, see Terfelt *et al*. 2011). For a comprehensive review of graptolite zones in the Tremadocian, see Cooper (1999). The local Scandinavian zonation has been discussed e.g. by Westergård (1909), Bulman (1954), Tjernvik (1958), Spjeldnæs (1963, 1985), Bruton *et al*. (1982, 1988), Maletz & Erdtmann (1987) and Maletz *et al*. (2010). In the Nærsnes section in Norway, probably the most complete described from Scandinavia, the FAD of *Rhabdinopora socialis* is located just above a thin basal Ordovician interval characterised by *Rhabdinopora preparabola*, leaving no room for a separate *Rhabdinopora parabola* Zone, as recognised in some schemes. In the Flagabro core, south-east Skåne, *R. parabola* and *R. socialis* also appear immediately above the boundary, defined by the FAD of *Rhabdinopora desmograptoides* (see Tjernvik 1958). At Limensgade on Bornholm, *R. socialis* has its FAD 0.2 m above limestone nodules with *Parabolina acanthura*, taken to indicate the Furongian *Acerocare ecorne* Zone (Poulsen 1922; von Jansson 1979). Whether the 0.2 m thick unfossiliferous shale in between is of Ordovician or Cambrian age is unknown. The Tremadocian is treated as one unit ('superzone') in the current study; the zonation is shown in Fig. 3.

Alum Shale geochemistry and chemostratigraphy on Bornholm

The Alum Shale Formation is famous for its high TOC (total organic carbon) content and syngenetic enrichment of chalcophile elements (As, Cd, Cu, Pb, Ni, Zn) and redox-sensitive elements (U, V, Mo). There has been major focus on the latter group due to its economic potential (Armands 1972; Hessland & Armands 1978; Andersson *et al*. 1985; Leventhal 1991;

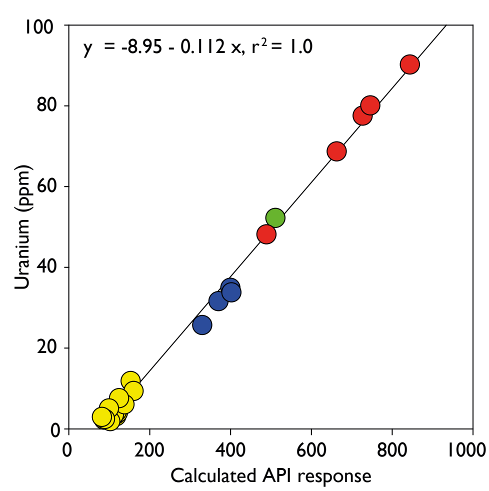


Fig. 4. Uranium concentration versus modelled API (American Petroleum Institute unit) response from measured U, K and Th in the Billegrav-2 well. API response calculated as 4 × Th (ppm) + 8 × U (ppm) + 16 × K (wt%), following Ellis & Singer (2007). Legend as in Fig. 5. Data are presented in Table 2.

Buchardt *et al*. 1997; Lecomte *et al*. 2017) as well as its bearing on the depositional environment (Schovsbo 2000, 2001, 2002a; Gill *et al*. 2011). Of the enriched elements, uranium has a huge impact on the gamma-ray (hereafter GR) log due to its high radiation. Correlations of the Alum Shale based on the GR log thus essentially represent a uranium chemostratigraphy (Fig. 4). As guidance for the correlation we have numbered several, usually readily traceable intra-superzone GR excursions. The labelled fluctuations are mostly maxima, as GR lows caused by limestone nodules occur semi-randomly in the formation and, hence, may mislead correlation.

Schovsbo (2002a) published average uranium contents for the *Agnostus pisiformis* Zone (38 ppm), the lower and upper parts of the *Olenus* Superzone (average 43 ppm and 92 ppm, respectively), the combined *Protopeltura* and *Peltura* Superzones (113 ppm) and the Lower Ordovician (average 73 ppm) on Bornholm, but no formation average was provided. Based on the calibrated spectral GR log of the Billegrav-2 core the average uranium content of the formation is estimated at 58 ppm with an average content of 27 ppm in the Miaolingian, 74 ppm in the Furongian and 49 ppm in the Lower Ordovician strata (Table 1). The strong stratigraphical control on the enrichment is particularly evident when plotting the U-log readings in a histogram since the Miaolingian and Furongian sample populations are almost mutually exclusive, apart from the relatively low uranium content in Furongian carbonate concretions and the lower part of the *Olenus* Superzone (Fig. 5D).

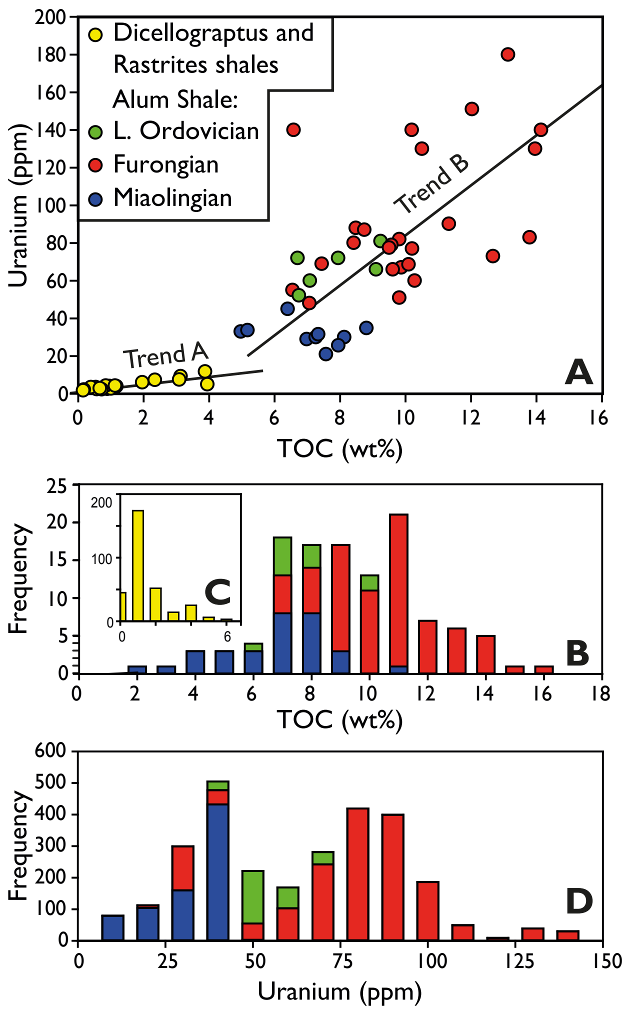


Fig. 5. Geochemical data from lower Palaeozoic black shales on Bornholm. **A**: TOC versus uranium content for Alum, Dicellograptus and Rastrites Shales on Bornholm. Trends A and B illustrate the different proportionality between organic material and U content in the Dicellograptus and Rastrites Shales vs the Alum Shale. **B**: Histogram of TOC contents in the Alum Shale, Bornholm, divided into its main stratigraphic units (shale facies only). **C**: Histogram of TOC contents in the Dicellograptus and Rastrites Shales. **D**: Histogram of U contents calculated from spectral gamma-ray scanning of the Alum Shale in the Billegrav-2 core, Bornholm, divided into main stratigraphic units. Maturity of the shales (measured on graptolite and vitrinite-like particles, Petersen *et al*. 2013) is 2.3 % Ro (Buchardt *et al*. 1986). Data from Warming *et al*. (1994) and Schovsbo (2012), combined with unpublished reports for the Billegrav-2, Skelbro-2 and Sommerodde-1 wells.

Table 1. Total organic carbon and uranium content in lower Palaeozoic shales on Bornholm

	Total organic carbon (wt%)[1]						Uranium content (ppm)[2]					
Stratigraphy	**Mean**	**Median**	**Std. dev.**	**Min**	**Max**	**N1**	**Mean**	**Median**	**Std. dev.**	**Min**	**Max**	**N2**
Rastrites shale	1.1	0.8	0.9	0.0	4.9	180	4.9	4.3	2.5	0.5	18	6138
Lindegård Formation	0.2	0.1	0.2	0.0	0.8	50	2.8	2.7	1.1	0.1	6.8	1445
Dicellograptus Shale	1.2	0.3	1.6	0.0	5.2	89	4.4	4.1	2.2	0.7	16	2145
Alum Shale Fm, total	8.8	8.7	2.6	1.3	15.1	118	58	61	28	2.5	136	2797
L. Ordovician	7.3	6.6	1.3	5.5	9.9	31	49	46	8	38	68	299
Furongian	10.0	10.1	2.0	6.4	15.1	76	74	77	23	18	136	1720
Miaolingian	6.2	6.9	1.9	1.3	10.3	11	27	31	10	2.5	41	778

[1]Based on TOC data from Skelbro-1, Skelbro-2, Billegrav-2 and Sommerodde-1.
N1: Number of analysed samples

[2]Based on calibrated GR spectral log from the Billegrav-2 core.
N2: Number of measurements.

The uranium level in the Alum Shale on Bornholm is comparable to that in Skåne (Schovsbo 2002a) and southern Norway (Schovsbo *et al*. 2018), but is much lower than in the Furongian of south central Sweden and Öland (Hessland & Armands 1978; Andersson *et al*. 1985; Schovsbo 2002a). The strong geographical control on the uranium enrichment is possibly related to water column dynamics in the Alum Shale sea. Schovsbo (2002a) thus showed that the uranium concentration in the *'Peltura scarabaeoides'* Zone is inversely correlated to its thickness (see also Andersson *et al*. 1985) and U enrichments seemingly reflect condensed intervals. Such horizons are suspected to represent flooding events (i.e. abrupt sea-level rises accompanied by reduced sedimentary influx).

No strong trace-element enrichment is seen in the Dicellograptus and Rastrites Shales in the Billegrav-2 well. In these formations, the uranium content averages 2.8–4.9 ppm (Table 1) and the concentrations are closely related to the TOC content (Trend A in Fig. 5A). In the Alum Shale, the enrichment of uranium exhibits a more general correlation with the TOC level (trend B in Fig. 5A), and is not as closely related to the TOC content as in the Dicellograptus and Rastrites Shales.

The Scandinavian Alum Shale has an average organic carbon content of 9 wt%, with local TOC concentrations reaching 25 wt% in the Furongian strata of south central Sweden (Schovsbo 2002a; Gautier *et al*. 2014). On Bornholm, the highest measured content is 15.2 wt% and the average TOC content of the entire formation is 8.8 wt% (Fig. 5B, Table 1). The Miaolingian, Furongian and Tremadocian intervals exhibit average TOC contents of 6.2 wt%, 10.0 wt% and 7.3 wt%, respectively. The average TOC content in the other lower Palaeozoic shales on Bornholm are much lower and only a few samples reach values > 4 wt% (Table 1).

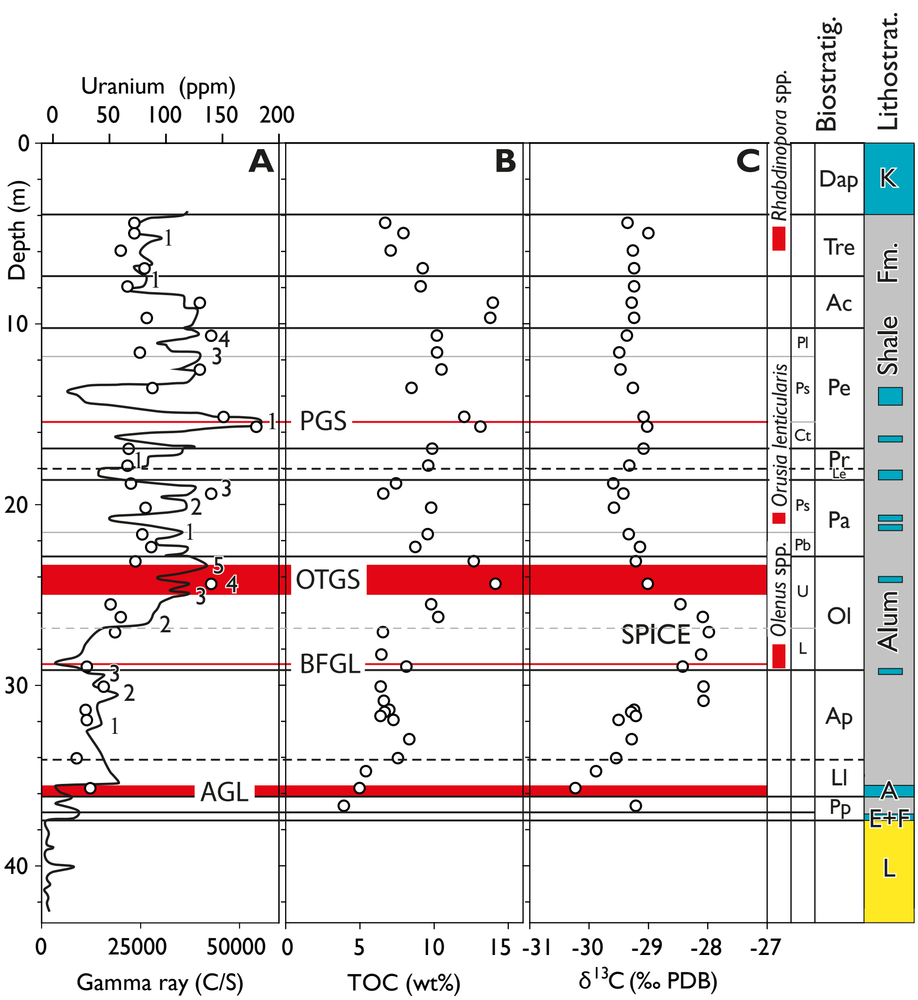


Fig. 6. Simplified lithology and biozonation of the Skelbro-1 well. Identification of the superzone boundaries is based on GR wireline log correlation with the Gi-2 well in south-eastern Skåne, see text. Vertical red bars to the right indicate findings of fossils in the core (Pedersen 1989, fig. 2). The small numbers 1 and up to 5 in A indicate correlatable minor gamma spikes (see Fig. 16). **A**: Gamma-ray wireline log (digitised from Pedersen & Klitten 1990) and core U measurements (Warming *et al*. 1994). **B**: TOC contents (Buchardt *et al*. 1986). **C**: $\delta^{13}C$ isotope composition of organic carbon (Buchardt *et al*. 1986); for remarks on the SPICE event, see text. The position of the gamma-ray log markers PGS (*Peltura* Gamma Spike), OTGS (*Olenus* Triple Gamma spike), BFGL (Base Furongian Gamma Low) and AGL (Andrarum Gamma Low) are shown with horizontal red lines. Other abbreviations: L, Læså Formation.; E, Exsulans Limestone Bed; F, Forsemölla Limestone Bed; A, Amalgamated Hyolithes + Andrarum Limestone beds; K, Komstad Limestone Formation; Pp, *Paradoxides paradoxissimus* Superzone; Ll, *Lejopyge laevigata* Zone; Ap, *Agnostus pisiformis* Zone; Ol, *Olenus* Superzone; Pa, *Parabolina* Superzone; Le, *Leptoplastus* Superzone; Pr, *Protopeltura* Superzone; Pe, *Peltura* Superzone; Ac, *Acerocarina* Superzone; Tre, Tremadocian; Dap, Dapingian. See Fig. 14 for explanation of abbreviated zonal designations. Location of the well is shown in Fig. 2.

In Skåne, the TOC content in the Alum Shale increases in a stepwise manner up through the formation (Schovsbo 2001). A prominent upward increase in TOC content can also be seen on Bornholm, especially from the base of the *A. pisiformis* Zone culminating in the *Olenus* Triple Gamma Spike in the upper part of the *Olenus* Superzone, and again from the basal part of the *Parabolina* Superzone culminating in the *Peltura* Gamma Spike within the lowermost part of the *Peltura* Superzone (Fig. 6, see also Fig. 8 below).

Distinctive perturbations in the $\delta^{13}C$ record have been used as a tool for global correlation in the Cambrian. During Alum Shale deposition the most prominent event is the +2 ‰ Steptoean positive carbon isotope excursion (SPICE) (Saltzman *et al*. 1998) that occurs in the lower to middle part of the *Olenus* Superzone (Schovsbo 2002b; Ahlberg *et al*. 2009; Hammer & Svensen 2017). Carbon isotope data from Bornholm were presented already by Buchardt *et al*. (1986) from the Skelbro-1 core (Fig. 6); these data in fact outline the SPICE which at that time was not recognised as a global event. The analysed samples exhibit a gradual shift towards more positive $\delta^{13}C$ values from the Andrarum Limestone Bed and to the middle of the *Olenus* Superzone (Fig. 6). Two samples indicating −28.07 ‰ $\delta^{13}C$ in the *A. pisiformis* Zone appear inconsistent with the $\delta^{13}C$ curve for the Alum Shale established elsewhere (Ahlberg *et al*. 2009; Hammer & Svensen 2017) and we suspect that samples have been mislabelled. Future re-investigation of sections on Bornholm will have to verify whether this suspicion is correct.

Analytical methods

Spectral gamma-ray and bulk density scannings of the Skelbro-2 and Billegrav-2 cores were made in the Core Analysis Laboratory at the Geological Survey of Denmark and Greenland (GEUS), using a density scanner equipped with a Cs source for determining the bulk density. The scanning was performed at a

Table 2. Geochemistry of shale samples from the Billegrav-2 core

Lab. No.	Sample	Formation	Series	Depth m	TOC wt%	TIC wt%	Th[1] ppm	U[1] ppm	K[2] (wt%)	GR API[3]
20025	1	Rastrites shale	Llandovery	5.28	1.0	0.1	9.7	4.1	2.8	116
20026	2	"	"	10.70	0.5	0.1	11.3	3.1	3.0	117
20027	3	"	"	14.97	0.5	0.0	11.0	3.5	2.7	116
20028	4	"	"	19.95	3.9	0.1	7.1	11.8	1.9	153
20029	5	"	"	23.18	2.3	0.1	8.5	7.4	2.4	131
20030	6	"	"	24.90	3.1	0.3	10.5	9.3	2.7	160
20031	7	"	"	29.99	1.2	0.0	11.0	4.0	2.8	121
20032	8	"	"	35.10	0.6	2.6	8.4	2.4	2.1	87
20033	9	"	"	41.15	0.9	2.5	9.0	2.6	2.1	91
20034	10	"	"	42.74	1.0	2.2	9.5	2.8	2.2	96
20035	11	"	"	45.00	0.8	0.0	10.1	4.3	2.8	119
20036	12	"	"	50.90	1.1	0.1	9.3	4.3	2.6	113
20037	13	"	"	56.60	0.4	1.3	10.2	3.5	2.7	112
20038	14	Rastrites shale	Llandovery	61.37	0.2	3.1	8.2	2.2	2.3	87
20039	15	Lindegård Mudst.	U. Ordovician	69.53	0.2	1.2	10.7	1.9	2.8	103
20040	16	Dicellogr. Shale	"	74.99	2.0	0.3	9.6	6.0	3.2	138
20041	17	"	"	76.89	3.1	0.3	6.6	7.6	2.3	124
20042	18	"	"	80.47	3.9	0.4	6.6	5.0	2.0	99
20043	19	"	"	86.68	0.7	0.6	7.2	2.4	2.6	89
20044	20	Dicellogr. Shale	U. Ordovician	93.47	0.7	0.3	8.2	2.9	1.6	82
20045	21	Alum Shale	L. Ordovician	96.76	6.7	0.4	11.6	52.2	2.9	511
20046	22	"	Furongian	98.90	7.1	0.4	12.1	48.1	3.5	489
20047	23	"	"	101.57	9.5	0.4	12.4	77.5	3.6	727
20048	24	"	"	102.93	11.3	0.6	15.5	90.2	3.8	844
20049	25	"	"	105.90	10.1	0.8	12.3	68.7	4.0	663
20050	26	"	"	110.98	8.4	0.6	11.9	80.0	3.6	746
20051	27	"	Furongian	113.35	7.9	0.1	14.0	25.7	4.3	330
20052	28	"	Miaolingian	115.75	8.8	0.6	14.0	34.9	4.0	400
20053	29	"	"	116.86	7.3	0.2	13.6	31.6	4.0	370
20054	30	Alum Shale	Miaolingian	119.90	5.2	0.1	14.5	33.8	4.6	402

[1]ICP-MS REE method. [2]ICP-MS TotalQuant. [3]Calculated as 4 × Th (ppm) + 8 × U (ppm) + 16 × K (wt%), see Ellis & Singer (2007).

