BULLETIN OF THE GEOLOGICAL SOCIETY OF DENMARK · VOL. 72 · 2023

Wireline log stratigraphy of the lower Cambrian Læså Formation, Bornholm, Denmark

ARNE THORSHØJ NIELSEN & KURT KLITTEN

Geological Society of Denmark
https://2dgf.dk

Received 17 May 2023
Accepted in revised form
16 October 2023
Published online
27 November 2023

Nielsen, A.T. & Klitten, K. 2023. Wireline log stratigraphy of the lower Cambrian Læså Formation, Bornholm, Denmark. Bulletin of the Geological Society of Denmark, Vol. 72, pp. 175–205. ISSN 2245-7070.
https://doi.org/10.37570/bgsd-2023-72-07

A detailed correlation of the lower Cambrian Læså Formation on southern Bornholm, Denmark, is based on gamma ray and formation resistivity wireline logs from 25 water supply wells and 5 scientific boreholes. The interpretation hinges on comparison with the wireline log suite obtained in the fully cored Borggård-1 borehole that penetrated the formation in its entirety. The Norretorp Member, 102.9 m thick in Borggård-1, consists predominantly of intensively bioturbated siltstone. Several levels are strongly glauconitic and usually also contain phosphorite nodules. Fine-grained sandstone beds, 0.5–20 cm thick and interpreted as tempestites, occur throughout the unit; a few thicker sandstone layers consist of stacked tempestites. However, many sandstone beds, primarily in the upper 2/3 of the member, have been partly or totally obliterated by the pervasive bioturbation. The overlying Rispebjerg Member, 3.5 m thick in Borggård-1, is dominated by well-cemented medium to coarse-grained quartz sandstone. The variable lithology of the Læså Formation is illustrated by photos of core samples from Borggård-1.

The studied wells are located on different fault blocks with 18 km between the easternmost and westernmost well sites. The Norretorp Member is of almost similar thickness throughout the study area whereas the Rispebjerg Member is 2.2–5.6 m thick. The essentially unchanging thickness of the Læså Formation and the sheet-like distribution of tempestites demonstrate that the intense faulting of southern Bornholm post-dates deposition.

The Norretorp Member is divided into a lower log-unit (57 m thick in Borggård-1) characterized by a moderately variable gamma ray log pattern and an upper log-unit (46 m thick in Borggård-1) exhibiting a more uniform gamma radiation of overall lower intensity. The log-units reflect a more common occurrence of glauconite and phosphorite in the lower part of the member and a higher sand content in the upper part. These lithological differences are also reflected by a generally higher resistivity and P-wave velocity in the upper log-unit. Seven thicker sandstone horizons (15–80 cm thick), labelled S1 to S7, are laterally persistent within the Norretorp Member. Four additional horizons, referred to as MGL [multiple gamma low], MGH [multiple gamma high], MM [middle marker] and GH [gamma high], are also laterally widespread. A readily identifiable red-brown horizon is located at 4.4–5.9 m above the base of the Læså Formation in Borggård-1: it appears to be developed throughout the study area.

Keywords: Lower Cambrian, Læså Formation, wireline log correlation, Bornholm, Denmark.

Arne Thorshøj Nielsen [arnet@ign.ku.dk], Department of Geosciences and Natural Resource Management, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark. Kurt Klitten [kk@geus.dk], Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.

Lower Cambrian strata comprise much of the pre-Quaternary bedrock across southern Bornholm (Fig. 1). The local succession is *c.* 300 m thick and divided into the Nexø, Hardeberga and Læså formations (Fig. 2); for lithostratigraphic details, see Nielsen & Schovsbo (2007). Especially the sandstone-dominated Nexø and Hardeberga formations are important aquifers and many water supply wells have been drilled into these units. However, approximately 125 wells penetrate also parts of the overlying Læså Formation, the focus of this study, although this siltstone-dominated unit is less important for the local water supply as the produced water often contains much ochre and the yield is comparatively low. Most of the boreholes reaching the Læså Formation are shallow private water wells where wireline logs have not been acquired, wherefore it is impossible to undertake detailed intraformational correlation. Currently, wireline logs of different recording age are available from 30 wells penetrating various parts of the Læså Formation (Tables 1–2). All wells on Bornholm are registered in the JUPITER database hosted by the Geological Survey of Denmark and Greenland (henceforth GEUS), including information on whether wireline log data are available (https://www.geus.dk/produkter-ydelser-og-faciliteter/data-og-kort/national-boringsdatabase-jupiter/). Regarding lithostratigraphic records in the JUPITER database, it should be noted that the 'Green shales' (the traditional name for the Læså Formation) in many wells are registered as 'shale' or 'clay shale'.

The Læså Formation is subdivided into a lower Norretorp Member and an upper Rispebjerg Member (Fig. 2; see Nielsen & Schovsbo 2007 for details and older names). These subunits are, respectively, 102.9 m and 3.5 m thick in the fully cored Borggård-1 borehole (Fig. 3), which currently is the only complete section of the Læså Formation known from Bornholm (for location, see Fig. 1). The Norretorp Member consists of intensively bioturbated siltstone intercalated by common thin sandstone beds, whereas the overlying Rispebjerg Member chiefly consists of medium- to coarse grained well-cemented quartz sandstone. The Norretorp Member was described in some detail by Hansen (1936) and he enumerated 101 localities with

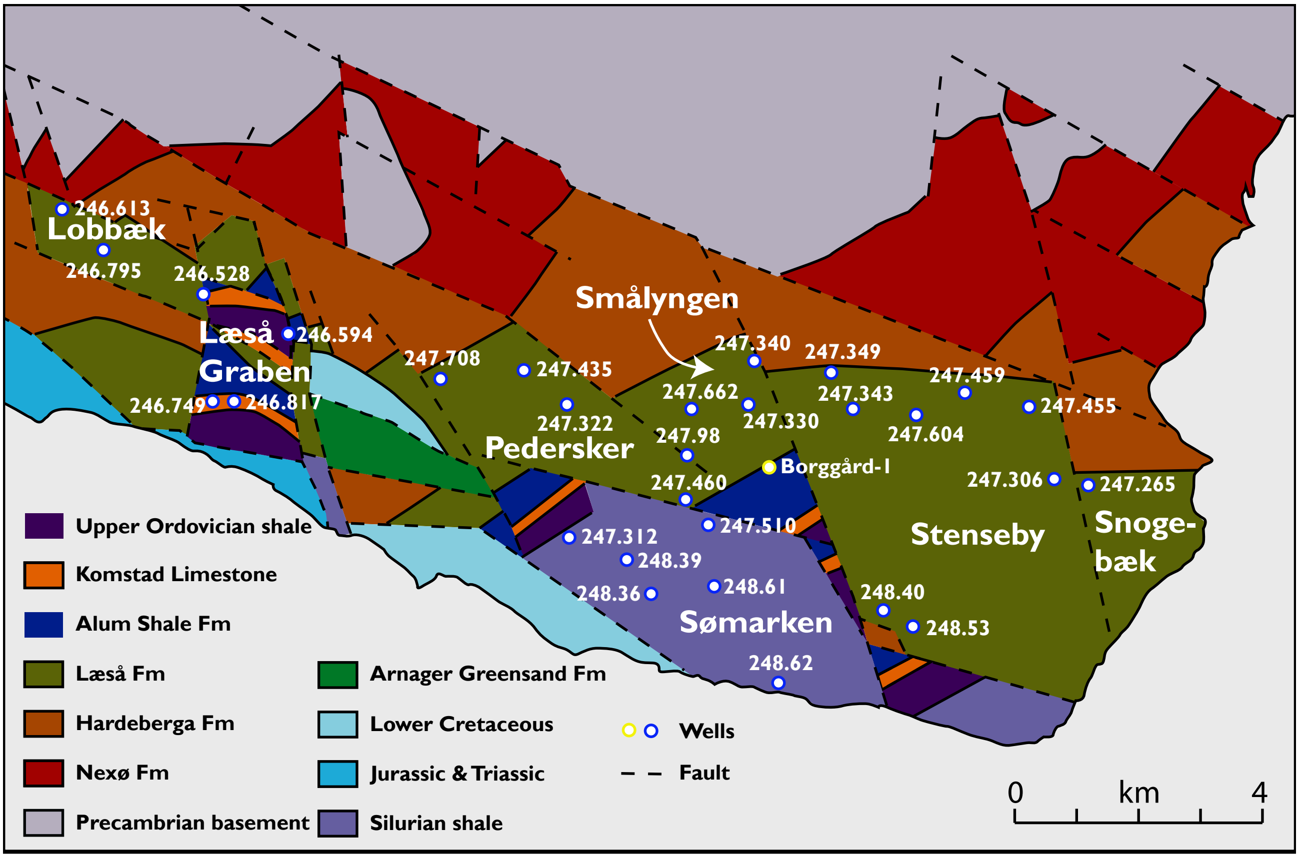


Fig. 1. Location of the studied wells. They are identified by their unique DGU well number; for exact locations, see the Jupiter database hosted by GEUS. The informal names of the tectonic blocks introduced here for easy reference are also shown: Lobbæk (note that well 246.528 probably is located within the Læså Graben, see text), Læså Graben, Pedersker, Smålyngen, Sømarken, Stenseby and Snogebæk. The slightly modified base map is adopted from Gry (1977) with some changes in the Pedersker–Smålyngen area based on unpublished revised mapping (ATN in prep.).

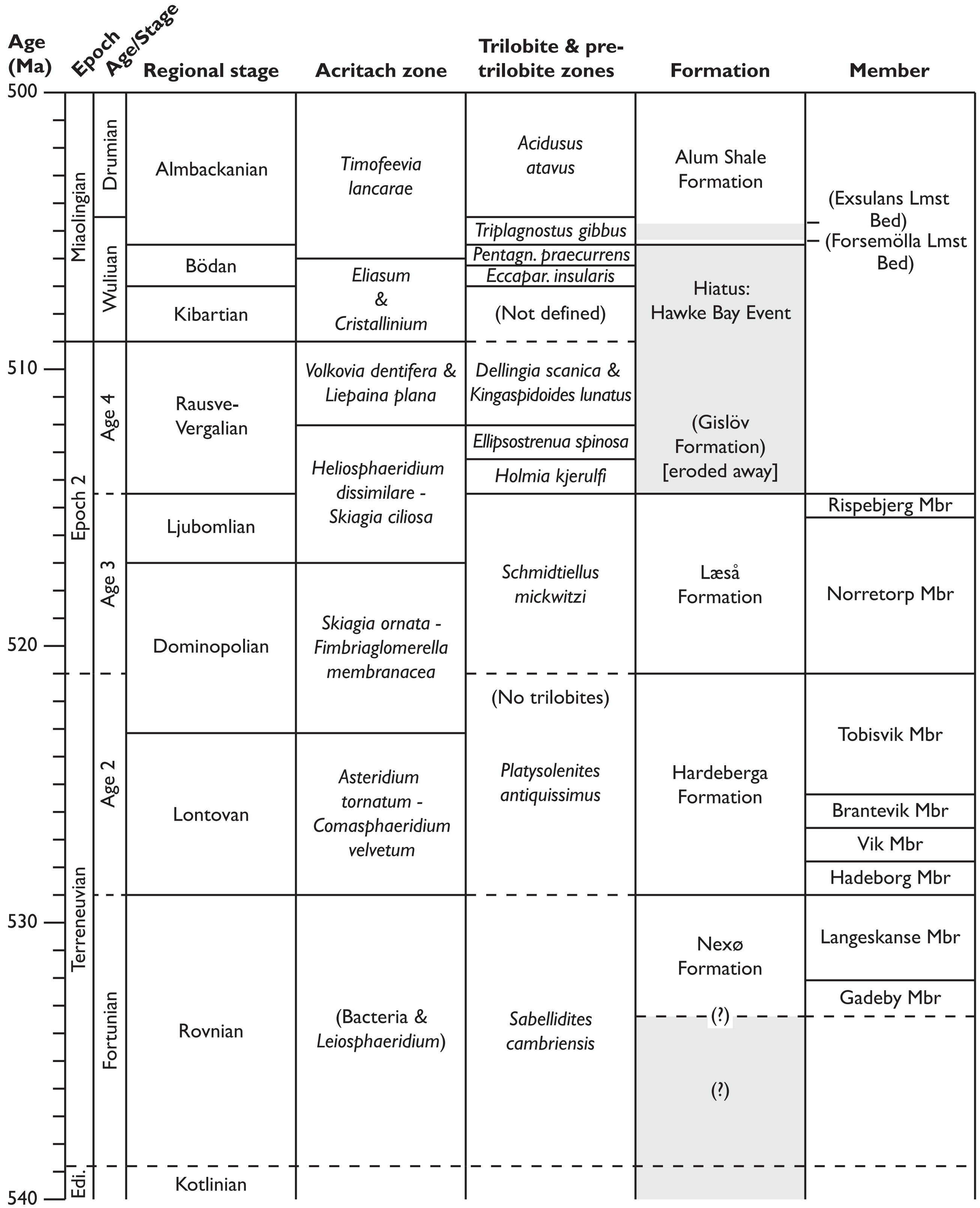


Fig. 2. Litho- and chronostratigraphy of the lower Cambrian on Bornholm. Based on Nielsen & Schovsbo (2007, 2011, 2015), Weidner & Nielsen (2014), Nielsen & Ahlberg (2019) and Cederström *et al.* (2022). Approximate ages are according to Peng *et al.* (2020). Hiatuses are marked by grey shading; for remarks on the Gislöv Formation, see text. Abbreviations: *Pentagn.* = *Pentagnostus*; *Eccapar.* = *Eccaparadoxides*.

'Green shales' on southern Bornholm and left another 30 sites unnumbered (Hansen 1936, pl. IX). The unit and to some extent its fossil content have since then been addressed by C. Poulsen (1967), Surlyk (1980), Clausen & Vilhjálmsson (1986), Moczydłowska & Vidal (1992), Nielsen & Schovsbo (2011) and Clemmensen *et al.* (2011). The lithostratigraphy and lithology of the 316 m deep Borggård-1 borehole are briefly summarized by Nielsen *et al*. (2006) and Nielsen & Schovsbo (2007, 2011).

The aim of the present paper is to correlate the Læså Formation in wells with wireline logs, based on comparison with the gamma ray and resistivity logs from Borggård-1, and to investigate the lateral variation of the formation across southern Bornholm, if any. Local differences in thickness on the different fault blocks would be indicative of active tectonism during deposition.

Geological setting

Baltica was located at high southerly latitudes during the Cambrian and characterized by a cool temperate climate with very limited deposition of carbonates (e.g. Torsvik *et al*. 1990; Torsvik & Rehnström 2001; Cocks & Torsvik 2005; Nielsen & Schovsbo 2011). The lower Cambrian succession of Bornholm (Fig. 2) records deposition during a gradually rising sea level (Nielsen & Schovsbo 2007, 2011). The lower part of the Nexø Formation, the Gadeby Member, was thus deposited in a fluvial environment punctuated by at least one short-lived marine incursion whereas the overlying Langeskanse Member was deposited under fluvially influenced shallow marine conditions. Fully marine conditions prevailed during deposition of the succeeding Hardeberga Formation, which is dominated by clean quartz sandstones, but also includes several metres thick mudstone intercalations deposited in mid shelf settings (Hadeborg and Brantevik members). With a sharp boundary, most likely an unconformity associated with a hiatus (Nielsen & Schovsbo 2011), follows the Læså Formation. A basal quartz conglomerate with glauconite and pebbles of black shales was reported by V. Poulsen (1966) and C. Poulsen (1967), but no such conglomerate is developed in the Borggård-1 core and no studies have reported it from outcrops on southern Bornholm (e.g. Grönwall 1916; Hansen 1936; Nielsen & Schovsbo 2011). The Norretorp Member records a marked deepening of the depositional environment although the area appears to have been continuously above storm wave-base throughout deposition. The sea level varied recurrently with a general upwards shallowing trend. Deepening events were associated with precipitation of glauconite and phosphorite, whereas shallowings were accompanied by increased frequency of sandy tempestites. The shallowings were also accompanied by intensified bioturbation, which destroyed many thin sand beds by mixing with the siltstone. The Rispebjerg Member in the uppermost part of the Læså Formation signals a significant shallowing that eventually culminated with a full regression, which is traceable throughout Scandinavia (Nielsen & Schovsbo 2011). This craton-wide forced regression presumably reflects a glacio-eustatic sea level fall. This interpretation is corroborated by the observation that the regressive trend was interrupted by short-lived sea level rises, associated with precipitation of phosphorite and glauconite in the Rispebjerg Member (e.g. de Marino 1980). Quartz grains in the upper part of this member are generally well-rounded (Hansen 1936; de Marino 1980) and reworking of aeolian sand is inferred (Surlyk 1980). However, the presence of trace fossils (C. Poulsen 1967; see also de Marino 1980) as well as glauconite and phosphorite at some levels show that the aeolian component must have been reworked in a marine environment or simply blown into the sea.

After deposition of the Læså Formation, the sea level rose very significantly, probably driven by deglaciation, and this event was associated with precipitation of phosphorite in the uppermost part of the Rispebjerg Member (cf. Grönwall 1916; Hansen 1937; Nielsen & Schovsbo 2007, 2011). This rise in sea level heralded a >100 Myr period where outer shelf conditions generally prevailed in the Bornholm area. The condensed fine-grained deposits that were deposited initially in this deep late early Cambrian sea, in Skåne (southern Sweden) referred to as the Gislöv Formation (Fig. 2), were eroded away again on Bornholm in connection with the Hawke Bay Event around the early/mid Cambrian boundary (Nielsen & Schovsbo 2015). Reworked lower Cambrian fossils incorporated into the overlying Forsemölla and Exsulans limestone beds (C. Poulsen 1942; V. Poulsen 1965, 1966) attest to the former presence of the Gislöv Formation also on Bornholm (for lithostratigraphy, see Nielsen & Schovsbo 2007).

