Lower Cretaceous (Hauterivian–Aptian) pelagic carbonates in the Danish Basin: new data from the Vinding-1 well, central Jylland, Denmark

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Understanding of the shallow shelf system in the Danish Basin during the Early Cretaceous has benefitted significantly from studying the previously overlooked Hauterivian–Aptian section of the Vedsted Formation of the Vinding-1 drill core. The presence of chalks in this section demonstrates that carbonate-rich pelagic sediment accumulated locally in the siliciclastic-dominated Danish Basin and that benthic carbonate production was insignificant. The area was not a carbonate platform in the Early Cretaceous and does not indicate any reworked carbonate supply from platform environments in the vicinity. The scarcity of benthic macrofossils in the cored section is due to the lack of a specialised boreal chalk fauna at that time, and the adjacent nearshore environment apparently did not support any substantial benthic carbonate production. A revised biostratigraphy of the cored section is presented based primarily on calcareous nannofossils, supported by foraminifera, ostracods, and belemnites. Four lithofacies describe the spectrum from marlstone to slightly marly chalk, and the facies succession characterises four depositional units recording two discrete transgressive–regressive cycles. The study provides a depositional record that permits sequence stratigraphic correlation to the Valdemar and Adda Fields in the Central Graben.

Keywords: Danish Basin, Lower Cretaceous, chalk and marl, old wells, biostratigraphy.

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Hauterivian–Aptian chalks of the Tuxen and Sola Formations in the Danish Central Graben, North Sea, are important both due to their hydrocarbon reservoir potential (Copestake *et al.* 2003; Jakobsen *et al.* 2004, 2005; van Buchem *et al.* 2017), and from a palaeoecological and palaeoceanographic point of view as a unique Early Cretaceous precursor to the Late Cretaceous chalk sea of northern Europe (Ineson 1993; Ineson *et al.* 1997; Mutterlose 1998; Bischoff & Mutterlose 1998; Löb & Mutterlose 2012; Mutterlose & Bottini 2013).

Renewed focus on these Lower Cretaceous carbonate reservoirs has underlined the requirement for detailed predictive models of this complex layered heterogeneous chalk–marl reservoir (e.g., van Buchem *et al.* 2017) and this demands a refined depositional and palaeogeographical understanding of the successions. Central to the understanding of the carbonate component of the dual carbonate–siliciclastic system are the relative roles of pelagic and benthic carbonate production in the accumulation of reservoir-quality chalks in the Central Graben. In addition to a detailed study of the carbonates of the Tuxen and Sola Formations, a better understanding of the regional palaeogeography is required to assess the potential role of benthic carbonate production in the shelf regions bordering the Central Graben. In particular, the eastern parts of the Danish Basin may potentially have exported significant carbonate sediment to the Danish Central Graben (Fig. 1). In this context, vintage exploration wells in the Danish Basin were screened and investigated, focussing particularly on wells with significant cored sections in the Lower Cretaceous Vedsted Formation.

The aim of this paper is to present a previously overlooked cored Hauterivian–Aptian carbonate-rich section of the Vedsted Formation from the Vinding-1 well and to correlate the sequences to the Central Graben.

Geological and stratigraphic setting

Danish Basin

The intracratonic Danish Basin is separated from the stable Precambrian Baltic shield by the Fennoscandian Border Zone to the north-east and bounded by the Ringkøbing –Fyn High towards the south (Fig. 1). The basin comprises a Permian to Cenozoic sedimentary succession formed due to Late Carboniferous to Early Permian crustal extension followed by subsidence controlled by thermal cooling and local faulting (Sorgenfrei & Buch 1964; Nielsen 2003). Subsidence accelerated during the Late Jurassic and the depositional area gradually increased in size and depth (Vejbæk 1989, 1997). Previous studies have suggested that continuous deposition is recorded in the north-western part of the Danish Basin from the Late Jurassic to the Early Cretaceous, with hiati recorded along the boundaries of the basin (Larsen 1966). A general shallowing of the basin towards the Ringkøbing –Fyn High characterised the same period (Nielsen 2003). Halokinetic related movements affected the Danish Basin from the middle to the Late Triassic. The Sorgenfrei –Tornquist Zone was repeatedly reactivated during the Triassic, Jurassic and Early Cretaceous, although movement was minor compared to the tectonic events of the Late Carboniferous to Early Permian and the Late Cretaceous (Mogensen & Korstgård 2003).

From the Valanginian to the early Barremian, the Central Graben and the Danish Basin experienced an overall sea-level rise and the climate generally became more arid, and consequently less siliciclastic material entered the area (Ruffell 1991; Ineson 1993; Hardenbol *et al.* 1998; Mutterlose 1998; Copestake *et al.* 2003; Haq 2014, van Buchem *et al.* 2017). By the late Hauterivian to early Barremian, pelagic carbonate production was dominant in areas remote from clastic input and in sediment starved zones. Some beds contained nannoconids (a group of calcareous nannofossils) and coincide with increased nutrient and clay input connected to short-term sea-level falls and greenhouse conditions (Mutterlose 1998; Copestake *et al.* 2003; Löb & Mutterlose 2012; Mutterlose & Bottini 2013).

The Barremian to Aptian boundary is marked by a major change in the palaeoceanographic setting caused by a widespread transgression that altered marine circulation patterns and was probably linked to an increase in sea-floor spreading rate that peaked in the early Aptian (Ruffel 1991; Mutterlose 1998; Copestake *et al.* 2003). During the Aptian, several transgressions and regressions characterised the Danish Basin and new seaways between the Tethys and the Boreal Realm opened via northern France and southern England (Mutterlose & Böckel 1998). These palaeoceanographic changes from restricted marginal seas to widespread homogenous pelagic-dominated seas resulted in the extinction of various floral and faunal elements in the Tethyan and Boreal realms followed by the evolution of new genera and species (Mutterlose 1998).

Lower Cretaceous stratigraphy

The Vedsted Formation of the Danish Basin spans the Valanginian to Albian and is named after the Vedsted-1 borehole in Jylland (Larsen 1966; Table, 1). The lower boundary of the Vedsted Formation coincides with the transition from marine silty clay to less silty clay (Larsen 1966). The Rødby Formation, which overlies or in some places was possibly deposited at the same time as the upper part of the Vedsted Formation, consists of marine red marlstones and marly chalks (Table, 1). Its base is suggested to be late Aptian or early Albian in age in the Danish Basin (Sorgenfrei & Buch 1964).

The lower part of the Vedsted Formation is equivalent to the Valhall Formation in the Danish Central Graben (Table 1). The upper Vedsted Formation is time-equivalent to the Tuxen Formation (Hauterivian to late Barremian; Heilmann-Clausen 1987; Thomsen 1987), the succeeding Sola Formation (late Barremian to early Albian; Jensen *et al.* 1986) and the Rødby Formation (from late Aptian, Sorgenfrei & Buch 1964 mainly in the Albian, Heilmann-Clausen 1987 to possibly early Cenomanian, Jensen *et al.* 1986).

To the east, Danish Lower Cretaceous deposits outcrop on Bornholm and include latest Ryazanian to

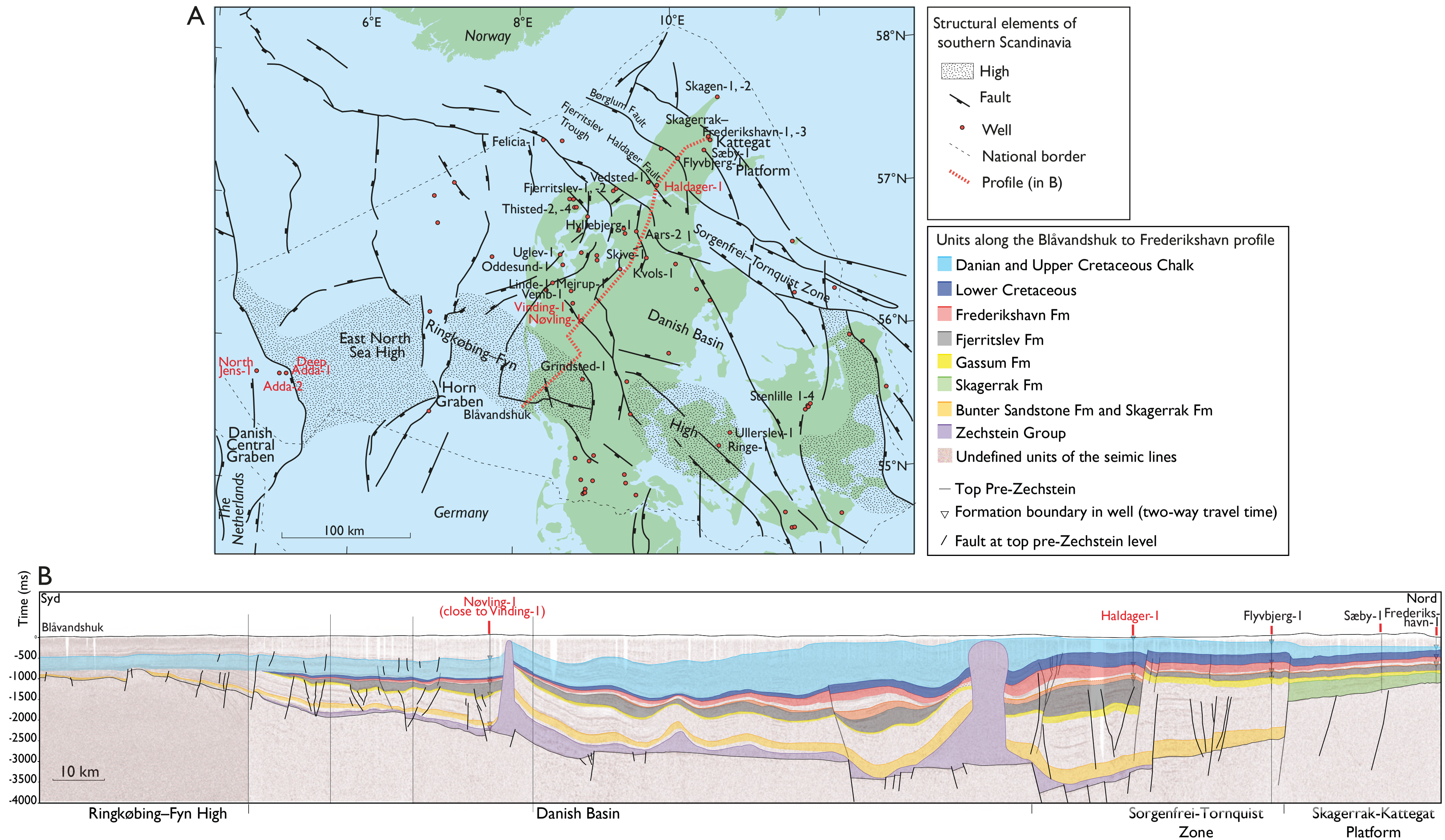


Fig. 1. A: Map of the Danish Basin highlighting the relevant wells, structural highs, faults, and the location of the profile illustrated in B. The Vinding-1, Haldager-1 and Nøvling-1 wells under focus here are indicated in red. The North Jens, Adda-2 and Deep Adda wells from the Danish Central Graben mentioned in the text are also shown in red. **B:** Seismic profile from Blåvandshuk in the south to Frederikshavn in the north (Vosgerau *et al.* 2016); the location of the profile is indicated in Fig. 1A. The profile is derived from the geothermal potential maps at https://dybgeotermi.geus.dk and used with permission. Lower Cretaceous is shown in dark blue. Nøvling-1 is close to Vinding-1 and they both appear on the same side of the fault.