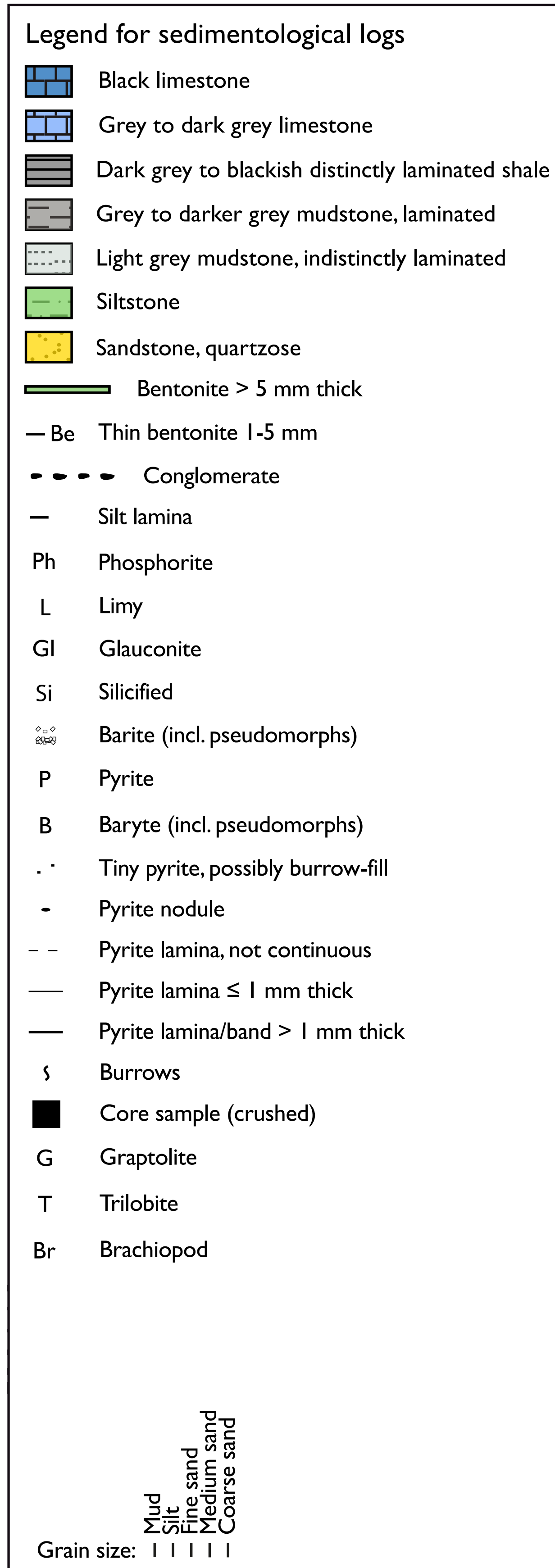
TOC: Total organic carbon. TIC: Total inorganic carbon (=total carbon–TOC).

speed of 1 cm/min and the vertical resolution is 1 cm. Calibration of the scanner was made by running in-house standards with known densities. The density scanning is very sensitive to imperfections such as cracks, fractures and drilling damages, and also to poor alignment of the core within the scanner. Generally, the cores were in very good condition and extra care was taken to align them directly under the sensor and to fit broken core pieces together to minimise measuring errors. However, filtration of the density data was made to remove low readings caused by cracks and poor core alignment following the filtering procedure described by Bjerager *et al*. (in press).

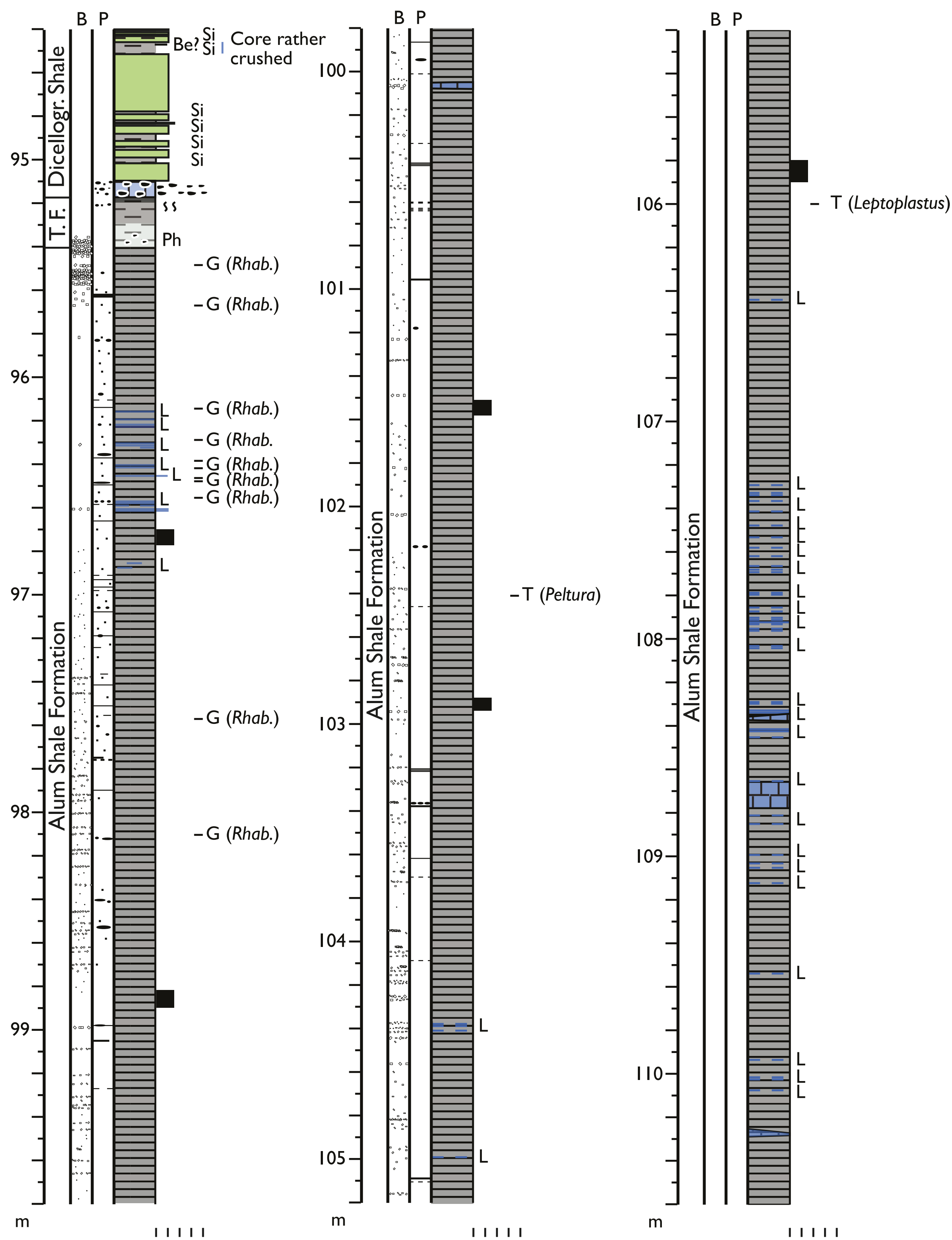
Thirty samples from the Billegrav-2 core were analysed using an Inductively Coupled Plasma Mass Spectrometer (Elan 6100 ICP-MS) at GEUS to provide calibration data for the spectral gamma-ray log. Crushed samples were dissolved in HF and HNO_3 acid for two days at 130°C. Element concentrations were determined using the Perkin Elmer TotalQuant software that provides semi-quantitative concentrations for 66 elements and a GEUS in-house REE method that provides quantitative concentrations for 24 elements (Schovsbo *et al*. 2018). Calibration data used for the spectral core scanner are shown in Table 2.

Total organic carbon (TOC), total carbon (TC) and total sulphur (TS) contents were measured on acid-pre-treated samples in a LECO CS-200 carbon/sulphur analyser at GEUS. Dissolution of carbonate was done by treating 0.05 g dried sample with 2M HCl solution at 65°C for 2 hours. The powdered samples were placed together with iron accelerator material in an oven and heated to 1300°C, and the evolved gases were measured by infrared absorption.

Apart from the Sommerodde-1 and Skelbro-1 wells, all other wireline logs presented in this paper were recorded by GEUS. Logging in the Sommerodde well was conducted by the consulting company Rambøll, and the GR log shown from Skelbro-1 (Fig. 6) is an old analog log made by the Institute for Technical Geology at the Technical University of Denmark and later digitised by GEUS. All boreholes were open wells, i.e. without well screens, but the wells did have a casing pipe in the Quaternary section; in the St. Bukkegård well this casing extends down into the Alum Shale (see below).



▶▼ **Fig. 7.** Lithological log of the core interval 94.4–125.9 m in the Billegrav-2 well, comprising the lowermost part of the Dicellograptus Shale, the Komstad Limestone, the Tøyen Formation (abbreviated T.F.), the Alum Shale Formation and the uppermost part of the Læså Formation. The core is 55 mm in diameter. The section is shown as two consecutive logs on pp 247–248. Location of the well is shown in Fig. 2 and correlation is shown in Fig. 8.



B P
Si
Be? Si
Core rather crushed
Dicellogr. Shale
T. F.
Si
Si
Si
Si
95
Ph
– G (Rhab.)
– G (Rhab.)
96
L
L
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– G (Rhab.)
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= G (Rhab.)
= G (Rhab.)
– G (Rhab.)
97
Alum Shale Formation
– G (Rhab.)
98
– G (Rhab.)
99
m
100
101
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103
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105
Alum Shale Formation
– T (Peltura)
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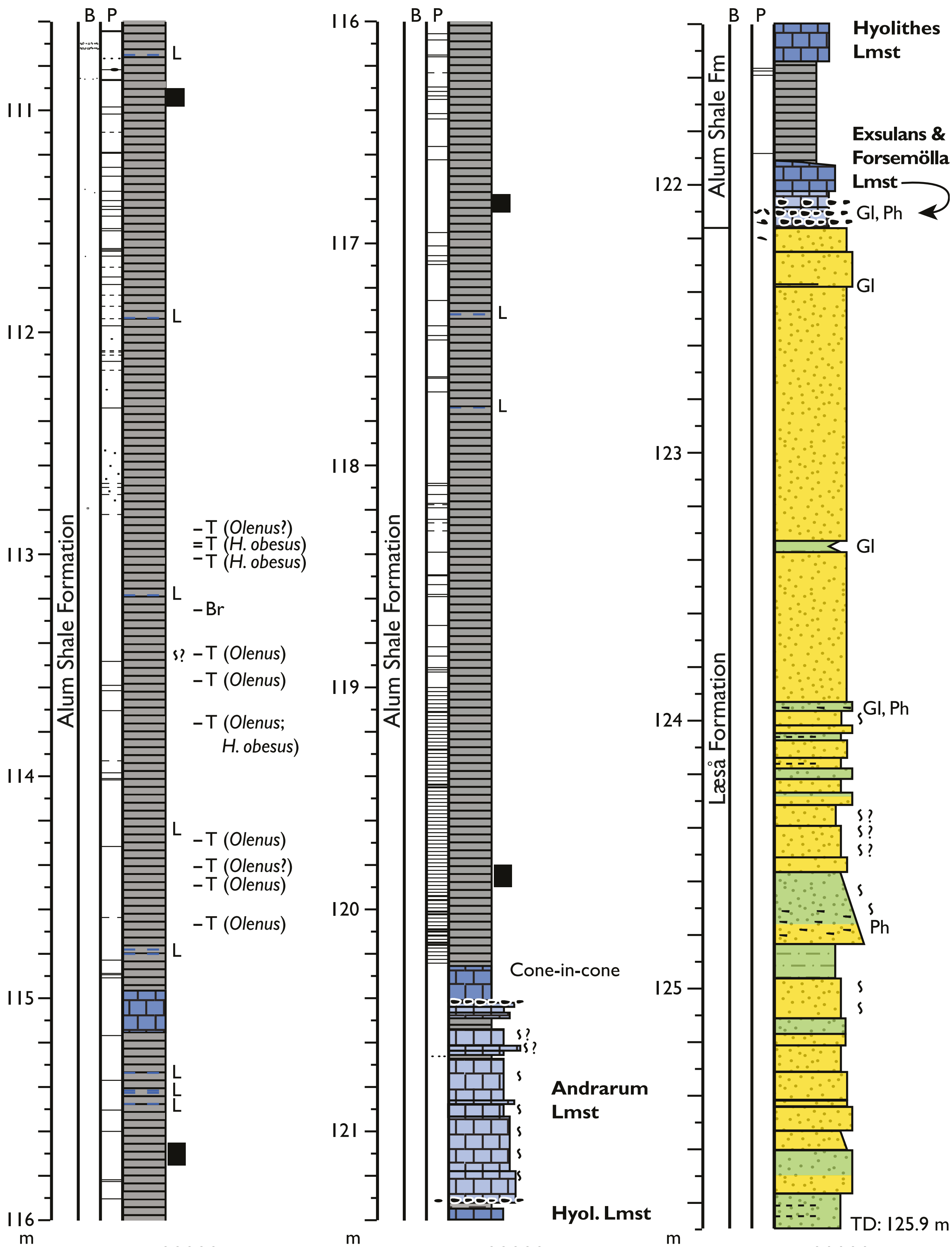
106
– T (Leptoplastus)
107
108
109
110
Alum Shale Formation
L


B
P
111
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115
116
m
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–T (*Olenus?*)
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H. obesus)
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–T (*Olenus?*)
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–T (*Olenus*)
L
L
L
L
Alum Shale Formation
116
117
118
119
120
121
L
L
Cone-in-cone
Andrarum
Lmst
Hyol. Lmst
122
123
124
125
Alum Shale Fm
Læså Formation
Hyolithes
Lmst
Exsulans &
Forsemölla
Lmst
Gl, Ph
Gl
Gl
Gl, Ph
Ph
TD: 125.9 m

Results

The Alum Shale and Tøyen Formations in the Billegrav-2 well

The Billegrav-1 well, drilled in 1984 and described by Pedersen (1989), did not reach the Alum Shale Formation. The fully cored Billegrav-2 well (DGU 248.61), drilled in 2010 to a depth of 129.5 m, was located *c.* 700 m further south (Fig. 2) and penetrated to the lower Cambrian Norretorp Member of the Læså Formation (Schovsbo *et al.* 2011). The Alum Shale Formation was encountered between 95.4 and 122.2 m and the total thickness is thus 26.8 m (Fig. 7). Gamma-ray, sonic velocity, formation resistivity, density and optical televiewer wireline logs were obtained in the drill hole (Fig. 8; see also Schovsbo *et al.* 2015b), and spectral gamma-ray and density scannings have been made of the core. The Billegrav-2 well is henceforth referred to as Bi-2; the core has hitherto remained undescribed.

The thin lower Miaolingian interval (120.2–122.2 m) below the traditional *Lejopyge laevigata* Zone comprises the Andrarum (120.41–121.33 m) and Hyolithes (121.35–121.53 m) Limestone Beds, underlain by shale (121.53–122.03 m) and the amalgamated Exsulans (122.03–122.09 m) and Forsemölla (122.09–122.17 m) Limestone Beds, in turn resting unconformably on the 'lower' Cambrian Læså Formation. Fossils have not been encountered in this part of the core (no systematic splitting has been undertaken). The core interval *c.* 98.1–120.4 m comprises the upper part of the Miaolingian (traditional *L. laevigata* + *A. pisiformis*

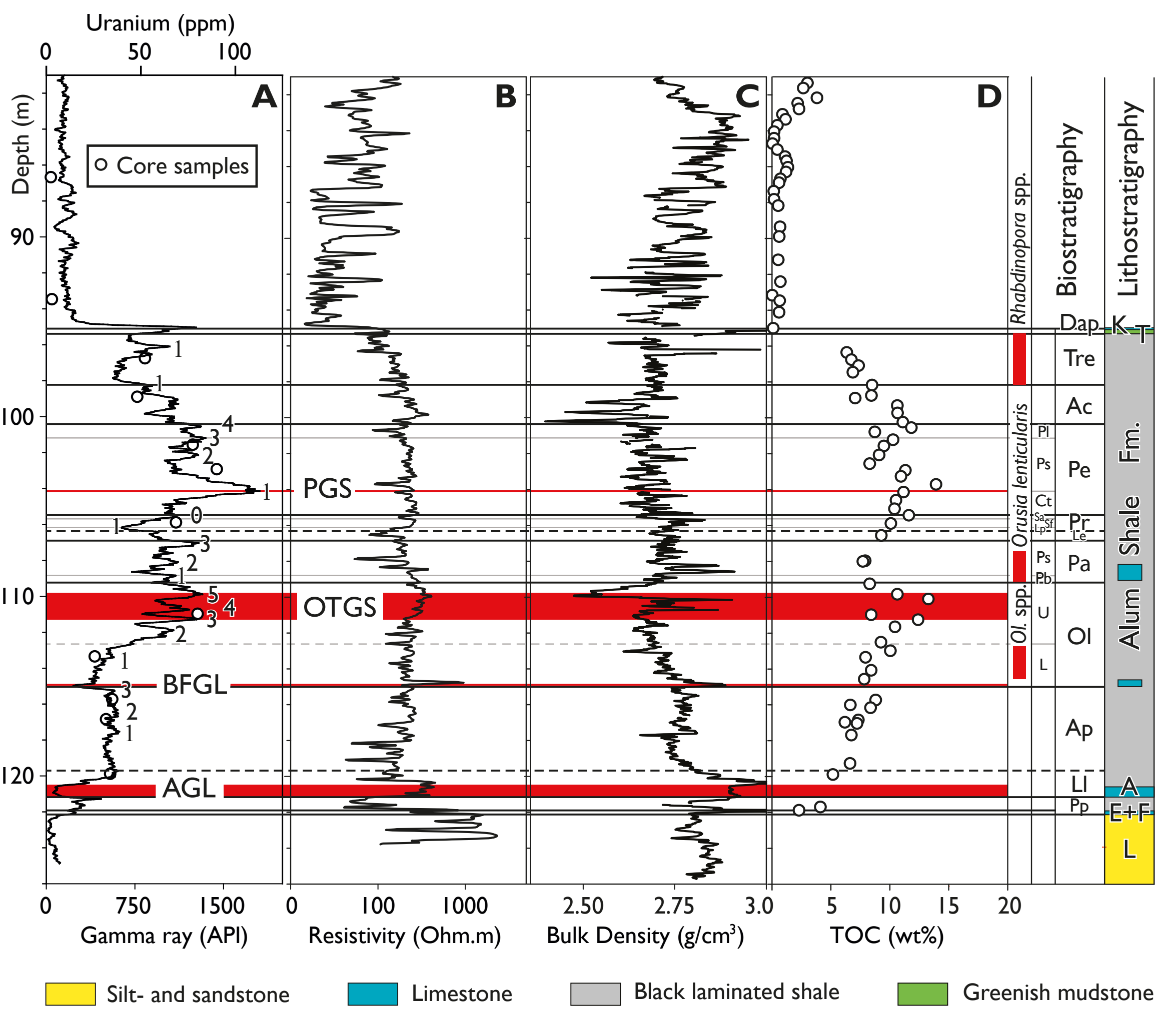

Fig. 8. Simplified lithology and biozonation between 81.0 and 125.9 m in the Billegrav-2 well, covering the interval from the Komstad Limestone to the bottom of the well. The biozonation is based on GR wireline log correlation with the Gi-2 well in southeastern Skåne, see text. **A**: GR wireline log and core U measurements. The small numbers 1 and up to 5 indicate correlatable minor gamma spikes. **B**: Wireline resistivity log. **C**: Core scanning of bulk density, **D**: TOC content. Legend and abbreviations as in Fig. 6; abbreviated zonal designations as in Fig. 14; T, Tøyen Formation. Wireline log, core scanning and core measurements are from Schovsbo (2011, 2012) and Schovsbo *et al.* (2011). For location of the well, see Fig. 2.

Zones) and the Furongian. Common *Olenus* spp. and a few *Homagnostus obesus* occur between 112.9 and 114.7 m (Fig. 7), proving that this interval represents the lower part of the *Olenus* Superzone. GR log correlation shows that the Miaolingian/Furongian boundary is located at 115.0 m in the well (Fig. 8) and the limestone between 115.0–115.2 m probably corresponds to the unfossiliferous limestone seen just below the base of the Furongian in the Læså section (see Poulsen 1923, locality 2).

The Furongian shale contains very few limestone concretions and the registered fossil content is low. The core interval 107.4–109.2 m yielded abundant brachiopods (*Orusia lenticularis*) characteristic of the *Parabolina* Superzone (Fig. 7). The *Leptoplastus* Superzone is located around 106.0 m as suggested by findings of several *Leptoplastus* cranidia at this level. They resemble *L. neglectus*, characteristic of the eponymous zone in the basal *Protopeltura* Superzone (Fig. 3), but the determination must be regarded as preliminary. A cranidium of a pelturid trilobite from 102.41 m indicates that this level (probably) represents the *Peltura* or (less likely) the *Acerocarina* Superzone; *Peltura* cranidia cannot be safely assigned to species.

Graptolites (*Rhabdinopora* spp.) are common in the Ordovician part of the core (Fig. 7) with a lowermost occurrence noted at 98.1 m. The Cambro–Ordovician boundary is located at 98.2 m according to the GR log correlation (Fig. 8). *Rhabdinopora* ranges to the very top of the Alum Shale Formation in the Bi-2 core, and the *Adelograptus tenellus* and *Bryograptus kjerulfi* Zones known from Limensgade (Poulsen 1922) seem to be absent.