Lithology of the Læså Formation

As stated in the introduction, the Læså Formation comprises two members (Fig. 2). The thick Norretorp Member forms the lower part of the formation and consists of siltstone intercalated by thin, mostly 1–15 cm thick, very fine-grained sandstone beds (Hansen 1936; C. Poulsen 1967, fig. 3; Surlyk 1980; Clausen & Vil-

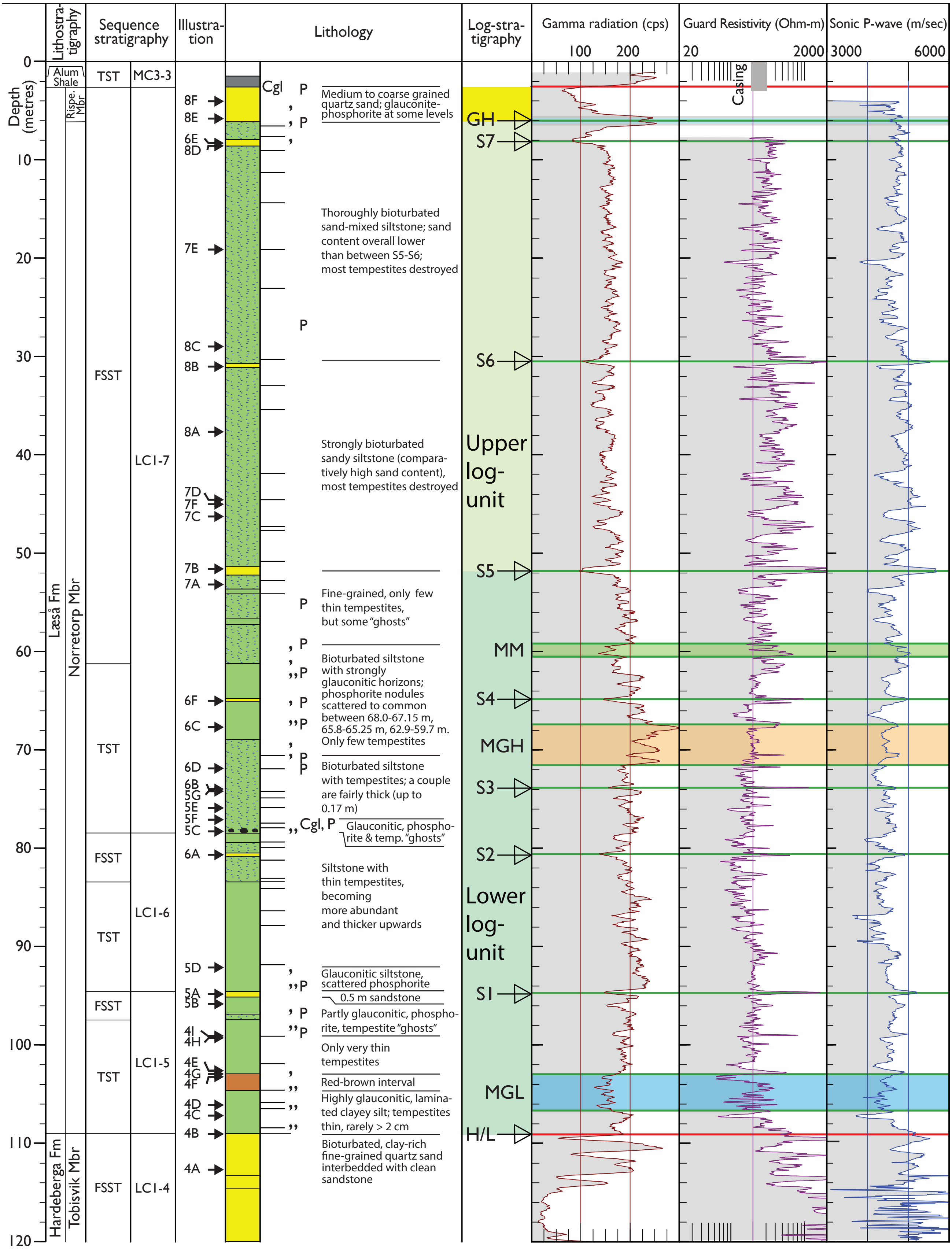


Fig. 3. Log stratigraphy of the Borggård-1 borehole (DGU no. 247.627). The tentative sequence stratigraphical interpretation and slightly modified synoptic lithology log are based on Nielsen & Schovsbo (2011). For legend, see Fig. 9. The column with numbers to the left of the lithological section refers to photos shown in Figs 4–8.

hjálmsson 1986; Nielsen & Schovsbo 2011). Most parts of this unit are intensively bioturbated, except near the base. The sandstone interbeds occur with variable frequency through the member, but numerous beds have been partially or completely obliterated by the pervasive bioturbation. Such sand beds are now seen as bioturbated 'ghost' layers with nebulous boundaries or simply as an increased sand content in the siltstone; the latter phenomenon is especially characteristic of the upper ≈half of the Norretorp Member. Several levels are rich in glauconite, primarily in the lower and middle part of the unit, often accompanied by small phosphorite nodules, up to a few cm long; the vertical distribution of phosphorite and glauconite enrichment within the member is indicated in Fig. 3. However, scattered grains of glauconite are seen throughout the unit and small flakes of detrital muscovite are also omnipresent. Despite the somewhat variable lithology, it is generally impossible to identify which part of the relatively thick member that is exposed in individual outcrops, as the lithology overall appears quite uniform and most outcrops expose only a few metres. No distinctive, readily recognizable lithological marker levels are present, except for a red-brownish horizon, *c.* 1.5 m thick, located at 104.6–103.1 m in Borggård-1. To our knowledge, this marker horizon is poorly exposed only in the Læså at loc. 74 *sensu* Hansen (1936), but it is recorded in several non-cored water supply wells (e.g. 247.390, 247.411, 247.604, 248.59) and appears to be developed throughout southern Bornholm. Hansen (1936) did not identify this distinctive horizon.

The Rispebjerg Member, forming the very top of the Læså Formation, consists predominantly of medium- to coarse-grained well-cemented sandstone (e.g. de Marino 1980). As the uppermost part of the Norretorp Member contains frequent sandstone beds, it is occasionally difficult to pinpoint the boundary between the Norretorp and Rispebjerg members in outcrops and drill-cores. For description of levels with phosphorite and glauconite within the Rispebjerg Member, see de Marino (1980) and Nielsen & Schovsbo (2007, 2011; see also Fig. 3). Note that the unit also contains reworked phosphorite and glauconite.

Age of the Læså Formation

A plethora of small fossils have been described from the Norretorp Member on Bornholm, but the great majority of taxa are endemic and without biostratigraphic significance (C. Poulsen 1967). A sparse trilobite fauna, indicative of the *Schmidtiellus mickwitzi* Zone, has been recorded from the Norretorp Member in Skåne (Bergström 1981; Ahlberg 1984 and references therein; see also Nielsen & Schovsbo 2011), but so far, no trilobites have been found in this unit on Bornholm. A rich acritarch flora was described by Moczydłowska & Vidal (1992), demonstrating that the Norretorp Member spans the *Skiagia ornata–Fimbrioglomerella membranacea* and *Heliosphaeridium dissimilare–Skiagia ciliosa* acritarch zones. The zonal boundary is not precisely located but is assumed associated with the glauconite-phosphorite rich interval approximately in the middle of the unit (≈40–50 m above the base) and the biozonal boundary possibly coincides with the LC1-6/LC1-7 sequence boundary (cf. Nielsen & Schovsbo 2011; see Fig. 3). The fossil evidence suggests that the lower part of the Læså Formation represents the Dominopolian Regional Stage and the upper part the Ljubomlian Regional Stage, i.e. Cambrian unnamed Series 2, global stage 3 (Fig. 2; see Nielsen & Schovsbo 2011 for details). Absolute dating of the Cambrian is currently imprecise (cf. Peng *et al.* 2020) and correlation of the Baltoscandian regional stages with the global stages is highly tentative. The absolute age span indicated for the Læså Formation in Fig. 2 thus remains speculative, but loosely indicates that deposition lasted for ≈6.5 Myr, resulting in an average depositional rate of ≈1.6 cm/1000 yrs. This is up to 8 times higher than seen in the overlying Furongian Alum Shale (cf. Zhao *et al.* 2020, supplementary fig. 5), but slow enough to permit extensive bioturbation.

Regional distribution of the Læså Formation

The Læså Formation is known from Bornholm and Skåne (southern Sweden) as well as the offshore German G-14 exploration well, located some 80 km SW of Bornholm (Nielsen & Schovsbo 2007, 2011). Although it is significantly thinner in Skåne than on Bornholm, the exact thickness is generally unknown, but seems to be around 30 m in the Lund area in western Skåne and around 20 m in SE Skåne (Nielsen & Schovsbo 2007, 2011). The formation is even thinner, only 3–6 m, in deep wells in SW Skåne (Sivhed *et al.* 1999). This markedly reduced thickness compared to Bornholm is surprising, considering that the clastics were supplied from the north at this stage (Nielsen & Schovsbo 2011), so the sediment reaching Bornholm must, broadly speaking, have bypassed the Skåne region (*s.l.*). A more proximal location of that region on the early Cambrian shelf is in accordance with the sandier lithology of the Norretorp Member in Skåne compared to Bornholm (cf. Nielsen & Schovsbo 2007, 2011 and references therein). In some parts of Skåne, the Læså Formation is even absent as seen in the Albjära and Tängelsås wells (Nielsen & Schovsbo 2011, p. 237 and references therein). The Læså Formation also appears to be absent in the Danish Terne-1 offshore well in Kattegat northwest of Skåne (Schovsbo 2011), whereas the strong condensation of the Læså Formation in the German G-14 well south of Bornholm (for interpretation, see Nielsen & Schovsbo 2011) possibly reflects its distal position relative to the clastic source area. This may also be the explanation for the thinness or possible absence of the Læså Formation in the Slagelse-1 well on Sjælland (cf. C. Poulsen 1974), but in both cases uplift is also possible. For further remarks on the thickness of the Læså Formation, see 'Discussion'.

Wireline logging: methods and data quality

This study is based on gamma radiation wireline logs from Bornholm supplemented in most wells by a formation resistivity or induction log. To date, wireline logging reaching the Læså Formation on Bornholm has been carried out in 30 wells, mostly non-cored water supply wells (Table 2). However, the obtained logs have never been analysed to any degree of detail (Sørensen 1978; Pedersen & Klitten 1990; Nielsen *et al*. 2006). Wireline logging is essential for intra-unit correlation of the Norretorp Member; in non-logged wells, it is unknown which part of the member that is present unless the top or the base is included in the drilled section.

The majority of the data at hand originates from wireline logging conducted by GEUS, using digital equipment manufactured by Robertson Geo Ltd (Tables 1–2). Five newer data-sets were recorded by Rambøll, Water Centre South and GEO using the same digital equipment as GEUS or similar equipment manufactured by Century Geophysical LLC (Table 2). A few older logs were obtained in the seventies and eighties by the Institute of Technical Geology at the Technical University of Denmark and by the consulting company T. Sørensen (Terraqua), in both cases recorded by equipment with either continuous analogue data-print output or as discrete readings per 25 cm depth. Both of these older log types have subsequently been digitized by GEUS using the software DIDGER. These early recordings do not have the same resolution as the logs recorded by digital equipment, but even so, as can be seen from the wells that have been re-logged (e.g. 247.435, Fig. 11), they actually provide a quite accurate depiction of the overall log pattern.

All of the gamma ray logs, irrespective of their recording age, logging operator or equipment manufacturer, were measured by a NaJ-crystal scintillation detector that records the total radiation within a radius of 15–25 cm. It is emphasized that only the gamma radiation pattern is considered in this study, and not the specific values. This approach is chosen as the radiation level in a particular well is affected by the size of the NaJ-crystal, the diameter of the well and the logging speed. Even when the gamma radiation probe is calibrated to API units instead of counts per second (cps), the readings are still affected by the diameter of the well and the logging speed (API: see Table 1).

The gamma radiation of rocks is due to a content of uranium and thorium and several decay products thereof, as well as potassium-40. The radioactive elements may be associated with organic matter or occur as trace elements in minerals, in the present case notably glauconite, phosphorite and clay.

Spectral gamma ray logs are recorded in Borggård-1 and 246.795 (Table 2), but they are in need of calibration and are not shown. Like a standard gamma ray

Table 1. Legend for Table 2 and log panels

X: Logs recorded by GEUS using digital equipment. In the log panels these are just labelled 'Gamma' and 'Resistivity'.
(X): Gamma ray spectral log, recorded by GEUS using digital equipment.
VCS: Recorded by Water Centre South using digital equipment.
GEO: Recorded by Geo using digital equipment.
RB: Recorded by Rambøll using digital equipment.
DTU: Recorded by the Institute of Technical Geology/Technical University of Denmark (digitized paper prints).
TS: Recorded by T. Sørensen (Terraqua) (digitized paper prints).
SN: Short Normal 16"; resistivity logs digitized from paper prints (see text).
LN: Long Normal 64"; resistivity logs digitized from paper prints (see text).
SL: Short Lateral 4'8"; resistivity logs digitized from paper prints (see text).
IND: Resistivity logs calculated as the inverse of conductivity logs recorded by GEUS using digital equipment.
API: Units that are based on an artificially radioactive concrete block at the University of Houston, Texas, USA, defined to have a gamma radiation of 200 American Petroleum Institute (API) units.
CPS: Counts per second.

log, a spectral gamma ray log counts the total radiation intensity, but the magnitude and spectrum of the energy from the gamma radiation is also recorded. Based on this, the amount of each emitting element can be determined provided that the probe is adequately calibrated (for details, see Andersen 2001).

P-wave sonic logs have been available from two scientific boreholes (Table 2). This log type essentially shows the same variations as the resistivity log (Fig. 3).

Resistivity or conductivity logs are available from most of the studied wells (Table 2). They provide indications of the lithology, porosity and nature of

Table 2. Læså Formation: Wells with wireline logs. Gamma ray logs recorded by GEUS with digital equipment are shown in the log panels with only the name ‘Gamma’. Gamma ray logs recorded by Water Centre South, Rambøll or GEO are identified by the initials VCS, RB or GEO, respectively. Old gamma ray logs digitized from paper prints are named either DTU Gamma or TS Gamma, referring to the logging operator. Non-logged wells with Rispebjerg Member are also listed. In the Jupiter database, this sandstone is furthermore registered as present in 246.533, 247.147 and 247.254. However, revised mapping shows that the sandstone in 246.533 and 247.254 represents the Hardeberga Formation and the Langeskanse Member, respectively, whereas the lithostratigraphical identification of the sandstone overlying the Norretorp Member in 247.147 is unresolved. It may represent the Rispebjerg Member, but alternatively it represents a veneer of the Lower Cretaceous Rabekke Formation.

	Fault block	DGU well Id. No.	Well name	Depth interval (m) with Rispebjerg Member	Depth interval (m) with Norretorp Member	Hardeberga Formation reached	Gamma (Gamma spectral)	Gamma digitized	Resistivity(GLOG probe)	Resistivity digitized	Induction resistivity	Logging year
1.	Lobbæk	246.613	Lobbæk Ww		2.3–36	Yes	X		X		X	2001
2.	Lobbæk	246.795	Lobbæk Ww		2.3–75	Yes	X (X)		X			2004
3.	Lobbæk ?	246.528	Gravgærde	>1.4–4.3	4.3–35	No	X		X		X	2006
4.	Læså Graben	246.594	Bukkegård	37.8–40.8	40.8–48	No	X		X		X	2017
5.	Læså Graben	246.749	Skelbro-1	37.5–41.2	41.2–43.0	No		DTU		SL+SN		1985
6.	Læså Graben	246.817	Skelbro-2	42.0–42.9	Not reached	No	X		X		X	2010
7.	Pedersker	247.708	Smålyngsv. Å2		2.5–21	Yes	GEO					2022
8.	Pedersker	247.435	Smålyngsv. Å3		2.2–25	Yes		TS		SL		1974
							VCS					2019
9.	Pedersker	247.322	Smålyngsv. Å8		2.0–52	Yes	X		X			2002
10.	Pedersker	247.460	Sømarken Ww		4.2–77	No	X		X			2002
11.	Pedersker ?	247.98	Pedersker Ww		2.0–60	No	X		X			2002
12.	Smålyngen	247.662	Smålyngsværket		10.0–49	Yes	VCS					2019
13.	Smålyngen	247.330	Smålyngsv. N1		3.0–63	Yes		TS				1976
							VCS					2018
14.	Smålyngen	247.340	Smålyngsv. N2		1.0–18	Yes		TS				1976
							X		X			2002
15.	Smålyngen	247.627	Borggård-1	2.6–6.1	6.1–109.0	No	X (X)		X			2006
16.	Sømarken	247.312	Sømarken Ww. 4	81.3–86.1	86.1–113	No		DTU		SN+SL		1988
							X					1997
17.	Sømarken	247.510	Billeshøj	78.4–82.6	82.6–92	No		DTU		LN+SL		1984
18.	Sømarken	248.36	Sømarken Ww. 2	139.7–144.0	144.0–147	No		TS				1978
19.	Sømarken	248.39	Sømarken Ww. 3	98.7–101.7	101.7–108	No	X		X		X	2002
20.	Sømarken	248.61	Billegrav-2	122.2–124.8		No	X		X		X	2010
21.	Sømarken	248.62	Sommerodde-1	245.7–247.5	247.5–251	No	RB		RB		RB	2013
							X					2013
22.	Stenseby	247.349	Smålyngsv. N3		7.0–22	Yes	X		X			2000
23.	Stenseby	247.343	Møllevang		6.5–52	No		TS		LN+SL		1976
24.	Stenseby	247.604	Bodilsker		3.5–67	No	X		X		X	2002
25.	Stenseby	248.40	Strandmark Ww.		3.0–87	No	X		X		X	2002
26.	Stenseby	248.53	Strandmark Ww.		4.0–93	No	X		X			2004
27.	Stenseby	247.459	Balka		4.5–32.5	Yes	X		X			2002
28.	Stenseby	247.455	Balka Ww.		5.5–29	Yes	X		X		X	2002
29.	Stenseby	247.306	Snogebæk Ww.		2.0–50.5	Yes	X		X		X	2002
30.	Snogebæk	247.265	Snogebæk Ww.		4.0–14	Yes	X		X			2004
Additional wells with Rispebjerg Member, but without wireline-logs												
31.	Not named	246.372	Vasegårdsvej	>?5.0–7.0	? 7.0–9.6	No						
32.	Lobbæk?	246.373	Gravgærde access road	>3.8–4.75	? 4.75–	No						
33.	Sømarken	247.101B	Eskildsgård	<29.5–30.5	? 30.5–36.5	No						
34.	Not named	248.11	Dueodde hotel	~ 7.1–8.0	? 8.0–8.2	No						
35.	Not named	248.16	Dueodde hotel	~ 8.1–12.0	? 12.0–14.8	No						

pore fluids (i.e. salinity) of the rock units. In pure sandstones or limestones, both usually characterized by low gamma radiation, a low porosity is reflected by low conductivity and high resistivity. Clays on the other hand typically have high gamma radiation combined with high conductivity and low resistivity because of the negatively charged surface of clay, which cause surface adsorption of cations. These cations are capable of dissociation making them prone for ionic conductance, thereby increasing the conductivity (e.g. McNeill 1980).