Table 1. Stratigraphy and main lithologies of the onshore Lower Cretaceous in North-west Europe compared to Vinding-1 from the Danish Basin.

		Stage	Formations: Danish Central Graben	Formations: Danish Basin	Vinding-1	Denmark (outcrops)	NW Germany (outcrops)	Helgoland, Dünen Island (partly outcropping)	NE England (outcrops)	S England (outcrops)
Lower Cretaceous	**Albian**	late								
		early	Rødby Fm		Chalk	*Ammonites of early Albian age in the Lower Cenomanien Arnager Greensand conglomerate indicate previous deposits on Bornholm*	Condensed section		Poorly lithified mudstones and calcareous mudstones. Greensand common around the Aptian/Albian boundary	
	Aptian	late								
		early	Sola Fm		Marly chalk, slightly marly chalk and marlstone		Dark laminated clays	Laminated dark clays (Fishschiefer) and pale clays		Sandstone and grey clay
	Barremian	late					Finely laminated clay	Dark grey clays and marly clays	Clay and marl beds, mid-Barremian Cementstone	Dark grey to black laminated clays and marls beds, mid-Barremian cementstone
		early			Marly chalk					
	Hauterivian	late	Tuxen Fm	Vedsted Fm	Glauconitic marlstone and marlstone		Clay		Clay	
		early	Valhall Fm		Silt and sandy shale					
	Valanginian	late					Clay, sandstone horizons and sideritic nodules		Phosp nodule bed	
		early	Leek Mb		*Not studied*					
	Berriasian/ Volgian	late	Mandal Fm	Frederikshavn Fm/ Børglum Fm		Sand, silt and clay with plantfragments	Mud, sandstone and coal		Clay, ironstone, nodular beds	
		early								

The upper Vedsted Formation is time equivalent to the Tuxen Formation, the succeeding Sola Formation and the Rødby Formation in the Danish Central Graben. Outcrops of Lower Cretaceous age in Denmark are rare. Early Albian on Bornholm are in italics because the unit is only confirmed as early Albian ammonites in a Cenomanian conglomerate. The north-west Germany data are from Ruffel (1991); Mutterlose (1992); Mutterlose & Böckel (1998); Löb & Mutterlose (2012). The lower Albian is represented by a condensed section and the upper Albian is not present in Germany (Ruffel 1991; Vejbæk et al. 2010). Data on Dünen Island, Helgoland, are from Bishoff & Mutterlose (1998). Data from Speeton, NE England are from Ruffel (1991).

earliest Valanginian nearshore and terrestrial deposits of the Rabekke, Robbedale and Jydegård Formations (Gravesen *et al.* 1982; table 1). These formations are older than the North Sea Tuxen and Sola formations and are possibly time-equivalent with the lowermost Vedsted Formation. In southern Sweden, Lower Cretaceous strata (50–300 m thick) are encountered in deep boreholes in fault-bounded basins. These Valanginian to Hauterivian deposits are dominated by argillaceous sandstones, locally calcareous and rich in glauconite and phosphate (Lindström & Erlström 2011). The Arnager Greensand Formation crops out on Bornholm; the lower part comprises a phosphatic conglomerate that contains reworked nodule clasts yielding a rich early Albian ammonite fauna enclosed in a glauconitic sandstone matrix containing a foraminifera and ammonite fauna suggesting a Cenomanian age (Kennedy *et al.* 1980). This indicates that the Bornholm area was transgressed in earliest Albian time and the deposits were subsequently eroded, phosphatised and relict clasts deposited during a subsequent transgression in the Cenomanian (Kennedy *et al.* 1980). There is no record on Bornholm of deposits from the Barremian–Aptian period.

Vinding-1 well

Brief well history

The Vinding-1 well was only the second deep-test well drilled in the Danish Basin. It was drilled in 1947 and is situated to the south-east of Holstebro (08°41′56″E and 56°17′26″N; Fig. 1). The cored section from 4615′–4262′ (1409.7 to 1299.1 m) spanning cores 25 to 29 (Fig. 2) is Early Cretaceous in age according to Fazekas (1947). The present study focuses on the 4278′–4262′ interval (1303.9 to 1299.1 m) of core 25. Geological descriptions of Vinding-1 are found in an unpublished completion report (Fazekas 1947). The report can be downloaded from GEUS' homepage (frisbee.geus.dk, search for Vinding).

Measurements of the $CaCO_3$ content of the Lower Cretaceous deposits were carried out using the titration method (Fazekas 1947). $CaCO_3$ content ranges from 1–13% in beds older than late Hauterivian and 42– 69% in the lowermost Barremian part (Fig. 2). In the lower Aptian strata, the $CaCO_3$ content ranges from 62–82% and in the upper Albian from 79–88%.

Planktonic and benthic foraminifera were identified for biostratigraphic purposes at the drill site (Fazekas 1947). Ammonites from 4406′6″–4399′ dated this interval as being of early Hauterivian age (Fazekas 1947). O.B. Christensen identified the ostracods in the late 1960s, but the data were never published or included in any of the existing databases at the Geological Survey of Denmark and Greenland (GEUS). Identifications were written directly onto the microscope slides and these notes have been incorporated into the present study.

Chronostratigraphy

Early work carried out on Vinding-1 suggested the presence of 452′ (137.8 m) of Lower Cretaceous deposits as follows: 'Neocomian' (old term for Berriasian, Valanginian and partly Hauterivian) from 4707′–4540′ (1434.7–1383.8 m), Hauterivian from 4540′–4280′ (1383,8–1304,5 m), lower Barremian from 4280′–4277′ (1304.5–1303.6 m) and upper Albian from 4277′–4255′ (1303.6–1296.9 m; Fazekas 1947). The lack of upper Barremian, Aptian, lower and middle Albian was believed to be due to a regional unconformity based on correlation with several other cores in the Danish Basin (Larsen 1966).

The present study confirms the presence of Hauterivian strata from 4540′–4280′ in Vinding-1 and

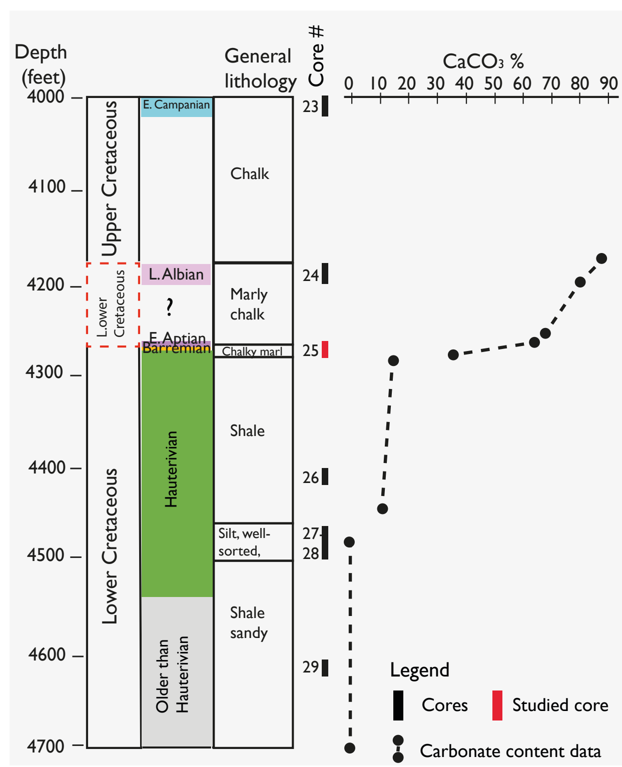
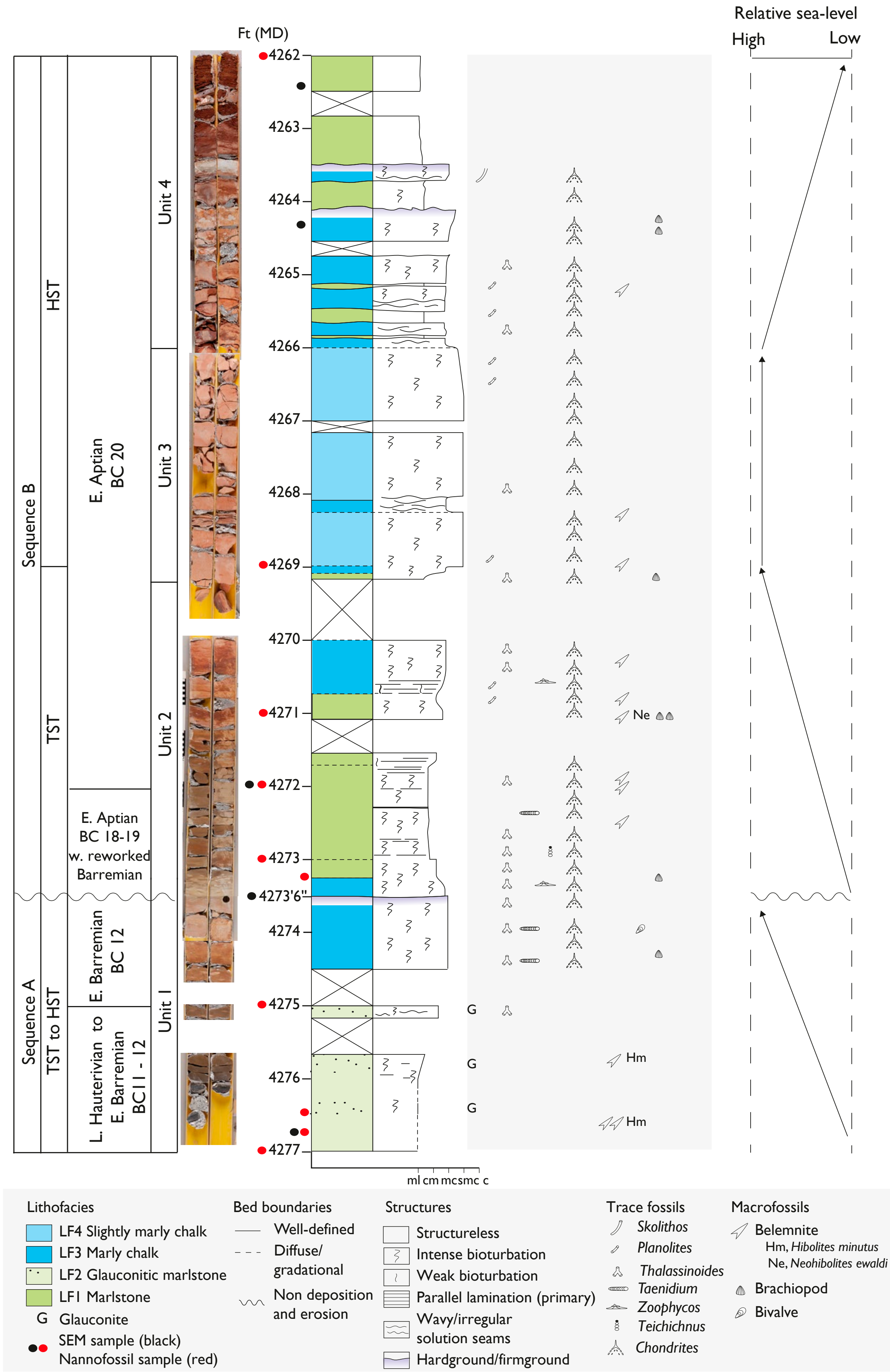