On Bornholm, the Alum Shale Formation unconformably overlies the Komstad Limestone Formation in all sections described so far (e.g. Pedersen & Klitten 1990; Nielsen 1995), but in the Bi-2 core a light grey to greenish mudstone, 0.22 m thick (95.17–95.39 m), is interspersed between these units. The mudstone contains scattered, small, black phosphorite nodules (Fig. 9A–B) showing that the thin unit does not represent bleached Alum Shale. The lithology is identical to the lower part of the Tøyen Formation in Skåne and Oslo of Floian age (Hunnebergian regional Stage) and the thin unit is taken to represent an erosional remnant of that formation. The lower boundary is obscure due

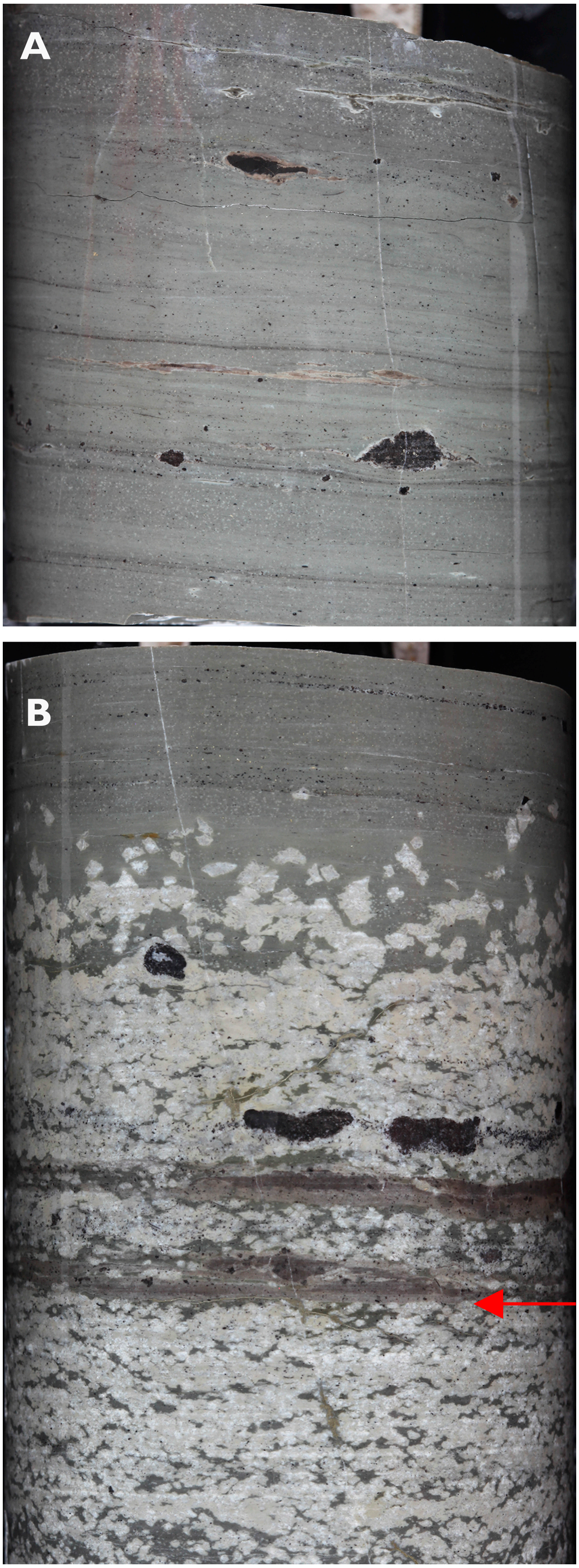

Fig. 9. Photos of the Tøyen Formation and its boundary to the Alum Shale in the Billegrav-2 core. Diameter of the core is 55 mm. **A**: Core interval 95.29–95.39 m, slightly glauconitic greenish mudstone with scattered phosphorite nodules. **B**: Core interval 95.33–95.44 m. Basal part of the unit, showing the indistinct lower boundary against the Alum Shale Formation (at arrow). The whitish lithology is baryte (or pseudomorphs after this mineral, see Callisen 1914) precipitated during diagenesis.

to common baryte, but is likely located just above a bed of amalgamated baryte crystals (Fig. 9B). Despite being indistinct, the boundary must represent a significant unconformity; at this level the upper part of the Ordovician Alum Shale and the Bjørkåsholmen Formation are missing (as well as equivalents of the lowermost parts of the Tøyen Formation in Skåne). The Tøyen Formation is in turn unconformably overlain by the Komstad Limestone Formation of which only the basal conglomerate is preserved in the Bi-2 well (95.10–95.17 m). It is unconformably overlain by the Upper Ordovician Dicellograptus Shale.

The Tøyen Formation (Owen *et al*. 1990) is well known from Skåne and the Oslo area where it is several tens of metres thick, even exceeding 100 m in north-western Skåne (fig. 41 in Nielsen 1995 and references therein). The Tøyen Formation comprises a lower, generally greenish to light greyish part, often with occasional sandstone stringers (Oslo) or limestone beds and nodules (Skåne), and an upper dark grey to blackish part. In the Oslo area these lower and upper subunits are formally separated as members (Owen *et al*. 1990). In the Bi-2 well, the thin Tøyen Formation cannot be discerned on the GR wireline log (Fig. 8), but see remarks on the Sømarken-3 and Sømarken-4 wells below.

Other fully cored wells on Bornholm

The Alum Shale Formation of Bornholm has been penetrated by four fully cored wells (Skelbro-1, Skelbro-2, Billegrav-2 and Sommerodde-1) that have all been investigated by geophysical wireline logging; for location, see Fig. 2. A fifth cored well, Hjulmagergård-1, spudded in 2012, proved to be located in a fault zone and had to be abandoned shortly after entering the Alum Shale Formation (Schovsbo *et al*. 2015b). A sixth cored well, Vasagård-1, was drilled in 1982 on the meadow northwest of Vasagård, Læså, in order to test newly developed drilling equipment. The drilling penetrated the upper part of the Alum Shale Formation (10.0–19.6 m) but the recovered short core has never been investigated and wireline logging was not performed. The Komstad Limestone is 4.7 m thick in this well.

The Skelbro-1 well (DGU 246.749), abbreviated Sk-1, was drilled in 1984 and described by Pedersen (1989). It was spudded on top of the Komstad Limestone within the abandoned limestone quarry at Skelbro (Fig. 2) and penetrated to a depth of 43 m with TD in the uppermost part of the Læså Formation (Norretorp Member). It was the first fully cored well that penetrated the Alum Shale Formation on Bornholm in its entirety;

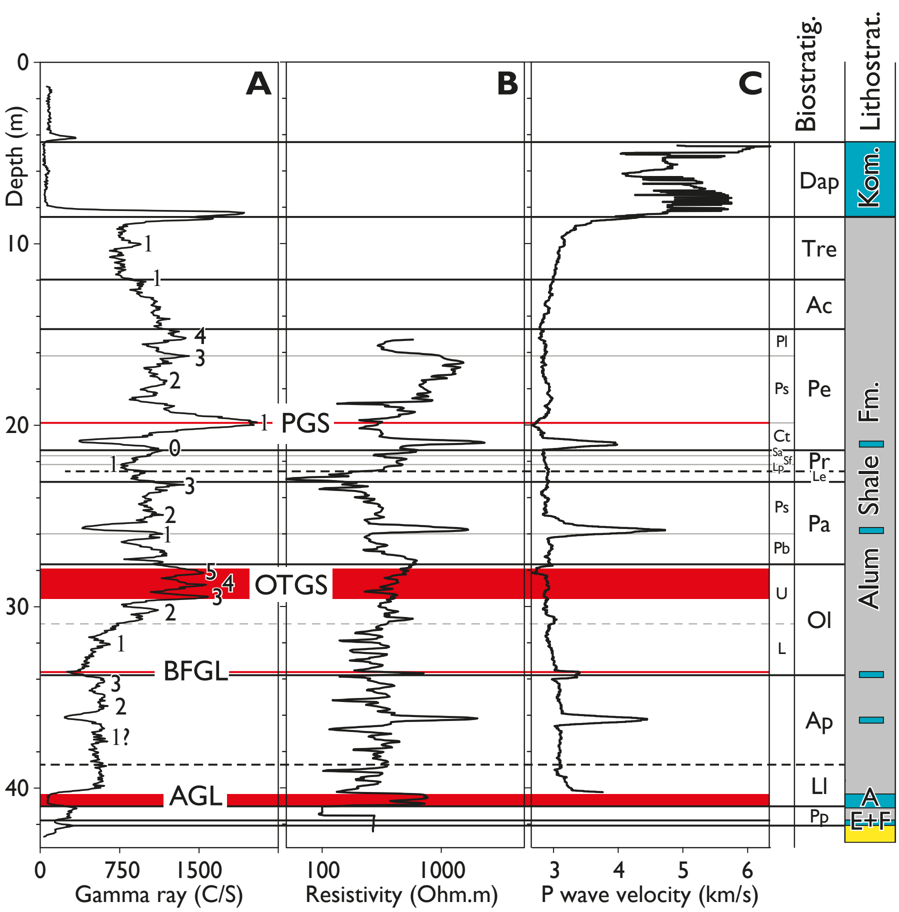

Fig. 10. Simplified lithology and biozonation of the Skelbro-2 well. The biozonation is based on GR wireline log correlation with the Gi-2 well in south-eastern Skåne, see text. **A**: Gamma-ray wireline log. The small numbers 1 and up to 5 indicate correlatable minor gamma spikes. The basal 0.5 m of the GR log is based on spectral gamma scanning of the core. **B**: Resistivity wireline log. The used type of logging tool does not provide reliable readings until 11 m below water table (at 4 m depth in this well). **C**: P-wave velocity from sonic wireline log. Legend and abbreviations as in Fig. 6; abbreviated zonal designations explained in Fig. 14. Wireline log and core measurements are from Baumann-Wilke *et al*. (2012). For location of the well, see Fig. 2.

a GR log was published by Pedersen & Klitten (1990) (here re-illustrated in Fig. 6). The total thickness of the formation in this well is 33.5 m. The diameter of the core is only 1 inch (2.5 cm) and no search for fossils was undertaken. However, the base of the Furongian is undoubtedly located close to 29 m, as indicated by the high abundance of trilobites, likely *Olenus*, at 28–29 m in the core (Fig. 6). The core interval rich in brachiopods at 20.5–21 m represents the *Parabolina* Superzone. The horizon with graptolites at 6 m is indicative of the Tremadocian.

The Skelbro-2 well (DGU 246.817), abbreviated Sk-2, was drilled in 2010 immediately adjacent to the abandoned Duegård Komstad Limestone quarry some 275 m east of the Sk-1 well (Fig. 2). Spectral gamma and density scanning of the core have been made (not shown) in combination with GR, sonic velocity and formation resistivity wireline logging of the drill hole (Fig. 10); see also Schovsbo *et al*. (2011) and Baumann-Wilke *et al*. (2012). The Komstad Limestone is 4.1 m thick with the top encountered at 4.4 m below ground level immediately below Quaternary deposits. It is underlain by a 33.5 m thick Alum Shale Formation, corresponding to the thickness encountered in the Sk-1 well. At 42.9 m the well was terminated in the Rispebjerg Member of the Læså Formation.

The Sommerodde-1 well (DGU 248.62), abbreviated So-1, was drilled in 2012. A comprehensive suite of wireline logs was obtained in the drill hole, including GR, sonic velocity, formation resistivity and optical televiewer logs (Fig. 11; see also Schovsbo *et al*. 2015b). The top of the 0.6 m thick Komstad Limestone was encountered at 217.3 m (cored depth). The underlying Alum Shale Formation is 27.9 m thick with the base located at 245.7 m. The well terminated in the Norretorp Member of the Læså Formation at 250.3 m. The Alum Shale interval of the core has not been studied in detail. A few specimens of *Olenus* were observed on bedding

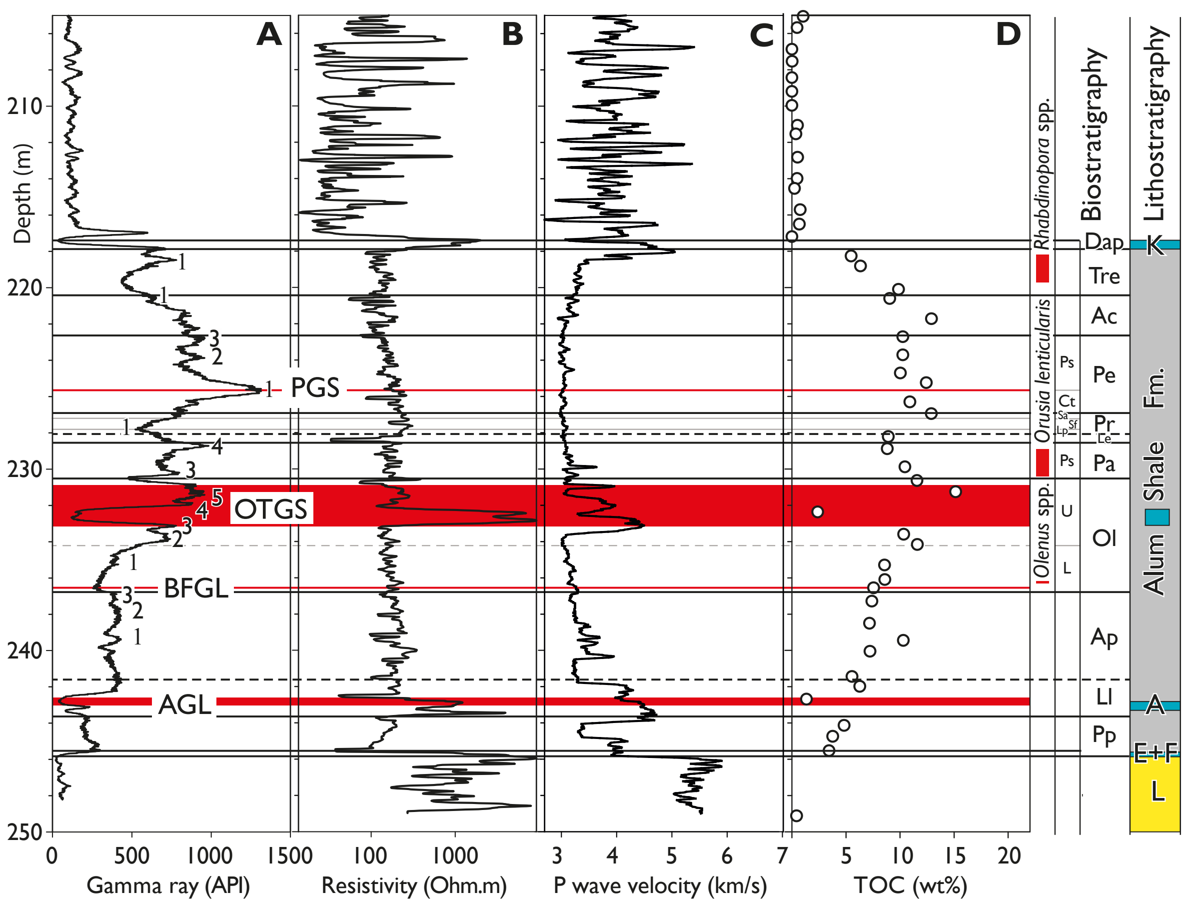

Fig. 11. Simplified lithology and biozonation in the lower part of the Sommerodde-1 well from the Komstad Limestone to the bottom of the well. The biozonation is based on GR wireline log correlation with the Gi-2 well in south-eastern Skåne, see text. **A**: Gamma-ray wireline log. The small numbers 1 and up to 5 indicate correlatable minor gamma spikes. **B**: Resistivity wireline log. **C**: P-wave velocity from sonic wireline log. **D**: TOC content in the core. The double peak on the P-wave velocity log at the two significant limestone beds just below the OTGS and the AGL is a flawed response often seen at such beds when a single transmitter sonic probe is applied. Legend and abbreviations as in Fig. 6; abbreviated zonal designations explained in Fig. 14. For location of the well, see Fig. 2.

planes at 236.2–236.3 m (Fig. 11); the brachiopod *Orusia lenticularis* is common at 228.9–230.4 m and *Rhabdinopora* occurs at 218.2–219.7 m. The Forsemölla Limestone Bed is 9 cm thick and the Exsulans Limestone Bed *s.str.* is 11 cm thick. The base of the Hyolithes Limestone Bed is located at 243.55 m and the top at 243.20 m, which is the base of the 74 cm thick Andrarum Limestone Bed.

Non-cored water wells with wireline logging data

Five non-cored water wells penetrate the Alum Shale Formation (or nearly so). Wireline logs have previously been obtained in Billeshøj-1, Sømarken-2, Sømarken-3, and Sømarken-4 (see Pedersen & Klitten 1990; Schovsbo *et al*. 2015b) and the fifth well, St. Bukkegård-1, was logged in connection with this study.

The St. Bukkegård well (DGU 246.594), henceforth referred to as the Bu-1 well, is located just north of Limensgade in the Læså area (Fig. 2). It was drilled in 1972 and penetrated Alum Shale from *c*. 3.1 m (directly below the Quaternary) to a depth of 37.8 m (Fig. 12). Hence, the Alum Shale Formation seems to be at least 34.7 m thick in the well, which is the maximum thickness recorded on Bornholm. The well was terminated at 48 m within the Læså Formation. A GR log and an induction conductivity log were obtained by GEUS in November 2017. Note that an iron casing affects the log signals in the uppermost 4 m of the well (Fig. 12). The site was visited by ATN at a time when a large silo was under construction just 15 m west of the well site and here the base of the overlying Komstad Limestone was exposed in a shallow excavation. Nonetheless, Ordovician Alum Shale seems to be missing in the well trace (Fig. 12).

The Billeshøj-1 well (DGU 247.510) was drilled in 1984. A GR log was published by Pedersen & Klitten (1990) and shows that the top of the Komstad Limestone is located at *c*. 49.3 m and the unit is *c*. 1.6 m thick. The underlying Alum Shale Formation is *c*. 26.7 m thick. The Sømarken-2 well (DGU 248.36) was drilled in 1969. A GR log of comparatively low resolution was published by Pedersen & Klitten (1990). It shows that the top of the Komstad Limestone is located at *c*. 108.7 m and that the unit is *c*. 2.5 m thick. The underlying Alum Shale Formation is *c*. 28.4 m thick. Modern digital wireline logging has not been made in these two wells and they are not discussed further.

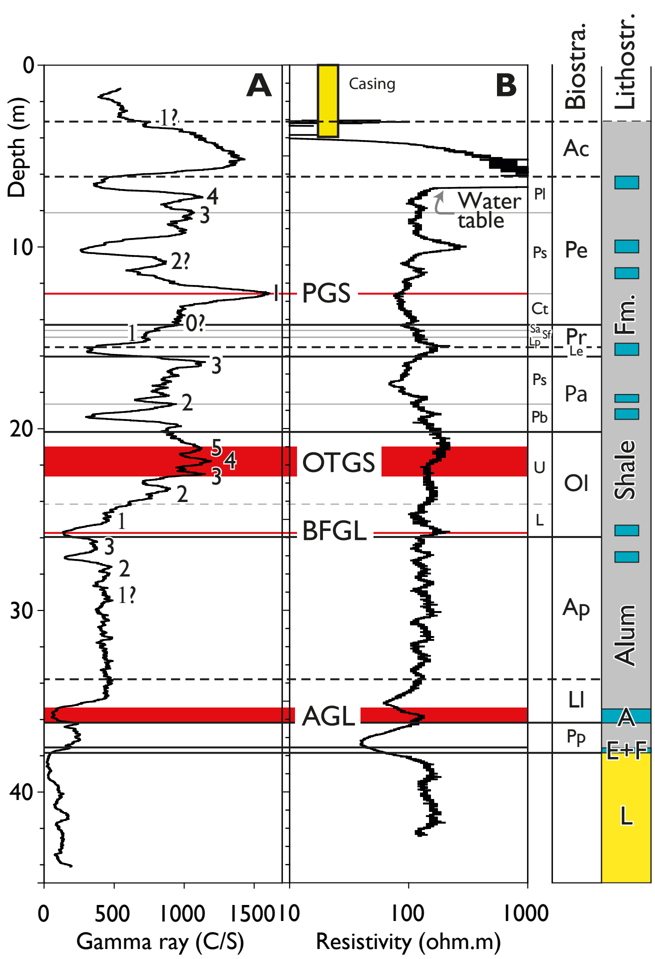

Fig. 12. Simplified lithology and biozonation of the Alum Shale in the uncored well at St. Bukkegård (Bu-1). The biozonation is inferred based on GR wireline log correlation with other wells on southern Bornholm and the Gislövshammar wells in Skåne (Fig. 16). For remarks on the boundary between the *Peltura* and *Acerocarina* Superzones, see the text section on the latter superzone. The resistivity log is calculated from an induction conductivity log, and the very high resistivity in the uppermost part of the well is caused by the dry shale above the water table at 6.8 m depth. The Ordovician Alum Shale Formation seems to be absent at the drill site, and the Furongian strata are directly overlain by Quaternary deposits. The latter exhibit very high radiation levels, likely due to a content of Alum Shale, and it is unclear precisely where the boundary between the Alum Shale and the Quaternary is located, also due to the iron casing in the upper 4 m of the well. **A**: Gamma-ray wireline log. The small numbers 1 and up to 5 indicate correlatable minor gamma spikes. **B**: Resistivity wireline log. Legend and abbreviations as in Fig. 6; abbreviated zonal designations explained in Fig. 14. For location of the well, see Fig. 2.