Most of the resistivity and conductivity logs at hand were recorded using digital tools, either a focusing guard resistivity probe or an induction conductivity probe; the former has a vertical resolution of *c.* 5 cm. The guard resistivity probe can only measure in uncased sections of a well and below the water table in the borehole. The content of dissolved ions in the stagnant fresh water in the boreholes was in all cases sufficient to make this log type working. The induction conductivity probe provides a log of the entire well profile including sections with PVC casing and screen as well as sections above the water table, but also this tool cannot measure in sections with steel casing. The induction probe is a dual induction (DUIN) tool, which in the same run provides two logs with different penetration depths. However, compared to the guard resistivity probe it is of lower resolution. In wells with an induction log covering significantly more of the upper section than the guard resistivity log, the induction log has been used for this study by calculating resistivity as the inverse of conductivity, based on the DUIN long-space conductivity log penetrating deepest into the formation. The resulting resistivity logs are illustrated using the name 'IND'. Old resistivity logs digitized from paper prints are named SN, LN or SL, corresponding, respectively, to 16″ normal, 64″ normal and 4′8″ short lateral electrode configuration. Of these, the 16″ probe has high resolution, but short penetration depth, while the 64″ probe has slightly lower resolution but higher penetration and the 4′8″ probe even more so.

Similarly to the gamma ray logs, only the resistivity log pattern is considered in this study, and not the specific level of recorded resistivity. This approach is adopted because the well diameter combined with the conductivity of the stagnant water in the borehole affect the recorded resistivity to different degrees for different probe types. Moreover, the various types of probes have dissimilar penetration depths into the formation.

All stated thicknesses are drilled thickness and no attempts have been made to correct for stratal tilt. In most fault blocks, the strata slope 3–8°.

Results

Wireline log stratigraphy

The gamma ray log pattern of the Læså Formation is significantly more uniform with lower radiation intensity and absence of conspicuous peaks compared to the overlying Alum Shale Formation (see Pedersen & Klitten 1990; Schovsbo *et al*. 2015; Nielsen *et al*. 2018). Still, based on the gamma ray log motif supported by the resistivity and sonic log patterns, the Norretorp Member can be subdivided into a lower and an upper log-unit (Fig. 3). The lower log-unit is characterized by slightly higher average gamma radiation levels with oscillations of greater amplitudes while the upper log-unit exhibits generally lower gamma radiation and the oscillations are of low amplitude throughout. Conversely, the resistivity (as well as the P-wave velocity log [the latter log type is available only for Borggård-1]) are more variable and both show generally higher average readings in the upper than in the lower log-unit. The combined log pattern reflects a higher sand content in the upper unit (mixed with the silt due to the pervasive bioturbation), and the more common presence of phosphorite and glauconite in the lower unit.

In addition to the two main log-units, it is also possible to trace seven individual, relatively thick (0.15–0.8 m) sandstone layers in most of the studied wells across southern Bornholm. These markers, labelled S1 to S7 (Fig. 3 and subsequent log panels), are characterized by gamma ray minima corresponding to peaks in resistivity- and P-wave velocity. Marker S5 forms the boundary between the lower and upper main log-units.

Four intervals distinguished by a characteristic gamma ray log motif are labelled as the MGL (multiple gamma low), MGH (multiple gamma high), MM (middle marker) and GH (gamma high) markers. The latter is located at the transition between the Norretorp and Rispebjerg members and serves as a marker of that boundary. There is no distinctive log-marker of the boundary between the Hardeberga and Læså formations, and the log-motifs in the uppermost part of Hardeberga Formation vary between wells. However, the boundary interval is consistently characterized by a significant upwards fall in resistivity, and the distinctive gamma ray log pattern in the basal Norretorp Member is readily recognizable. For further remarks on this boundary, see section on the 'Hardeberga Formation' below and 'Discussion'.

The Læså Formation is unconformably overlain by the Alum Shale Formation. The sharp boundary is marked by a rapid, significant increase in gamma radiation and a concurrent upwards decline in resistivity and the transition is thus easily identifiable on wireline logs. Regarding potential minor uncertainties, see 'Discussion'.

Borggård-1: Lithology versus wireline log pattern

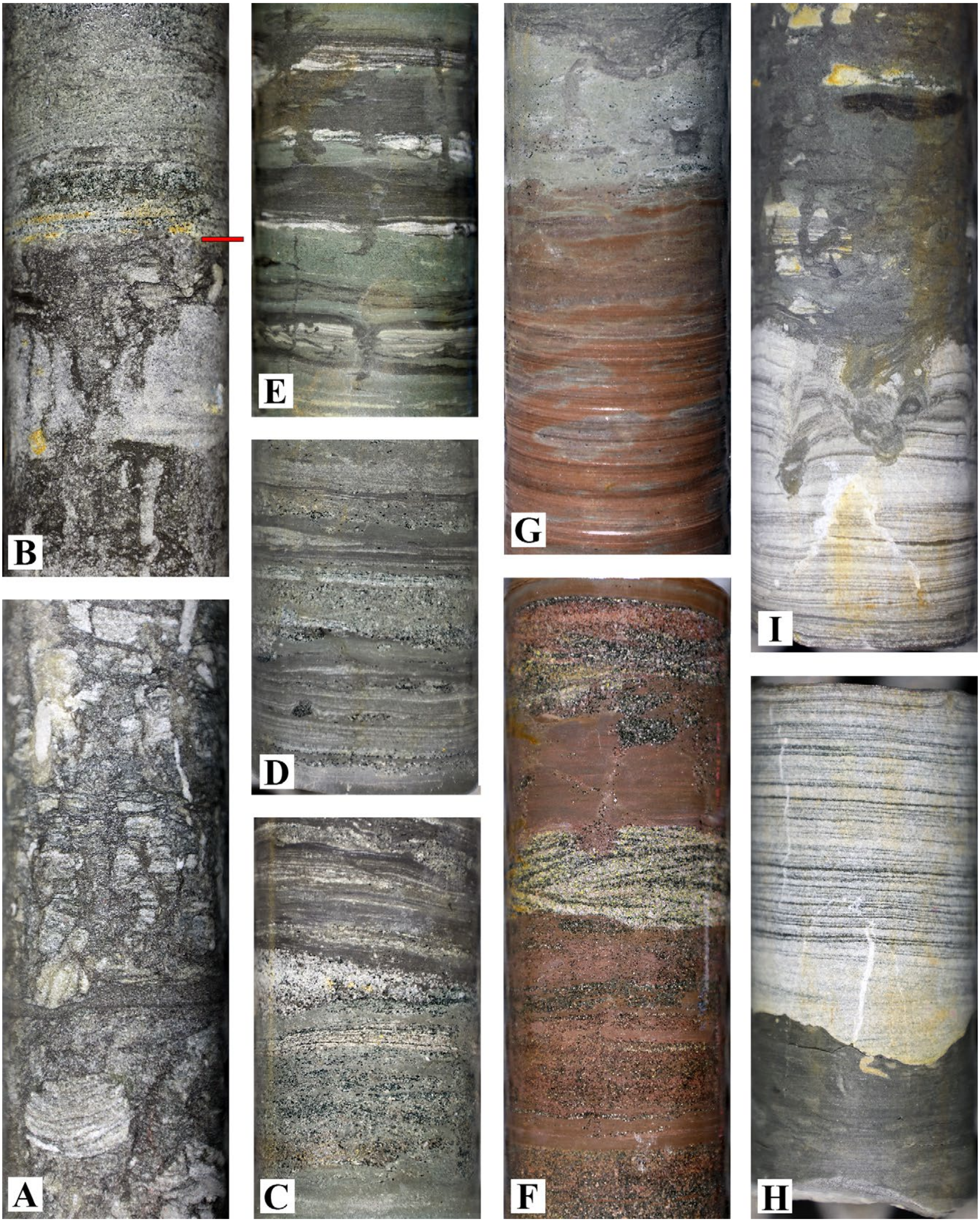
The lithology of the Læså Formation in Borggård-1 was briefly summarized by Nielsen & Schovsbo (2011). Their review is here emended based on renewed inspection of the core. All depths stated below refer to levels in Borggård-1; a summary of the lithological characteristics is included in Fig. 3 and examples of the variable lithology are illustrated in Figs 4–8. The levels of the photographed core pieces are shown in Fig. 3.

Hardeberga Formation. The topmost part of the Hardeberga Formation contains several horizons that are intensively bioturbated with *Skolithos*, *Diplocraterion*, and *Planolites* as the characteristic trace fossils. These intervals consist of comparatively impure sandstone (Fig. 4A–B) and the content of clay and probably also organic matter (cf. Hansen 1936, p. 104) are most likely the reason for the gamma ray peaks associated with these levels. In the Borggård-1 core, the uppermost 0.5 m of the Hardeberga Formation consists of such bioturbated impure sandstone, so the gamma ray log response of the lithologically sharp lower boundary of the Læså Formation (Fig. 4B) is obscured by a rise in gamma radiation commencing at 0.5 m below the boundary. For further remarks on the variable log pattern in the upper part of the Hardeberga Formation between wells, see 'Discussion'.

Log interval H/L–S1. The boundary between the Hardeberga and Læså formations is marked by the abrupt appearance of glauconite and the concomitant decrease of grain size (Fig. 4B). It is labelled as H/L in the log-panels and is characterized by an upwards rise in gamma radiation and a significant general fall in resistivity taking place across *c*. 1 m. The lower *c*. 6 m of the Norretorp Member (109.0–103.1 m) is dominated by non-bioturbated to slightly bioturbated, clayey silt, partially laminated, with frequent thin glauconitic sandstone interbeds (rarely > 2 cm thick) interpreted as distal tempestites (Fig. 4C–D). The glauconite grains in these thin interbeds are fairly large (probably reworked), so they appear coarse-grained. Despite the glauconite content, the upper half of this interval is characterized by comparatively low gamma radiation (the MGL log-marker, 106.2-103.1 m) combined, except in the uppermost part, with high resistivity, compared with the Læså Formation in general. The MGL log-marker includes a distinctive red-brown horizon at 104.6–103.1 m (Fig. 4F–G) and maybe a hematite content is responsible for the low resistivity at the very top of this interval. It is possible that the low gamma radiation of the MGL log-marker is caused by a diminished content of glauconite (in the thin sandstone interbeds) and absence of phosphorite. The overlying 4.4 m of siltstone (103.1–98.7 m) contains mainly very thin sandstone beds without coarse glauconite grains and some intervals of the siltstone are rather bioturbated (Fig. 4E; see also siltstone below and above the sandstone illustrated in Fig. 4H–I). One of the thicker sandstone beds from this interval is illustrated in Fig. 4H–I. Then follows a partly glauconitic horizon (98.7–95.1 m), which originally contained a few thin sandy interbeds, now recognized only as bioturbated 'ghost' layers (Fig. 5B). No surviving sand beds were observed between 97.5–95.1

▼ **Fig. 4.** Examples of lithology in the Borggård-1 core (Norretorp Member and top of the Hardeberga Formation). All core pieces were photographed wet; their location within the section is shown in Fig. 3. Diameter of core is 55 mm; it was not slabbed prior to photography and the edges of the rounded core are occasionally slightly out of focus. **A**. Bioturbated impure sandstone in the uppermost part of the Hardeberga Formation, 112.78–112.63 m. This lithology has a high gamma radiation (Fig. 3). See also the lower part of B. **B**. Boundary between the Hardeberga and Læså formations at 109.0 m (indicated by thin red line). The sharp contact is assumed representing an unconformity (Nielsen & Schovsbo 2011). The upper 0.5 m of the Hardeberga Formation is strongly bioturbated and clay-rich; the overlying Læså Formation is characterized by the appearance of glauconite and a decrease of grain size. The shown core represents 109.07–108.92 m. **C–D**. Laminated siltstone intercalated by thin, partly glauconitic sandstone layers, 107.23–107.13 m (C) and 106.15–106.07 m (D). The comparatively coarse-grained glauconite is probably reworked. Note the near absence of bioturbation. **E**. Thin layers of laminated siltstone, in part slightly glauconitic, interlayered by very thin sandstone beds. The bioturbation is modest and insufficient to destroy the layering. 102.67–102.57 m. **F**. Upper part of the red-brown interval near the base of the Læså Formation (see text) with thin layers of siltstone and glauconitic sandstone, in part cross-bedded, 103.38–103.23 m. **G**. Uppermost fine-grained (silty) part of the red-brown interval and basal part of overlying bioturbated greenish siltstone, slightly glauconitic, 103.22–103.07 m. From this level upwards, the bioturbation intensity increases through the Norretorp Member. **H**. Lower part of laminated sandstone bed (tempestite) with erosive lower boundary, overlying strongly bioturbated siltstone, 99.32–99.20 m. The upper part of the sandstone bed is shown in I. **I**. Upper part of the laminated sandstone bed (tempestite) shown in H, 99.20–99.05 m. The top is bioturbated and several centimetres of the bed have been mixed with the 'host' siltstone. The siltstone above is intensively bioturbated (mottled appearance) and contains phosphorite nodules (black).

m. The entire interval between the MGL and the S1 marker exhibits an overall gentle upwards increase in gamma radiation, but this trend is punctuated by two significant minima at 98.7 m (sandstone bed) and 96.0 m ('ghost' sand bed), which are also reflected by resistivity peaks in the otherwise rather stable resistivity log.



Log interval S1–S2. Between 95.1–94.6 m follows a fine-grained, intensively bioturbated sandstone horizon (Fig. 5A) that forms the log-stratigraphical marker labelled S1. It is, in turn, overlain by *c*. 2.6 m of siltstone (94.6–92.0 m), glauconitic to strongly glauconitic in the lower *c*. 1.5 m and intensively bioturbated (Fig. 5D), with scattered but often comparatively large phosphorite nodules. This lower part is characterized by relatively high gamma radiation (Fig. 3) that represents the peak of the upwards increase in gamma radiation above the MGL marker (see above). The high radiation is likely connected to the content of glauconite and phosphorite. Then follow *c*. 11 m of siltstone (92.0–80.97 m) with thin sandstone beds, becoming more frequent (about 10–15 cm between the beds above level 86.5 m) and slightly thicker upwards, which probably is the reason why this interval exhibits a decreasing upwards trend in gamma radiation albeit with several oscillations. It is remarkable, however, that the resistivity log also shows a generally decreasing trend through this interval, despite the upwards increasing sand content. The higher resistivity in the lowermost 5 m of this interval is associated with a slightly higher P-wave velocity, which according to conventional log interpretation indicates lower porosity, i.e. higher cementation or stronger compaction. The gamma radiation minimum terminating this interval upwards is associated with a relatively thick sandstone intercalation at 80.97–80.5 m, referred to as log-marker S2 (Fig. 6A). It consists of two stacked sandstone beds.

Log interval S2–S4. The siltstone lithology with frequent intercalations of thin sandstone beds continues above log-marker 2 (80.97–80.5 m) for another 2.2 m (up to 78.3 m). This succession is capped by a thin phosphorite conglomerate at 78.73 m (Fig. 5C), which is not recognizable on the wireline logs. It is overlain by a glauconitic and partly phosphoritic interval (78.73–76.8 m). This succession originally contained thin sand beds that are now mixed with the silty 'host' sediment; the bioturbation is pervasive (Fig. 5F). Then follow another 9 m of intensively bioturbated siltstone (76.8–67.8 m; Fig. 5G) interspersed by comparatively frequent sandstone beds in the lower part (Figs 5E, 6D), including a couple that are fairly thick (up to 0.17 m). The thicker sandstone beds are associated with resistivity peaks and gamma ray minima and a relatively thick sandstone bed at 74.1–73.9 m is laterally traceable as log-marker S3 (Fig. 6B). Overall, the gamma radiation increases upwards above the S2 bed, culminating at the top of the MGH log-marker (71.5-67.15 m), which represents maximum radiation level for the entire Læså Formation. This is due to occurrence of phosphorite from 71.5 m and upwards, and a strongly glauconitic horizon with scattered to common phosphorite nodules between 68.0–67.15 m (peak of the MGH marker; Fig. 6C).

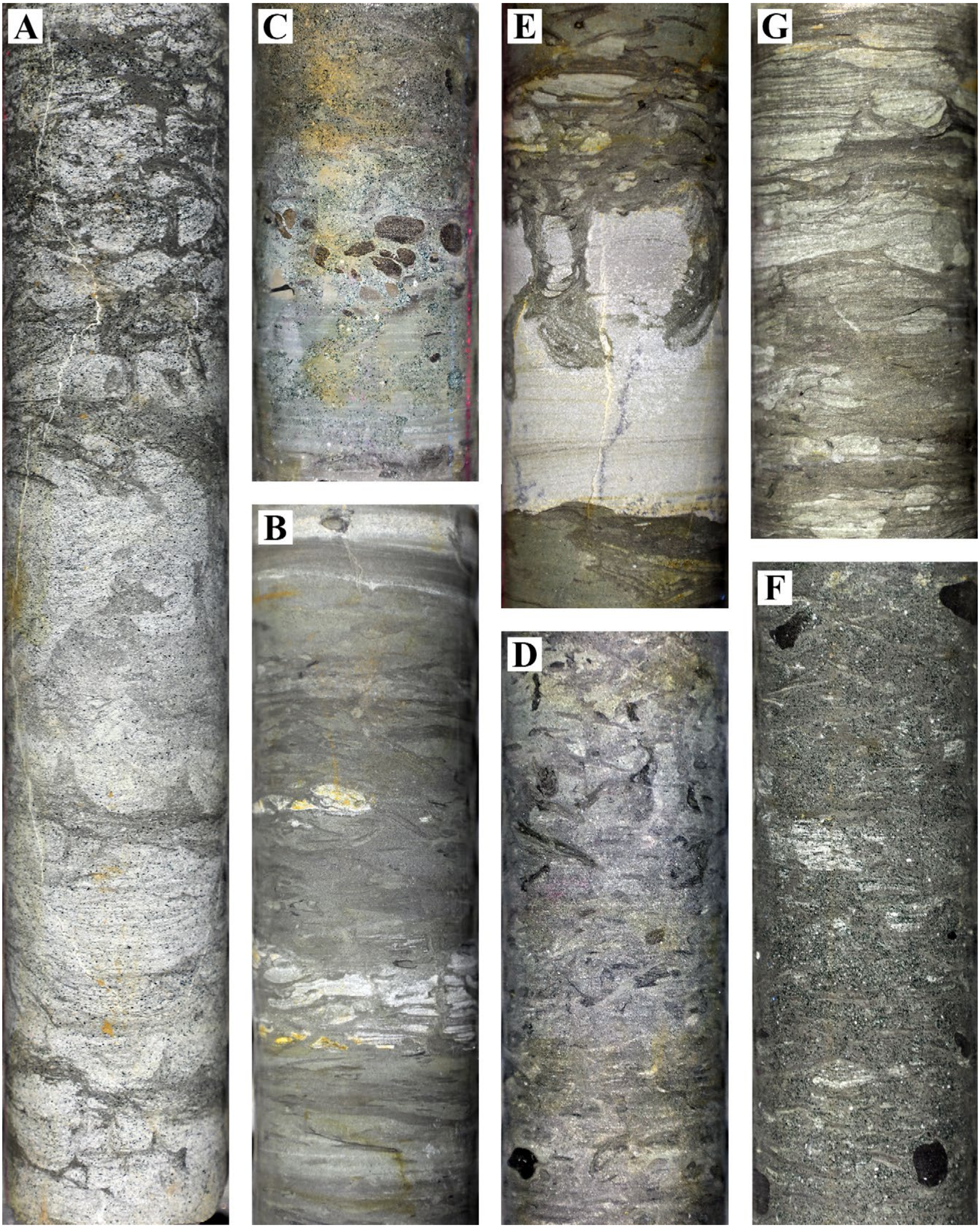
Above 67 m only a few surviving sandstone interbeds are observed due to the intense bioturbation, but here and there occur small patches of sand that indicate the original presence of tempestites, now obliterated. The sand-mixing is probably the reason why the gamma radiation decreases through the interval immediately above the MGH marker. However, another interval with phosphorite and glauconite occurs at 65.8–65.25 m but is only associated with an inconspicuous gamma ray peak.