Fig. 2. Revised dating (new Aptian and Albian data from Lower Cretaceous; previously dated as Santonian), general lithology (from the original core descriptions) and $CaCO_3$ content of the Lower Cretaceous and the lower part of the Upper Cretaceous of the Vinding-1 well. The $CaCO_3$ content was analysed in nine selected samples (Fazkas 1947).



Ft (MD)
Relative sea-level
High
Low
4262
4263
4264
4265
4266
4267
4268
4269
4270
4271
4272
4273
4273'6"
4274
4275
4276
4277
Sequence B
Sequence A
HST
TST
TST to HST
E. Aptian BC 20
E. Aptian BC 18-19 w. reworked Barremian
E. Barremian BC 12
L. Hauterivian to E. Barremian BC11 - 12
Unit 4
Unit 3
Unit 2
Unit 1
G
Ne
Hm
ml cm mc smc c
Lithofacies
LF4 Slightly marly chalk
LF3 Marly chalk
LF2 Glauconitic marlstone
LF1 Marlstone
G Glauconite
SEM sample (black)
Nannofossil sample (red)
Bed boundaries
Well-defined
Diffuse/ gradational
Non deposition and erosion
Structures
Structureless
Intense bioturbation
Weak bioturbation
Parallel lamination (primary)
Wavy/irregular solution seams
Hardground/firmground
Trace fossils
Skolithos
Planolites
Thalassinoides
Taenidium
Zoophycos
Teichichnus
Chondrites
Macrofossils
Belemnite
Hm, Hibolites minutus
Ne, Neohibolites ewaldi
Brachiopod
Bivalve

a succession older than Hauterivian from 4707′–4540′, as previously suggested (Fazkas 1947). However, a revised interpretation of the Barremian, Aptian and Albian successions is presented here based on new nannofossil biostratigraphy and previously unpublished foraminifera and ostracod biostratigraphic data. The revised data suggest upper Hauterivian to lower Barremian from 4277–4275′ (1303,6–1303 m); lower Barremian at 4274′ (1302,7 m); lower Aptian from 4273′2′′–4262′ (1302.5–1299.1 m) and upper Albian deposits from 4195′–4180′ (1278.6–1274.1 m; Fig. 2). The revised ages are discussed in the paragraph on biostratigraphy and palaeoecology. Our new data suggest a revised thickness of the Lower Cretaceous in Vinding-1 of at least 512′ (156.1 m), since neither the Lower to Upper Cretaceous boundary nor the Upper Jurassic to Lower Cretaceous boundaries are confirmed in this study. Beds with the revised age of late Albian in this study were previously dated as Santonian (Fazekas 1947).

Unfortunately, wireline log data do not exist for the Vinding-1 well. In the original studies only a general lithological description of the Lower Cretaceous succession based on cuttings along with measured $CaCO_3$-percentages were produced (Fig. 2).

Material and methods

The original Vinding-1 material consists of rock samples, cuttings, and prepared microfossil samples (ostracods and foraminifera, both benthic and planktonic) and is generally of good quality. The newly slabbed core from 4277′–4262′ (15′ or 4.57 m; Fig. 3) is important for improving our understanding of the Lower Cretaceous strata of the Danish Basin and for comparison with the Danish Central Graben.

The seven original foraminifera slides have been restudied for the 4277′–4260′ interval. Ostracod taxonomy undertaken by O.B. Christensen has been reviewed in this study and compared with published data of Neale (1973) and Slipper (2009). Ten new nannofossil samples were selected from a variety of facies for the present study (Fig. 3). Nannofossil smear slides were prepared using the techniques described by Bown & Young (1998) and analysed using a Leica DM 2500 P microscope, applying the simple relative abundance counting technique. The BC nannofossil zonation scheme of Bown *et al.* (1998) and the LK scheme of Jeremiah (2001) were applied. Additional nannofossil identification was carried out using scanning electron microscope (SEM) images.

A detailed core description was made at a scale of 1:5 for the 4277′–4262′ (1303.6–1299.1 m). The core had 94% recovery (Fig. 3). Macrofossils were identified directly from the core material and trace fossils were described from the slabbed core surface.

Polished slabs embedded in epoxy were made for scanning electron microscopy (SEM) studies of selected facies. The SEM laboratory at GEUS is equipped with a ZEISS Sigma 300VP field emission SEM, which uses a Bruker energy dispersive x-ray (EDX) analytical system. High-resolution backscattered electron (BSE) images were obtained from selected representative samples. Selected sites on the samples were chosen for SEM-EDX spot micro-analysis and element mapping including identification of the different clay minerals. For all analyses, SEM parameters remained constant and a set of fixed magnifications were used to provide optimal conditions for comparative studies of textures, nannofossils and mineralogy.

Biostratigraphy and palaeoecology

Nannofossils

Ten core samples were collected for nannofossil biostratigraphy from the 4277′–4262′ interval (Fig. 4). The samples were taken from red and olive-green marlstone, chalky marlstone, marly chalk and from slightly marly chalk lithologies.

The samples generally reveal high abundance and diversity nannofossil assemblages. The stratigraphically lowermost samples (4277′–4275′) are dominated by *Watznaureria barnesiae* and *Zeugrhabdotus noeliae*. *Zeugrhabdotus scutula* and *Assipetra infracretacea* are consistently present. A late Hauterivian to early Barremian (BC11–12, LK21–20D) age is indicated, tentatively supported by the absence of *Nannoconus abundans*, the marker species for the overlying nannofossil zone (Fig. 4).

A single sample at 4274′ is dated as BC12 (LK20D; early Barremian) based on the co-occurrence of *Assipetra terebrodentarius, Nannoconus pseudoseptentrionalis* and *Rhagodiscus pseudoangustus* and the absence of

◀ **Fig. 3.** Sedimentological log of Vinding-1, including core photos and distribution of facies, structures, trace fossils and macrofossils. The abbreviations: ml is marl, cm is chalky marl, mc is marly chalk, smc is slightly marly chalk and c is chalk. The units and the relative sea-level changes refer to the depositional history explained in the text. The biozones are based on nannofossils. The samples taken for nannofossil biostratigraphy are indicated by the red dots and for detailed SEM studies with black dots.

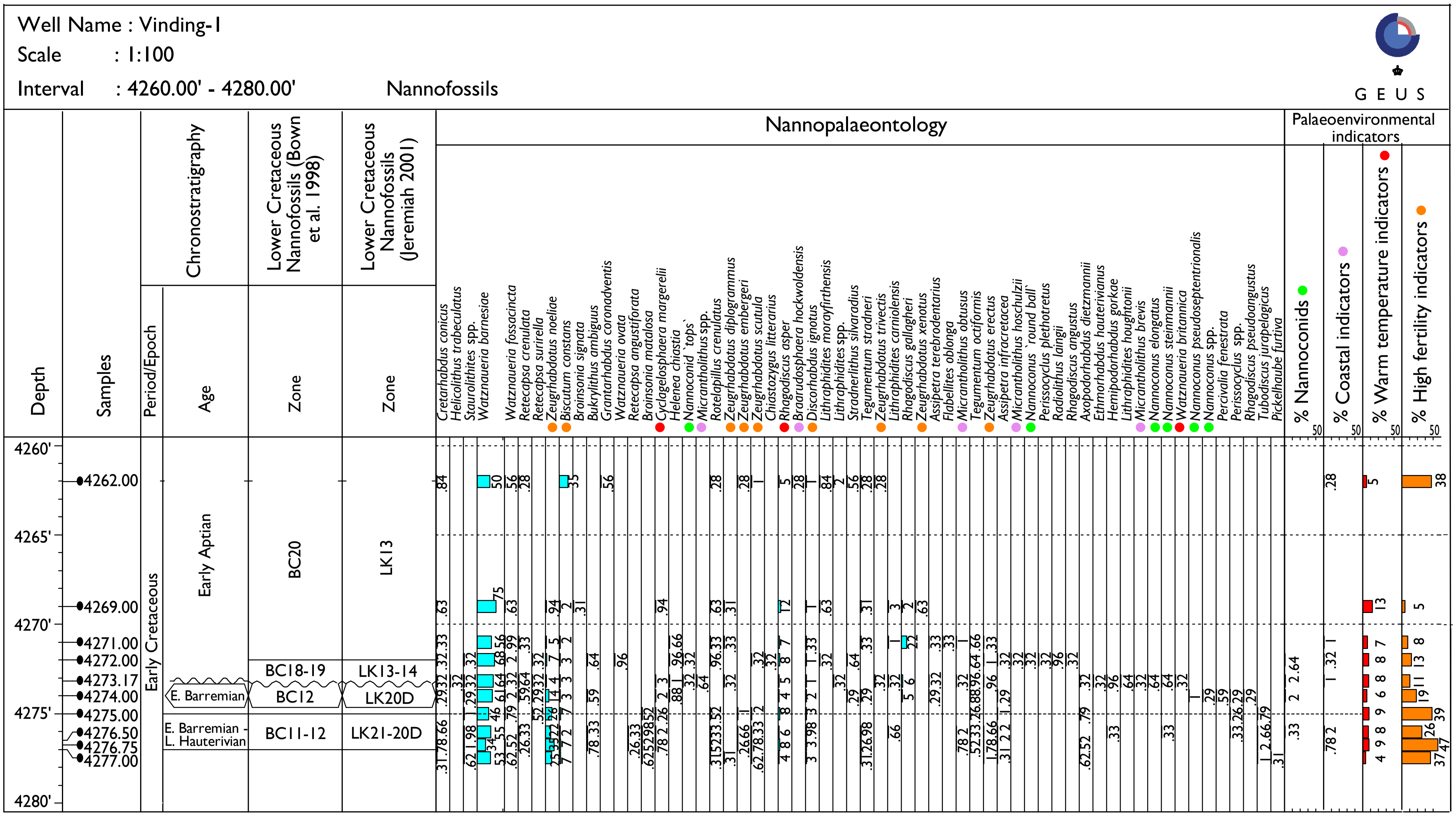


Fig. 4. Nannofossil biostratigraphic distribution chart (percentage distribution) for the late Hauterivian to early Aptian of the Vinding-1 well. Thickness of blue boxes indicates relative proportion (percentage) of each taxa in each sample. In addition, palaeoenvironmental indicators are grouped as percentages of the whole nannofossil assemblage. Nannoconids - green, coastal indicators - lilac, warm water indicators - red, high fertility indicators - orange.

the marker for BC13 (*N. abundans*). A single specimen of *Rhagodiscus gallagheri* (FO in the early Aptian) was recorded. Given the consistent Barremian floral assemblage, and sedimentological continuity with the underlying core (see description below), this rare record of an Aptian affinity is considered an artefact, probably due to sample contamination or bioturbation.