The Sømarken-3 (DGU 248.39) and Sømarken-4 (DGU 247.312) water wells were both drilled in 1974. They are henceforth referred to as Sø-3 and Sø-4, respectively. GR logs were published by Pedersen & Klitten (1990), but much improved modern digital wireline logging has recently been made in both wells (Fig. 13 and Schovsbo *et al*. 2015b). The top of the Komstad Limestone is located at 68.2 m in Sø-3 and at 50.2 m in Sø-4. The unit is 1.3 m and 1.5 m thick, respectively, in these wells. The underlying Alum Shale Formation is 29.2 m thick in Sø-3 and 29.5 m thick in Sø-4. The very thin Tøyen Formation present in the Bi-2 core cannot be identified on the wireline logs from that well (Fig. 8), but in the GR logs from the Sø-3 and especially the Sø-4 well a minor low is seen immediately below the Komstad Limestone, which theoretically could be due to the presence of a thin Tøyen Formation (≤ 30 cm) (compare low GR readings in this formation in the Gi-2 well, Fig. 14). In Sø-3, a marked low in the resistivity log is evident at the same level, which is another indication that a thin Tøyen Formation may be present; no lows of the same magnitude are observed in the underlying Alum Shale. However, without cores the interpretation of

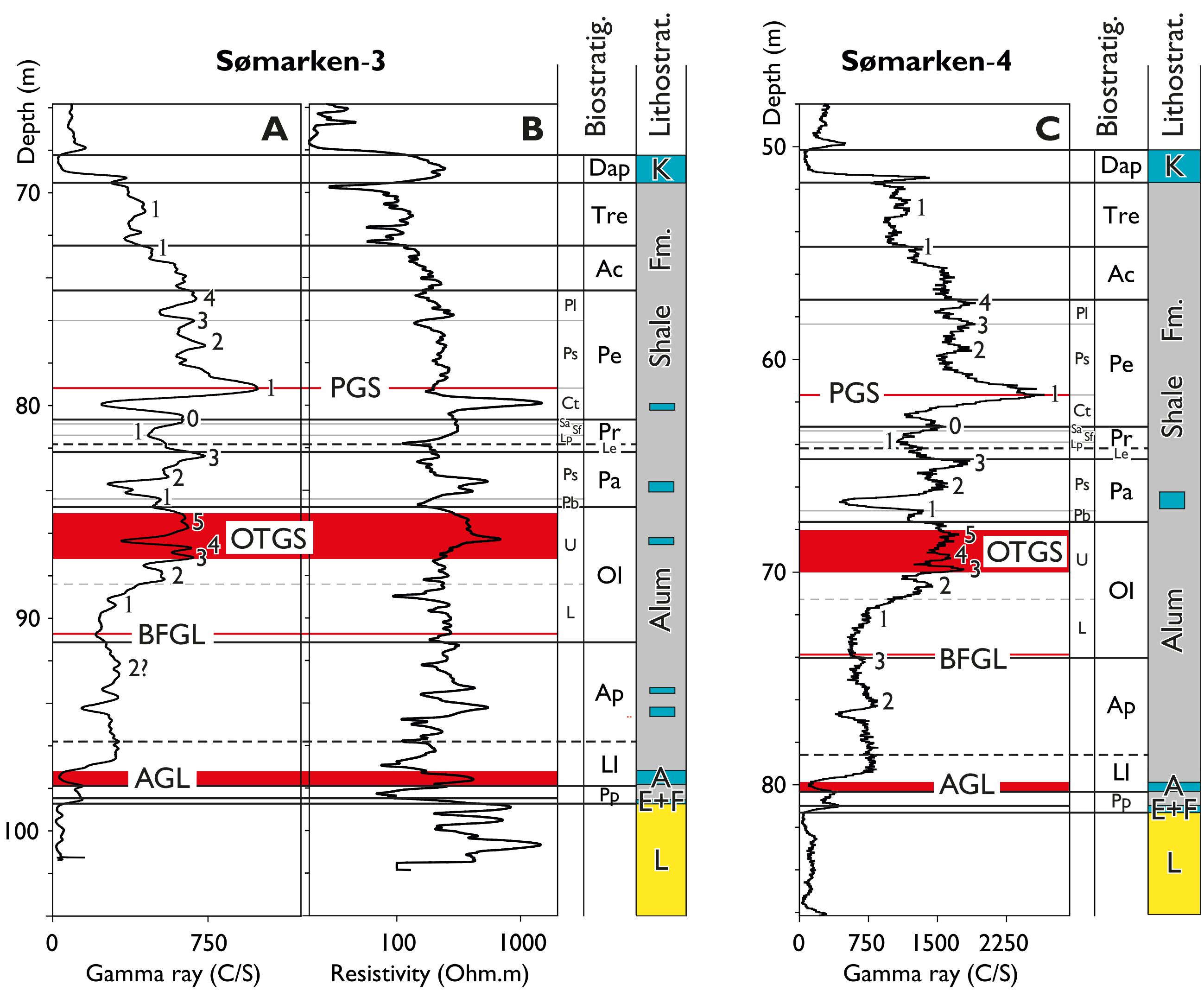

Fig. 13. Simplified lithology and biozonation of the Alum Shale interval in the uncored Sømarken-3 and Sømarken-4 wells. The biozonation is based on GR wireline log correlation with other wells on southern Bornholm (Fig. 16), see text. **A**: Gamma-ray wireline log from the Sø-3 well. The small numbers 1 and up to 5 indicate correlatable minor gamma spikes. **B**: Resistivity wireline log from the Sø-3 well. **C**: Gamma-ray wireline log from the Sø-4 well. It is possible that a thin Tøyen Formation is present in these wells, see text. Legend and abbreviations as in Fig. 6; abbreviated zonal designations explained in Fig. 14. Gamma-ray logs from these wells were first shown by Pedersen & Klitten (1990). The shown wireline logs were measured by GEUS in the Sø-3 and Sø-4 boreholes in 2003 and 1997, respectively. The different magnitude of the gamma radiation in the two wells is caused by differences in detector size. For location of the wells, see Fig. 2.

such a thin unit remains inconclusive; if present, the Alum Shale Formation is slightly thinner than stated. The Sø-3 well was referred to as the Bavnegård well by Poulsen (1978) who briefly summarised the drilled succession.

Other water wells

The Alum Shale Formation has been encountered in a few additional water wells on southern Bornholm, none of which have been wireline logged. The formation is recorded as > 39 m thick in a well at Lille Munkegård (DGU 246.544), but this drill site is located immediately adjacent to a fault and the thickness is regarded as unreliable. The Alum Shale Formation is > 30 m thick in the water well at Lille Duegård (DGU 246.476). This site may also be located adjacent to a fault, but further considerations are meaningless without wireline logs. Near Sø-4, water wells at Eskildsgård (DGU 248.101b) and Vossegård (DGU 247.148) penetrate the lower 14.5 m and upper 6 m of the Alum Shale Formation, respectively.

Gislövshammar-1 and -2, Sweden

The fully cored Gislövshammar-2 (Gi-2) well in southeastern Skåne, Sweden, *c.* 8 km south of Simrishamn, constitutes the type section of the Alum Shale Formation (Buchardt *et al.* 1997; Schovsbo 2001, 2002a; Nielsen & Schovsbo 2007). The well, drilled in 1991, is located approximately 125 m due south of the older Gislövshammar-1 well site drilled in 1941–42 (Westergård 1942, 1944). In that borehole, the Alum Shale above the Andrarum Limestone Bed is 61.3 m thick. The equivalent interval is 64.0 m in Gi-2, suggesting that one or more undetected minor faults are present in Gi-1. According to the description, minor portions of the Gi-1 core were badly crushed (18–21 m, 22.6–23.6 m, 29.7–32.7, 90.9–91.1 and 98.9–93.2 m), with a core loss of up to 50% (Westergård 1942, 1944). At a depth of 25–26 m the Alum Shale dipped 25–30° and contained narrow fissures filled with calcite. Similar fissure fillings were observed at other levels but apparently not associated with faults, according to Westergård.

The Gi-2 well is 105.9 m deep and penetrated Middle Ordovician to lower Cambrian strata. Here a 19.2 m thick Tøyen Formation is intercalated between the Komstad Limestone and the Alum Shale formations. The thin bed in the Gi-1 well identified as 'Ceratopyge Limestone' by Westergård (1942) belongs in our interpretation to the Tøyen Formation and there seems to be no Bjørkåsholmen Formation developed at Gislövshammar.

In Gi-2, the top of the Alum Shale Formation was encountered at 23.2 m and the base at 103.1 m. The well terminated in the Norretorp Member of the Læså Formation at 105.9 m. A wireline GR log was run in the hole when the drilling had reached a depth of 91.2 m; below this depth a GR log has been constructed based on measurements of the uranium content in the core (Fig. 14; see also Schovsbo 2002a).

For description of the detailed biozonation of the Gi-1 core, see Westergård (1942, 1944); the zones are listed in Table 3. A crude biozonation was sketched for the Gi-2 core by Nielsen & Buchardt (1994), based on fossils incidentally exposed on the bedding planes. A few additional fossil levels were added by Schovsbo (2001). However, the core has not been systematically split in the search for fossils like the older Gi-1 core (ranges of fossils in the core are indicated in Fig. 14). Nonetheless, as can be seen in Fig. 14, the zonal thicknesses established in the Gi-2 core match in detail the comprehensive biozonation established for the Gi-1 core by Westergård (1942, 1944). No particular zone is significantly thicker in the Gi-2 well compared with the Gi-1 well (Table 3), suggesting that the minor difference in thickness of the upper part of the Alum Shale referred to above is not due to a single fault. We further note that the strata dip only *c.* 5° at the Gi-1 drill site and maybe as much as 11° at the Gi-2 drill site (Nielsen 1995, p. 10), so the real thickness difference may be slightly less than 2 m.

Comparison has also been made with the GR log pattern and crude biozonation established in the cored Fågeltofta-2 and Albjära-1 wells in Skåne in order to further strengthen the biostratigraphic calibration of the GR log pattern. The latter unpublished data will be presented in a separate paper on the Alum Shale Formation of Skåne.

Wireline log correlation of wells on Bornholm

Previous work

The Alum Shale Formation in Billeshøj-1, Sø-2, Sø-3, Sø-4 and Sk-1 was correlated based on GR wireline logs by Pedersen & Klitten (1990). The thin Alum Shale below the Andrarum Limestone Bed with rather low GR intensity was separated as unit B1. The Alum Shale between the Andrarum Limestone Bed and the horizon here referred to as the Ol-2 spike (for explanation, see below) has a higher radiation and was separated as unit B2. Then follows Alum Shale with very high radiation, referred to as unit B3, with an upper boundary corresponding to the highest radiation levels in the basal part of the *Acerocarina* Superzone. The uppermost part of the Alum Shale Formation has a lower radiation – although not as low as B2 – and was separated as unit B4. Schovsbo *et al.* (2011, 2015b) recognised the same units in the Bi-2 and So-1 wells. The log stratigraphical scheme was further elaborated by Schovsbo *et al.* (2018), discussing correlation with Skåne and southern Norway.

Gamma radiation characterisation of the superzones

Four prominent GR maxima and minima were named by Schovsbo *et al.* (2018), viz. the AGL, BFGL, OTGS and PGS (see below), but in addition to these major fluctuations, many less conspicuous GR spikes can also consistently be recognised in the investigated

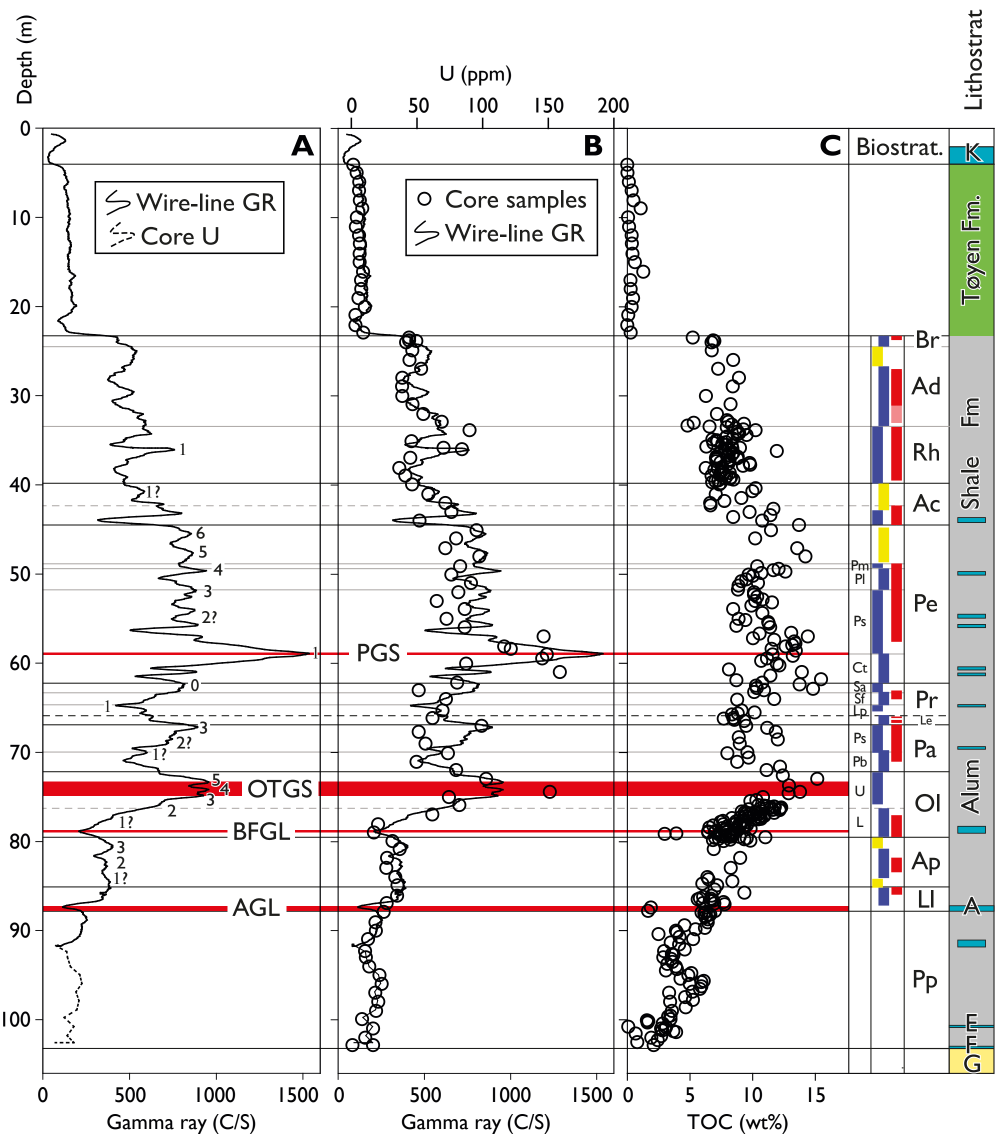

Fig. 14. Simplified lithology and biozonation of the Gislövshammar-2 well in south-eastern Skåne. Identification of the biozone boundaries (listed in Table 3) are guided by comparison with the detailed biozonation established in the adjacent Gislövshammar-1 well (Westergård 1942, 1944). Vertical red bars to the right indicate findings of biostratigraphically diagnostic fossils in the Gi-2 core (Nielsen & Buchardt 1994; Schovsbo 2001); light red bars indicate the presence of fossils tentatively but not safely suggesting zonal assignment. The adjacent blue and yellow bars indicate biozonation and barren intervals, respectively, in the nearby Gi-1 well (Westergård 1942, 1944); the zig-zag pattern reveals the zones discerned by Westergård (see Table 3 for details; zones in the basal *Acerocarina* Superzone are not differentiated). The Gi-1 data are fitted to the depths of the Gi-2 well via comparison with the fossils found in the latter well and thicknesses of zones. Note that the lower boundary of the *A. pisiformis* Zone is defined by the LAD of *L. laevigata* (Axheimer *et al.* 2006) and thus deviates from the boundary used by Westergård (1942, 1944). **A**: Wireline gamma-ray log. A running average of U measurements has been used to reconstruct the GR curve below 92 m (shown with dashed line). The small numbers 1 and up to 6 indicate correlatable minor gamma spikes. **B**: Wireline gamma-ray log and U core measurements. **C**: TOC content in the Gislövshammar-2 core. Legend and abbreviations as in Fig. 6. Other abbreviations: G: Gislöv Formation; Rh: *Rhabdinopora*; Ad: *Adelograptus*; Br: *Bryograptus*; L: Lower; U: Upper; Pb: *Parabolina brevifrons*; Ps: *Parabolina spinulosa*; Lp: '*Leptoplastus postcurrens*'; Sf: *Sphaeropthalmus flagellifer*; Sa: '*Sphaeropthalmus angustus*'; Ct: *Ctenopyge tumida*; Ps: '*Peltura scarabaeoides*'; Pl: *Parabolina lobata*; Pm: '*Parabolina megalops*'. Wireline log and core measurements are from Schovsbo (2001, 2002a); the GR log was made in 1991 using analog recording and has lower resolution than the modern digital logs available from Bornholm. For location of the well, see Fig. 1.

Table 3. Thicknesses (metres) of zones in the Alum Shale Formation in the Gislövshammar-1 and -2 wells, Sweden.

	Gislövshammar-1		Gislövshammar-2	
Interval	**Thickness**	**Depth interval**	**Thickness**[1]	**Depth interval**[1]
Komstad Limestone	–	–	[9.5][2]	2.0 – 4.0
Tøyen Formation	>12.3	7.2 – 19.5	19.2	4.0 – 23.2
Alum Shale Formation:				
Bryograptus kjerulfi Zone	1.2	19.5 – 20.7	0.8 (1.3)	23.2 – 24.0 (24.5)
Graptolites absent	2.2	20.7 – 22.9	3.0 (2.2)	24.0 – 27.0
Adelograptus tenellus Zone	6.7	22.9 – 29.6	6.5 (6.8)	27.0 (26.7) – 33.5
Rhabdinopora spp. zones	6.4	29.6 – 36.0	6.3	33.5 – 39.8
Tremadocian total	16.5	19.5 – 36.0	16.6	23.2 – 39.8
Trilobite barren interval	3.0	36.0 – 39.0	2.6	39.8 – 42.4
Acerocare ecorne Zone	–	(not found)	–	(not found)
Westergaardia scanica Zone	0.5	39.0 – 39.5		
Peltura costata Zone	0.5	39.5 – 40.0	2.1	42.4 – 44.5
Acerocarina granulata Zone	0.6	40.0 – 40.6		
Acerocarina Superzone total	4.6	36.0 – 40.6	4.7	39.8 – 44.5
Trilobite barren interval	3.9	40.6 – 44.5	4.4	44.5 – 48.9
'Parabolina megalops' Zone	0.5	44.5 – 45.0	(0.5)	48.9 – (49.4)
Parabolina lobata Zone	2.4	45.0 – 47.4	(2.4)	(49.4) – (51.8)
'Peltura scarabaeoides' Zone	7.1	47.4 – 54.5	(7.2)	(51.8) – (59.0)
Ctenopyge tumida Zone	3.3	54.5 – 57.8	(3.3)	(59.0) – (62.3)
Peltura Superzone total	17.2	40.6 – 57.8	17.8	44.5 – 62.3
'Sphaerophthalmus angustus' Zone	1.0	57.8 – 58.8	(0.8)	(62.3) – 63.1
Sphaerophthalmus flagellifer Zone	1.5	58.8 – 60.3	1.0 (1.7)	63.1 – 64.1(64.8)
'Leptoplastus neglectus' Zone	0.7	60.3 – 61.0	1.8 (1.1)	64.1(64.8) – 65.9
Protopeltura Superzone total	4.3	57.8 – 61.0	3.6	62.3 – 65.9
Leptoplastus Superzone total	1.1	61.0 – 62.1	1.0	65.9 – 66.9
Parabolina spinulosa Zone	3.1	62.1 – 65.2	(3.2)	66.9 – (70.1)
Parabolina brevispina Zone	2.4	65.2 – 67.6	(2.1)	(70.1) – (72.2)
Parabolina Superzone total	5.5	62.1 – 67.6	5.3	66.9 – 72.2
Upper *Olenus* Superzone	5.4	67.6 – 73.0	(4.1)	(72.2) – (76.3)
Lower *Olenus* Superzone	1.4	73.0 – 74.4	(3.3)	(76.3) – 79.6
Olenus Superzone total	6.8	67.6 – 74.4	7.4	72.2 – 79.6
Trilobite barren interval	1.0	74.4 – 75.4	1.7 (1.2)	79.6 – 81.3 (80.8)
Agnostus pisiformis Zone	2.9	75.4 – 78.3	2.9 (3.4)	81.3 (80.8) – (84.2)
Trilobite barren interval	0.8	78.3 – 79.1	0.9	(84.2) – 85.1
Agnostus pisiformis Zone	4.7	74.4 – 79.1	5.5	79.6 – 85.1
Lejopyge laevigata Zone	2.5	79.1 – 80.8	2.2	85.1 – 87.3
Andrarum Limestone	0.8	80.8 – 81.6	0.6	87.3 – 87.9
Paradoxides paradoxissimus Superzone	15.3	81.6 – 96.9	15.3	87.9 – 103.1
Total Alum Shale Fm: Logged thickness	–	–	79.9	23.3 – 103.1
Total Alum Shale Fm: Cored thickness	77.4	19.5 – 96.9	79.8	23.3 – 103.1

[1]Numbers in brackets are thicknesses and levels deduced from comparison with the Gi-1 well

[2]Thickness in exposure at Gislövshammar (Nielsen 1995)

wells. For convenience, we refer to these minor peaks as e.g. the Ol-2 or the Pa-2 spike, referring to the abbreviated superzone name and spike number as shown in the respective GR logs (see e.g. Fig. 10). It should be kept in mind that limestone concretions introduce distinct lows in the GR logs. Despite being eye-catching, these lows should be ignored when correlating the GR log pattern as the concretions occur semi-randomly in the succession. For this reason, the GR log interpretation is most reliably done by combining the GR curve with a lithologically sensitive log tool such as the sonic velocity log, the formation resistivity log or the density log, as a way to detect whether or not GR lows reflect limestone nodules or not. This is obviously only a problem in non-cored wells.

The following features in the GR logs have been used for tracing the superzonal boundaries on Bornholm, guided by correlation with the well-constrained biozonation of the Gi-2 succession in Skåne (Figs 14, 15).