Similarly to the underlying S1–S2 interval, there is also in the S2–S4 log interval a tendency that the resistivity and gamma radiation show broad-scale co-variance, indicating that the variation is not only controlled by the sand/clay ratio, but also by the content of glauconite and phosphorite, and maybe by variability in the porosity and/or cementation (affecting the resistivity).

Log interval S4–S5. A relatively thick sandstone bed at 65.26–65.0 m (Fig. 6F) is traceable as log-marker S4 (Fig. 3). A glauconitic interval with some phosphorite is seen between 62.9–59.7 m, but at the same time the sand content increases upwards from 62.4 m with a further increase above 60.4 m, occurring as small patches of whitish sand, so the gamma radiation is comparatively low and the resistivity high. A gamma ray low and corresponding resistivity peak are laterally traceable as log-marker MM. This is not a sandstone layer per se, but a *c*. 3 m thick interval

▼ **Fig. 5.** Examples of lithology in the Borggård-1 core (Norretorp Member); the location of each photographed core piece is shown in Fig. 3. For other photography details, see Fig. 4. **A**. Part of sandstone marker bed S1, slightly glauconitic (reworked?) and bioturbated; shown core piece represents 94.98–94.69 m. S1 comprises at least three individual beds. **B**. Moderately bioturbated siltstone with thin sandstone interbeds, in part mixed up with the host sediment due to the bioturbation, 95.93–95.75 m. **C**. Phosphorite conglomerate at 78.73 m overlying an erosive surface, suggested to represent the LC1-6/LC1-7 sequence boundary by Nielsen & Schovsbo (2011) (Fig. 3). The matrix is sand-mixed glauconitic siltstone. The core piece represents 78.78–78.67 m. **D**. Strongly bioturbated siltstone, slightly glauconitic with sporadic small phosphorite nodules, 92.22–92.08 m. **E**. Laminated sandstone bed (tempestite) at 75.88–75.81 m. Lower boundary erosive, upper boundary irregular due to bioturbation. The core piece represents 75.91–75.76 m. **F**. Strongly bioturbated glauconitic siltstone with scattered phosphorite nodules, 77.16–77.00 m. Patches of obliterated sandy light grey interbeds can also be seen. **G**. Strongly bioturbated heterolithic silt-sandstone, immediately below marked bed S3, 74.24–74.11 m.

(62.4–59.0 m) with a higher sand content. Above this level and all through to log-marker S7, the occurrence of glauconite and phosphorite are sparse. Overall, the strata overlying marker bed S4 up to core level 53.6 m are fairly fine-grained with only a few thin sandstone beds, although it is obvious that some tempestites have



been destroyed by bioturbation. The interval between 54.33–53.6 m appears a little darker, laminated, and includes a few thin sandstone beds; this horizon has low resistivity but is otherwise not obvious to trace on the wireline logs. Then follows more sand-mixed, intensively bioturbated siltstone.

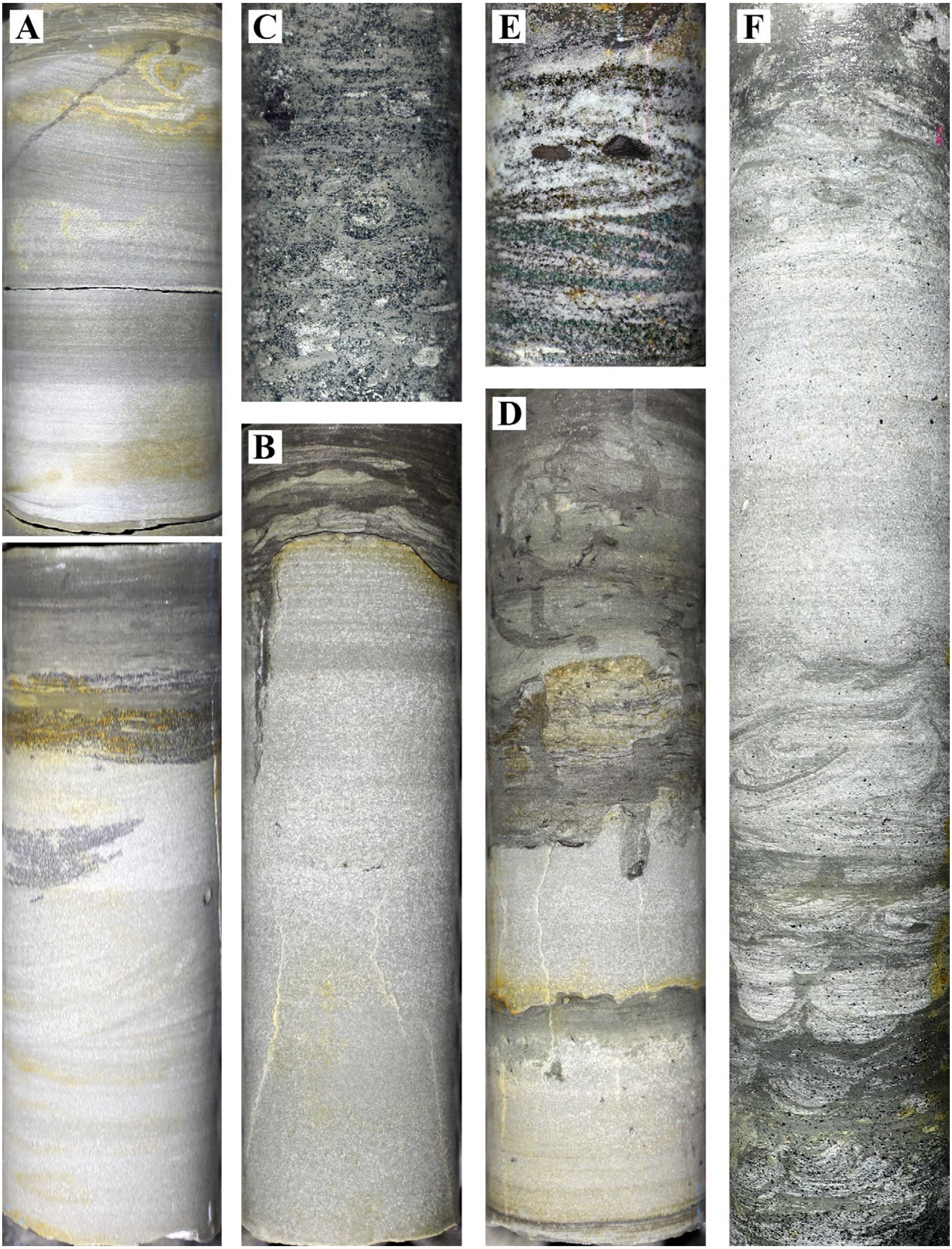
The entire log interval S4–S5 is characterized by a slight upwards decline in average gamma radiation intensity, culminating in the minimum associated with log-marker S5. The resistivity varies opposite to the gamma radiation, indicating that the variation of both parameters is mainly controlled by the clay/sand ratio, reflecting an increased sand content upwards.

Log interval S5–S6. A comparatively thick but thoroughly bioturbated sandstone bed between 52.19–51.46 m constitutes log-marker S5 (Fig. 7B). The sand-mixed, intensively bioturbated siltstone continues above this horizon and only the thickest storm beds have escaped mixing with the 'host' sediment (Fig. 7D). In log interval S5–S6, forming the lower part of the upper log-unit, the gamma ray log pattern exhibits only small oscillations and no vertical changes in average radiation level is observed. Conversely, the resistivity log exhibits frequent oscillations with comparatively large amplitudes, reflecting a variable and quite high sand content. Both the resistivity and the P-wave velocity show higher average levels and higher variation amplitudes than in any other part of the Norretorp Member (Fig. 3). Like in the S4–S5 interval, the gamma radiation and resistivity vary inversely, indicating that the log pattern reflects changing sand/clay ratios. The same general lithology of strongly bioturbated and quite sandy siltstone continues all the way upwards to marker bed S6, but some variation in the silt/sand ratio is seen in intervals that are too thin to be detailed here (illustrated in Figs 7C, 7F, 8A). The comparatively uniform gamma ray log pattern with low average radiation intensity is probably caused by the mixed sand-silt lithology in combination with the lower resolution of the gamma probe relative to the resistivity probe (see methods).

Log interval S6–S7. A comparatively thick sandstone layer at 31.06–30.68 m is traceable as log-marker S6 (Fig. 8B) and this horizon divides the upper log-unit into two subunits. Above S6, the gamma radiation is thus clearly more monotonous than between marker beds S5–S6. Although all three log types available from Borggård-1 indicate that the S5–S7 interval overall contains more sand than the underlying Norretorp Member, the detailed log pattern indicates that the sand is more homogeneously distributed in the S6–S7 interval than between S5–S6. This is also observable in the Borggård-1 core, where the interval between S6–S7 is a little darker (due to relatively higher silt content) than below S6 and more intensively bioturbated (Figs 8C, 8D [lower part]). However, short sections of the succession are similar to the more silt rich facies between S5–S6 with well-defined lighter coloured sandy patches intercalated in the siltstone (compare Fig. 7C). An example of hummocky cross stratification (HCS) within a tempestite is shown in Fig. 7E.

Log interval S7–Alum Shale Formation A sandstone dominated section at 8.61–7.80 m forms marker S7 (Figs 6E, 8D) that generates a significant low in the gamma ray log in Borggård-1 (Fig. 3). This horizon consists of several stacked sandstone beds. Above this layer, the gamma radiation intensity increases upwards to culminate in the GH log-marker, which is very distinct in some (incl. Borggård-1) but not all wells (see e.g. Fig. 10). This marker bed is located at the boundary between the Norretorp and Rispebjerg members (6.5–5.5 m in Borggård-1). The lower part is formed by a thin sandy siltstone containing glauconite just below the Rispebjerg Member and which likely is the reason for the high gamma radiation at this level. The glauconite is rather coarse-grained (probably reworked), like seen in the thin sandstone beds in the lowermost part of the Norretorp Member (log interval H/L–S1). There is also surprisingly high gamma radiation in the basal part of the Rispebjerg Member (upper part of the GH marker), due to the presence of glauconite and scattered small phosphorite nodules (apparently reworked).

▼ **Fig. 6.** Examples of lithology in the Borggård-1 core (Norretorp Member); the location of each photographed core piece is shown in Fig. 3. For other photography details, see Fig. 4. **A**. Sandstone marker bed S2, comprising stacked tempestites, laminated and cross-bedded, 80.96–80.70 m. The illustration is composed of two photos. **B**. Sandstone marker bed S3, 74.11–73.96 m. Base of photo corresponds to the base of the bed (the core piece shown in Fig. 5G is located immediately below S3). Note the bioturbated top of the bed. The apparent "lamination" are scratches made by the drill bit on the core surface. **C**. Strongly bioturbated sand-mixed silt with a high content of glauconite and some phosphorite, 67.70–67.60 m. **D**. Stacked tempestites, both with erosive bases and bioturbated tops and overlain by bioturbated siltstone. The core piece represents 72.00–71.80 m. **E**. Part of marker bed S7. Cross-bedded medium grained glauconitic sandstone with reworked clasts of phosphorite, 8.29–8.21 m. See also Fig. 8D. **F**. Sandstone marker bed S4 and adjacent siltstone; the shown core piece represents 65.02–65.31 m. S4 consists of a lower bioturbated sand-mixed silt bed (with high sand content) overlain by a more clean sandstone bed, bioturbated at the top. S4 overlies highly bioturbated strongly glauconitic sand-mixed siltstone.


A
C
E
F
B
D

The Rispebjerg Member (6.1–2.6 m, Figs 8E–F) is in Borggård-1 characterized by a sharp upwards decrease in gamma radiation (Fig. 3). No resistivity log is available for this interval in Borggård-1 because the 10 m long insulated bridle cable at the top of the guard resistivity probe had to be fully below water to ensure proper function. Since the top of a temporary PVC-work-casing was 3 m above terrain to avoid artesian water to overflow, no readings could be obtained in the upper 8 m of the well.

There seems to be a few centimetres thick horizon approximately 0.5 m below top of the Rispebjerg Member in the Øleå outcrop section containing non-reworked glauconite and pyrite associated with phosphorite (Hansen 1937, pp. 162–163; 'phosphorite I' of de Marino 1980). This thin horizon is also recognizable in the Skelbro-1 core (cf. Pedersen 1989) whilst it is strongly weathered in the Borggård-1 core, being close to ground level at the well site. The horizon is too thin to be traced on the gamma ray log.

The top of the Rispebjerg Member in the Borggård-1 core is impregnated by phosphorite, and the gamma radiation increases sharply from immediately below top of the sandstone. This may be the case also in other wells (e.g. Sommerodde-1, see section on the Sømarken block), but generally the boundary between the Læså and Alum Shale formations is readily identified on wireline logs by the marked upwards rise in gamma radiation and decrease of resistivity. For remarks on the thin amalgamated Forsemölla–Exsulans limestone bed at the base of the Alum Formation and its influence on the log pattern, see 'Discussion'.

Wireline log correlation of the Læså Formation

As stated previously, the Læså Formation is penetrated in its entirety only by the Borggård-1 borehole (Fig. 3). As can be seen from Figs 9–14, in combination representing a *c.* 18 km long ESE-WNW oriented section across southern Bornholm from Lobbæk to Snogebæk (Fig. 1), the Norretorp Member is of surprisingly uniform thickness throughout the area (Fig. 15). The overlying Rispebjerg Member, which is 3.5 m thick in Borggård-1, reaches a verified maximum thickness of 3.7 m in the Skelbro-1 drill core (Pedersen 1989; Nielsen & Schovsbo 2011), but a greater thickness, 5.6 m, is indicated by the log correlation of 247.312 (Sømarken-4; Fig. 10). Wells penetrating the Rispebjerg Member are listed in Table 2.

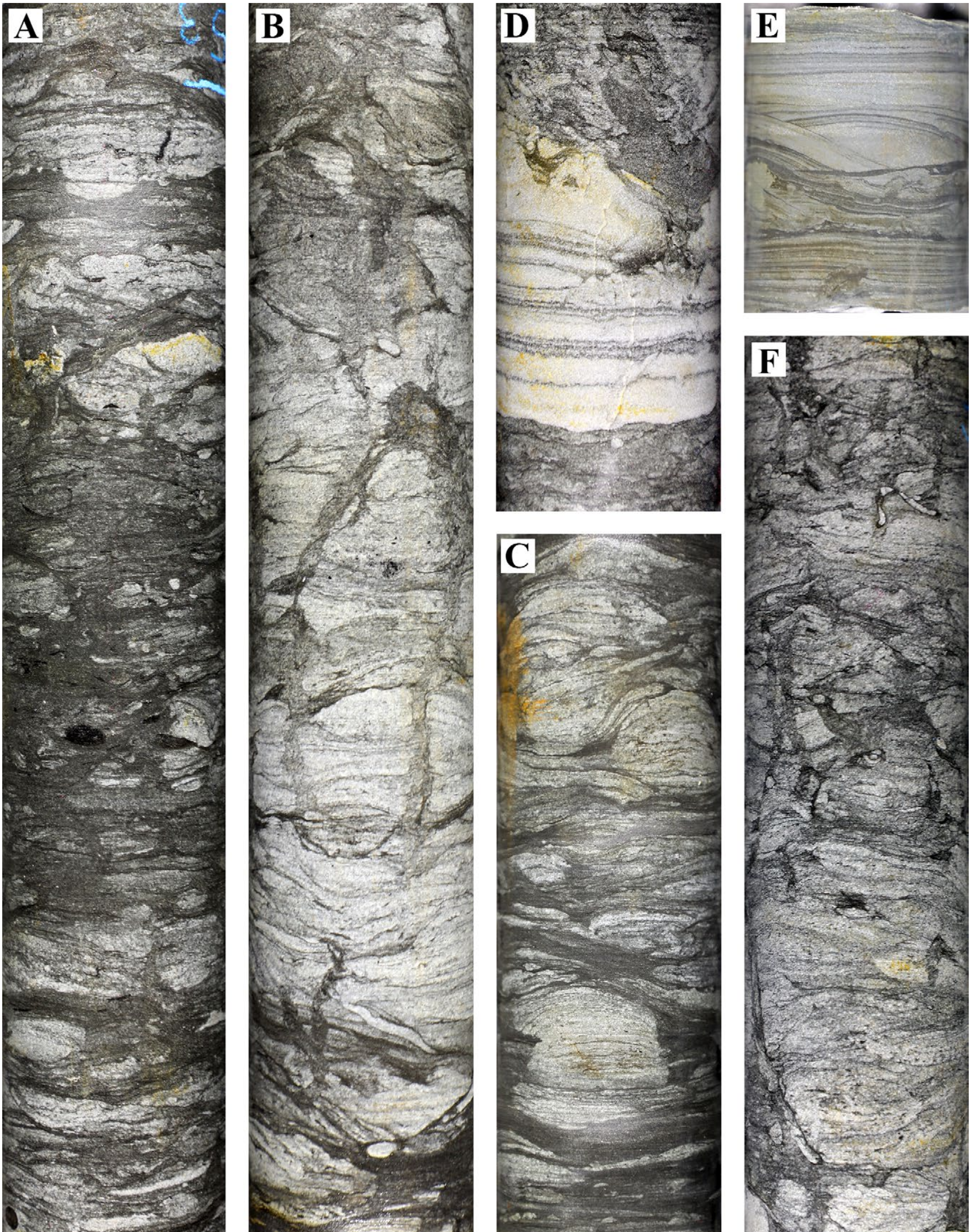
Lobbæk block

On this fault block, only two wells with Læså Formation, 246.613 and 246.795, are wireline logged (Figs 1, 9) and they both represent the lower part of the unit. Well 246.528, indicated on Fig. 1 as also situated on the Lobbæk block, is probably rather located within the Læså Graben according to revised mapping by the first author.