The sample at 4273.17′/4273′2′′ (Fig. 4) comprises a mixed nannofossil assemblage with elements from the Barremian or older (*Ethmorhabdus hauterivianus*, *Perissocyclus plethotretus*, *Micrantholithus brevis*) and those indicative of the Aptian (*Rhagodiscus gallagheri*, *Lithraphidites houghtonii*). It is interpreted as being early Aptian in age, BC18–19 (LK13–14) with reworked older material. This is compatible with the position of the sample immediately above a hardened, erosional surface (Figs 4; 9).

The samples from 4272′–4262′ include *Broinsonia signata*, *Grantarhabdus coronadventis*, *Radiolithus laingii*, *Flabellites oblonga*, *Rhagodiscus angustus*, *Braarudospahera hockwoldensis*, *Lithraphidites morayfirthensis*, *Lithraphidites houghtonii* and common *Rhagodiscus gallagherii*, dating this section as early Aptian (BC20, LK13).

The biostratigraphic data indicate a hiatus between 4274′ and 4273′ 2′′ spanning mid to late Barremian zones BC13 to BC17 (LK20C–15).

Foraminifera, ostracods and macrofossils

The low diversity and high abundance foraminifera assemblage of the 4272′–4262′ interval was originally dated as Albian and an early–middle Barremian age was assigned to the 4277′– 4272′ level (Fazekas 1947). The original foraminifera slides have been restudied in the current project and the biostratigraphic results of these support the present nannofossil biostratigraphy. *Lenticulina muensteri* and *Gavelinella sigmoicosta* in the sample from the 4278′–4275′ interval indicate an early Barremian age. *Hedbergella delrioensis*, and *Hedbergella planispira* together with *Gavelinella barremiana* in the sample from the 4260′–4265′ interval suggest an early Aptian age.

A Barremian age is assigned to the 4277′1′′–4276′7′′ interval due to occurrences of the ostracod *Cythereis acuticostata* (Neale 1973). *Pontocyriella rara* is assigned an Aptian and Albian age and dates the 4272′5′′–4262′ interval (Slipper 2009). *Pontocyriella rara* is assigned an Aptian and Albian age and date the 4272′5′–4262′′ interval (Slipper 2009). A Barremian age is assigned to the 4277′1′′–4276′7′′interval due to occurrences of *Cythereis acuticostata* (Neale 1973). The following species were also found in the 4277′–4262′ interval: *Eocytheropteron* sp., *Schuleridea* sp., *Neocythere* (*Physocythere*) sp., *Eucythere* sp., but none of them have any biostratigraphic relevance. The ostracod data thus supports the nannofossil biostratigraphy.

Three specimens of the belemnite *Hibolithes minutus* were found in the marlstone from 4277′–4276′ (Fig. 5A) indicating an early Barremian to earliest Aptian age (Mutterlose 1998; Alsen & Mutterlose 2009). The *H. minutus* occurring in Vinding-1 is believed to represent the Barremian dwarf morphotype as described by Alsen & Mutterlose (2009). *H. minutus* is recorded from the Barremian beds of the Speeton Clay (Rawson & Mutterlose 1983). A specimen of the belemnite *Neohibolites ewaldi* (Stolley 1911) was found in the marlstone at 4271′1′′ (Fig. 5B). This earliest Aptian to early late Aptian species (Mutterlose 1998) has a wide distribution in north-western Europe (Mutterlose 1992; Mutterlose & Wiedenroth 2009; Malkoc *et al.* 2010). Other belemnites encountered in the core from 4276′6′′ to 4262′ are too fragmented to identify. The belemnite data support the nannofossil ages.

Palaeoecology

Nannofossils, foraminifera and belemnites are included in the palaeoecological analysis. The samples from 4277′–4275′ display high abundances of the nannofossil *Zeugrhabdotus noeliae* suggesting relatively high nutrient levels in the surface waters. However, species richness remains relatively high (17–25) indicating that surface waters were not eutrophic (Fig. 4). From 4274′–4269′, *Z. noeliae* is very low in abundance indicating oligotrophic surface waters at this level. *Rhagodiscus asper* (a warm-water indicator) remains stable, with low values throughout the section (Fig. 4). *Micrantholithus* spp. are suggested to be coastal indicators; these are only found in low numbers attesting to the relative offshore location of Vinding-1 during the Barremian to Early Aptian (Fig. 4).

Samples 4278′–4275′, 4275′–4270′ and 4270′–4265′ are conspicuous by the absence of planktonic foraminifera and their diverse calcareous benthic fauna including *Lenticulina* spp., *Dentalina* spp., *Conorboides* spp., *Saracenaria* spp. and common *Gavelinella* spp. A

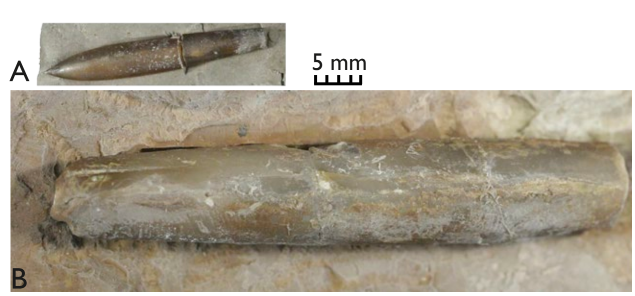
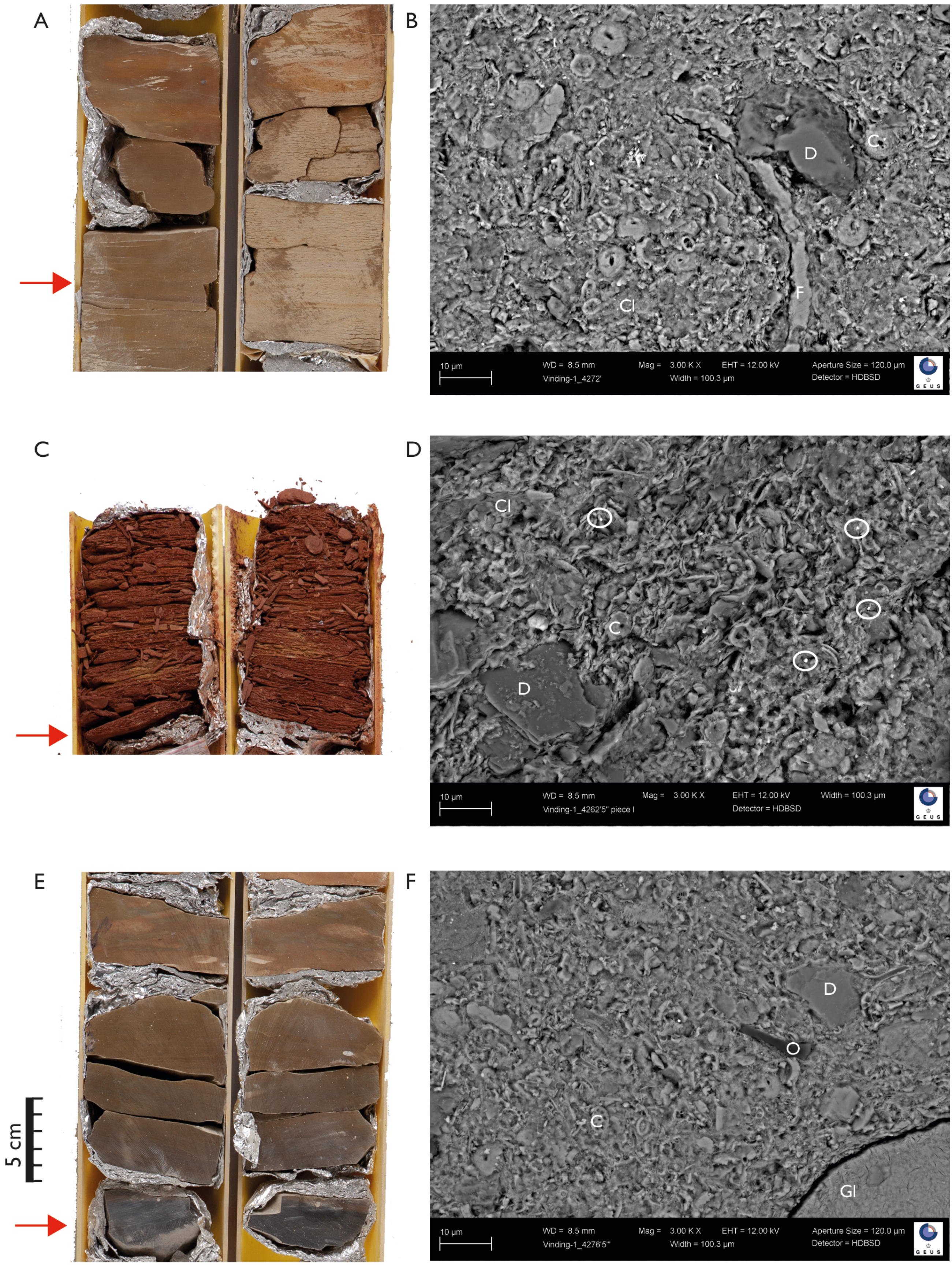


Fig. 5. A: *Hibolithes minutus* at 4276′6′′–4277′. **B:** Fragments of possible *Neohibolites ewaldi* at 4271′1′′.