- The base of the Alum Shale Formation is characterised by a small GR peak that likely reflects the phosphorite and glauconite content of the basal conglomerate. The amalgamated Forsemölla and Exsulans limestone beds at the base of the

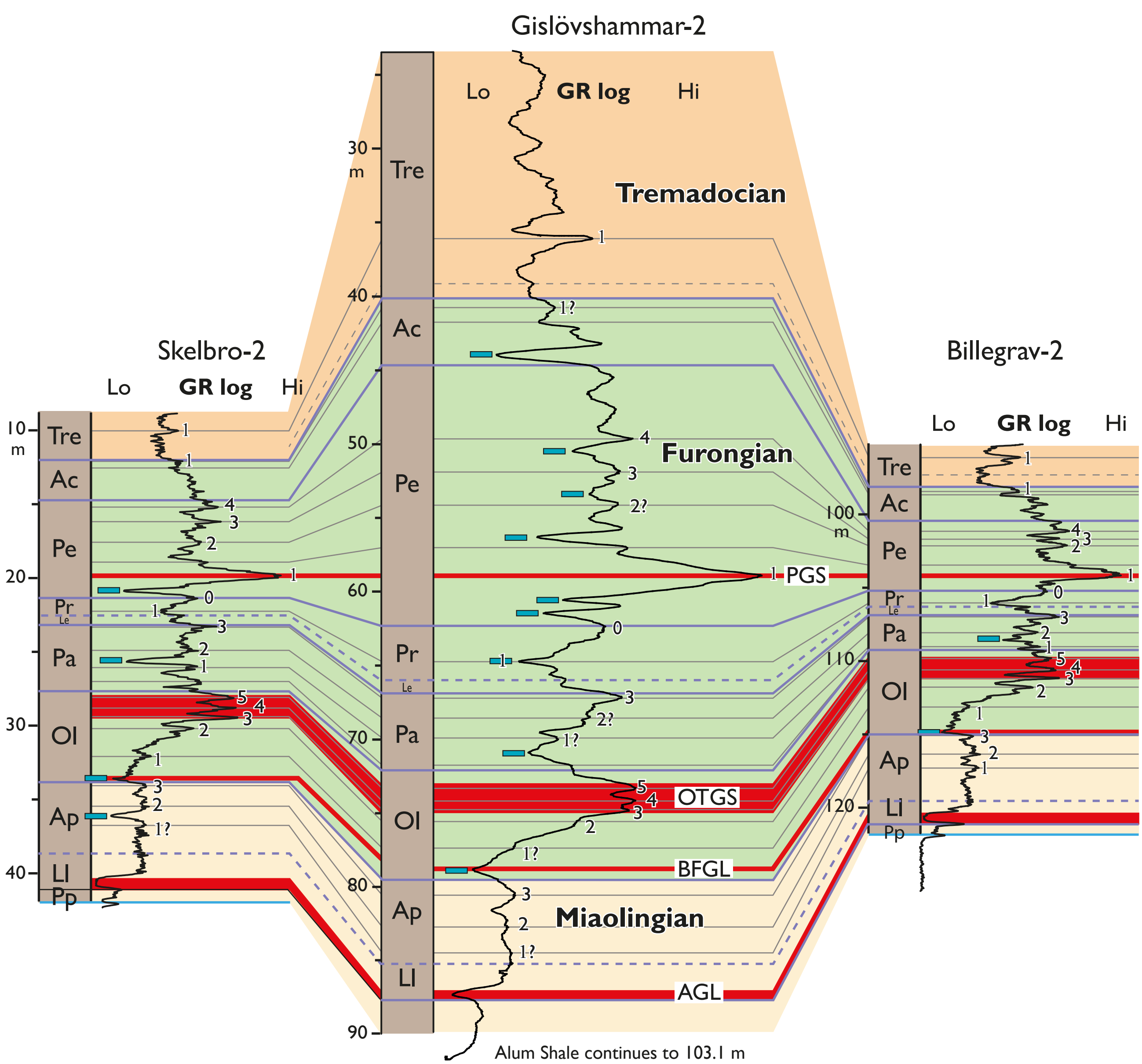

Fig. 15. Correlation of the Alum Shale in the Skelbro-2 and Billegrav-2 wells on Bornholm with the Gislövshammar-2 well in south-eastern Skåne, based on wireline GR logs. Logs for each of these wells are presented in Figs 8, 10 and 14. The small blue bars adjacent to the GR curves indicate limestone intercalations (producing GR lows). The thin grey lines trace minor GR oscillations, and the thicker light blue lines show superzone boundaries. Legend and abbreviations as in Fig. 6.

Alum Shale Formation are also identifiable using lithology-sensitive tools (sonic velocity, formation resistivity or density logs).

- The immediately overlying Alum Shale facies has a low and only slightly fluctuating gamma radiation (*Paradoxides paradoxissimus* Superzone).
- The combined Hyolithes + Andrarum Limestone Beds are signalled by a distinct low in the GR response, named the Andrarum Gamma Low (AGL) by Schovsbo *et al*. (2018) (lower part of the *Paradoxides forchhammeri* Superzone). However, due to averaging by the logging tool of the markedly different GR signal from the shale/limestone lithologies (the socalled shoulder-bed effect), the top and base of the amalgamated limestone are difficult to pick precisely on the GR logs. Better definitions of the limestone boundaries are typically obtained on the resistivity and/or the density log.
- The GR motif in the Miaolingian shale above the Andrarum Limestone Bed is rather uniform with only minor fluctuations. The boundary between the *L. laevigata* and *A. pisiformis* Zones is inconspicuous in terms of GR response, but comparison with the Gi-2 well suggests that it approximates a horizon with maximum GR values close above the Andrarum Limestone Bed. Despite being unremarkable, this minor peak is traceable in all wells (Fig. 16). The sonic logs available from the So-1 and Sk-2 wells show a decreasing p-wave velocity up through the interval excluding the peak velocities created by limestone intercalations.
- The lower boundary of the *Olenus* Superzone (i.e. base Furongian) is located immediately below (~ 0.1–0.2 m in the wells on Bornholm) a very distinctive GR minimum named the Base Furongian Gamma Low (BFGL) by Schovsbo *et al*. (2018). Identification of the lower boundary of the superzone is corroborated by findings of diagnostic fossils in Sk-1, Bi-2 and So-1 as well as Gi-2.
- The BFGL is upwards followed by a steep gradual increase in the GR level, leading up to the OTGS marker (see below). This very distinctive increase in gamma radiation is readily identified in all wells; it includes a couple of minor GR peaks labelled Ol-1 and Ol-2 (Fig. 16).
- The upper part of the *Olenus* Superzone is characterised by very high radiation levels with three intra-superzone GR peaks, numbered OL-3 to Ol-5 and collectively termed the *Olenus* Triple Gamma Spike (OTGS) by Schovsbo *et al*. (2018).
- The lower boundary of the *Parabolina* Superzone is located on the falling limb of the OTGS marker and is well-defined in all wells (Fig. 16). The position of the boundary is corroborated by findings of fossils in Sk-1, Bi-2 and So-1 as well as Gi-2.
- The *Parabolina* Superzone is characterised by a general upwards increase in the GR intensity. However, the GR log pattern is usually rather fluctuating due to the common presence of limestone.
- The upper boundary of the *Parabolina* Superzone is located immediately above a conspicuous GR maximum labelled Pa-3 at the very top of the superzone (Fig. 16).
- The *Leptoplastus* Superzone is thin and only tentatively identified. It appears to be represented by just one GR 'wiggle' interspersed between the Pa-3 spike in the uppermost part of the *Parabolina* Superzone and a pronounced low forming the lower part of the *Protopeltura* Superzone.
- The *Leptoplastus*/*Protopeltura* superzone boundary seems to be marked by a minor GR peak. Despite being inconspicuous, it is traceable in all wells on Bornholm (Fig. 16).
- The *Protopeltura* Superzone, especially the lower part, is characterised by a lower GR level than the overlying *Peltura* Superzone (Pr-1, Fig. 16). In the uppermost part of the *Protopeltura* Superzone the GR readings increase rapidly upwards as an initial part of the rise leading to the PGS marker (see below).
- The *Protopeltura*–*Peltura* superzonal boundary is located at the Pe-0 spike perturbating the general GR rise leading to the PGS marker (see below). The boundary is occasionally obscured by the occurrence of limestone concretions with very low GR intensity.
- The *Peltura* Superzone is an overall high GR interval including the conspicuous PGS peak in the lower part (*Peltura* Gamma Spike, Schovsbo *et al*. 2018). This major peak represents the highest GR level in the entire Alum Shale Formation. From there the GR intensity decreases upwards but remains overall high in the *Peltura* Superzone; three smaller GR maxima can be traced consistently on Bornholm in the upper part of the superzone (labelled Pe-2–4 in Fig. 16).
- The boundary between the *Peltura* and *Acerocarina* Superzones is located on the falling limb of the GR log immediately above the Pe-4 spike that terminates the overall high GR level characteristic of the *Peltura* Superzone. Although being rather inconspicuous, this boundary is readily traceable between wells (Fig. 16). The sonic log (available from only So-1 and Sk-2) shows a gradually increasing p-wave velocity from that boundary and upwards.
- The *Acerocarina* Superzone is characterised by an overall upwards falling GR level intermediate between that of the underlying *Peltura* Superzone and the overlying Tremadocian interval. The lower half to two-thirds of the superzone is characterised by a fairly high GR level that abruptly falls to a lower

level in the upper part of the superzone (Fig. 16). In the Gi-2 well, this pronounced fall coincides broadly with the boundary between the fossiliferous lower part (*A. granulata* to *W. scanica* Zones) and the unfossiliferous upper part of the superzone (Fig. 14). The only exception to this pattern is the Bu-1 well, where the lower main part of the *Acerocarina* Superzone exhibits very high gamma radiation, almost as high as the PGS. This motif is also known from wells in central and western Skåne, but is less distinct in south-eastern Skåne and is not seen in the other Bornholm wells.

- The base of the Ordovician is located immediately above the small Ac-1 spike intersecting the general upwards fall in GR intensity that characterises the *Acerocarina* Superzone. In the Gi-2 well, where the Tremadocian is much expanded and stratigraphically more complete than on Bornholm, the Cambro-Ordovician boundary, identified by the FAD of graptolites, is located slightly above the Ac-1 peak (Fig. 14). The position of the boundary is constrained by the incoming of graptolites in the Bi-2 core (Fig. 8); graptolites have also been found in the Ordovician interval in the Sk-1 and So-1 cores (Figs 6, 11).
- Above the Cambro-Ordovician boundary, the GR intensity further decreases into the Ordovician and becomes clearly lower than in the *Acerocarina* Superzone. An omnipresent GR spike is labelled Tre-1 (Fig. 16). This maximum coincides with a graptolite-rich horizon within the *R. flabelliformis flabelliformis* Zone, known from the exposure at Limensgade and the Sk-1 core, as well as at various places in Skåne, e.g. the Flagabro well (Tjernvik 1958). The Tre-1 spike is also recognisable in the Gi-2 well (Fig. 14).
- The uppermost part of the Alum Shale, 0.5–0.6 m thick, exhibits an upwards increasing GR signal in most wells (and where it does not this may be due to the presence of a thin Tøyen Formation). This is likely associated with a high phosphorite content with raised levels of uranium (see Poulsen 1922 for description of the Limensgade section).
- The Tøyen Formation in the Bi-2 core cannot be identified on the logs, probably because it is too thin. The minor fall in GR intensity seen in the Sø-3 well, and especially in the Sø-4 well, immediately below the basal Komstad Limestone conglomerate peak (see below) may reflect the presence of a thin Tøyen Formation. In Sø-3, a marked low in the resistivity log is also seen at the same level, which is rather remarkable. However, without cores the presence of a thin Tøyen Formation remains speculative.
- The conglomerate at the base of the Komstad Limestone Formation is associated with a distinct maximum in the GR log and high formation resistivity readings (e.g. Fig. 10). The latter is related to the carbonate matrix, whereas the high GR intensity reflects the common phosphorite nodules and elevated glauconite content. The underlying Alum Shale Formation is characterised by low resistivity values and this log type is best for picking the boundary precisely.
- The Komstad Limestone is characterised by low GR intensity associated with high resistivity readings. The top of the limestone is placed below a small GR spike that may reflect the phosporite conglomerate at the base of the Dicellograptus Shale, an increased TOC level in the blackish uppermost part of the limestone (Nielsen 1995) or a combination of these factors.

Correlation and thickness variations of superzones on Bornholm

***Paradoxides paradoxissimus* Superzone**

This superzone comprises the amalgamated Forsemölla and Exsulans Limestone Beds and the overlying Alum Shale up to the Hyolithes Limestone Bed (Fig. 3). The composite basal limestone, which is recognised in all investigated wells, is up to 0.25 m thick. The individual limestone beds cannot be discerned in wireline logs, but the composite unit is recognised by having very low GR values above the basal conglomerate GR peak, usually associated with a distinct spike in the resistivity log. A drop in resistivity coinciding with a rise in gamma radiation characterises the Alum Shale interval between the Exsulans and Hyolithes limestones. This shale is 0.5–1.95 m thick with minimum thickness in the Bi-2 well and maximum thickness in the So-1 well. Berg-Madsen (1985b) reported a thickness of only 0.1 m in Øleå below Ringborgen, but our re-measurement in 2017 showed this Alum Shale interval to be *c.* 0.5–0.6 m thick at this locality.

The entire *P. paradoxissimus* Superzone varies in thickness from 0.8–1.5 m in the Bu-1, Sk-1, Sk-2, Sø-3, Sø-4 and Bi-2 wells, to 2.15 m in the So-1 well (cored thickness). No systematic thickness variation across southern Bornholm is observed (Fig. 16, Table 4).

***Paradoxides forchhammeri* Superzone**

This superzone comprises the Hyolithes and Andrarum Limestone Beds and the lower part of the overlying Alum Shale, assigned to the (traditional) *Lejopyge laevigata* and *Agnostus pisiformis* Zones (Fig. 3). The boundary between the latter zones is inconspicuous in the GR logs, but comparison with the log pattern in the Gi-2 well suggests a thickness of 0.9–1.6 m of the *L. laevigata* Zone on Bornholm (Table 5). This interpretation must be considered tentative, but it corresponds fairly well with the zonal thickness measured in the exposure at Borggård, Øleå,

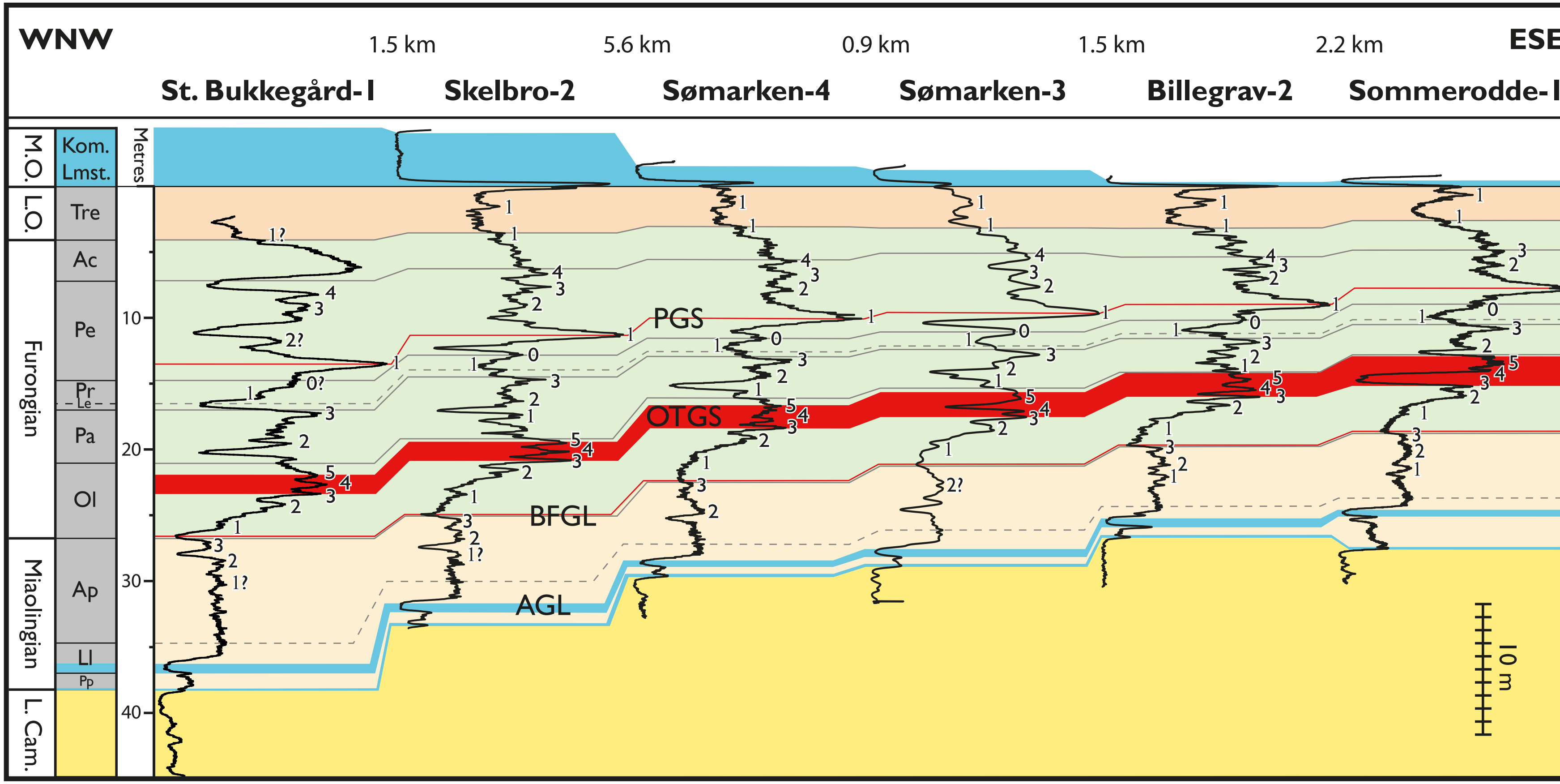

Fig. 16. Correlation of the Alum Shale interval in the St. Bukkegård-1, Skelbro-2, Sømarken-4, Sømarken-3, Billegrav-2, and Sommerodde-1, based on GR wireline logs. The distance in kilometres between the individual wells is indicated in the upper line. The numbers 1 and up to 5 adjacent to the logs indicate correlatable minor maxima or minima in the gamma-ray log, referred to by a prefix consisting of the first two letters in the superzone name and the number, e.g. Pa-2, Ol-1 etc. Legend and abbreviations as in Fig. 6 with the addition that M.O. = Middle Ordovician and Kom. Lmst. = Komstad Limestone. Logs for each well are shown in Figs 8, 10, 11, 12 and 13. Location of the correlation profile is indicated in Figure 2.

by Poulsen (1923) (boundary somewhere between 0.8 and 2.1 m above the Andrarum Limestone Bed) and Berg-Madsen (1986) (boundary between 1.5 and 1.6 m above the Andrarum Limestone Bed). However, there is no indication of a thinner development of the *L. laevigata* Zone in the Sk-2 and Bu-1 wells, on the contrary (Table 5). These wells are located close to the outcrop at Kalby, Læså, where the *L. laevigata* Zone was stated to be only ~ 0.65 m thick by Berg-Madsen (1986), based on findings of a conodont of assumed late Cambrian age (the same marker as used in the Øleå section). The Kalby section was the only site where Grönwall (1899, 1902) found *L. laevigata*, but he did not state the range and it is likely restricted to the anthraconite nodules immediately overlying the Andrarum Limestone Bed. The overlying *A. pisiformis* Zone is 4.6–5.0 m thick in most of the investigated wells and very thick, 7.8 m, in the Bu-1 well (Table 5).

The total thickness of the Miaolingian shale overlying the Andrarum Limestone Bed varies in thickness between 5.6 and 6.4 m except for the Bu-1 well, where it is 9.4 m. Overall, the *Paradoxides forchhammeri* Superzone shows no systematic thickness variation between wells (Table 4) and it is almost of the same thickness as in south-eastern Skåne. In fact, it is even thicker in the Bu-1 well, where the *A. pisiformis* Zone is remarkably thick. Note that the *L. laevigata*/*A. pisiformis* zonal boundary in the Gi-2 well (at 85.1 m) is defined by the LAD of *L. laevigata* following Axheimer *et al*. (2006); this boundary differs from the zonal definition used by Westergård (1942, 1944).

Olenus Superzone

Trilobites occur in great profusion in the lower part of the *Olenus* Superzone throughout Scandinavia (e.g. Westergård 1922; Lauridsen & Nielsen 2005 and references therein), and this fossiliferous level is usually recognisable in cores even without splitting. The GR log motif of the superzone is also very characteristic, and it is easily identified on wireline logs (see above).

The *Olenus* Superzone is 5.7–6.4 m thick across southern Bornholm and does not show notable thickness differences between the Læså and Øleå areas (Table 4). In the Gi-2 well, the *Olenus* Superzone is 7.4 m thick (Table 3), so the interval is slightly thinner on Bornholm. The GR log pattern is essentially similar between south-eastern Skåne and Bornholm (Fig. 15), strongly suggesting that the upper *Olenus scanicus*–*Olenus rotundatus* Zone with bradorid arthropods (‘*Polyphyma*/*Beyrichia*’ *sensu* Westergård 1922, 1942, 1944, 1947) is developed also on Bornholm, but the index trilobites have not been found. This upper part of the *Olenus* Superzone corresponds to the OTGS marker in the GR logs. The informal boundary between the lower and upper parts of the superzone (Fig. 3) is located approximately midway between the Ol-1 and Ol-2 spikes (Fig. 14).

Parabolina Superzone

This superzone comprises two zones (Fig. 3). The lower *Parabolina brevispina* Zone is 2.4 m thick in the Gi-1 well (Table 3) and seems to be characterised by low GR levels in the Gi-2 well, but the GR intensity

Table 4. Thicknessses and depth intervals (metres) of formations and superzones in wells on Bornholm.