The gamma ray log motif in the two wells differs more from the Borggård-1 than seen in wells on other fault blocks. The radiation level and amplitudes are thus higher in 246.795, especially in the middle part of the Norretorp Member (Figs 9, 15). This is especially remarkable given that the well diameter is approximately three times larger than in Borggård-1 (225 mm vs. 75 mm) and everything else being equal, the greater distance to the side wall should be expected to result in lower readings (the same logging tool and logging speed were used in both wells). The correlation with Borggård-1 shows that there are no marked differences in thickness although the upper part of the succession in 246.795 maybe is *c.* 5 metres thicker (Fig. 9). However, log-marker S5 cannot be identified convincingly due to the lack of a resistivity log in the upper 23 m of 246.795 (due to a PVC-casing). The greater gamma radiation amplitudes in that well indicate that the succession contains more glauconite and phosphorite than in Borggård-1. The reason for this remains unclear but must somehow relate to different conditions during deposition.

The gamma ray log pattern in the boundary interval between the Hardeberga and Læså formations, particularly in the upper part of the Hardeberga Formation, also differs slightly from that seen in Borggård-1. However, in both 246.795 and 246.613, the formational boundary is characterized by a significant upwards decline in resistivity (Fig. 9). At the same time, the gamma radiation increases into the Læså Formation, but as several oscillations are seen in the gamma ray log motif in the uppermost part of the Hardeberga Formation, this change is less obvious.

▼ **Fig. 7.** Examples of lithology in the Borggård-1 core (Norretorp Member); the location of each photographed core piece is shown in Fig. 3. For other photography details, see Fig. 4. **A**. Sand-mixed siltstone, bioturbated, with a few phosphorite nodules in the middle less sandy and darker interval. The core piece represents 53.27–52.98 m. **B**. Bioturbated stacked sandstone, comprising the upper part of marker bed S5, 51.80–51.50 m. **C**. Sand-mixed strongly bioturbated siltstone, 46.51–46.34 m. This moderately silt-rich facies only accounts for *c.* 1/10 of the succession between markers S5–S6, but is more common between markers S6–S7. **D**. Laminated sandstone with erosive basis and bioturbated top. This is one of the few tempestites in the upper log-unit of the Norretorp Member that survived mixing by bioturbation, 44.59–44.52 m. **E**. Cross-bedded (HCS) sandstone bed, 19.13–19.07 m. **F**. Sand-dominated bioturbated sand-siltstone. This facies accounts for *c.* 1/7 of the succession between markers S5–S6. 45.20–44.97 m.


A
B
D
E
C
F

Well 246.528 penetrates the lower *c*. 3 m of the Rispebjerg Member and the upper 34 m of the Norretorp Member. The boundary between these members is readily identified by comparison with the Borggård-1 gamma ray log. Further downhole, the gamma ray log pattern is indistinct, but marker bed S6 is identified by its resistivity peak, bounded upwards by decreasing resistivity and downwards by a rather fluctuating log response. This resistivity log motif strongly resembles that seen in Borggård-1. It is not possible to correlate convincingly between 246.528 and 246.795 (cf. Fig. 9) due to insufficient overlap, but the lowermost part of the section in 246.528 may correlate with the very top of the 246.795 profile, as tentatively indicated in Fig. 9. If so, the total thickness of the Læså Formation is *c*. 100 m in the area, i.e. slightly less than in Borggård-1.

Note that the upper part of the succession in 246.528 erroneously is recorded as Nexø sandstone in the Jupiter database.

Læså Graben

Short sections of the Læså Formation have been drilled in 10 wells in this small onshore graben, but wireline logs have been acquired in only 246.594 (Bukkegård) and 246.749 (Skelbro-1; fully cored) (Fig. 10). Of these, 246.594 reaches ~10 metres into the formation, whereas only 6.5 m were drilled in 246.749 (for description, see Pedersen 1989). A third well, 246.817 (Skelbro-2), reached just 0.9 m into the Læså Formation why the wireline logs from this fully cored borehole are not shown (see Nielsen *et al*. 2018, fig. 10). For remarks on 246.528, presumably also located within the Læså Graben, see section on the Lobbæk block above.

The boundary between the Læså and Alum Shale formations is readily identified by a sharp upwards increase in gamma radiation and a concomitant lowering of resistivity in both 246.594 and 246.749 (Fig. 10). In the former well, the upper sandstone-dominated part of the Rispebjerg Member has a log motif resembling that in Borggård-1, whereas the log pattern around the GH marker differs. This interval consists of thin sandstone beds with glauconite and phosphorite intercalated in siltstone, so the gamma radiation is relatively high, but variable. The log pattern through the Rispebjerg Member is rather different in 246.749, most probably because these older logs are of low resolution.

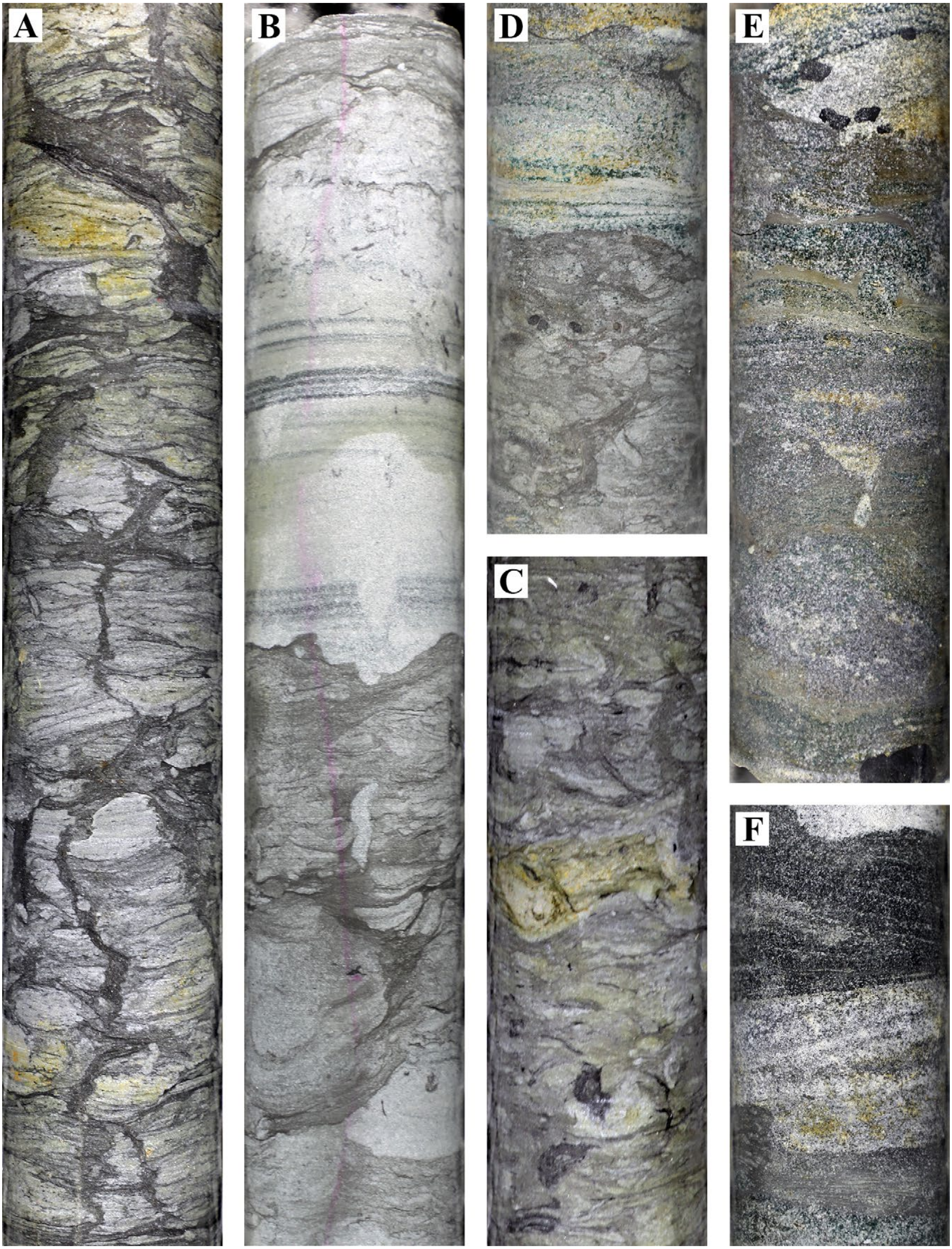
Sømarken block

The pre-Quaternary bedrock in this fault block consists predominantly of Silurian shales (Fig. 1) and the Læså Formation is comparatively deeply buried. In consequence, only the top part of the unit has been reached by a few wells (Fig. 10).

The logs from 247.312 and 247.510 indicate that the Rispebjerg Member at least locally is relatively thick in the Sømarken block, in these wells measuring *c*. 5.6 m and *c*. 4.3 m, respectively. The resistivity logs from 247.312 are older than the gamma ray log and have been digitized from paper prints. Still, they are useful for identifying the Rispebjerg Member despite their low resolution. Both logs shown for 247.510 are also digitized from paper prints. In this well, the gamma ray log has an indistinct, blurred motif throughout the Læså Formation, which most likely reflects that the intended water supply well was abandoned and not flushed prior to logging, so the lower part of the well was probably contaminated with material from the overlying organic-rich shales. The resistivity log penetrates deeper into the sidewall and allows recognition of the Rispebjerg Member. Four additional wells with wireline logs, 248.36, 248.39, 248.61 and 248.62, only reach into the very top of the Læså Formation (Fig. 10); the thickness of the Rispebjerg Member in these wells are listed in Table 2. The log motif between marker S7 and the upper half of the Rispebjerg Member is rather variable between the wells, like described for the Læså Graben (Fig. 10). However, the GH marker seems to be traceable, although its specific log response differs from well to well.

Only 247.312 reached a little deeper into the upper part of the Norretorp Member below marker bed S7

▼ **Fig. 8.** Examples of lithology in the Borggård-1 core (Norretorp Member); the location of each photographed core piece is shown in Fig. 3. For other photography details, see Fig. 4. **A**. Bioturbated sand-siltstone with high sand content. This facies accounts for more than 1/3 of the succession between markers S5–S6. 37.81–37.52 m. **B**. Lower part of the composite sandstone marker S6 overlying bioturbated sand-mixed siltstone; note the irregular erosive lower boundary of the marker bed. The illustrated core piece represents 31.06–30.75 m. **C**. Intensively bioturbated 'mottled' siltstone; this moderately silt-rich facies accounts for *c*. 1/8 of the succession between markers S6–S7 (upper part of the upper log-unit). The sand content is lower than generally seen in the lower part of the upper log-unit (i.e. between markers S5–S6). A few black phosphorite nodules can be seen. 29.27–29.09 m. **D**. The sharp lower boundary of marker S7, which in the shown lower part consists of glauconitic sandstone. The marker bed overlies bioturbated sand-mixed siltstone with a few small phosphorite nodules. The shown core represents 8.70–8.55 m. See also Fig. 6E. **E**. Medium-grained sandstone, partially glauconitic and with reworked phosphorite nodules, 5.83–5.65 m. Several erosional surfaces can be seen. **F**. Medium-grained sandstone, partially glauconitic. The black layer is due to impregnation with phosphorite. Several erosional surfaces can be seen. 4.06–3.95 m.


A
B
D
E
C
F

(*c.* 25 m). The gamma ray log pattern in this part of the Norretorp Member is monotonous, and therefore difficult to correlate confidently, but the drilled interval appears to be similar to the equivalent section in Borggård-1 although identification of marker bed S6 remains uncertain (Fig. 10).

Pedersker block

Wireline logs are available from four wells in this block (Fig. 11). No resistivity log has been acquired in 247.708, and only digitized older logs cover the H/L boundary interval in 247.435. The location of 247.98 relative to faults is discussed below in the section on the Smålyngen block; it may alternatively be located on the Pedersker block.

The gamma ray log motif at the transition between the Hardeberga and Læså formations is somewhat variable between the wells on this fault block and identification of the formational boundary is nonobvious due to the absence of a distinct gamma radiation minimum (i.e. clean sandstone bed) shortly below top of the Hardeberga Formation like seen in Borggård-1 (Fig. 11). Hence, it is inferred that the Læså Formation is underlain by 2–3 m of bioturbated, clay-rich sand-

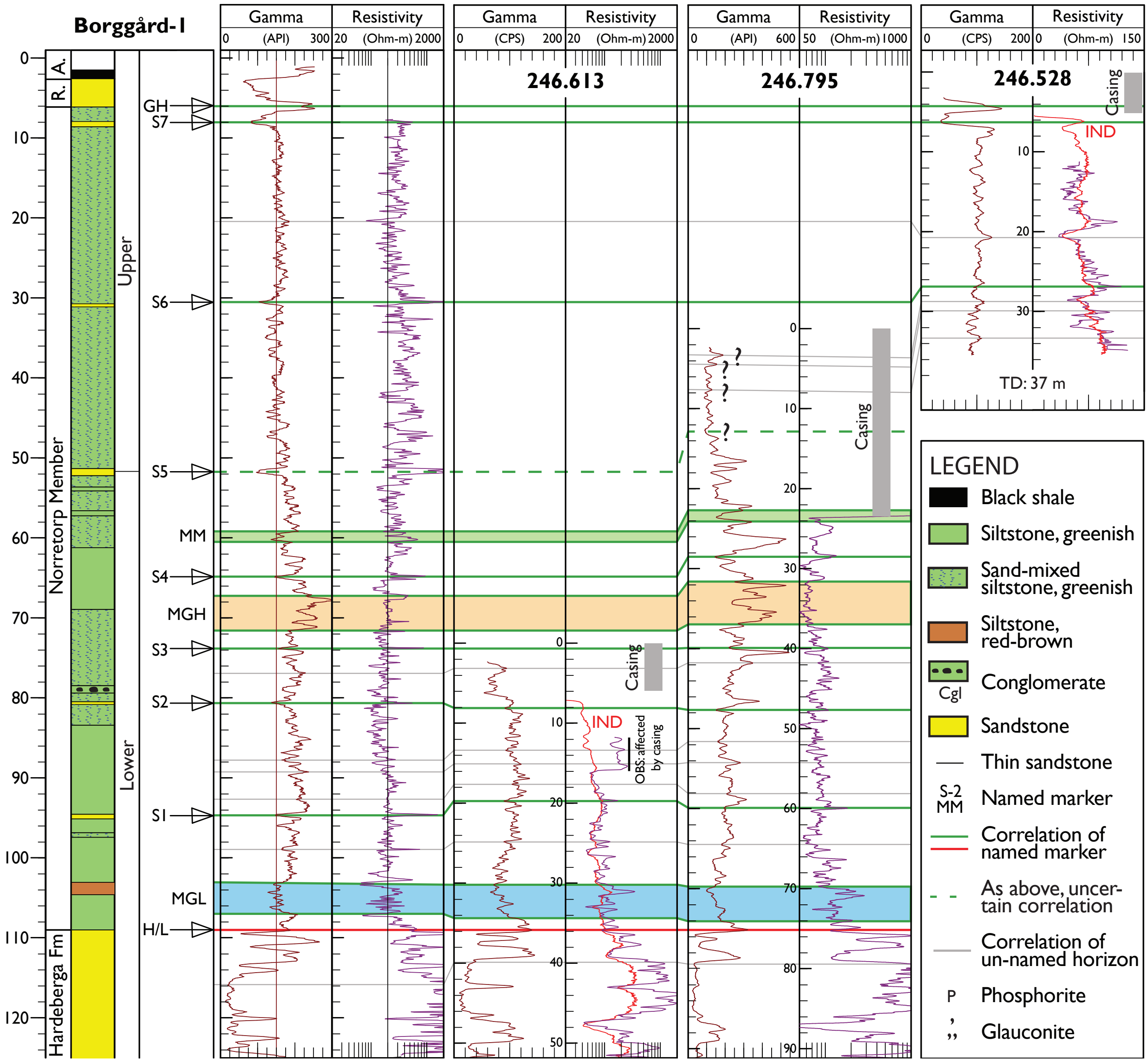


Fig. 9. Log panel showing correlation of the Læså Formation in the Lobbæk block; for location of wells, see Fig. 1. The base and top of the Læså Formation serve as datum planes for correlation. The Quaternary section of the logs is not shown. Legend is common for all log panels (Figs 3, 9–14), see also Tables 1–2.

stone in the Pedersker block, making the formational boundary comparatively indistinct on gamma ray logs. However, correlation of peaks and troughs below and above the boundary assists its recognition and identification of the boundary is especially aided by the nearly similar log pattern in the lowermost part of the Læså Formation in all three wells penetrating this level, and which is straightforward to correlate with Borggård-1 (Fig. 11).

The middle and upper parts of the Læså Formation are logged in 247.322 and 247.460. The gamma ray and resistivity log motifs are both closely comparable to those seen in Borggård-1 and correlation is unambiguous (Fig. 11). Likewise, there are no observable differences in thickness of the Norretorp Member between the Pedersker block and the succession in Borggård-1.

Smålyngen block

Wireline logs are available from five wells in this block including Borggård-1 and 247.98 (Fig. 12). The latter well is situated very close to the fault separating the Pedersker and Smålyngen blocks according to revised mapping (ATN, unpublished; see Fig. 1) and a location on the Pedersker block cannot be entirely excluded. Only gamma ray logs are available from 247.662 and 247.330. In both wells, the digital log is supplemented with an older log digitized from paper prints, in order to obtain a longer log profile.

The gamma ray log motif at the transition between the Hardeberga and Læså formations is somewhat variable between the three wells penetrating this boundary (like described for the wells in the Pedersker block), but correlation of the gamma ray log motif above the boundary in combination with the upwards declining resistivity from the Hardeberga into the Læså Formation enable consistent recognition of the formational boundary in the individual wells (Fig. 12).