A
B
D
C
F
Cl
10 µm
WD = 8.5 mm
Vinding-1_4272'
Mag = 3.00 K X
Width = 100.3 µm
EHT = 12.00 kV
Aperture Size = 120.0 µm
Detector = HDBSD
C
D
Cl
C
D
10 µm
WD = 8.5 mm
Vinding-1_4262'5" piece I
Mag = 3.00 K X
EHT = 12.00 kV
Detector = HDBSD
Width = 100.3 µm
E
F
5 cm
D
O
C
Gl
10 µm
WD = 8.5 mm
Vinding-1_4276'5''
Mag = 3.00 K X
Width = 100.3 µm
EHT = 12.00 kV
Aperture Size = 120.0 µm
Detector = HDBSD

lack of planktonic foraminifera can be attributed to very shallow water depths (e.g. Gibson 1989), but in the Vinding-1 well case, facies analysis suggests that this explanation is unlikely. These samples contain *Gavelinella* spp. and *Lenticulina* spp. whose relatively common occurrence indicates well oxygenated sea-floor conditions and open marine circulation (King *et al.* 1989, Koutsoukos *et al.* 1990). It is therefore suggested that the paucity of planktonic formaminfera is probably not a primary signal but may be due to dissolution of their fragile tests compared with the more robust tests of benthic foraminifera (Nguyen *et al.* 2009).

Gavelinella spp. and *Lenticulina* spp. occupied epifaunal and shallow infaunal habitats and their relatively common occurrence indicates well oxygenated sea-floor conditions (Koutsoukos *et al.* 1990).

Samples from 4265′–4260′ include the planktonic foraminifera *Hedbergella delrioensis* and *Hedbergella planispira*. These are indicative of open marine but relatively shallow water, marginal epicontinental seas, with water depths of less than 100 m (Leckie 1987). This sample also contains the benthic foraminifera *Arenobulimina* spp. and *Gavelinella* spp, suggesting open circulation with oxygenated botttom waters (King *et al.* 1989).

The presence of the Tethyan belemnite genus *Neohibolites* represented by *N. ewaldi* in Vinding-1 represents a signal of the early Aptian sea-level rise recorded globally, as discussed in the introduction, and as indicated locally by the cored section (see below). The early Aptian is described as a period of marked turnover, from the belemnite family Oxyteuthididae to the belemnite genus *Neohibolites* (Mutterlose 1998).

Facies analysis and depositional history

The 15 ft (4.57 m) thick cored section is composed of four lithofacies that together describe the spectrum from marlstone to slightly marly chalk (Fig. 3). The occurrence of these facies in the cored section defines four depositional units recording two discrete transgressive–regressive cycles.

Lithofacies

LF1 Marlstone

This facies ranges from dark greenish-grey to deep brick-red in colour and includes both marlstone and chalky marlstone lithologies (Fig. 6A–D). It dominates units 2 and 4; the marlstone facies either passes gradually into marly chalk (LF3, Fig. 3, unit 2), or is interbedded with marly chalk on a scale of 2–15 cm, with abrupt boundaries (Fig. 3, unit 4). Though typically thoroughly bioturbated, primary horizontal lamination is evident in places, particularly in unit 2. *Chondrites* is the dominant ichnofossil in the marlstone facies, often a diminutive form with a diameter of 0.2–0.5 mm; *Thalassinoides*, *Taenidium* and *Planolites* are present in places, particularly in chalky marlstones at the transition into the marly chalk facies. Previous studies have measured a relative $CaCO_3$ content of 35–62% (Fazkas 1947). Glauconite grains occur locally. Macrofossils are rare and only belemnites of the species *Neohibolites ewaldi* and indeterminable brachiopods have been found.

Microscopically, the facies has a high clay content of predominantly smectite to illite and a detrital mineral content of quartz, K-feldspar, rutile and mica (Fig. 6B, D). The amount of coccolithic debris and other fossil fragments is relatively small. Finely distributed hematite is abundant, locally colouring this facies red, and appears also as larger grains (Fig. 6D). Pyrite is absent and carbonate cement is rare. The facies is slightly compacted and in parts porous.

LF2 Glauconitic marlstone

This facies is restricted to the lower two feet of the core (Fig. 3; 4277–4275′), which are unfortunately fragmentary and not fully recovered. It includes marlstone and chalky marlstone and differs from LF1 by its content of very fine sand – silt and abundant glauconite grains in the sand fraction (Fig. 6E–F). The facies is varicoloured,

◀ **Fig. 6.** Core photographs and SEM micrographs of marlstone (LF1) and glauconitic marlstone (LF2) facies. Note that the annotations on the SEM micrographs only indicate one example of each component: coccolith (C), foraminifera (F), detrital grains (D), clay (Cl), glauconite (Gl), organic matter (O). The scale bar is applicable to all core pieces. **A, B:** Yellow brown chalky marl (SEM level 4272′, location indicated by red arrow on core photo). Completely bioturbated with local lamination. Finely distributed clay (Cl; predominantly smectite–illite) and glauconite are common, carbonate cement is rare. **C, D:** Dark red marl (SEM level 4262′ 5″, location indicated by red arrow on core photo); often appears bioturbated but lamination locally recognisable. The facies has a high clay and detrital mineral content and only small amounts of fragmented coccoliths. Finely distributed haematite (white circles) contributes to the red colour. **E, F:** Green-grey glauconitic marl (SEM from 4276′10″, location indicated by red arrow on core photo). The bioturbation is intense and the lamination absent weak lamination occurs in places. Glauconitic grains are present macro- and microscopic. The clay and detrital mineral contents are moderately high and the coccoliths are well preserved.

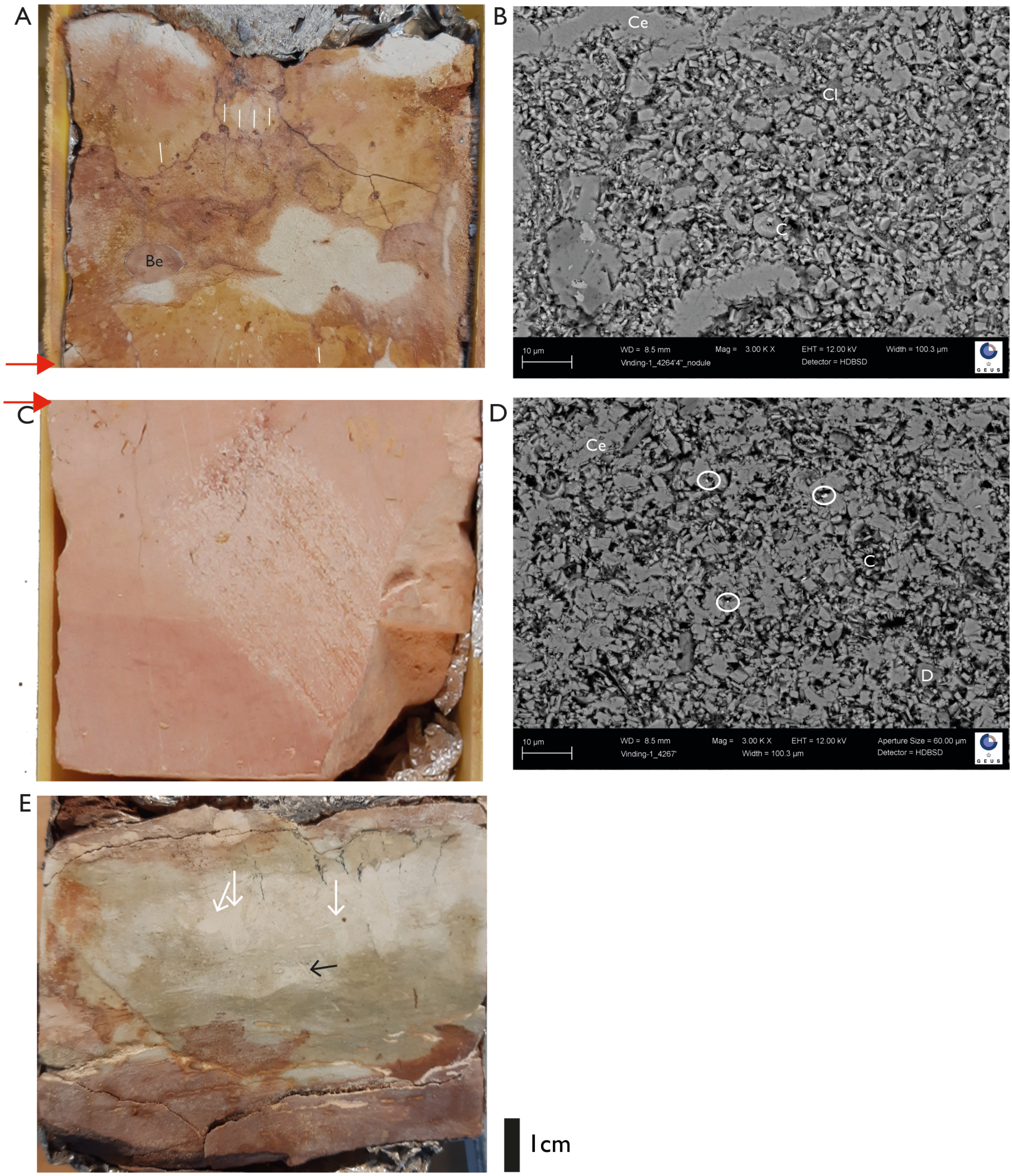


Fig. 7. Core photographs and SEM micrographs of the marly chalk (LF3; A, B, E) and slightly marly chalk (LF4; C, D) lithofacies. Note that the annotations on the SEM micrographs only indicate one example of each component; coccolith (C), cement (Ce), detrital grains (D), and clay (Cl), The scale bar is applicable to all core pieces. **A, B**: Marly chalk (SEM from 4264′4″, location indicated by red arrow on core photo). The sample is completely bioturbated with many cross-cutting burrows. Irregular chalk nodules occur locally (4264′2″) and are bored in places (indicated by white lines). The nannofossils (C) are well preserved but fragmented. Clay (Cl) is rare. Carbonate cement (Ce) is common. **C, D:** Slightly marly chalk (SEM from 4267′, location indicated by red arrow on core photo). The sample appears very homogenous and completely bioturbated. The red colour is due to finely distributed hematite (marked with white circles). The nannofossils (C) are strongly recrystalised and chalk cement (Ce) is common. Detrital grains (D) are rare. **E:** A hardground developed in marly chalk at level 4263′6″. The hardground appears completely bioturbated, vertical burrows (*Skolithos?;*white arrows) occurs locally. *Chondrites is* also common (black arrow).

from dark greenish grey to olive green-grey, locally mottled with reddish patches. The relative $CaCO_3$ content of this facies is approximately 33%, as measured in the previous study (Fazkas 1947). Lamination is absent and the structureless nature is probably due to thorough bioturbation; discrete trace fossils are rare, however. Macrofossils are predominantly belemnites of the dwarf species *Hibolithes minutus*, bivalves and vertebrate fragments.