	St. Bukkegård-1	Skelbro-2	Skelbro-16	Sømarken-3	Sømarken-4	Billegrav-2	Sommerodde-1
Komstad Limestone	[4.7][1]	4.1 (4.4–8.5)	>3.9 (0–3.9)	1.3 (68.2–69.5)	1.5 (50.2–51.7)	0.1 (95.1–95.2)[3]	0.6 (217.4–217.9)
Tøyen Formation	[0][1,2]	0	0	Thin?	Thin?	0.2 (95.2–95.4)[3]	0
Tremadocian	[4.0][2]	3.5 (8.5–12.0)	3.4 (3.9–7.4)	3.0 (69.5–72.5)[5]	3.0 (51.7–54.7)[5]	2.8 (95.4–98.2)[5]	2.5 (217.9–220.4)
Acerocarina Superzone	≥3.0 (3.1–6.1)	2.7 (12.0–14.7)	2.9 (7.4–10.2)	2.0 (72.5–74.5)	2.5 (54.7–57.2)	2.2 (98.2–100.4)	2.2 (220.4–222.6)
Peltura Superzone	8.1 (6.1–14.3)	6.7 (14.7–21.4)	6.7 (10.2–16.9)	6.1 (74.5–80.7)	6.0 (57.2–63.2)	5.1 (100.4–105.5)	4.3 (222.6–226.9)
Protopeltura Superzone	1.2 (14.3–15.5)	1.1 (21.4–22.5)	1.1 (16.9–18.0)	1.1 (80.7–81.8)	1.0 (63.2–64.2)	0.9 (105.5–106.4)	1.2 (226.9–228.1)
Leptoplastus Superzone	0.5 (15.5–16.0)	0.6 (22.5–23.1)	0.6 (18.0–18.6)	0.4 (81.8–82.2)	0.5 (64.2–64.7)	0.5 (106.4–106.9)	0.5 (228.1–228.5)
Parabolina Superzone	4.1 (16.0–20.2)	4.5 (23.1–27.7)	4.2 (18.6–22.9)	2.6 (82.2–84.8)	2.9 (64.7–67.6)	2.3 (106.9–109.2)	2.0 (228.5–230.5)
Olenus Superzone total	5.8 (20.2–26.0)	6.1 (27.7–33.8)	6.3 (22.9–29.2)	6.4 (84.8–91.1)	6.4 (67.6–74.0)	5.8 (109.2–115.0)	6.3 (230.5–236.8)
Paradoxides forchhammeri Superzone	10.2 (26.0–36.2)	7.2 (33.8–41.0)	7.0 (29.2–36.2)	6.8 (91.1–97.9)	6.3 (74.0–80.3)	6.2 (115.0–121.2)	6.8 (236.8–243.6)
Paradoxides paradoxissimus Superzone	1.7 (36.2–37.8)	1.1 (41.0–42.1)	1.3 (36.2–37.5)	0.8 (97.9–98.7)	0.9 (80.3–81.2)	1.0 (121.2–122.1)	2.2 (243.6–245.8)
Total Alum Shale Fm: Logged thickness	38.9[4]	33.6	33.5	29.2[5]	29.5[5]	26.9	28.0
Total Alum Shale Fm: Cored thickness	–	33.5	33.5	–	–	26.8	27.9

[1]Thickness in Vasagård-1. [2]Thickness at Limensgade. [3]Cored thickness. [4]Incl. 4 m Tremadocian at Limensgade. [5]A little thinner if Tøyen Fm is present.

[6]The GR log from this well is of low resolution; in particular the thickness of the P. paradoxissimus Superzone deviates from the drilled thickness (cf. Pedersen 1989)

The recorded drilled (isochore) thicknesses may be up to 2 % larger than the true stratigraphic thicknesses due to the dip of the strata, which on Bornholm and in SE Skåne typically is 5–10°. This concerns all thicknesses stated in this paper (Tables 3–5).

fluctuates due to the presence of limestone. The overlying *Parabolina spinulosa* Zone is 3.1 m thick in the Gi-1 core and is characterised by rising GR levels in the Gi-2 well, leading up to a quite prominent peak at the very top of the zone. The same log pattern with a marked reduction in GR intensity in the lower part of the superzone relative to the underlying OTGS marker, followed by an upwards rise culminating in an upper peak, also characterises the *Parabolina* Superzone on Bornholm (Fig. 16).

In the Sk-2 and Bu-1 wells, the total *Parabolina* Superzone is 4.5 and 4.1 m thick, respectively, which is thicker than the *P. spinulosa* Zone in the Gi-1 well (Table 3). Hence, since all Furongian zones and superzones on Bornholm are thinner than their counterparts in Skåne, and also because the GR log pattern of the superzone is very similar between the two areas (Fig. 15), we infer that the basal *P. brevispina* Zone is developed on Bornholm, at least in the Læså area. The *P. brevispina*/*P. spinulosa* zonal boundary approximates the Pa-1 spike in the Gi-2 well (Fig. 14) and adopting this boundary for Bornholm, the respective thicknesses of the two zones are shown in Table 5. The *Parabolina* Superzone shows a significant south-eastwards thinning from 4.1–4.5 m in the Bu-1, Sk-1 and Sk-2 wells to 2.0 m in So-1 (Table 4). The GR log-correlation indicates that it is primarily the lower part of the superzone that becomes thinner (Fig. 16) and perhaps no *P. brevispina* Zone is developed in the So-1 well (Table 5).

Parts of the superzone are exposed in the Øleå and Læså streams (Poulsen 1923, locs 4, 5, 6, 19, 21; see also Hansen 1945). It contains very abundant orthid brachiopods (*Orusia lenticularis*), which occasionally form coquinoid limestone. Limestone is present in most of the investigated wells (Bu-1, Sk-1, Sk-2, Bi-2, Sø-3, Sø-4). Brachiopods have been found in this superzone in the cores from Sk-1 (20.6–20.8 m), Bi-2 (107.4–109.2 m) and So-1 (228.9–230.4 m).

Leptoplastus Superzone

This superzone is the thinnest of all Furongian superzones and it is absent or incomplete at many sites in Scandinavia (Westergård 1922, 1947; Martinsson 1974, fig. 5). A full zonal suite is known only from Skåne (Ahlberg *et al*. 2006 and references therein). In the Oslo area, only the basal zone is missing (Rasmussen *et al*. 2015). On Bornholm, the *Leptoplastus* Superzone comprises only the upper two zones (Fig. 3). The entire superzone, 0.6 m thick, is exposed at Poulsen's (1923) locality 6 in the Læså section and the upper zone is also recorded from Poulsen's (1923) locality 22 in the

Table 5. Thicknesses and depth intervals (metres) of selected Furongian and Miaolingian zones in wells on Bornholm

	St. Bukkegård-1	Skelbro-2	Skelbro-1	Sømarken-3	Sømarken-4	Billegrav-2	Sommerodde-1
Peltura Superzone							
'Parabolina megalops' Zone	0?	0?	0?	0?	0	0	0
Parabolina lobata Zone	2.0 (6.1–8.1)	1.5 (14.7–16.2)	1.6 (10.2–11.8)	1.5 (74.5–76.0)	1.1 (57.2–58.3)	0.8 (100.4–101.2)	0
'Peltura scarabaeoides' Zone	4.5 (8.1–12.6)	3.7 (16.2–19.9)	3.6 (11.8–15.4)	3.2 (76.0–79.2)	3.4 (58.3–61.7)	2.9 (101.2–104.1)	3.0 (222.6–225.6)
Ctenopyge tumida Zone	1.7 (12.6–14.3)	1.5 (19.9–21.4)	1.5 (15.4–16.9)	1.5 (79.2–80.7)	1.5 (61.7–63.2)	1.4 (104.1–105.5)	1.3 (225.6–226.9)
Protopeltura Superzone							
'Sphaerophthalmus angustus' Zone	0.3 (14.3–14.6)	0.3 (21.4–21.7)	Log	0.2? (80.7–80.9)	0.2 (63.2–63.4)	0.2 (105.5–105.7)	0.3 (226.9–227.2)
Sphaerophthalmus flagellifer Zone	0.4 (14.6–15.0)	0.5 (21.7–22.2)	too	0.5 (80.9–81.4)	0.5 (63.4–63.9)	0.5 (105.7–106.2)	0.6 (227.2–227.8)
'Leptoplastus neglectus' Zone	0.5? (15.0–15.5)	0.3 (22.2–22.5)	crude	0.4 (81.4–81.8)	0.3 (63.9–64.2)	0.2 (106.2–106.4)	0.3 (227.8–228.1)
Parabolina Superzone							
Parabolina spinulosa Zone	2.7 (16.0–18.7)	2.9 (23.1–26.0)	2.9 (18.6–21.5)	2.3 (82.2–84.5)	2.4 (64.7–67.1)	1.9 (106.9–108.8)	2.0 (228.5–230.5)
Parabolina brevispina Zone	1.5 (18.7–20.2)	1.7 (26.0–27.7)	1.4 (21.5–22.9)	0.3 (84.5–84.8)	0.5 (67.1–67.6)	0.4 (108.8–109.2)	0
Olenus Superzone							
Upper *Olenus* Superzone	4.0 (20.2–24.2)	3.2 (27.7–30.9)	4.0 (22.9–26.9)	3.6 (84.8–88.4)	3.7 (67.6–71.3)	3.4 (109.2–112.6)	3.7 (230.5–234.2)
Lower *Olenus* Superzone	1.8 (24.2–26.0)	2.9 (30.9–33.8)	2.3 (26.9–29.2)	2.7 (88.4–91.1)	2.7 (71.3–74.0)	2.4 (112.6–115.0)	2.6 (234.2–236.8)
Paradoxides forchhammeri Superzone							
Agnostus pisiformis Zone	7.8 (26.0–33.8)	4.9 (33.8–38.7)	5.0 (29.2–34.1)	4.7 (91.1–95.8)	4.6 (74.0–78.6)	4.7 (115.0–119.7)	4.8 (236.8–241.6)
Lejopyge laevigata Zone	1.6 (33.8–35.4)	1.6 (38.7–40.3)	1.4 (34.1–35.5)	1.4 (95.8–97.2)	1.4 (78.6–79.9)	0.9 (119.7–120.6)	1.2 (241.6–242.7)
Andrarum Limestone	0.8 (35.4–36.2)	0.7 (40.3–41.0)	0.6 (35.5–36.2)	0.7 (97.2–97.9)	0.4 (79.9–80.3)	0.6 (120.6–121.2)	0.9 (242.7–243.6)

Øleå section. In the Læså section much of the superzone is made up of limestone; in the studied wells, limestone is present only in Bu-1. We presume that the *Leptoplastus* Superzone corresponds to the basal GR-cycle (low/high couplet) of the interval immediately above the *Parabolina* Superzone. Despite being rather unremarkable, this 'wiggle' can be traced in nearly all wells (Fig. 16) and the interpretation is consistent with the GR log pattern and fossil distribution in the Gi-2 well in Skåne (Figs 14, 15). The tentative correlation suggests that the superzone is 0.4–0.6 m thick on Bornholm (Table 4), but due its thinness the relative measuring uncertainty is considerable.

***Protopeltura* Superzone**

This superzone is 0.9–1.2 m thick in the investigated wells which is markedly thinner than in Skåne (Westergård 1944; Table 3). It shows no systematic thickness differences across southern Bornholm (Table 4). We prefer a simplified subdivision of the superzone into only three zones (Fig. 3), following Westergård (1944, 1947). In the Gi-2 well, the GR minimum labelled Pr-1 coincides with the *'Leptoplastus neglectus'*/*Sphaerophthalmus flagellifer* zonal boundary (Fig. 14) and this intra-superzone marker is also recognisable on Bornholm (Fig. 16), although limestone locally obscures the GR signal in the interval. In the Gi-2 well, the overlying *S. flagellifer* Zone is characterised by strongly upwards increasing GR intensity, in turn followed by the *'Sphaerophthalmus angustus'* Zone that has a fairly uniform GR level, increasing but very slightly upwards (Fig. 14). Applying this pattern to the GR logs from Bornholm, a tentative correlation of zones has been attempted (Table 5; see also individual logs).

The *Protopeltura* Superzone is exposed at Poulsen's (1923) locality 6 in the Læså section with a stated total thickness of *c.* 1.1 m, which conforms to the thicknesses encountered in wells (Table 5). The trilobites reported by Poulsen (1923) are only indicative of the *S. flagellifer* and *'S. angustus'* Zones; the precise ranges were not specified. However, the basal *'L. neglectus'* Zone is quite thin in Skåne (0.3–0.9 m; Westergård 1942, 1944) and if thinner on Bornholm, as must be anticipated, it requires high resolution sampling to locate it. Hence, the apparent absence in the Læså section may reflect lack of discovery of the diagnostic trilobites. The *Leptoplastus* cranidia found at 106.0 m in the Bi-2 core actually bring *L. neglectus* to mind, but need further study to be safely identified. *'Ctenopyge' neglectus* var. *bornholmensis* described by Poulsen (1923) is not an indicator for the *'L. neglectus'* Zone as hinted at by Poulsen (1923) and Martinsson (1974, fig. 5); the associated fauna clearly shows a derivation of this endemic species from the *Leptoplastus crassicornis*–*Leptoplastus angustatus* Zone (ATN unpublished data). Assuming that the Pr-1 minimum marks the upper boundary of the *'L. neglectus'* Zone as in the Gi-2 well, the zone may be ~0.25–0.5 m thick on Bornholm (Table 5).

***Peltura* Superzone**

This superzone thins south-eastwards from 6.7–8.1 m in wells in the Læså area to 4.3 m in So-1 (Table 4). Approximately half of this thinning is due to overall condensation of the interval and the remaining reduction is due to truncation of the upper part of the superzone (Fig. 16, Table 5).

The superzone is in this study, again essentially following Westergård (1944, 1947), subdivided into the *Ctenopyge tumida*, *'Peltura scarabaeoides'*, *Parabolina lobata* and *'Parabolina megalops'* Zones, listed in ascending order (Fig. 3). In the Gi-2 well, the *C. tumida* Zone is characterised by rapidly upwards increasing GR readings culminating in the conspicuous PGS marker located at the boundary between the *C. tumida* and *'P. scarabaeoides'* Zones (Fig. 14). This pattern is readily identified in all wells on Bornholm (Figs 15, 16) where the *C. tumida* Zone thus delineated is 1.3–1.7 m thick (Table 5). In turn, the boundary between the overlying *'P. scarabaeoides'* and *P. lobata* Zones coincides with the Pe-3 peak in the Gi-2 well (Fig. 14), suggesting that the *'P. scarabaeoides'* Zone is 2.9 m–4.5 m thick on Bornholm (Fig. 16, Table 5; see also the individual logs). Finally, the boundary between the *P. lobata* and the *'P. megalops'* Zones in the Gi-2 well is located immediately above the Pe-4 peak (Fig. 14). Defined this way, the *P. lobata* Zone is 0.8–2.0 m across southern Bornholm except in the So-1 well, where it is thin or absent (Table 5). The Pe-4 peak (or lower levels) forms the top of the *Peltura* Superzone in all wells on Bornholm, and it is, accordingly, predicted that the rather thick *'P. megalops'* Zone (= *Peltura paradoxa* Zone in some schemes) of the Gi-2 well, totalling 4.9 m including the overlying trilobite-barren interval, has no counterpart on Bornholm. A similar gap is seen in all Alum Shale districts in south central Sweden (Martinsson 1974, fig. 5).

The *Peltura* Superzone is exposed at Poulsen's (1923) localities 6 and 7 in the Læså section near Vasagård and represents the *C. tumida, 'P. scarabaeoides'* and *P. lobata* Zones according to Poulsen (1923, fig. 2) (*Parabolina longicornis = P. lobata*). The *C. tumida* Zone was stated to be 2.1 m thick at locality 6, whereas the overlying *'P. scarabaeoides'* and *P. lobata* Zones are allegedly only 1.8 m thick altogether in the section. The *C. tumida* Zone is thus a little thicker than in the closest wells, whereas the overlying *'P. scarabaeoides'* Zone is drastically thinner than in all well sections on Bornholm (Table 5). Investigation of locality 6 is in progress to disentangle this vexing discrepancy. A major problem seems to be confident correlation between the main southern exposure and the northern part of the section, where the *P. lobata* Zone is exposed high up (see Poulsen 1923, fig. 2, his "G-level"). If, however, the limited thickness of the '*P. scarabaeoides'* Zone reported by Poulsen (1923) by and large is correct, the *P. lobata* Zone must be significantly thicker on Bornholm than inferred in this study. Further speculations on the conflicting thicknesses should await re-investigation of the Læså section including hand-held gamma logging.

Acerocarina Superzone

The uppermost Cambrian superzone is absent across much of south central Sweden and is best known from Skåne (Westergård 1944, 1947; Martinsson 1974; Weidner & Nielsen 2013). The superzone is also developed on Bornholm, where the uppermost *Acerocare ecorne* Zone was described from Limensgade by Poulsen (1923). Lower parts of the superzone are not exposed, except possibly in the Risebæk, but those outcrops have never been investigated.

In Gi-2, a limestone nodule causes a drop in gamma intensity at 43.5–44.5 m (Fig. 14). This limestone yielded *Parabolina heres heres* and the level appears to match the lower boundary of the *Acerocarina* Superzone recorded in the adjacent Gi-1 well (Westergård 1942, 1944). Immediately above the limestone, the GR intensity is high, thence decreases upwards with an abrupt fall in the middle of the superzone. A comparable log pattern (without limestone) is observed in the wells on Bornholm (Fig. 16), except Bu-1 (discussed below), and the *Acerocarina* Superzone is, accordingly, inferred to encompass the interval with upwards waning GR intensity above the *Peltura* Superzone. Defined this way, the superzone includes 2.7–2.9 m of strata in the Sk-1 and Sk-2 wells, thinning south-eastwards to 2.0–2.5 m in the Øleå area (Fig. 16; Table 4).

The log pattern in the uppermost part of the Bu-1 well deviates markedly from this GR motif. Here the GR intensity is low immediately above the Pe-4 peak due to the presence of a rather thick limestone nodule (Fig. 12) and then becomes almost as high as in the PGS marker. In wells in western Skåne (e.g. Albjära-1), a similar interval with very high gamma radiation is seen in the lowermost part of the *Acerocarina* Superzone.

The age of the limestone near the *Peltura*/*Acerocarina* Superzone boundary in the Bu-1 well can only be guessed at. Large limestone nodules are present in the *Parabolina lobata* Zone in the Læså section (Poulsen 1923, fig. 2) and limestone is also frequently encountered at the base of the *Acerocarina* Superzone in Skåne, as for instance in the Gislövshammar wells. Based on comparison with the zonal thicknesses in the Sk-1 and Sk-2 wells, and the observation that the Pe-4 spike is double-peaked in Sk-2 and only single-peaked in Bu-1, we assume that the discussed limestone interval lies at the very top of the *Peltura* Superzone. If so, the *Acerocarina* Superzone is ~3.0 m in the Bu-1 well.

In the Gi-1 and Gi-2 wells, only the lowermost 1.6–2.1 m of the 4.6 m thick *Acerocarina* Superzone contains fossils and this basal part actually represents the three lower zones of the superzone (Table 3). In the Gi-2 well, the last occurrence of trilobites is shortly below the abrupt intra-superzone fall in GR intensity which is thus a rough proxy for the top of the *Westergaardia illaenopsis*–*Westergaardia scanica* Subzone *sensu* Westergård (1944). Then follows a thick unfossiliferous interval, and the *A. ecorne* Zone has not been identified in the Gislövshammar wells. Correlation of individual zones between Skåne and Bornholm based on the GR log pattern is not possible, but the upper part of the superzone, corresponding to the barren interval in the Gislövshammar wells, is comparatively much thinner on Bornholm.

Tremadocian

On Bornholm the Ordovician Alum Shale is best known from the abandoned quarry at Limensgade (Grönwall 1916; Poulsen 1922). The latter author reported a thickness of *c*. 2.5 m, which von Jansson (1979) later corrected to 4 m after finding graptolites at a lower level. The oldest dateable Tremadocian represents the *Rhabdinopora flabelliformis socialis* Zone (von Jansson 1979) and the basal *Rhabdinopora preparabola* Zone is either missing or not graptolitic (Fig. 3).

The Cambro–Ordovician boundary is indicated in wireline logs as a further and fairly significant drop of GR intensity above the small Ac-1 peak at the top of the *Acerocarina* Superzone. The general GR intensity is overall low in the Tremadocian interval relative to the Furongian, although not as low as in the Miaolingian. Identification of the lower boundary is corroborated by fossil evidence in the Bi-2 well, where graptolites turn up at 98.1 m (Fig. 8). In Gi-2, the graptolites appear slightly higher above the Ac-1 peak than on Bornholm (Fig. 14).

The small GR peak labelled Tre-1 is associated with a graptolite-rich horizon in the *Rhabdinopora flabelliformis flabelliformis* Zone in the middle of the Tremadocian (at 6 m in the Sk-1 core, Fig. 6; a densely graptolitic level at *c*. 2.5 m below the Komstad Limestone at Limensgade, corresponding to the base of the Ordovician identified by Poulsen 1922). This minor GR peak is readily identified in all wells on Bornholm (Fig. 16) and it is actually also recognisable in the expanded section in the Gi-2 well (Fig. 14).

The Tremadocian is 3.4–3.5 m thick in the Sk-1 and Sk-2 wells, thinning slightly south-eastwards to the Øleå area where the interval is *c*. 3 m in most wells with a minimum of 2.5 m recorded in the So-1 well (Table 4). In south-eastern Bornholm, the Tremadocian comprises only the *Rhabdinopora* interval and no *Adelograptus tenellus* and *Bryograptus* Zones are developed.

Discussion

Stratigraphy

The biozonal boundaries often do not coincide precisely with obvious GR peaks or lows, but correlation of the log pattern between wells provides a very robust correlation of superzones (Fig. 16) and frequently even of zones, when they are more than ~0.5 m thick. The outlined correlation suggests that the *Olenus scanicus–O. rotundatus* and *Parabolina brevispina* Zones are developed on Bornholm although the latter may only occur in the Læså area. None of these zones have been proven to date by fossil findings. It is also likely that a thin *'Leptoplastus neglectus'* Zone is developed in the lower part of the *Protopeltura* Superzone. The fossiliferous lower part of the *Acerocarina* Superzone, known from the Gislövshammar wells, also seems to be developed on Bornholm, but it is unfeasible to differentiate the individual zones based on the GR log pattern. The *'Parabolina megalops'* Zone in the upper *Peltura* Superzone seems to be absent on Bornholm (or, at least, is very thin).

Depositional environment and uranium enrichment

The Alum Shale was deposited extremely slowly, which in combination with the prevailing low oxygen conditions at the seafloor caused a strong enrichment of many trace elements (e.g. Armands 1972; Andersson *et al*. 1985; Buchardt *et al*. 1997). Nielsen & Schovsbo (2015) concluded that the Miaolingian–Tremadocian oxygen crisis was a global phenomenon which seemingly was locally amplified in the epicontinental sea covering Scandinavia, likely due to uplift of the outer margins of Baltica, creating silled basin conditions. Coinciding with onset of the SPICE-event at the base of the Furongian (Fig. 6; Ahlberg *et al*. 2009; Hammer & Svensen 2017), the oxygen deficiency was intensified in the Alum Shale sea until even the distal inner shelf bottom environment became dysoxic (Nielsen & Schovsbo 2015). The cause is uncertain, but the intensified low-oxygen conditions may to some extent have been triggered by the lower sea level in the early Furongian hampering exchange of water masses across the submarine sills fringing Baltica. Whatever the case may be, a strong enrichment of trace elements is seen in the Alum Shale from the early Furongian onwards, including uranium enrichment, and the GR intensity steadily increases through the *Olenus* Superzone to culminate in the OTGS marker horizon. Above this level, the GR intensity overall remains high throughout the Furongian but exhibits numerous fluctuations, creating a unique GR log pattern. The PGS marker in the *Peltura* Superzone signals maximum radiation levels. The reason(s) for the many fluctuations remains to be studied, but sea-level variations are undoubtedly an important controlling factor via the influence on sedimentary influx/condensation, storm-wave erosion and oxygen level at the seafloor (decreasing with depth); sea-level stand may also have regulated water exchange across the sills, thus affecting the general oxygen level in the basin as speculated above.