The upper part of the Læså Formation is wireline logged only in 247.98 (Fig. 12). The monotonous gamma ray log motif is closely comparable to the one seen in

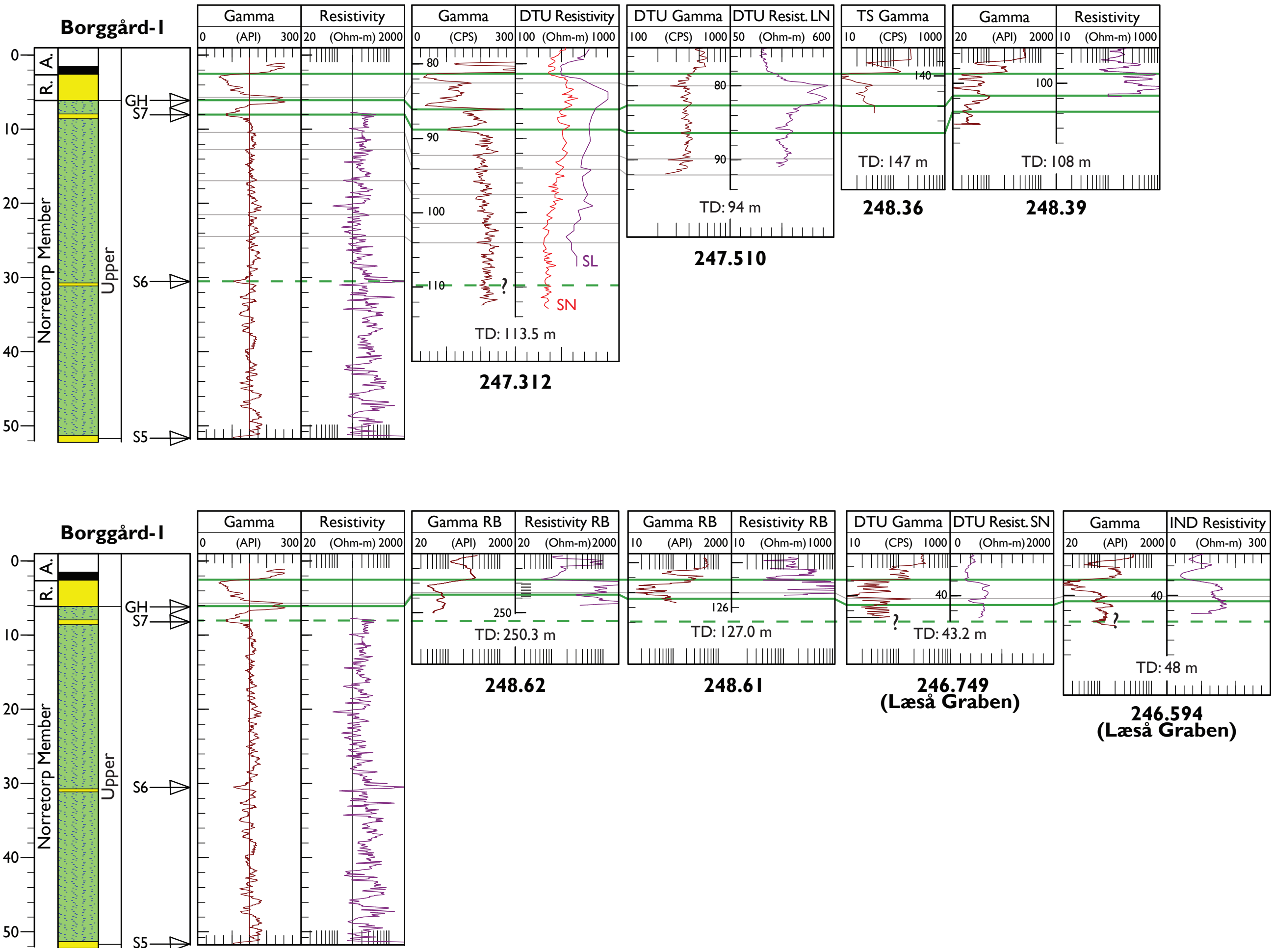


Fig. 10. Log panel showing correlation of the Læså Formation in the Sømarken block and the Læså Graben; for location of wells, see Fig. 1. The top of the Læså Formation serves as datum plane for correlation. Legend in Fig. 9 and Tables 1–2. Abbreviations: R: Rispebjerg Member, A: Alum Shale.

Borggård-1, but it is not possible to confidently recognize marker bed S6. Unfortunately, the resistivity log does not cover this near-surface part of the well section due to the length of the bridle cable (10 m). The succession in 247.98 is correlated with 247.330 using marker bed S3 as datum (Fig. 12). The log correlation indicates that the lower and middle parts of the Norretorp Member are a few metres thicker in the other wells on the Smålyngen block compared with the corresponding interval(s) in Borggård-1, with the greatest difference in 247.98. However, as mentioned above, this well is located very close to the fault separating the Smålyngen and Pedersker blocks (ATN, unpublished mapping; see Fig. 1) and it is possible that the marginally greater thickness is due to an increased tilt of strata associated with the fault.

Stenseby and Snogebæk blocks

The Læså Formation constitutes the bedrock in a relatively large area in SE Bornholm (Fig. 1). On the current geological map, this area consists of the Stenseby and Snogebæk blocks, but this is an oversimplification as additional faults undoubtedly are present. However, due to the uniform lithology of the Norretorp Member and sparsity of wells with wireline logs in the area, these internal faults are currently impossible to map. There are very few exposures in that part of Bornholm (Hansen 1936) and those reported are small and not particularly informative, whereas the Norretorp Member is encountered in more than 60 wells, but wireline logs are available from only nine wells at present, of which 247.265 is located on the Snogebæk block (Fig. 1). In the Jupiter

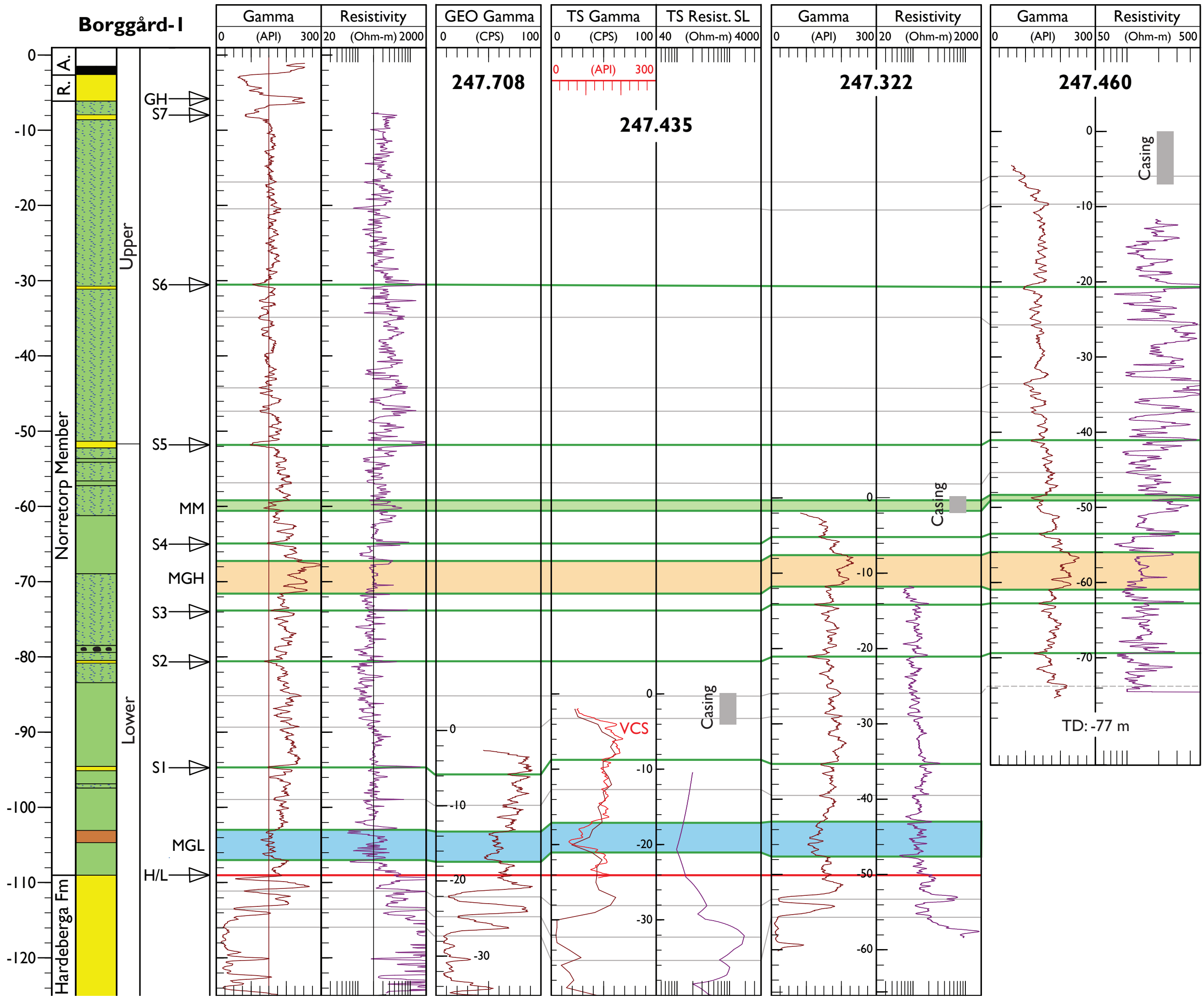


Fig. 11. Log panel showing correlation of the Læså Formation in the Pedersker block; for location of wells, see Fig. 1. The base of the Læså Formation and log-marker S6 serve as datum planes for correlation. The Quaternary section of the logs is omitted. Legend in Fig. 9 and Tables 1–2.

database, the entire succession penetrated by the latter well is registered as "Balka sandstone" (i.e. Hardeberga Formation), but the log correlation shows that the Hardeberga/Læså formational boundary is located at ~13.0 m in the borehole (Fig. 12).

The wells located in the northern part of the Stenseby block (viz. 247.343, 247.349. 247.604, 247.459 and 247.455; Figs 13–14), together with 247.265 on the Snogebæk block (shown on Fig. 12 due to space limitations), encountered only the lower part of the Norretorp Member, whereas the deep 248.40 and 248.53 in the SW corner of the Stenseby block penetrate most of the Norretorp Member (Fig. 14). The latter well was deepened subsequently from 94 m to 116 m, reaching 19 m into the Hardeberga Formation, but this lower part of the borehole has not yet been wireline logged. The drilled section includes the lower *c.* 92 m of the Norretorp Member and the log correlation to Borggård-1 indicates that another *c.* 10–11 m may be missing at the top, provided the thickness of the uppermost Norretorp Member is comparable between the two wells (Fig. 14). Hence, the total original thickness of the Norretorp Member in the area is similar to the thickness recorded in Borggård-1. It is evident that the lower part of the Norretorp Member below marker S6 is thinner in 248.53 than in Borggård-1, but seemingly the uppermost part of the unit immediately above this marker is a little thicker, almost levelling out the thickness difference (Fig. 14). If that trend continues upwards, the total thickness of the Læså Formation in the area may even have been a little larger than in Borggård-1. Overall, the gamma ray log pattern in wells on the Stenseby and Snogebæk blocks is similar to Borggård-1, albeit with minor internal variation in 248.40 and 248.53 (Fig. 14).

In 247.455 and 247.306, the Læså Formation appears to be underlain by 'clean' Hardeberga Formation

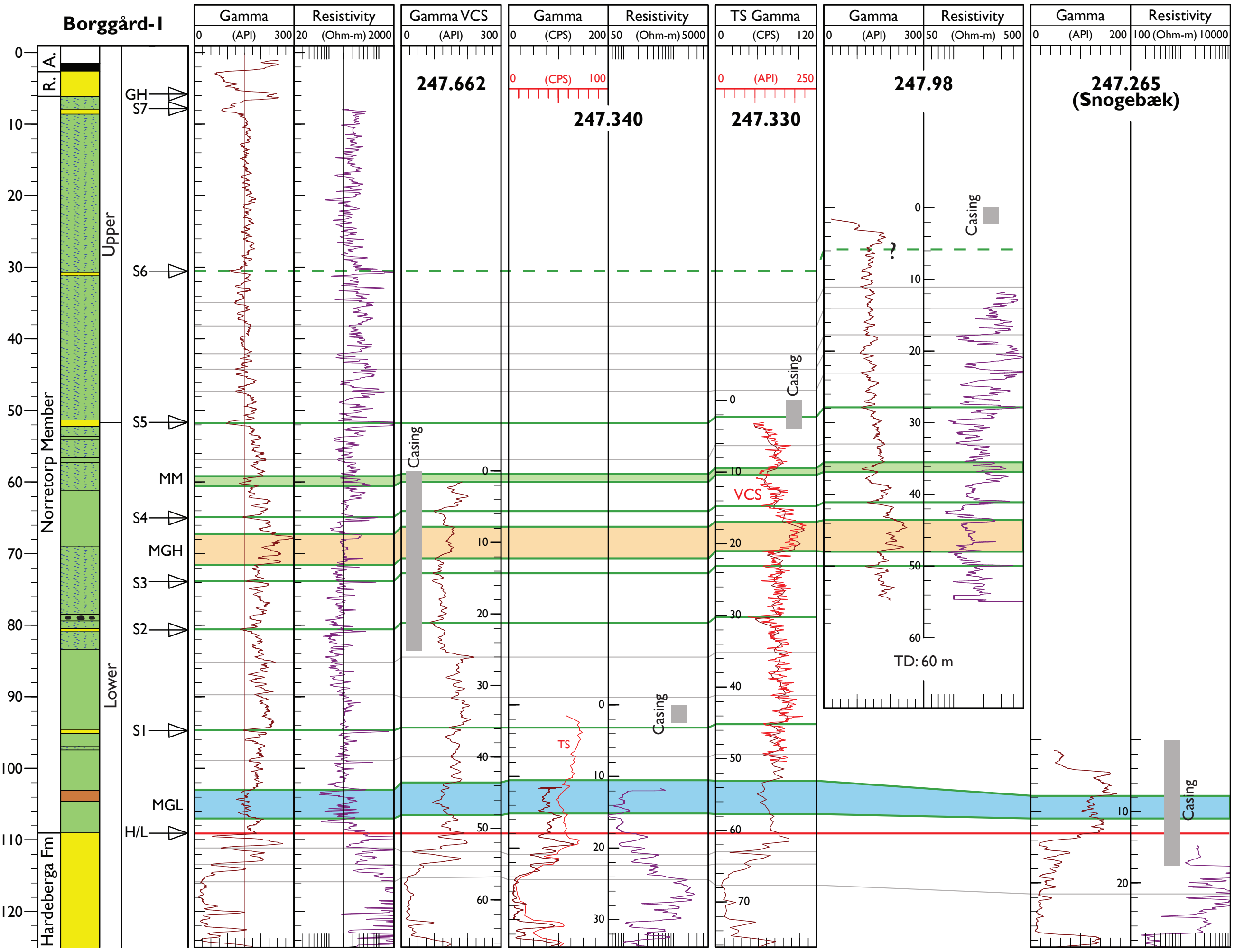


Fig. 12. Log panel showing correlation of the Læså Formation in the Smålyngen block; for location of wells, see Fig. 1. Well 247.265 located on the Snogebæk block is also included (due to space constraints in Figs 13–14). The base of the Læså Formation and log-marker S3 serve as datum planes for correlation. The Quaternary section of the logs is omitted. Legend in Fig. 9 and Tables 1–2.

without interbeds of impure sandstone and here the formational boundary is very distinct on both the gamma ray and resistivity logs, whereas the log motif in 247.349 is closer to that seen in Borggård-1 (Fig. 13). In 247.265 on the Snogebæk block (Fig. 12), the gamma ray log pattern at the Hardeberga/Læså formational boundary is intermediate between that of 247.349, 247.455 and 247.306.

The steel casing dampens the gamma radiation in 247.306 and 248.40, and thus skews the gamma ray log motif in the upper part of the MGH marker in 247.306 (Fig. 14). In that well, this log-marker is identified by comparison with the adjacent wells in the northern part of the Stenseby block that have a more similar log pattern than the deep wells in the SW corner of the Stenseby block. In 248.40, the 40 m steel casing attenuates the gamma radiation signal of the Norretorp succession down to and including the MM marker.