Microscopically, the facies differs from the marlstone facies with respect to the presence of abundant micron to mm-sized grains of glauconitic and phosphatic-calcitic composition and abundant framboidal and euhedral pyrite (Fig. 6F). Some organic material is also preserved. The clay and detrital mineral contents are lower than in LF1, but still moderately high. The coccoliths are well preserved.

LF3 Marly chalk

This lithofacies ranges in colour from dark red to reddish mid-brown, locally pale yellowish brown (Fig. 7A–B). Well-defined ichnofabrics are developed with prominent *Thalassinoides*, *Planolites* and *Taenidium* traces, though *Chondrites* networks dominate overall. *Zoophycos* is also possibly present. *Skolithos* occurs at a hardground at level 4263′6″ (Fig. 7E). *Chondrites* occurs both as diminutive forms, < 0.5 mm in diameter, in the background marly chalk, but also as larger forms (1–2 mm diameter) within the fill of *Thalassinoides*. The clay component is disseminated in the marly chalk facies in the lower half of the section (below 4270′) but commonly forms discrete solution seams in the upper core (Fig. 3). Locally, nodular chalk fabrics, hardgrounds, and erosional surfaces (Figs 8A–B, E; 9) occur. The irregular nodules have microscopic borings indicating exposure on the sediment surface (Fig. 7A). The inferred hardground and major hiatus at 4273′6″ is clearly observed at the macroscopic scale (Fig. 8A–B). However, in the SEM the change across the boundary is insignificant and observed as an increase in nannofossils (including nannoconids) and a change from small clay grains in between the coccolithic debris to larger pieces of clay in the youngest sample (Fig. 8E). The relative $CaCO_3$ content is 69–80% measured in a previous study (Fazkas 1947). Macrofossils are indeterminable belemnites, brachiopods and pectinid bivalves.

Microscopically the marly chalk is homogenous and relatively porous with a high preservation of coccoliths and coccospheres. Carbonate cement is common. Clays are finely distributed; no pyrite and only little hematite was encountered.

LF4 Slightly marly chalk

This facies forms a discrete interval (4269′–4266′) of pale reddish pink, homogeneous chalk that is completely bioturbated (Fig. 7C–D). *Chondrites* traces are observed throughout, distinguished by their slightly darker fill. Deformation bands ('hairline fractures') are common in this cleaner chalk facies. Fazkas (1947) reported a relative $CaCO_3$ content of more than 80% in this lithology. Indeterminable belemnites are found.

Microscopically, the slightly marly chalks are very homogenous and more porous than the marly chalks (Fig. 7D). The nannofossils are strongly recrystalised and carbonate cement is common. The facies contains very little clay and quartz. Finely distributed hematite colours the facies red.

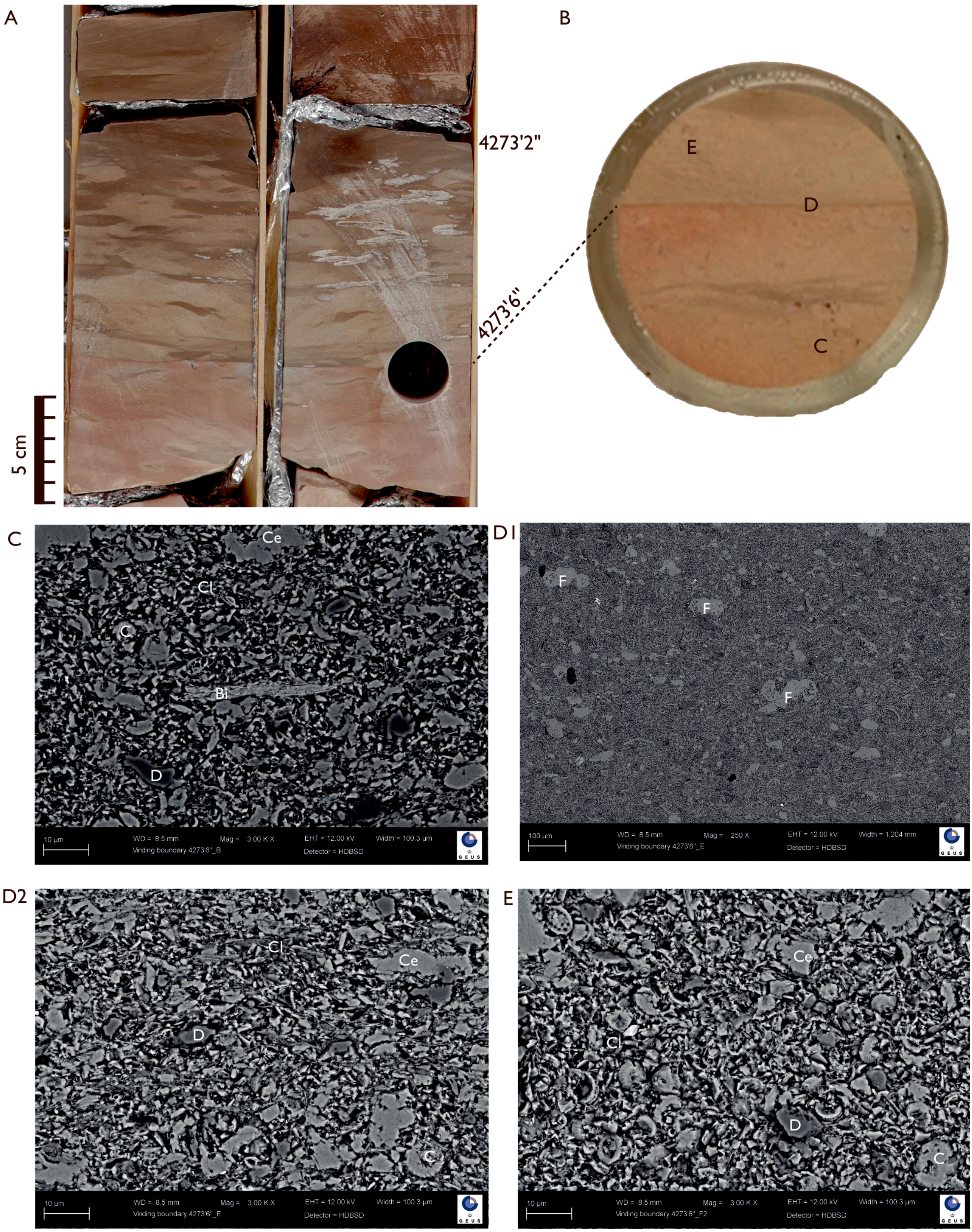
Facies succession and depositional history

The four lithofacies described above (Fig. 3) record a marine depositional environment in which the pelagic production of carbonate sediment was significant, at times dominating over the hemipelagic supply of mud in this setting in the central part of the Danish Basin. The alternation of clay-rich and clay-poor facies, constrained by the integrated biostratigraphic data, allows us to infer the sea-level history of this condensed Hauterivian–Aptian section and to relate this to the evolution of the wider North Sea region.

Unit 1 (4277′–4273′6″; late Hauterivian, BC11–12 to early Barremian, BC12)

Although the lower levels of the core are fragmentary, the existing material shows an upward transition from sandy, glauconitic marlstone (LF2) to bioturbated marly chalk (LF3), capped by an erosion surface. This transition from LF2 to LF3 is accompanied by an upward increase in the density and diversity of trace fossils. Lamination is locally weakly preserved in the glauconitic marlstones, but the scarcity of depositional structures overall suggests a bioturbated fabric. The succeeding marly chalk, in contrast, shows a complex well-defined biogenic fabric of cross-cutting *Thalassinoides*, the fill of which is re-burrowed by *Taenidium* and *Chondrites*. Intervening 'matrix' chalk is crowded by diminutive *Chondrites* networks. The capping erosional surface abruptly truncates the biogenic fabric of the marly chalk (Fig. 8). It has a gently scoured relief of a few millimetres and a thin dark, red-stained coating (< 1 mm thick). Possible borings were locally noted at this surface, but not confirmed in the SEM.

Interpretation. The gradual shift from hemipelagic


A
B
4273'2"
4273'6"
5 cm
E
D
C
C
Ce
Cl
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Bi
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D1
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F
F
D2
Cl
Ce
D
C
E
Ce
Cl
D
C

siliciclastic mud-dominated to pelagic carbonate mud-dominated sedimentation is suggestive of a relative rise in sea-level resulting in drowning and/or lateral translation of sediment sources and basinal facies belts (Fig. 3). Alternatively, a decrease of run-off can also be due to a shift towards more arid conditions. This change is also in accordance with the change to a more arid climate during the period, as reported in the literature (e.g. Ineson 1993; Copestake *et al.* 2003). The ubiquity of glauconite grains in the marlstone facies is indicative of a reduced background sedimentation rate in this setting (e.g. Odin & Matter 1981), and the complex cross-cutting and biogenically reworked ichnofabric in the marly chalk facies records increasing condensation (e.g., Taylor *et al.* 2003). The dominance of the living chambers (*Thalassinoides*) of an active epifauna in the upper marly chalks may reflect an increasingly favourable benthic environment as hemipelagic siliciclastic mud supply decreased. The erosional surface capping unit 1 corresponds to an inferred hiatus accounting for much of the Barremian stage (see discussion under biostratigraphy) and records a significant relative sea-level fall. It is not clear whether the erosional processes were submarine or subaerial in nature, though the absence of evidence of meteoric diagenesis on the subjacent carbonates favours submergent, shallow-marine processes. Staining and potential boring of the erosional surface, and the nature of the trace fossil fabric in the succeeding sediments, following but never penetrating the surface, is indicative of a hardened, cemented horizon, possibly a marine hardground.

Unit 2 (4273′6′′–4269′; early Aptian (BC18–19, with reworked Barremian) and early Aptian (BC20))

This interval comprises a thin basal marly chalk bed (LF 3) that grades rapidly up into a marlstone package (LF1) that dominates the unit. The carbonate component increases upwards and chalky marls and marly chalks dominate the upper levels (Fig. 3). Incomplete core recovery obscures much of the upper part of the unit. The marly chalks and chalky marlstones show a more diverse trace fossil assemblage, characterised particularly by *Thalassinoides*, whilst the marlstones though often fully bioturbated, exhibit an impoverished *Chondrites* ichnofauna. As noted earlier, the burrows immediately above the basal erosion surface follow but never penetrate the surface. Primary lamination is noted locally, particularly in the marlstone facies.