The GR intensity is closely linked to the uranium concentration in the Alum Shale which in turn is broadly linked to the TOC content (Fig. 5). Hence, the upwards fall in GR intensity above the PGS marker may signal gradually improved ventilation of the bottom environment, with reduced preservation of organic matter. This scenario is corroborated by the rarity of calcite-shelled fossils, notably trilobites, in the upper part of the *Acerocarina* Superzone as well as in the Tremadocian interval, which is ascribed to early dissolution of the skeletons in the near-surface sediment due to periodic oxygenation of pyrite (see Schovsbo 2001 for details). In effect, mainly the insoluble organic-walled graptolites and phosphatic brachiopods are preserved. Eventually the western margin of Baltica subsided in the late Tremadocian, restoring normal oxygen conditions in the Scandinavian epicontinental sea and terminating deposition of the Alum Shale (Nielsen & Schovsbo 2015).

Isostasy

The Miaolingian *Paradoxides paradoxissimus* Superzone is stratigraphically incomplete on Bornholm and very strongly condensed in comparison with Skåne (Fig. 17A; Table 3 vs. Table 4). We ascribe this to isostatic uplift of Bornholm that commenced in the latest 'early' Cambrian (Cambrian series 2), associated with the so-called Hawke Bay Event (Nielsen & Schovsbo 2015). We envisage that the uplift was a gentle broad crest aligned with the southern margin of Baltica, originally elevated some 150 m relative to the pre-uplift situation (Nielsen & Schovsbo 2015, fig. 56). The flanks of the crest were sloping merely ~2 m per kilometre northwards and southwards, and the submarine sill was by no means a prominent topographical feature in the seascape. Nonetheless, it had a marked influence on deposition due to the exceptional general flatness of the seafloor and the overall strong clastic starvation of the epicontinental sea. The Hawke Bay uplift was initially accompanied by minor erosion that removed the uppermost lower Cambrian on Bornholm (for details, see Nielsen & Schovsbo 2011, 2015), but shortly into the Miaolingian the area appears to have been inundated again, despite the uplift, and then became characterised by sedimentary bypass. The renewed flooding was due to a combination of subsidence and a strongly rising sea level (Nielsen & Schovsbo 2015, fig. 56).

In addition to the missing upper 'lower' Cambrian and condensed Miaolingian strata on Bornholm, the outlined uplift scenario is corroborated by palaeontological evidence. The Miaolingian *Acidusus atavus* fauna described from Bornholm by Weidner & Nielsen (2014) contains a significantly higher percentage of polymerid 'normal' trilobites than the coeval strata in Skåne. Several of these 'normal' trilobite species are otherwise unknown from the Scandinavian Alum Shale Formation. This is clearly suggestive of a relatively well oxygenated local bottom environment, supporting the notion of a shallower position of Bornholm on the shelf relative to Skåne.

Due to the uplift, initial deposition in the Miaolingian consisted exclusively of autochthonous bioclastic limestone, formed by disintegrated calcite skeletons of the local shelly fauna. These limestone 'events' (Forsemölla, Exsulans and 'Atavus' Limestone Beds, but also the later Hyolithes and Andrarum Limestone Beds, see Fig. 3) record major sea-level lowstands that allowed a rich shelly fauna to temporarily invade the normally rather inhospitable oxygen-deficient Alum Shale seafloor. In detail, deposition took place during earliest sea-level rise after maximum lowstand; for more detailed remarks on these 'transgressive' limestones, see Nielsen & Schovsbo (2015, pp. 297–299). Eventually, deposition of Alum Shale facies began on Bornholm in the late part of the *A. atavus* Chron (Fig. 3). Nielsen & Schovsbo (2015) inferred that the recommencement of clastic sedimentation was due to a combination of sea-level rise and some measure of subsidence of the Bornholm area in the aftermath of the Hawke Bay uplift. However, it is inferred that Bornholm remained uplifted relative to Skåne all through to the Late Ordovician. As a result of the slightly higher topographical position of Bornholm on the shelf, erosion associated with the major sea-level lowstands that took place prior to deposition of the Hyolithes and the Andrarum Limestone Beds was intensive and removed most of the *Ptychagnostus punctuosus* Zone and virtually all of the *Goniagnostus nathorsti* Zone. The latter is represented only by a mixed lag deposit incorporated into the Hyolithes Limestone (Fig. 3). These erosive events in combination with the uplifted state of Bornholm are suggested to be the main reason for the variable but overall insignificant thickness of the *Paradoxides paradoxissimus* Superzone on the island (Table 4), as the Alum Shale mud was readily winnowed and removed as a result of the lowered storm wave base during sea-level lowstands.

As can be seen from Figs 16 and 17 (and Table 4), the stratigraphic interval between the Andrarum Limestone Bed and the *Parabolina* Superzone is fairly uniformly developed across southern Bornholm. The *Agnostus pisiformis* Zone is also nearly of the same thickness as in south-eastern Skåne, locally even thicker (Bu-1, Table 4 vs. Table 3). This is suggestive of isostatic quiescence during this interval (Fig. 17A) after significant subsidence of the area. At the same time, the sea level rose strongly and reached a Cambrian maximum during the *A. pisiformis* Chron, at which stage deposition of Alum Shale facies reached as far east as Gotland (Ahlberg 1989). For these reasons, the seafloor in the Bornholm area came well out of reach of storm waves and no recycling of mud occurred.

The Furongian is reduced in thickness on Bornholm relative to Skåne, with condensation slowly commencing in the *Olenus* and *Parabolina* Superchrons, accelerating in the *Leptoplastus* Superchron and culminating in the *Protopeltura* and *Peltura* Superchrons (Fig. 17A). This is taken to indicate a new phase of mild isostatic uplift of the southern margin of Baltica, but maybe the slightly lower general sea level during the Furongian relative to the late Miaolingian highstand also played a part, as storm-driven winnowing may have removed mud during intermittent lowstand intervals. This is a plausible explanation for the absence on Bornholm of biozones in the basal *Leptoplastus* and uppermost *Peltura* Superzones (Fig. 3), as these zones are known only from deep outer shelf sites (Skåne and the Oslo region, see Martinsson 1974, fig. 5). The thinning of the lower part of the *Parabolina* Superzone from Sk-2 to So-1 may also relate to erosion or at least non-deposition during a transient sea-level lowstand (the *Parabolina brevispina* Zone is likewise developed only in marginal offshore facies of the Alum Shale, suggestive of a generally low sea level in the early *Parabolina* Superchron, cf. Martinsson 1974, fig. 5). This interpretation entails 1) that Bornholm was located higher on the shelf than Skåne during the Furongian and 2) that there must have been a slight difference in topographic elevation between the Læså and Øleå areas, and this also fits well with the general thinning of the *Protopeltura*, *Peltura* and *Acerocarina* Superzones towards south-east on Bornholm (Fig. 16, Table 4). Every Furongian superzone is thus as thick or thicker in the Bu-1, Sk-1 and Sk-2 wells compared with the four other wells treated here, and the thinning takes place across a distance of only a few kilometres (Fig. 16). We ascribe this to rejuvenation of gentle isostatic uplift of the southern margin of Baltica during the Furongian (Fig. 17). The isostatic adjustments may be part of more widespread tectonic disturbances in Scandinavia at this time. The largest of the spectacular 'subsidence cones' in the lower Cambrian Hardeberga Formation, developed at many sites in south-eastern Skåne, thus has a core of disturbed Alum Shale (youngest preserved level: *Olenus truncatus* Zone), suggestive of Furongian earthquake activity (see Lindström 1967 for details). The 'subsidence cones' are associated with fractures striking WNW–ESE, an orientation essentially parallel with the southern margin of Baltica. Likewise, the youngest trilobites found in Alum Shale filled fissures in the basement in the Göteborg area are of early Furongian age (Martinsson 1968, Samuelson 1975). These fissures also strike WNW–ESE.

Within Baltica, the Ordovician Alum Shale has its thickest development in south-eastern Skåne and the Tremadocian is here four times thicker than in the Læså area of Bornholm (Tables 3 and 4). This is suggestive of local subsidence of south-eastern Skåne during the earliest Tremadocian. However, both south-eastern Skåne and Bornholm were uplifted later in the Tremadocian as the *Bryograptus* Zone is very thin or truncated in both areas and even the

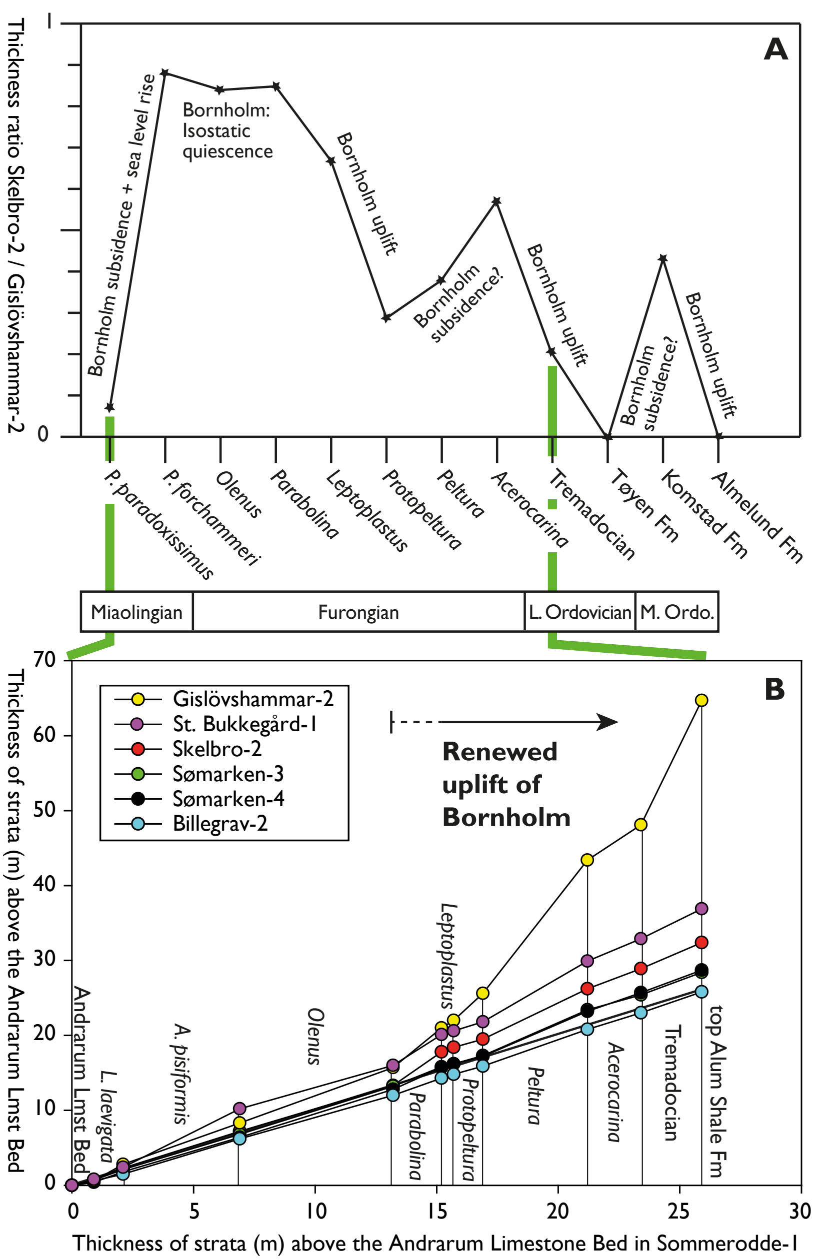

Fig. 17. Summary figure illustrating the isostatic movements of the Bornholm area through time. The plots are based on the thicknesses listed in Tables 3 and 4. **A**: Comparison of thicknesses in the Skelbro-2 and Gislövshammar-2 wells, revealing periods of uplift and subsidence of Bornholm relative to Skåne. The Almelund Formation is known from the Killeröd area (see Nielsen 1995 for references; in that paper the unit is referred to as the Upper Didymograptus Shale). **B**: Comparison of thicknesses between wells on Bornholm and Gislövshammar-2 in Skåne, relative to the succession in the Sommerodde-1 well. It is obvious that in the later part of the Furongian Skåne subsided more than Bornholm did. Sømarken-3 and -4 overlap and Sommerodde-1 and Billegrav-2 overlap, so that only Sømarken-4 and Billegrav-2 are visible on the figure.

Bjørkåsholmen Formation is locally absent in south-eastern Skåne (as on Bornholm). From then on, the Bornholm area appears to have been more extensively uplifted until the Late Ordovician and characterised by clastic by-pass, although the local presence of a thin veneer of Tøyen Formation in the Bi-2 well (and maybe also the Sø-3 and Sø-4 wells) indicates that the uplift history may be more complicated with periods of deposition alternating with periods of erosion (Fig. 17A). The sedimentary break is also interrupted by the Middle Ordovician Komstad Limestone that denotes a 2nd order sea-level lowstand (see Nielsen 1995, 2004) with increased ventilation of the seafloor, so that a shelly fauna could thrive and produce an autochthonous bioclastic limestone – as periodically in the Miaolingian (see above). However, deposition of the Komstad Limestone conceivably also reflects a transient subsidence of the Bornholm area (Fig. 17A). We note that limestone deposition here started earlier than in Skåne, again corroborating a higher position of Bornholm on the shelf, and the Komstad Limestone is also significantly thinner than in Skåne (Nielsen 1995). To complicate matters further regarding interpretation of the Komstad Limestone, climatic changes may also have favoured more prolific limestone formation during the Ordovician (C.M.Ø. Rasmussen *et al*. 2016 and references therein).

A Mid Ordovician phase of uplift after deposition of the Komstad Limestone was associated with increasing erosion of the unit in a south-eastwards direction on Bornholm; only the basal conglomerate is preserved in the Bi-2 well and the limestone is much thinner in all wells in the Øleå area compared with the Læså area. This uplift extended far into Skåne (Nielsen 1995, fig. 42) and seems to have been a quite prominent event only surpassed in magnitude by the terminal 'early' Cambrian Hawke Bay Event. The Komstad Limestone is everywhere on Bornholm overlain by Ordovician strata of Late Ordovician (Sandbian) age, and the extensive hiatus is indicative of a long period of uplift (~10 myr).

The general uplift of Bornholm from the latest early Cambrian to the Late Ordovician is the reason why the Miaolingian to Ordovician succession on the island is strongly condensed and stratigraphically incomplete relative to Skåne (Nielsen 1995, figs 41–42). The Alum Shale Formation is also comparatively thin in the German offshore well G-14 (Piske & Neumann 1993; Franke *et al*. 1994) and the Slagelse-1 well on Sjælland (Poulsen 1974), measuring, respectively, 32.3 m and 29 m in total, and the Ordovician is also thin in these wells (for location, see Fig. 1). This is taken to suggest that the uplift extended westwards from Bornholm along the southern margin of Baltica (see also Buchardt *et al*. 1997, fig. 7).

The recurrent isostatic adjustments of the southern margin of Baltica are surmised to have been triggered by stress changes related to contemporaneous plate tectonic processes in the adjacent Tornquist Sea (Nielsen & Schovsbo 2015).

The new data corroborate the suggestion of Nielsen (1995) and Nielsen & Schovsbo (2015) that the southern plate edge of Baltica was subjected to uplift through much of the Miaolingian, Furongian and Ordovician, eventually ending with the formation of a Caledonian foreland basin in the early Silurian (or latest Ordovician) involving major downwarp of the southern margin of the continent.

Conclusions

The Scandinavian Alum Shale Formation has a unique and highly characteristic GR log motif due to its generally very high but variable uranium content. Wireline GR logs obtained in boreholes are therefore extremely useful for correlation of the 'hot' formation locally as well as regionally. The present study has established a correlation of wells on Bornholm, Denmark, with the type section in south-eastern Skåne, Sweden.

The Miaolingian interval on Bornholm is characterised by relatively low GR radiation. Fluctuations are insignificant except for the ≤ 1 m thick amalgamated Hyolithes + Andrarum Limestone Beds that create a distinct GR low (the Andrarum Limestone Gamma Low, AGL), which is a fixed point for correlation. A conspicuous drop in GR intensity (the Base Furongian Gamma Low, BFGL) marks the Miaolingian/Furongian boundary. From this level upwards, the GR intensity increases very significantly, reaching a first high in the upper part of the *Olenus* Superzone (*Olenus* Triple Gamma Spike, OTGS). A second and even more prominent high, the *Peltura* Gamma Spike (PGS), is seen in the lower part of the *Peltura* Superzone. Above the PGS, the gamma radiation decreases slightly in the upper part of the *Peltura* Superzone and more strongly so in the *Acerocarina* Superzone. The general GR level of the Tremadocian is even lower, although not as low as in the Miaolingian. The upwards decrease in GR intensity reflects a lower TOC content that, in turn, probably signals an increasing oxygen concentration in the latest Furongian to Early Ordovician depositional environment.

The general thinning of the Alum Shale Formation from Skåne to Bornholm is inferred related to isostatic uplift of the southern margin of Baltica, which commenced in the latest 'early' Cambrian (Hawke Bay Event). The slow recommencement of sedimentation in the mid Miaolingian is taken to reflect a rise in sea level combined with some measure of subsidence of the Bornholm area, which still was within reach of storm-wave reworking during sea-level lowstand events. As a result the local succession is very thin and stratigraphically incomplete. The late Miaolingian was a period of isostatic quiescence and high sea level without interludes of reworking, and shale of this age is uniformly distributed across southern Bornholm. The interval has, broadly speaking, the same thickness as in south-eastern Skåne. From the *Olenus* Superzone upwards, an increasing condensation of the succession is observed on Bornholm relative to Skåne. Within Bornholm, the Furongian strata are also consistently thicker in the Læså area compared with the Øleå area. This is suggestive of a Furongian phase of mild uplift of the southern margin of Baltica. Renewed uplift of the Bornholm area including parts of south-eastern Skåne also seems to have taken place in the late Tremadocian. The discovery of a thin Tøyen Formation in the Bi-2 core above the Alum Shale Formation indicates that yet another subsidence/uplift event took place in the late Early Ordovician prior to deposition of the Komstad Limestone, which started in the earliest Mid Ordovician. This longer-lasting depositional phase probably reflects a transient subsidence of the Bornholm area coinciding with a major sea-level lowstand, shifting (autochthonous) limestone deposition down-slope.

The recurrent small-scale isostatic adjustments probably relate to stress changes associated with ongoing plate tectonic processes in the adjacent Tornquist Sea, which was under closure.

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References

Ahlberg, P. 1989: Cambrian stratigraphy of the När 1 deep well, Gotland. Geologiska Föreningens i Stockholm Förhandlingar 111, 137–148.

Ahlberg, P. & Terfelt, F. 2012: Furongian (Cambrian) agnostoids of Scandinavia and their implications for intercontinental correlation. Geological Magazine 149, 1001–1012.

Ahlberg, P., Månsson, K., Clarkson, E.N.K. & Taylor, C.M. 2006: Faunal turnovers and trilobite morphologies in the upper Cambrian *Leptoplastus* Zone at Andrarum, southern Sweden. Lethaia 39, 97–110.

Ahlberg, P., Axheimer, N., Babcock, L.E., Eriksson, M.E., Schmitz, B. & Terfelt, F. 2009: Cambrian high-resolution biostratigraphy and carbon isotope chemostratigraphy in Scania, Sweden: first record of the SPICE and DICE excursions in Scandinavia. Lethaia 42, 2–16.

Andersson, A., Dahlman, B., Gee, D.G. & Snäll, S. 1985: The Scandinavian Alum Shales. Sveriges Geologiska Undersökning Serie Ca 56, 1–50.

Armands, G. 1972: Geochemical studies of uranium, molybdenum and vanadium in a Swedish alum shale. Stockholm Contributions in Geology XXVII, 1–148.

Axheimer, N., Eriksson, M.E., Ahlberg, P. & Bengtsson, A. 2006: The middle Cambrian cosmopolitan key species *Lejopyge laevigata* and its biozone: new data from Sweden. Geological Magazine 143, 447–455.

Baumann-Wilke, M., Bauer, K., Schovsbo, N.H. & Stiller, M. 2012: P-wave traveltime tomography for a seismic characterization of black shales at shallow depth on Bornholm, Denmark. Geophysics 77, 53–60.

Berg-Madsen, V. 1985a: The Middle Cambrian of Bornholm, Denmark: A stratigraphical revision of the lower alum shale and associated anthraconites. *Geologiska Föreningens i Stockholm* Förhandlingar 106 (for 1984), 357–376.

Berg-Madsen, V. 1985b: A review of the Andrarum Limestone and the upper alum shale (Middle Cambrian) of Bornholm, Denmark. Bulletin of the Geological Society of Denmark 34, 133–143.

Berg-Madsen, V. 1986: Oversigt over det reviderede Mellem Kambrium på Bornholm. Dansk Geologisk Forening, Årsskrift for 1985, 1–13.

Bjerager, M., Kjøller, C., Olivarius, M., Olsen, D., Schovsbo, N.H. in press: Sedimentology, geochemistry and reservoir properties of Upper Jurassic deep marine sandstones (Hareelv Formation) in the Blokelv-1 borehole, Jameson Land Basin, East Greenland. Geological Survey of Denmark and Greenland Bulletin 42.