Discussion

Log stratigraphy

The outlined log stratigraphy, based on 11 intraformational horizons that consistently can be recognized on nearly all wireline logs, provides a detailed frame for correlation of the Læså Formation across southern Bornholm. The suite of logs available from the fully cored Borggård-1 scientific borehole serves as reference section for the outlined correlation (Fig. 3). The Norretorp Member is divided into two log-stratigraphical units. The lower log-unit (57 m thick in Borggård-1) is characterized by moderately variable and comparatively high average gamma radiation whilst the resistivity is generally low and exhibits little variation. The upper log-unit (46 m thick in Borggård-1) is distinguished by having gently fluctu-

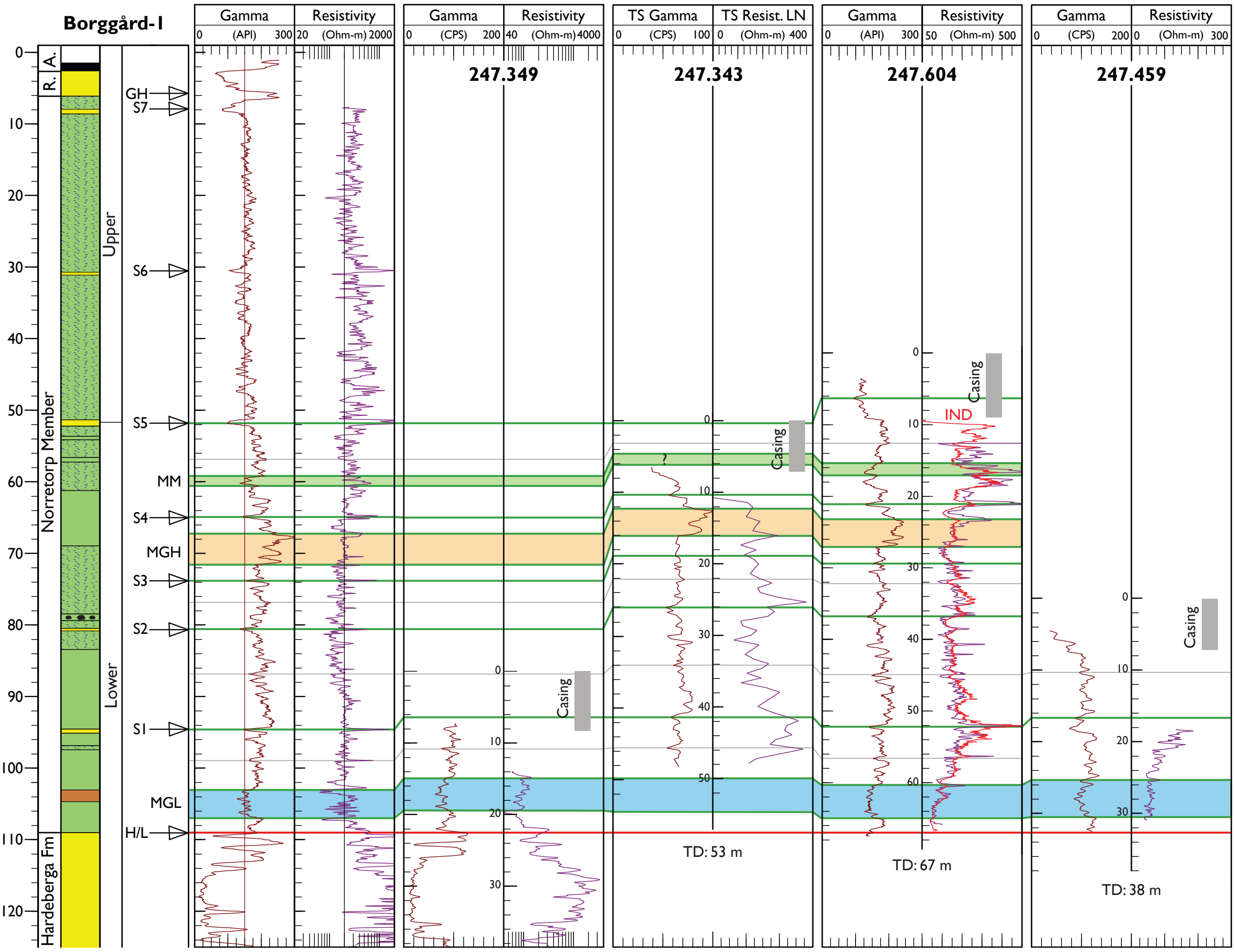


Fig. 13. Log panel showing correlation of the Læså Formation in the northern part of the Stenseby block (see also Fig. 14); for location of wells, see Fig. 1. The base of the Læså Formation serves as datum plane for correlation. The Quaternary section of the logs is omitted. Legend in Fig. 9 and Tables 1–2.

ating and relatively low gamma radiation throughout whereas the resistivity is comparatively high and more variable. These main log-units are further subdivided by recognition of seven thin sandstone horizons (labelled S1 to S7), marked by gamma radiation minima and corresponding resistivity peaks. The S5 marker forms the boundary between the lower and upper main log-units of the Norretorp Member and the S6 marker divides the upper log-unit into a lower part, characterized by comparatively high and variable resistivity associated with somewhat variable gamma readings, and an upper part with slightly lower average resistivity and a very uniform gamma ray log motif. Besides, four intervals with characteristic high or low gamma intensity, labelled MGL, MGH, MM and GH, can be traced consistently in nearly all wells across southern Bornholm that penetrate the respective stratigraphic intervals. The GH marker is an indicator for the boundary between the Norretorp and Rispebjerg members. In addition to the labelled marker levels, numerous minor log-peaks also appear traceable between the wells and which further support the correlation (cf. Figs 9–15). However, these supplementary subordinate ties, which occasionally are picked at different levels on the individual fault blocks, are not commented on any further.

In 247.306 and 247.455, the uppermost Hardeberga Formation consists entirely of clean sandstone and here the formational boundary towards the Læså Formation is distinct (Fig. 14) but in the other 12 wireline logged wells continuing into the Hardeberga Formation, the uppermost 5–7 metres of this unit include 2–3 horizons, occasionally several thinner beds, characterized by high gamma radiation and low resistivity (see log panels for the individual fault blocks). The Borggård-1 core discloses that these high

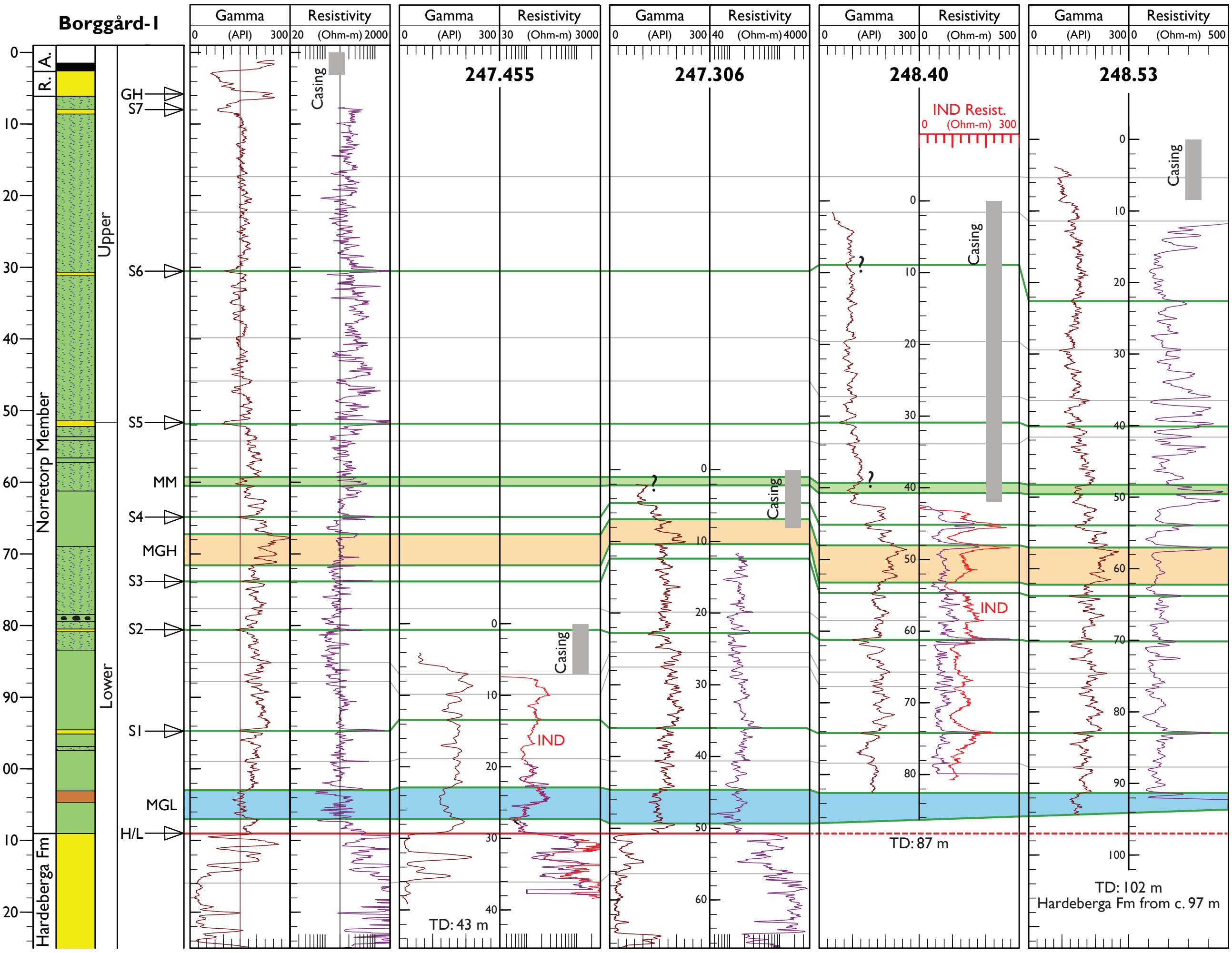


Fig. 14. Log panel showing correlation of the Læså Formation in the Stenseby block, continued (see also Fig. 13); for location of wells, see Fig. 1. The base of the Læså Formation serves as datum plane for correlation except for 248.40, where log-marker S1 is used as datum. The Quaternary section of the logs is omitted. Legend in Fig. 9 and Tables 1–2.

gamma radiation intervals represent impure clayey sandstone that is thoroughly bioturbated, and which most probably also contains organic matter. The impure sandstone horizons are separated by clean sandstone beds showing the reverse log motif, i.e. low gamma radiation and high resistivity. Due to the high gamma ray peaks associated with the impure sandstone horizons, it is not always possible to readily pinpoint the boundary between the Hardeberga and Læså formations on the wireline logs. The formational transition is, however, invariably characterized by a marked upwards decline in resistivity (typically across *c*. 1 m) and it is usually also associated with a rather inconspicuous minor gamma radiation spike exactly at the boundary (see e.g. Fig. 3). Even more importantly, the lowermost part of the Læså Formation has a very characteristic gamma ray log motif including the MGL marker that is consistently and routinely recognizable between wells (e.g. Fig. 15). Probably due to the bioturbated clayey interbeds, the uppermost part of the Hardeberga Formation is significantly less hard to drill than the underlying main part of the unit. In fact, during drilling of Borggård-1, the formational boundary was recognized only after core take up. Probably for this reason, the boundary between the Hardeberga and Læså formations seems to be picked some metres too deep in many non-cored water supply wells and caution should be taken when using the specific depth information in the Jupiter database on the formational boundary in wells without wireline logs.

Near the top of the Læså Formation, the distinctive GH peak serves as marker for the boundary between the Norretorp and Rispebjerg members. Between the studied wells, the gamma ray log motif around this boundary varies quite significantly and the Rispebjerg Member is most readily identified when a resistivity log is also at hand (see especially Fig. 10). Above the GH marker, the gamma radiation intensity typically decreases, whereas the resistivity increases markedly up through the Rispebjerg Member, as should be expected due to the sandy lithology. However, also this pattern is surprisingly variable between wells, probably due to the common presence of reworked glauconite and phosphorite in the sandstone (as seen in the drill cores from Borggård-1, Billegrav-2 and Sommerodde-1). Upwards, the gamma radiation intensity increases abruptly at the base of the Alum Shale Formation whilst the resistivity decreases. Accordingly, the upper boundary of the Læså Formation is straight forward to identify on wireline logs albeit with an uncertainty of a few decimetres introduced by phosphorite impregnation of the very top of the Rispebjerg Member in combination with the occurrence of the thin Forsemölla–Exsulans limestone bed (10–20 cm thick) at the base of the Alum Shale Formation. This amalgamated limestone, like the underlying sandstone, may be anticipated to have low gamma radiation response and high resistivity, and, hence, is difficult to distinguish on wireline logs, not least due to its thinness. The uncertainty regarding pinpointing the formational boundary on wireline logs is at the scale of a few decimetres.

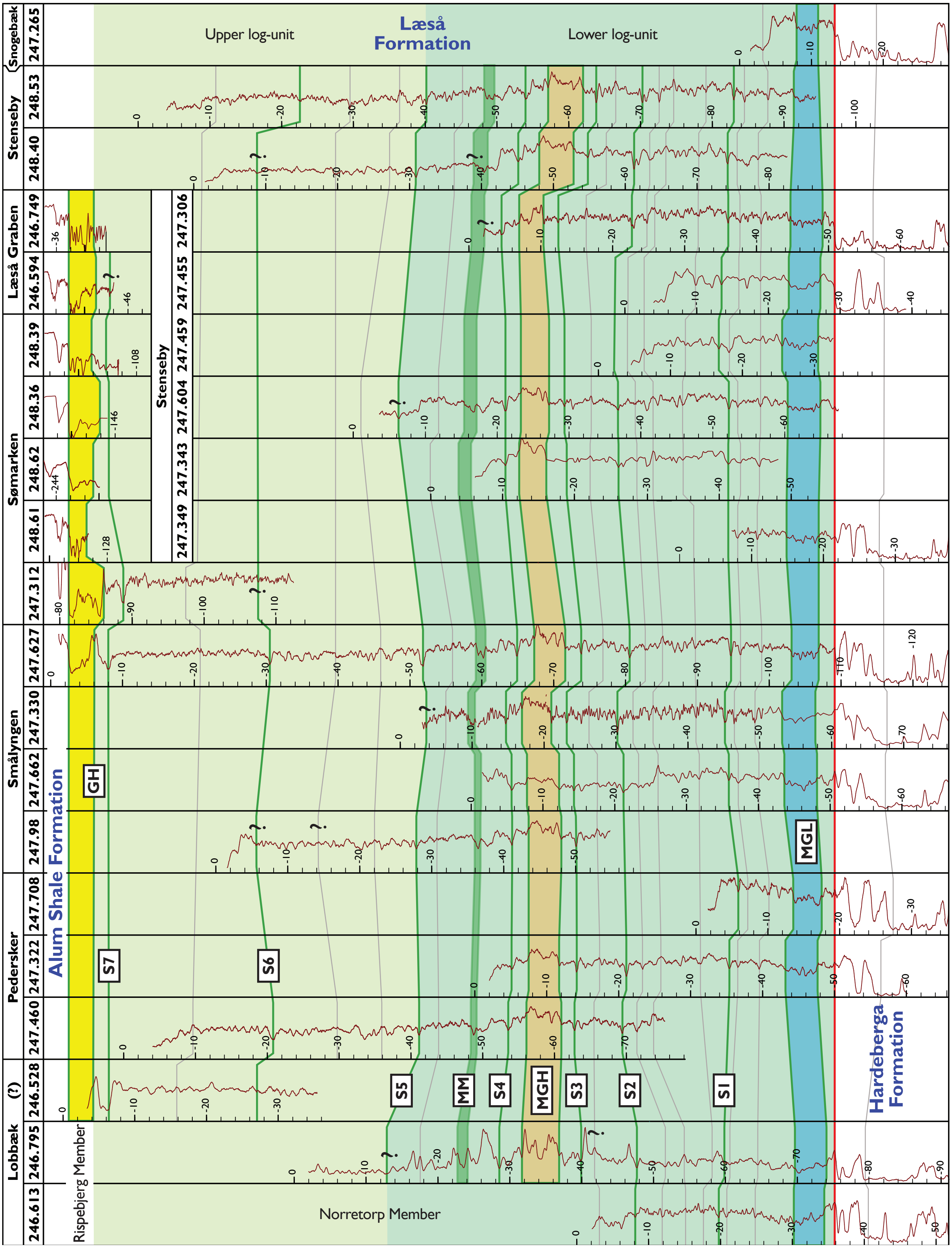
Depositional environment

Hamberg (1991) suggested, based on studies in Skåne, that the intensively bioturbated clayey sandstone horizons in the Hardeberga Formation represent summer periods with calm weather and intense biological activity alternating with stormy winter seasons during which the clean sandstones were deposited. If so, the palaeoenvironment must have been very shallow during deposition of the uppermost part of the Hardeberga Formation on Bornholm and deposition was exceedingly fast.

The shift to deposition of the finer-grained and glauconitic Læså Formation is indicative of a significant sea level rise that outpaced sedimentary supply. Although the Læså Formation was deposited in a moderately deep shelf setting, the sea-floor remained within reach of episodic storm activity throughout deposition, as indicated by the common fine-grained, thin sandstone beds in the Norretorp Member. It is an open question how deep the storm wave base was in the area during the early Cambrian, but storms may have been intense as the adjacent ocean was sizeable (e.g. Cocks & Torsvik 2005). It is also possible that some of the sandstone beds, notably in the lower part of the Norretorp Member, were deposited by (storm generated?) bottom currents below the storm wave base per se. However, in order to investigate this speculation, more detailed studies of the sedimentary structures in the sandstone beds must be undertaken.

The depth varied during deposition of the Læså Formation as evidenced by the variable frequency and thickness of the interbedded tempestites as well as the recurring horizons enriched in glauconite and

▼ **Fig. 15.** Well panel showing correlation of gamma ray logs from the Læså Formation across southern Bornholm. The profile is oriented roughly NW–SE (compare Fig. 1), except for the short well sections in the Sømarken block and the Læså Graben that are shown above the Stenseby block wells due to space constraints. For details, see the individual log panels from the various fault blocks (Figs 9–14). The log of the Quaternary section has been omitted in all wells. Note that a few correlations are based primarily on the resistivity log pattern (see the individual log panels). Legend in Fig. 9.


Snogebæk
247.265
Stenseby
248.53
248.40
Læså Graben
246.749
246.594
Sømarken
248.39
248.36
248.62
248.61
247.312
Smålyngen
247.627
247.330
247.662
247.98
Pedersker
247.708
247.322
247.460
(?)
246.528
Lobbæk
246.795
246.613
Stenseby
247.306
247.455
247.459
247.604
247.343
247.349
Upper log-unit
Læså Formation
Lower log-unit
Alum Shale Formation
Rispebjerg Member
Norretorp Member
Hardeberga Formation
GH
S7
S6
S5
MM
S4
MGH
S3
S2
S1
MGL

phosphorite (see also Nielsen & Schovsbo 2011). It should in this context be kept in mind that many sand beds, particularly in the ≈upper half of the Norretorp Member, have been obliterated by bioturbation, which is ubiquitous and generally extensive from immediately above the MGL marker and upwards. The upper ≈half of the Norretorp Member is thus sand-mixed and only a few thick tempestites have 'survived' bioturbation. The recognized lower and upper main log-units thus reflect the changing depth conditions during deposition of the Norretorp Member, with the lower log-unit being deposited in a relatively deep environment with repeated precipitation of glauconite and phosphorite due to the comparatively low sedimentary supply, whereas the upper log-unit signals the upwards shallowing associated with increased influx of sand.

The frequent sea level changes during deposition of the Læså Formation are suspected to reflect glacio-eustasy and the widespread regression, indicated by the Rispebjerg Member, was probably caused by an early Cambrian glacial interlude (cf. Nielsen & Schovsbo 2011). This sea level fall culminated in emergence of even the most distal locations on the Baltica palaeocontinent preserved in the geological record (Nielsen & Schovsbo 2011). The major 'Rispebjerg regression' was in turn succeeded by a very significant sea level rise in the late early Cambrian. This major rise led to deposition of the condensed, outer shelf Gislöv Formation (preserved only in Skåne, but inferred to have been originally present also in the Bornholm area) and the event has all the characteristics of a post-glacial sea level rise being rapid, significant (size order of 100 m) and taking place in pulses (cf. Nielsen & Schovsbo 2011). The forced 'Rispebjerg regression' and following abrupt sea level rise have significant potential for intercontinental correlation.