Interpretation. Marly chalks and marlstones in the lower 6 inches of the unit, immediately above the stained erosional surface, yielded an enigmatic biostratigraphic result, showing diagnostic nannofossil elements of several Barremian biozones (BC14–17) in addition to Early Aptian taxa (BC 18–19; see biostratigraphy above). Given the gradational, conformable transition upwards into marlstones that give a consistent early Aptian (BC20) age, it is considered likely that the lowermost bed is of early Aptian age (BC18–19) but contains a range of reworked Barremian nannofossils deposited during the initial onlap of the eroded surface. The upward transition to facies rich in pelagic carbonate (upper unit 2, unit 3) is indicative of progressive deepening, following the initial onlap (Fig. 3).

Unit 3 (4269′–4266′, early Aptian, BC20)

This unit comprises a uniform succession of pink, slightly marly chalk (LF4), interbedded locally with thin marly chalk beds (LF3; Figs 4; 8C–D). The chalk is intensively bioturbated though recognisable trace fossils are largely restricted to *Chondrites*.

Interpretation. This metre-thick interval of clay-poor chalk of early Aptian age is indicative of an essentially uninterrupted period of pelagic carbonate accumulation, with limited dilution by siliciclastic mud. It prob-

◀ **Fig. 8**. Core photographs and SEM micrographs of bioturbated marly chalk showing a sharp erosional surface with gently scoured relief (4273′6′′); this surface probably represents a hardground and is a major hiatus. Note that the annotations on the SEM micrographs only indicate one example of each component: coccolith (C), foraminifera (F), detrital grains (D), clay (Cl), cement (Ce), biotite (Bi). The scale bar is applicable to all core pieces. **A**: Core piece from 4273′–4274′. A biostratigraphic sample at 2474′ yielded an early Barremian age (BC12) whereas a sample from 4273′2′′ indicates an early Aptian age (BC18–19) with reworked Barremian nannofossils. These data indicate a major hiatus at the hardened erosional surface at 4273′6′′. **B:** Plug spanning the hiatal surface at 4273′6′′. Positions of SEM samples (C–E) are indicated on the plug photo. **C:** Abundant coccoliths both as fragments and complete shields; clay, predominantly kaolinite, between the coccoliths. Quartz, mica (biotite), and carbonate cement with small amounts of Mn and Mg present. **D1, D2:** Very similar to sample C, differing only in the presence of foraminifera and skeletal debris. The boundary is not evident on the SEM and no microscopic borings are identified on the pictures. **E:** This sample displays a marked increase in recognisable coccolith elements compared to samples C and D and exhibits higher nannofossil diversity and a relative increase in nannoconid elements.

ably represents the peak in relative sea level recorded in this core section (Fig. 3).

Unit 4 (4266′–4262′; early Aptian, BC20)

The uppermost unit of the core comprises interbedded marly chalks (LF3) and marlstones (LF1), the carbonate beds becoming thinner upwards such that the upper 2 ft of the core is dominated by dark brick-red marlstones. Hardground/firmground surfaces are developed capping marly chalk beds at two levels.

Interpretation. Unit 4 records a gradual shift from predominantly pelagic carbonate sedimentation to a hemipelagic siliciclastic mud-dominated regime. This probably reflects the basin-ward progradation of siliciclastic facies belts accompanying progressive shallowing of the basin (Fig. 3). It is possible that the chalk hardground surfaces at 4264′2′′ and 4263′7′′ represent depositional breaks, albeit shorter than the temporal resolution of the biostratigraphy (Fig. 7A–B).

Sequence stratigraphy

Based on the preceding analysis of lithofacies and the depositional history of the Vinding-1 cored section, the succession can be analysed in sequence stratigraphic terms (Fig. 3). The major hiatal surface at 4273′6′′ indicated

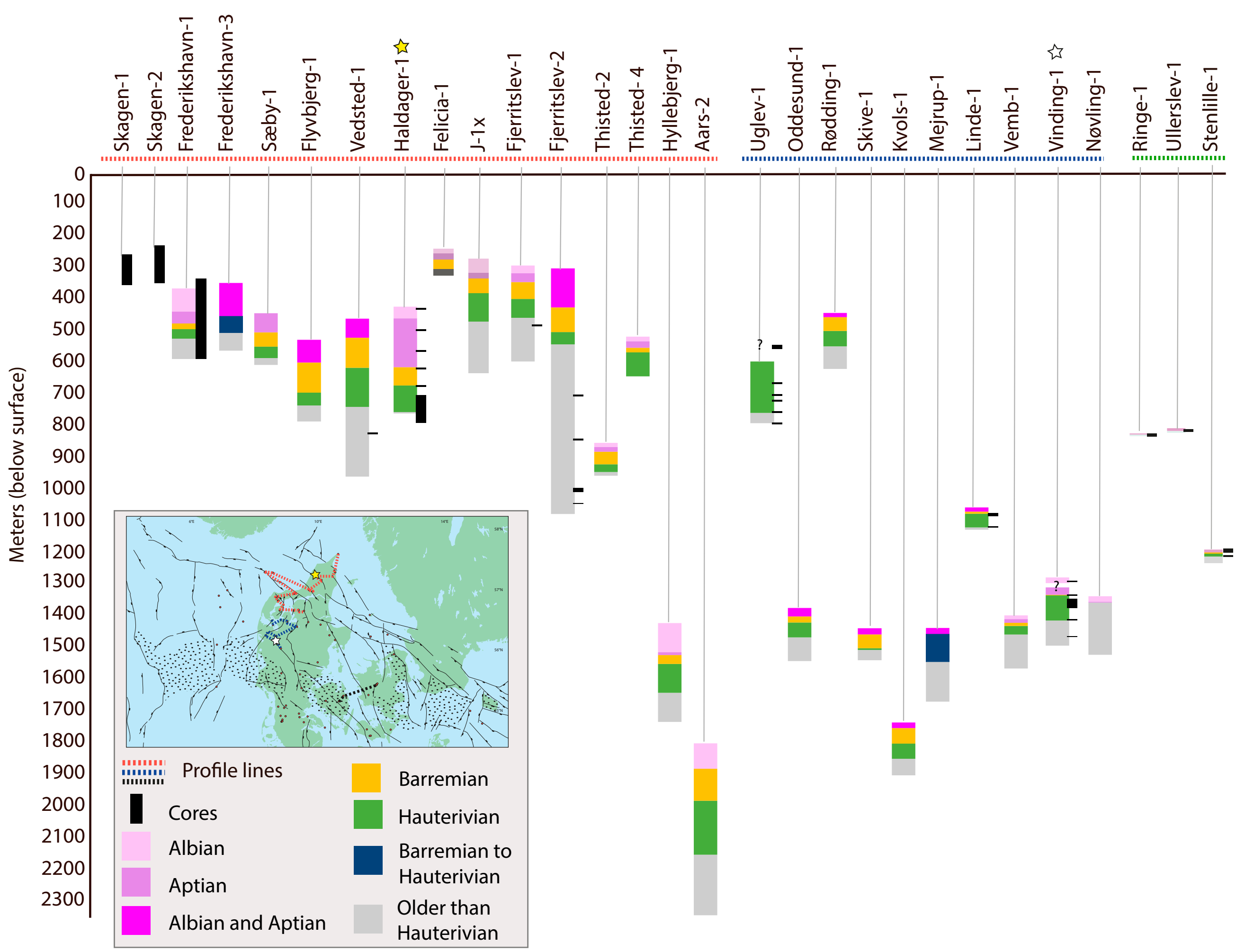

Fig. 9. Wells including strata of Early Cretaceous age in Jylland, north of the Ringkøbing –Fyn High. They are listed from north to south and then west to east, compiled in three profiles. Their positions is shown on fig. 1. The ages are based on data from well completion reports, geophysical logs and revised biostratigraphic data based on nannofossil data produced in this study. The inserted map shows the positions of the different profiles. The position of Haldager-1 is indicated with a yellow star, and the position of Vinding-1 with a white star. Ringe-1, Ullerslev-1 and Stenlille-1 are included for comparison. Core material, if present, is indicated in each of the wells (black bars). It is evident that very little core material is available. The question-marks in Vinding-1 and Uglev-1 refer to inadequate dating of boundaries.