Bruton, D.L., Erdtmann, B.-D. & Koch, L. 1982: The Nærsnes section, Oslo Region, Norway: a candidate for the Cambrian – Ordovician boundary stratotype at the base of the Tremadoc Series. In: Bassett, M.G. & Dean, W.T. (eds), The Cambrian–Ordovician boundary: Sections, Fossil Distributions and Correlations. National Museum of Wales, Geological Series 3, 61–69.

Bruton, D.L., Koch, L. & Repetski, J.E. 1988: The Nærsnes section, Oslo Region, Norway: trilobite, graptolite and conodont fossils reviewed. Geological Magazine 125, 451–455.

Buchardt, B. & Nielsen, A.T. 1985: Carbon and oxygen isotope composition of Cambro-Silurian limestone and antraconite from Bornholm: evidence for deep burial diagenesis. Bulletin of the Geological Society of Denmark 33, 415–435.

Buchardt, B., Clausen, J. & Thomsen, E. 1986: Carbon isotope composition of Lower Palaeozoic kerogen: Effect of maturation. Organic Geochemistry 10, 127–134.

Buchardt, B., Nielsen, A.T. & Schovsbo, N.H. 1997: Alun skiferen i Skandinavien. Geologisk Tidsskrift 3, 1–30.

Bulman, O.M.B. 1954: The graptolite fauna of the *Dictyonema* Shales of the Oslo region. Norsk Geologisk Tidsskrift 33, 1–40.

Callisen, K. 1914: Tenformede Tungspatkrystaller ("Pseudo-Gaylussit" og "Pseudo-Pirssonit") i Alunskiferen. Meddelelser fra Dansk Geologisk Forening 4, 245–258.

Clarkson, E.N.K. 2011: The life and times of the olenid trilobites. Geologické výzkumy na Moravě a ve Slezsku 18, 11–17.

Clarkson, E.N.K. & Taylor, C.M. 1995: The lost world of the olenid trilobites. Geology Today 11, 147–154.

Cooper, R.A. 1999: Ecostratigraphy, zonation and global correlation of earliest Ordovician planktic graptolites. Lethaia 32, 1–14.

Egenhoff, S., Fishman, N.S., Ahlberg, P. & Petrowsky, M. 2015: Sedimentology of SPICE (Steptoean positive carbon isotope excursion): A high-resolution trace fossil and microfabric analysis of the middle to late Cambrian Alum Shale formation, southern Sweden. Special paper of the Geological Society of America 515, 87–102.

Ellis, D.V. & Singer, J.M. 2007: Well logging for earth scientists. 2nd edition. Springer, Dordrecht, the Netherlands, 687 pp.

Ericsson, M. 2012: Stratigraphy, facies and depositional history of the Colonus Shale Trough, Skåne, southern Sweden. Dissertation in Geology at Lund University, master thesis 310, 40 pp. Department of Geology, Lund University.

Franke, D., Gründel, J., Lindert, W., Meissner, B., Schyultz, E. & Zagora, I. 1994: Die Ostseebohrung G 14 – eine Profilübersicht. Zeitschrift für Geologische Wissenschaften 22, 235–240.

Gautier, D.L., Schovsbo, N.H., Nielsen, A.T. 2014: Resource potential of the Alum Shale in Denmark. Unconventional Resources Technology Conference (URTeC). SPE-2014-1931754-MS. DOI 10.15530/urtec-2014-1931754.

Gill, B.C., Lyons, T.W., Young, S.A., Kump, L.R., Knoll, A.H. & Saltzman, M.R. 2011: Geochemical evidence for widespread euxinia in the Later Cambrian ocean. Nature 469, 80–83.

Graversen, O. 2009: Structural analysis of superposed fault systems of the Bornholm horst block, Tornquist Zone, Denmark. Bulletin of the Geological Society of Denmark 57, 24–49.

Grönwall, K.A. 1899: Bemærkninger om de sedimentære dannelser på Bornholm og deres tektoniske forhold. Danmarks Geologiske Undersøgelse, II. række 10, 1–52.

Grönwall, K.A. 1902: Bornholms Paradoxideslag og deres fauna. Danmarks Geologiske Undersøgelse, II. række 13, 1–250.

Grönwall, K.A. 1916: Palæozoiske Dannelser. In Grönwall, K.A. & Milthers, V.: Beskrivelse til Geologisk Kort over Danmark. Kortbladet Bornholm. Danmarks Geologiske Undersøgelse, I. Række 13, 43–86.

Hammer, Ø. & Svensen, H.H. 2017: Biostratigraphy and carbon and nitrogen geochemistry of the SPICE event in Cambrian low-grade metamorphic black shale, Southern Norway. Palaeogeography, Palaeoclimatology, Palaeoecology 468, 216–227.

Hansen, K. 1945: The Middle and Upper Cambrian sedimentary rocks of Bornholm. Danmarks Geologiske Undersøgelse, II. række 72, 1–81.

Henningsmoen, G. 1957: The trilobite family Olenidae with description of Norwegian material and remarks on the Olenid and Tremadocian Series. Skrifter utgitt av Det Norske Videnskaps-Akademi i Oslo. I. Matematisk-Naturvitenskapelige Klasse 1, 1–303.

Hessland, I. & Armands, G. 1978: Alunskiffer: underlagsmaterial, geologi. SIND, vol. 3, 1–146. Utredning från statens industriverk, Stockholm.

Hints, R., Soesoo, A., Voolma, M., Tarros, S., Kallaste, T. & Hade, S. 2014: Centimetre-scale variability of redox-sensitive elements in Tremadocian black shales from the eastern Baltic Palaeobasin. Estonian Journal of Earth Sciences 63, 233–239.

Høyberget, M. & Bruton, D.L. 2012: Revision of the trilobite genus *Sphaerophthalmus* and relatives from the Furongian (Cambrian) Alum Shale Formation, Oslo Region, Norway. Norwegian Journal of Geology 92, 433–450.

Johnstrup, F. 1874: Oversigt over de palæozoiske Dannelser paa Bornholm. Beretning 11'te skandinaviske Naturforskermøde i Kjøbenhavn 1873, 1–10.

Lauridsen, B.W. & Nielsen, A.T. 2005: The Upper Cambrian Trilobite *Olenus* at Andrarum, Sweden: a case of iterative evolution? Palaeontology 48, 1041–1056.

Lecomte, A., Cathelineau, M., Michels, R., Peiffert, C. & Brouand, M. 2017: Uranium mineralization in the Alum Shale Formation (Sweden): evolution of a U-rich marine black shale from sedimentation to metamorphism, Ore Geology Reviews. doi: http://dx.doi.org/10.1016/j.oregeorev.2017.04.021.

Leventhal, J.S. 1991: Comparison of organic geochemistry and metal enrichment in two black shales: Cambrian alum shale of Sweden and Devonian Chattanooga shale of United States. Mineralium Deposita 26, 104–112.

Lindström, M. 1967: "Funnel Grabens" and Early Paleozoic Tectonism in South Sweden. Geological Society of America Bulletin 78, 1137–1154.

Lindström, M. 1971: Vom Anfang, Hochstand und Ende eines Epikontinentalmeeres. Geologische Rundschau 60, 419–438.

Maletz, J. & Erdtmann, B.-D. 1987: *Adelograptus tenellus* (Linnarsson 1871): its astogenetic development and its stratigraphical and palaeogeographical distribution. Bulletin of the Geological Society of Denmark 35, 179–190.

Maletz, J., Egenhoff S. & Alonso, R. 2010: The Upper Tremadocian (Ordovician) graptolite *Bryograptus*: taxonomy, biostratigraphy and biogeography. Palaeontology 53, 59–75.

Martinsson, A. 1968: Cambrian palaeontology of Fennoscandian basement fissures. Lethaia 1, 137–155.

Martinsson, A. 1974: The Cambrian of Norden. In: Holland, C.H. (ed.), Lower Palaeozoic Rocks of the World. 2. Cambrian of the British Isles, Norden, and Spitsbergen, 185–283. London: John Wiley & Sons.

Michelsen, O. & Nielsen, L.H. 1991: Well records on the Phanerozoic stratigraphy in the Fennoscandian Border Zone, Denmark. Hans-1, Sæby-1, and Terne-1 wells. Danmarks Geologiske Undersøgelse Serie A 29, 1–37.

Moberg, J.C. 1898: En triolobit från Skånes Dictyograptusskiffer. Geologiska Föreningens i Stockholm Förhandlingar 20, 317–324.

Nielsen, A.T. 1995: Trilobite systematics, biostratigraphy and palaeoecology of the Lower Ordovician Komstad Limestone and Huk Formations, southern Scandinavia. Fossils & Strata 38, 1–374.

Nielsen, A.T. 2004: Ordovician sea level changes: A Baltoscandian perspective. In: Webby, B.D., Paris, F., Droser, M.L. & Percival, L.G. (eds.), the Great Ordovician Biodiversification Event, 84–93. Columbia University Press.

Nielsen, A.T. & Buchardt, B. 1994: Gislövshammar-2 shallow drill-hole in eastern Scania, Sweden: stratigraphy and geochemistry of the cored Lower Ordovician – Lower Cambrian strata. Unpublished Final report II, Pre-Westphalian Source Rocks in northern Europe, 1–30. Geological Institute, University of Copenhagen, Denmark.

Nielsen, A.T. & Schovsbo, N.H. 2007: Cambrian to basal Ordovician lithostratigraphy in southern Scandinavia. Bulletin of the Geological Society of Denmark 53, 47–92.

Nielsen, A.T. & Schovsbo, N.H. 2011: The Lower Cambrian of Scandinavia: depositional environment, sequence stratigraphy and palaeogeography**.** Earth-Science Reviews 107, 207–310.

Nielsen, A.T. & Schovsbo, N.H. 2015: The regressive Early–Mid Cambrian 'Hawke Bay Event' in Baltoscandia: Epeirogenic uplift in concert with eustasy. Earth-Science Reviews 151, 288–350.

Nielsen, A.T., Weidner, T., Terfelt, F. & Høyberget, M. 2014: Upper Cambrian (Furongian) biostratigraphy in Scandinavia revisited: definition of superzones. GFF 136**,** 193–197.

Nikolaisen, F. & Henningsmoen, G. 1985: Upper Cambrian and lower Tremadoc olenid trilobites from the Digermul peninula, Finnmark, northern Norway. Norges geologiske undersøkelse Bulletin 400, 1–49.

Owen, A.W., Bruton, D.L., Bockelie, J.F. & Bockelie, T. 1990: The Ordovician successions of the Oslo Region, Norway. Norges geologiske undersøkelse, Special Publication 4, 3–54.

Pedersen, G.K. 1989: The sedimentology of Lower Palaeozoic black shales from the shallow wells Skelbro 1 and Billegrav 1, Bornholm, Denmark. Bulletin of the Geological Society of Denmark 37, 151–173.

Pedersen, G.K. & Klitten, K. 1990: Anvendelse af gamma-logs ved korrelation af marine skifre i vandforsyningsboringer på Bornholm. Dansk Geologisk Forening Årsskrift 1987–89, 21–35.

Peng, S.C., Babcock, L.E., Robison, R.A., Lin, H.L., Rees, M.N. & Saltzman, M.R. 2004: Global Standard Stratotype-section and Point (GSSP) of the Furongian Series and Paibian Stage (Cambrian). Lethaia 37, 365–379.

Peng, S.C., Babcock, L.E. & Cooper, R.A. 2012: The Cambrian Period. In: Gradstein, M., Ogg, J.G., Schmitz, M.D. & Ogg G.M. (eds), The Geologic Time Scale 2012, 437–488. Elsevier.

Petersen, H.I., Schovsbo, N.H. & Nielsen, A.T. 2013: Reflectance measurements of zooclasts and solid bitumen in Lower Paleozoic shales, southern Scandinavia: Correlation to vitrinite reflectance.International Journal of Coal Geology 114, 1–18.

Piske, J. & Neumann, E. 1993: Tektonische Gliederung des praevariszischen Untergrundes in der suedwestlichen Ostsee. Geologisches Jahrbuch Reihe A-H 131, 361–388.

Poulsen, C. 1922: Om Dictyograptusskiferen på Bornholm. Danmarks geologiske Undersøgelse, IV. Række 1, 1–28. (Also printed in Meddelelser fra Dansk Geologisk Forening 6:8).

Poulsen, C. 1923: Bornholms Olenuslag og deres Fauna. Danmarks geologiske Undersøgelse, II. række 40, 1–83.

Poulsen, C. 1974: Further Contributions to the Knowledge of the Palaeozoic of Slagelse No. 1, Western Sealand. Danmarks geologiske Undersøgelse, II. Række 101, 1–42.

Poulsen, V. 1966: Cambro–Silurian stratigraphy of Bornholm. Meddelelser fra Dansk Geologisk Forening (Bulletin of the Geological Society of Denmark) 16, 117–137.

Poulsen, V. 1978: *Dalmanitina* beds (late Ordovician) on Bornholm. Danmarks geologiske Undersøgelse, Årbog 1976, 53–87.

Rasmussen, B.W., Nielsen, A.T. & Schovsbo, N.H. 2015: Faunal succession in the upper Cambrian (Furongian) *Leptoplastus* Superzone at Slemmestad, southern Norway. Norsk Geologisk Tidsskrift 95, 1–22.

Rasmussen, B.W., Rasmussen, J.A. & Nielsen, A.T. 2016: Biozonation of the Furongian (upper Cambrian) Alum Shale Formation at Hunneberg, Sweden. GFF 138, 467–489.

Rasmussen, B.W., Rasmussen, J.A. & Nielsen, A.T. 2017: Biostratigraphy of the Furongian (upper Cambrian) Alum Shale Formation at Degerhamn, Öland, Sweden. GFF 139, 92–118.

Rasmussen, C.M.Ø., Ullmann, C.V., Jakobsen, K.G., Lindskog, A., Hansen, J., Hansen, T., Eriksson, M.E., Dronov, A., Frei, R., Korte, C., Nielsen, A.T. & Harper, D.A.T. 2016: Onset of the main Phanerozoic marine radiation sparked by emerging Mid Ordovician icehouse. Nature Scientific Reports 6, p. 18884, doi:10.1038/srep18884, 9 pp.

Saltzman, M.R., Runnegar, B. & Lohmann, K.C. 1998: Carbon isotope stratigraphy of Upper Cambrian (Steptoean Stage) sequences of the eastern Great Basin: Record of a global oceanographic event. Bulletin of the Geological Society of America 110, 285–297.

Samuelson, L. 1975: Palaeozoic fissure filling and tectonism of the Göteborg area, southwestern Sweden. Sveriges Geologiska Undersökning Serie C 711, 3–43.

Schovsbo, N.H. 2000: Environmental fluctuations in the *Olenus* Zone (Upper Cambrian), southern Scandinavia: A geochemical approach. Bulletin of the Geological Society of Denmark 47, 53–62.

Schovsbo, N.H. 2001: Why barren intervals? A taphonomic case study of the Scandinavian Alum Shale and its faunas. Lethaia 34, 271–285.

Schovsbo, N.H. 2002a: Uranium enrichment shorewards in black shales: A case study from the Scandinavian Alum Shale. GFF 124, 107–116.

Schovsbo, N.H. 2002b: Carbon isotope stratigraphy of Middle Cambrian to Lower Silurian shales from Baltoscandia: implications for presumed climatic stability. Geochimica et Cosmochimica Acta 66, p. A687.

Schovsbo, N.H. 2003: Geochemical composition and provenance of Lower Palaeozoic shales deposited at the margins of Baltica. Bulletin of the Geological Society of Denmark 50, 11–27.

Schovsbo, N.H. 2011: Completion report Billegrav-2 well (DGU 248.61), Part 1: Down-hole logs, core scanning data and core photos. Geological Survey of Denmark and Greenland Report 2011/53, 1–18.

Schovsbo, N.H. 2012: Completion report Billegrav-2 well (DGU 248.61) Part 3: Results of core plug analysis. Geological Survey of Denmark and Greenland Report 2012/16, 1–52.

Schovsbo, N.H., Nielsen, A.T., Klitten, K., Mathiesen, A. & Rasmussen, P. 2011: Shale gas investigations in Denmark: Lower Palaeozoic shales on Bornholm. Geological Survey of Denmark and Greenland Bulletin 23, 9–12.

Schovsbo, N.H., Esbensen, K.H., Nielsen, A.T., Derbez, E., Gaucher, E.C., Poirier-Coutansais, X., Riou, A., Tallone, P. & Milton-Taylor, D. 2015a: Rock types in the Scandinavian Alum Shale resource play: Definitions and predictions. 77th EAGE Conference & Exhibition 2015, IFEMA Madrid, Spain 1–4 June 2015. Extended abstract Th N101 13, 5 pp.

Schovsbo, N.H., Nielsen, A.T. & Klitten, K. 2015b: The Lower Palaeozoic now fully cored and logged on Bornholm, Denmark. Geological Survey of Denmark & Greenland Bulletin 33, 9–12.

Schovsbo, N.H., Nielsen, A.T. & Erlström, M. 2016: Middle–Upper Ordovician and Silurian stratigraphy and basin development in southernmost Scandinavia. Geological Survey of Denmark and Greenland Bulletin 35, 39–42.

Schovsbo, N.H., Nielsen A.T., Harstad, A.O. & Bruton D.L. 2018: Stratigraphy and geochemical composition of the Cambrian Alum Shale Formation in the Porsgrunn core, Skien-Langesund district, southern Norway. Bulletin of the Geological Society of Denmark 66, 1–20.

Spjeldnæs, N. 1963: Some upper Tremadocian graptolites from Norway. Palaeontology 6, 121–131.

Spjeldnæs, N. 1985: Excursion-Guide Oslo. Graptolite Working Group of the International Palaeontological Association, Copenhagen 1985, 13 pp.

Terfelt, F. 2006: Review of uppermost Furongian trilobites from Scania, southern Sweden, based on type material. Palaeontology 49, 1339–1355.

Terfelt, F., Eriksson, M.E., Ahlberg, P. & Babcock, L.E. 2008: Furongian Series (Cambrian) biostratigraphy of Scandinavia - a revision. Norsk Geologisk Tidsskrift 88, 73–87.

Terfelt, F., Ahlberg, P. & Eriksson, M.E. 2011: Complete record of Furongian polymerid trilobites and agnostoids of Scandinavia – a biostratigraphical scheme. Lethaia 44, 8–14.

Terfelt, F., Eriksson, M.E. & Schmitz, B. 2014: The Cambrian–Ordovician transition in dysoxic facies in Baltica – diverse faunas and carbon isotope anomalies. Palaeogeography, Palaeoclimatology, Palaeoecology 394, 59–73.

Tjernvik, T.E. 1958: The Tremadocian beds at Flagabro in south-eastern Scania (Sweden). Geologiska Föreningens i Stockholm Förhandlingar 80, 259–276.

von Jansson, C. 1979: Zur biostratigraphie des Tremadociums auf Bornholm, Dänemark. Unpublished diplom thesis, 51 pp. University of Hannover.

Warming, B., Buchardt, B., Nielsen, A.T., Pukkonen, E., Schovsbo, N.H. & Wilken, U.G. 1994: Geochemical database for Lower Palaeozoic rocks in Baltoscandia. Final report VI, Pre-Westphalian Source Rocks in northern Europe, 1–91. Geological Institute, University of Copenhagen, Denmark.

Weidner, T. & Nielsen, A.T. 2013: The late Cambrian (Furongian) *Acerocarina* Superzone (new name) on Kinnekulle, Västergötland, Sweden. GFF 135, 30–44.

Weidner, T. & Nielsen, A.T. 2014: A highly diverse trilobite fauna with Avalonian affinities from the Middle Cambrian *Acidusus atavus* Zone (Drumian Stage) of Bornholm, Denmark, Journal of Systematic Palaeontology 12, 23–92.

Westergård, A.H. 1909: Studier öfver Dictyograptusskiffern och dess gränslager. Lunds Universitets Årsskrift N.F. 2, 5(3), 1–79. (Also printed in Meddelande från Lunds Geologiska Fältklubb serie B 4).

Westergård, A.H. 1922: Sveriges Olenidskiffer. Sveriges Geologiska Undersökning Serie Ca 18, 1–205.

Westergård, A.H. 1942: Stratigraphic results of the borings through the Alum Shales of Scania made in 1941–1942. Lunds Geologiska Fältklubb 185, 1–20.

Westergård, A.H. 1944: Borrningar genom Skånes alunskiffer 1941– 42. Sveriges Geologiska Undersökning Serie C 459, 1–45.

Westergård, A.H. 1946: Agnostidea of the Middle Cambrian of Sweden. Sveriges Geologiska Undersökning Serie C 477, 1–140.

Westergård, A.H. 1947: Supplementary notes on the Upper Cambrian trilobites of Sweden. Sveriges Geologiska Undersökning Serie C 489, 1–34.

Westergård, A.H. 1948: Non-agnostidean trilobites of the Middle Cambrian of Sweden. I. Sveriges Geologiska Undersökning Serie C 498, 1–32.

Westergård, A.H. 1950: Non-agnostidean trilobites of the Middle Cambrian of Sweden. II. Sveriges Geologiska Undersökning Serie C 511, 1–56.

Westergård, A.H. 1953: Non-agnostidean trilobites of the Middle Cambrian of Sweden. III. Sveriges Geologiska Undersökning Serie C 526, 1–58.

Yuanlong, Z., Jinliang, Y., Babcock, L.E., Qingjun, G., Jin, P., Leiming, Y., Xinglian, Y., Chunjiang, W., Gaines, R.R., Esteve, J., Ruidong, Y., Yuning, Y., Haijing, S. & Tongsu, T., submitted: Proposed global standard stratotype-section and point for the base of the Miaolingian Series and Wuliuan Stage (Provisional Cambrian Series 3 and Stage 5). Submitted to the International Subcommission on Cambrian Stratigraphy. 51 pp.