Despite the variable occurrence of glauconite, phosphorite and sandstone interbeds in the Norretorp Member, it is essentially impossible to identify in individual outcrops which part of the unit that is exposed. Hansen (1936) recognized five subdivisons of the 'Green shales' that broadly corresponds to the lower and upper log-units distinguished here, separated by a middle interval with glauconite and phosphorite (here assigned to the lower log-unit) and with thin lower and upper transitional units. However, most exposures could not be assigned to the respective subunits by Hansen (1936) and he also underestimated their thickness.

The only unique and readily identified lithological interval within the Norretorp Member is the red-brown horizon (Fig. 4F–G), located at 4.3–5.7 m above the base of the Læså Formation in Borggård-1. This characteristic horizon seems to be present in all wells penetrating this level, but it is poorly exposed in natural outcrops and has not been described previously. The deviating colour brings the approximately coeval 'Red and Green member' of the Torneträsk Formation in northern Sweden to mind (see Nielsen & Schovsbo 2011 and references therein), but the exact depositional conditions responsible for this striking intercalation in the lowermost part of the Norretorp Member remain uncertain. It may represent maximum flooding conditions during deposition of the Læså Formation and if so, the tentative MFS interpretation of sequence LC1-5 indicated in Fig. 3 (based on Nielsen & Schovsbo 2011) needs adjustment.

Syndepositional tectonism?

A significant shift in regional subsidence pattern occurred in southern Scandinavia associated with the Hawke Bay uplift event at around the early/mid Cambrian transition (Nielsen & Schovsbo 2015). Before that event, the regional slope was southwards from Skåne to Bornholm, whereas it reversed afterwards due to prolonged uplift of the southern margin of Baltica, lasting until around the Ordovician–Silurian transition (Nielsen & Schovsbo 2011, 2015). During this uplift interval, the southern margin of Baltica experienced recurrent isostatic adjustments, probably relating to pulses of plate tectonic reorganisation, and the Cambro–Ordovician Alum Shale and overlying Ordovician formations display thickness differences across southern Bornholm (Nielsen *et al.* 2018; see also Nielsen 1995, fig. 42). Still, there must have been some tectonic/isostatic unrest in southern Scandinavia also during the early Cambrian, as the Norretorp Member is considerable thinner and stratigraphically incomplete in Skåne compared with Bornholm, which is remarkable considering that the sedimentary supply to the Bornholm area broadly speaking must have been from the north (cf. Nielsen & Schovsbo 2011). In some parts of Skåne, the Norretorp Member is even absent (see introductory section on the regional distribution of the Læså Formation). The reduced thickness and local absence in Skåne is suggestive of differential uplift that apparently took place concurrently with downwarp of Bornholm. Despite this evidence for syndepositional tectonic activity, the Læså Formation is of surprisingly constant thickness throughout southern Bornholm, with possible variation between wells of only a few metres (Fig. 15). The Læså Formation may thus be only *c.* 100 m thick in the Lobbæk area, but confirmed figures are available only from Borggård-1, where the unit is 106.4 m thick. The possible thickness difference is not obvious from Fig. 15, using the Læså/Hardeberga and the Læså/Alum Shale boundaries as datums, see instead remarks on the Lobbæk block. The small differences in thickness may relate to the general clastic supply from the north, as it is an overall impression that at least the middle and lower parts of the Norretorp Member are thinning slightly in a southwards direction within the Stenseby block (see level of the MGH marker in Fig. 15).

On Bornholm, sandstone dykes described from the basement at Listed have been inferred to correlate in age with the Læså Formation due to their content of chlorite and minor glauconite (Bruun-Petersen 1975). Many of the sandstone dykes in the basement elsewhere on eastern Bornholm have also been described as greenish in colour (Ussing 1899, Grönwall 1916). A chlorite content has also been reported from a sandstone dyke at Vang on northern Bornholm (Katzung & Obst 1997). Other clastic dykes in the basement on Bornholm are seemingly filled with comparatively clean quartz sand without chlorite matrix (e.g. Grönwall 1916; see also Katzung & Obst 1997). This quartz sand presumably originates from the Hardeberga Formation (see also Grönwall 1916) and if the Hardeberga sand was not lithified at the time of fissure formation, it is likely that also the overlying Læså siltstone was not fully lithified either. Hence, the lithology of the sedimentary dykes on Bornholm may not be a valid indicator of their age. In Skåne, the largest of the spectacular 'funnel grabens' described from the Hardeberga Formation by Lindström (1967) contains disturbed Alum Shale in the centre, suggesting that these structures formed in the earliest late Cambrian (Furongian). Coeval Alum Shale fissure-fillings have been described from the basement near Göteborg (Samuelsson 1967) and this phase of disturbance may potentially also have affected Bornholm. In any case, even if the discussed clastic dykes are indicative of early Cambrian earthquake activity, the uniform thickness of the Læså Formation across southern Bornholm firmly establish a post-depositional age of the many faults in the area. The faulting likely commenced or at least had its main phase in the late Carboniferous–early Permian and was followed by several subsequent phases of fault activity (cf. Graversen 2009).

Conclusions

A log-stratigraphy is established for the lower Cambrian Læså Formation of Bornholm, Denmark, based on gamma ray and resistivity wireline logs from 30 wells and shallow scientific boreholes. The suite of logs available from the fully cored Borggård-1 scientific borehole serves as reference section for the outlined correlation.

The Norretorp Member, comprising the greater lower part of the Læså Formation, is divided into two log-stratigraphical units, characterized by different gamma ray and resistivity log patterns. These main log-units are further subdivided by recognition of seven thin sandstone horizons (labelled S1 to S7 and inferred to represent tempestites), marked by gamma radiation minima and corresponding resistivity peaks. Besides, four levels with characteristic high or low gamma radiation, named MGL, MGH, MM and GH, can be traced consistently in most wells. The two main log-units reflect a more common occurrence of glauconite and phosphorite in the lower part of the Norretorp Member and a higher sand content in the upper part.

The shift to deposition of the silty and glauconitic Læså Formation was due to a sea level rise that outpaced sedimentary supply and the formation was deposited in a moderately deep shelf setting. Even so, the sea-floor remained within reach of episodic storm activity throughout deposition, accompanied by deposition of thin, fine-grained sand beds. The depth varied during deposition of the Læså Formation with a general upwards shallowing. The lower and upper main log-units in the Norretorp Member bear out this shoaling, with the lower log-unit reflecting a relatively deep environment associated with repeated sedimentary starvation and precipitation of glauconite and phosphorite, whereas the upper log-unit reflects the upwards shallowing associated with increased influx of sand and intensification of bioturbation.

The recurring presence of glauconite and phosphorite and the variable occurrence of sandy tempestites (many of which have been mixed with the 'host sediment' due to bioturbation) are suggestive of minor sea level changes during deposition. The frequent sea level changes conceivably reflect glacio-eustasy and the significant and widespread regression, signalled by the Rispebjerg Member, was probably caused by an early Cambrian glacial interlude. This forced 'Rispebjerg regression' was in turn succeeded by a major sea level rise in the late early Cambrian, plausibly caused by de-glaciation. The regression and following abrupt sea level rise have considerable potential for intercontinental correlation.

A conspicuous red-brown horizon, *c*. 1.5 m thick, is located shortly above the base of the Læså Formation. This characteristic horizon seems to be present in all wells penetrating this level. It may represent maximum flooding conditions during deposition of the Læså Formation.

The Læså Formation is of essentially uniform thickness throughout southern Bornholm (100? to 106 m), demonstrating a post-depositional age of the many faults in the area. This is also in accordance with the sheet-like distribution of the abundant tempestites in the Norretorp Member. Sandstone dykes described from the basement at Listed have been previously inferred to correlate in age with the Læså Formation, potentially indicating syndepositional earthquake activity, but they may be younger, perhaps early late Cambrian (early Furongian).

Acknowledgements

The cost of drilling the Borggård-1 borehole was funded by Geocenter Copenhagen (grant 2-2006), Maersk Oil and Gas, Altinex Oil, Odin Oil, Wexco and Sparekassen Bornholms Fond, which is gratefully acknowledged. Jesper Furdal, Awell Brøndboring, is thanked for sharing log data from the recently drilled 247.708. Arden Bashforth, collections manager at the Natural History Museum of Denmark, kindly facilitated access to the Borggård-1 core. Constructive comments and suggestions by referees Gunver Krarup Pedersen and Niels Hemmingsen Schovsbo improved the final manuscript.

References

Ahlberg, P. 1984: Lower Cambrian trilobites and biostratigraphy of Scandinavia. Lund Publications in Geology 22, 37 pp.

Andersen, G. 2001: Program til beregning af gamma spektral logs fra boringer. Danmarks og Grønlands Geologiske Undersøgelse rapport 2001/80, 32 pp. http://dx.doi.org/10.34194/raekke3.v38.6943

Bergström, J. 1981: Lower Cambrian shelly faunas and biostratigraphy in Scandinavia. In: Taylor, M.E. (ed.): Short Papers for the Second International Symposium on the Cambrian System 1981. U.S. Geological Survey Open-File Report 81-743, 22–25. http://dx.doi.org/10.3133/ofr81743

Bruun-Petersen, J. 1975: Origin and correlation of the sandstone dykes at Listed, Bornholm, (Denmark). Bulletin of the Geological Society of Denmark 24, 33–44. http://dx.doi.org/10.37570/bgsd-1996-43-06

Cederström, P., Geyer, G., Ahlberg, P., Nilsson, C.H. & Ahlgren, J. 2022: Ellipsocephalid trilobites from Cambrian Series 2 and Stage 4, with emphasis on the taxonomy, morphological plasticity and biostratigraphic significance of ellipsocephalids from Scania, Sweden. Fossils and Strata 67, 131 pp. http://dx.doi.org/10.18261/9788215065779-2022-01

Clausen, C.K. & Vilhjálmsson, M. 1986: Substrate control of Lower Cambrian trace fossils from Bornholm, Denmark. Palaeogeography, Palaeoclimatology, Palaeoecology 56, 51–68. http://dx.doi.org/10.1016/0031-0182(86)90107-0

Clemmensen, L.B., Bromley, R.G. & Holm, P.M. 2011: Glauconitic deposits at Julegård on the south coast of Bornholm, Denmark dated to the Cambrian. Bulletin of the Geological Society of Denmark 59, 1–12. http://dx.doi.org/10.37570/bgsd-2011-59-01

Cocks, L.R.M. & Torsvik, T.H. 2005: Baltica from the late Precambrian to mid-Palaeozoic times: The gain and loss of a terrane's identity. Earth-Science Reviews 72, 39–66. http://dx.doi.org/10.1016/j.earscirev.2005.04.001

de Marino, A. 1980: Sandstones and phosphatized calcareous sediments of the Lower Cambrian Rispebjerg Sandstone, Bornholm, Denmark. Danmarks geologiske Undersøgelse II. række 113, 19 pp. http://dx.doi.org/10.34194/raekke2.v113.6904

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, 25–49. http://dx.doi.org/10.37570/bgsd-2009-57-02

Grönwall, K.A. 1916: Palæozoiske Dannelser. In Grönwall, K.A. & Milthers, V. 1916. Kortbladet Bornholm. Danmarks geologiske Undersøgelse I. række 13, 43–86. http://dx.doi.org/10.34194/raekke1.v13.6767

Gry, H. 1977: Bornholms undergrund. In Hansen, M. & Poulsen, V. (eds): Geologi på Bornholm, 2. edition, p. 4. Varv ekskursionsfører 1, København: Tidsskriftet Varv. [Gry is not credited as specific co-author of the map as in the first edition of the guide-book published 1969, but it is his unpublished mapping of the pre-Quaternary sediments on Bornholm that formed the basis for this map].

Hamberg, L. 1991: Tidal and seasonal cycles in a Lower Cambrian shallow marine sandstone (Hardeberga Fm.), Scania, Southern Sweden. In: Smith, D.G., Reinson, G.E., Zaitlin, B.A. & Rahmani, R.A. (eds): Clastic Tidal Sedimentology. Canadian Society of petroleum Geologists, Memoir 16, 255–274.

Hansen, K. 1936: Die Gesteine des Unterkambriums von Bornholm Nebst einigen Bemerkungen über die Tektonischen Verhältnisse von Bornholm. Danmarks Geologiske Undersøgelse II. række 62, 194 pp. http://dx.doi.org/10.34194/raekke2.v62.6850

Hansen, K. 1937: Sammenlignende studier over kambriet i Skåne og paa Bornholm. Meddelelser fra Dansk geologisk Forening 9, 151–182.

Katzung, G. & Obst, K. 1997: The sandstone dyke swarm of Vang, Bornholm (Denmark). Bulletin of the Geological Society of Denmark 44, 161–171. http://dx.doi.org/10.37570/bgsd-1998-44-10

Lindström, M. 1967: "Funnel Grabens" and Early Paleozoic tectonism in South Sweden. Geological Society of America Bulletin 78, 1137–1154. http://dx.doi.org/10.1130/0016-7606(1967)78[1137:fgaept]2.0.co;2

McNeill, J.D. 1980: Electrical Conductivity of Soils and Rocks. Geonics, Technical Note 5, 22 pp.

Moczydłowska, M. & Vidal, G. 1992: Phytoplankton from the Lower Cambrian Læså Formation on Bornholm, Denmark: biostratigraphy and palaeoenvironmental constrains. Geological Magazine 129, 17–40. http://dx.doi.org/10.1017/s0016756800008104

Nielsen, A.T. 1995: Trilobite systematics, biostratigraphy and palaeoecology of the Lower Ordovician Komstad Limestone and Huk Formations, southern Scandinavia. Fossils and Strata 38, 374 pp. http://dx.doi.org/10.18261/8200376583-1995-01

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. http://dx.doi.org/10.37570/bgsd-2006-53-04

Nielsen, A.T. & Schovsbo, N.H. 2011: The Lower Cambrian of Scandinavia: Depositional environment, sequence stratigraphy and palaeogeography. Earth-Science Reviews 107, 207–310. http://dx.doi.org/10.1016/j.earscirev.2010.12.004

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. http://dx.doi.org/10.1016/j.earscirev.2015.09.012

Nielsen, A.T. & Ahlberg, P. 2019: The Miaolingian, a new name for the 'Middle' Cambrian (Cambrian series 3): Identification of lower and upper boundaries in Baltoscandia. GFF 141, 162–173. http://dx.doi.org/10.1080/11035897.2019.1621374

Nielsen, A.T., Klitten, K. & Hansen, H.P.B. 2006: Borggård-1: En ny stratigrafisk kerneboring på Bornholm. Geologisk Nyt 2006(6), 18–24. http://dx.doi.org/10.7146/gn.v0i6.3560

Nielsen, A.T., Schovsbo, N.H., Klitten, K., Woollhead, D. & Rasmussen, C.M.Ø. 2018: Gamma-ray log correlation and stratigraphic architecture of the Cambro-Ordovician Alum Shale Formation on Bornholm, Denmark: Evidence for differential syndepositional isostasy. Bulletin of the Geological Society of Denmark 66, 237–273. http://dx.doi.org/10.37570/bgsd-2018-66-15

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. http://dx.doi.org/10.37570/bgsd-1988-37-13

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., Babcock, L. & Ahlberg, P. 2020: The Cambrian Period. In F.M. Gradstein, J.G. Ogg, M.D. Schmitz & G.M. Ogg (eds): Geologic time scale 2020, 565–629. Elsevier. http://dx.doi.org/10.1016/b978-0-12-824360-2.00019-x

Poulsen, C. 1942: Nogle hidtil ukendte fossiler fra Bornholms Exsulanskalk. Meddelelser fra Dansk Geologisk Forening 10, 212–235. http://dx.doi.org/10.1016/0012-8252(68)90138-4

Poulsen, C. 1967: Fossils from the Lower Cambrian of Bornholm. Det Kongelige Danske Videnskabernes Selskab Matematisk-fysiske Meddelelser 36(2), 48 pp.

Poulsen, C. 1974: Further contributions to the knowledge of the Palaeozoic of Slagelse no. 1, western Sealand. Danmarks Geologiske Undersøgelse II. Række 101, 42 pp. http://dx.doi.org/10.34194/raekke2.v101.6892

Poulsen, V. 1965: The Oldest Trilobite Remains from Denmark. Meddelelser fra Dansk Geologisk Forening 15, 559–560. http://dx.doi.org/10.37570/bgsd-1977-26-15

Poulsen, V. 1966: Cambro-Silurian stratigraphy of Bornholm. Meddelelser fra Dansk Geologisk Forening 16, 117–137.

Samuelsson, L. 1967. Breccia av paleozoiska bergarter 1.5 km väster om Bohus Fästning Kungälv. Geologiska Föreningen i Stockholm Förhandlingar 89, 448–459. http://dx.doi.org/10.1080/11035896709448385

Schovsbo, N.H. 2011: The Lower Palaeozoic sequence in the Terne-1 well. Danmarks og Grønlands Geologiske Undersøgelse Rapport 2011/98, 69 pp.

Schovsbo, N.H., Nielsen, A.T. & Klitten, K. 2015: The Lower Palaeozoic now fully cored and logged on Bornholm, Denmark. Geologic survey of Denmark and Greenland Bulletin 33, 9–12. http://dx.doi.org/10.34194/geusb.v33.4477

Sivhed, U., Wikman, H. & Erlström, M. 1999: Beskrivning till berggrundskartorna 1C Trelleborg NV och NO samt 2C Malmö SV, SO, NV och NO. Sveriges Geologiska Undersökning Af 191–194, 196 and 198, 143 pp.

Surlyk, F. 1980: Denmark. In Geology of the European countries, Denmark, Finland, Iceland, Norway, Sweden, 1–50. Dunod. (Published in cooperation with the Comité National Francais de Géologie (C.N.F.G.) on the occasion of the 26th International Geological Congress).

Sørensen, T. 1978: Geofysiske borehuls-logs i Nedre Kambrium på Bornholm. Dansk Geologisk Forening Årsskrift for 1977, 1–3.

Torsvik, T.H. & Rehnström, E.F. 2001: Cambrian palaeomagnetic data from Baltica: implications for true polar wander and Cambrian palaeogeography. Journal of the Geological Society (London) 158, 321–329. http://dx.doi.org/10.1144/jgs.158.2.321

Torsvik, T.H., Olesen, O., Ryan, P.D. & Trench, A. 1990: On the palaeogeography of Baltica during the Palaeozoic: new palaeomagnetic data from the Scandinavian Caledonides. Geophysical Journal International 103, 261–279. http://dx.doi.org/10.1111/j.1365-246x.1990.tb01768.x

Ussing, N.V., 1899: Sandstengange i Granit paa Bornholm. Danmarks Geologiske Undersøgelse II. række 10, 87–98. http://dx.doi.org/10.34194/raekke2.v5.6787

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. http://dx.doi.org/10.1080/14772019.2012.740080