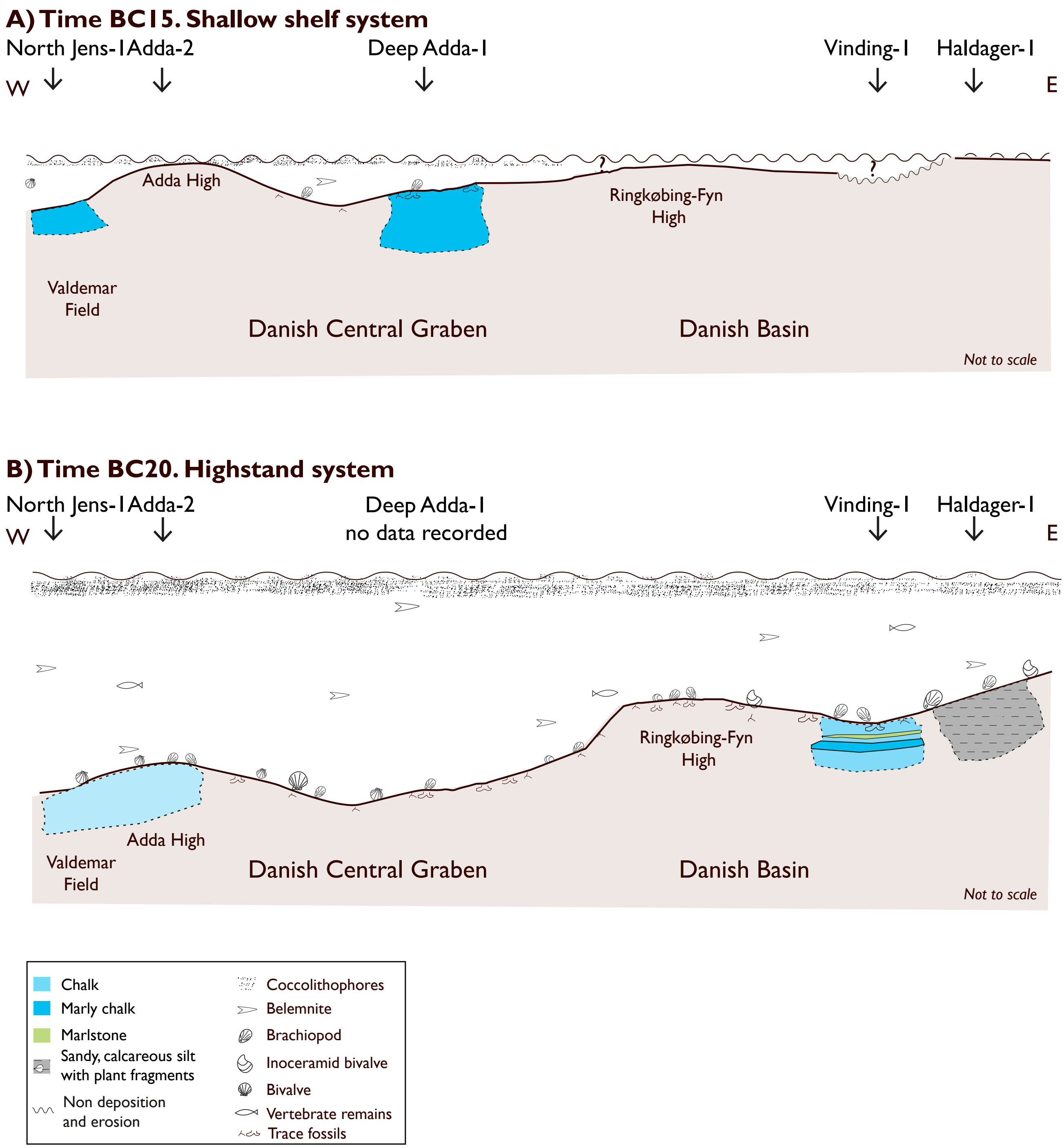

Fig. 10. Palaeoenvironmental reconstructions along a profile line from the Danish Basin (Haldager-1 and Vinding-1) in the east to the Danish Central Graben (Deep Adda-1, Adda-2, and North Jens-1) in the west. **A:** During lowstands (exemplified by BC15, late Barremian) land-derived sediments prograded basin-wards and deposition of marly chalk occurred in the Danish Central Graben (e.g. Valdemar Field and Deep Adda-1). Structural highs experienced winnowing or erosion and sediment accumulation was limited or absent (*e.g.* Adda High and Danish Basin). The Adda High was potentially within wavebase influence, but submergent. The Ringkøbing –Fyn High was shallow and possibly locally exposed. The question marks refer to our lack of coccolith data. **B:** During highstands (exemplified by BC20, early Aptian) siliciclastic sediments were sequestered in more marginal settings (*e.g.* sandy calcareous siltstones and slightly marly chalk to marl in the Danish Basin) and carbonate-rich deposition was favoured in distal parts of the basin (e.g. chalk deposition in the Valdemar Field area and on the Adda High).

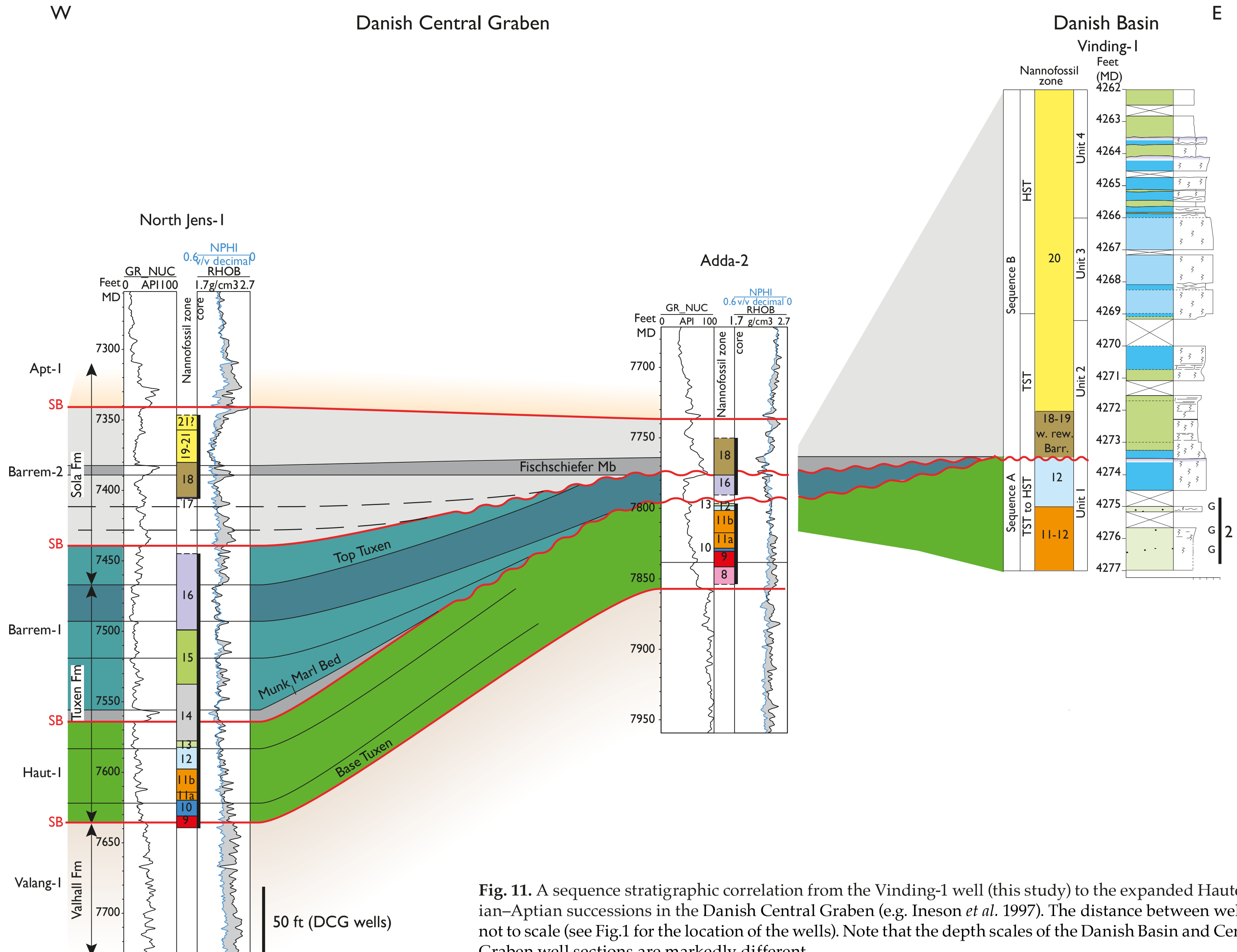

Fig. 11. A sequence stratigraphic correlation from the Vinding-1 well (this study) to the expanded Hauterivian–Aptian successions in the Danish Central Graben (e.g. Ineson *et al.* 1997). The distance between wells is not to scale (see Fig.1 for the location of the wells). Note that the depth scales of the Danish Basin and Central Graben well sections are markedly different.

by the combined biostratigraphic and sedimentological evidence clearly represents an important sequence boundary, recording relative sea-level fall and erosion. Correlation to the expanded Hauterivian–Aptian succession in the Danish Central Graben indicates that this boundary, though overtly a simple hardened erosion surface, probably represents a composite surface, the amalgamated result of several relative sea-level excursions (see discussion below).

The lower partial sequence (4277′–4273′6″, unit 1), referred to here as Sequence A, shows an upward transition from glauconitic marlstones to intensely bioturbated marly chalks. Showing characteristic features of condensation, this interval is tentatively referred to the transition from the transgressive (TST) to the early highstand (HST) systems tracts. This is compatible with the sequence stratigraphic interpretation of the coeval (BC 11–12) strata in the Danish Central Graben (see discussion below).

The upper partial sequence (4273′6″–4262′, units 2–4), referred to as Sequence B, shows a tripartite development: a marl-dominated lower portion (unit 2), 'cleaning up' into a clay-poor chalk succession (unit 3) that is capped by an interbedded marly chalk – marlstone unit (unit 4) that becomes increasingly marl-dominated upwards. This partial sequence is readily subdivided into the TST and HST (Fig. 3), the latter recording the early highstand (unit 3) when siliciclastics were sequestered landward and pelagic carbonate production dominated the distal reaches of the basin, and the late highstand (unit 4) when the rate of relative sea-level rise waned and mud-rich siliciclastics prograded basin-ward.

Pelagic carbonates in other parts of the Danish Basin

Previous studies concluded that sediment accumulation was continuous, although not uniform throughout the Danish Basin from the Late Jurassic to the Early Cretaceous (e.g. Larsen 1966). The subdivision of Lower Cretaceous strata onshore Denmark is based on a combination of petrophysical and biostratigraphic data but not many wells are fully cored (Fig. 9). The Frederikshavn-1, Haldager-1 and Ringe-1 wells have recently been re-dated using nannofossils and contain material from BC10 to BC20 (late Hauterivian to early Aptian). The data are unpublished. The Vedsted-1, Gassum-1, Uglev-1, Linde-1, Ullerslev-1, and Stenlille-1 wells have previously been dated and reported to contain strata from the upper Hauterivian to the lower Aptian. New nannofossil biostratigraphy is needed to confirm this. The Uglev-1 well is situated on a top of a salt diapir and has experienced an atypical structural history. The Lower Cretaceous sections in Ullerslev-1, Ringe-1 and Stenlille-1 are highly condensed (Fig. 9). The Frederikshavn-1 well represents the proximal part of the basin in the Early Cretaceous and exhibits some non-marine units; the cores in this well are very fragmented and encased in drilling mud so correlation with the listed wells is problematic.

New nannofossil data from the Haldager-1 well correlate with the Vinding-1 biostratigraphy (Fig. 9). Core pieces from the 2307′6″–2280′ interval of Haldager-1 are dated as BC10–13 (late Hauterivian to early Barremian) and the core section from 2195′–2180′ is dated as BC18–21 (early to late Aptian). No core is present from 2280′ to 2195′ so this interval is not dated. The Hauterivian to Barremian beds comprise sandy silt with well-preserved plant fragments. The Aptian cored interval of Haldager-1 is represented by sandy, calcareous silt with intercalations of very fine sand. Previous studies of this core piece gave an average value of 40% $CaCO_3$. The equivalent section from the early Aptian in Vinding-1 (BC20) has an average $CaCO_3$ content of 75%.

The carbonate content of the other Lower Cretaceous wells in the Danish Basin has not been studied in detail and was not consistently measured when the wells were drilled. Only scattered data are published by Larsen (1966): Skagen-2 (around 20%), Børglum-1 (20–50%), Vedsted-1 (60%), Haldager-1 (10–70%), Gassum-1 (around 20%), Ullerslev-1 (20–85%), Rødby-1 (60–80%) and Lavö-1 (20–40%).

The SEM study of Vinding-1 samples indicates that the high carbonate content is due to the high abundance of nannofossils and carbonate cement derived from dissolution of nannofossils during diagenesis (Figs 7; 8). It is most likely that the high carbonate content in other parts of the Danish Basin can also be related to pelagic carbonates.

The study demonstrates that in the late Hauterivian – early Aptian, the Vinding area was situated in a pelagic-dominated carbonate system with minor benthic influence on carbonate production. Macrofossils are very rare in the Haldager-1 and Vinding-1 cores. Only two belemnite species and a few unidentified bivalves and brachiopods were found in Vinding-1. In Haldager-1, a few bivalves and plant fragments were found. None of the macrofossils display the typical morphological adaptations for soft substrate that are commonly seen amongst Upper Cretaceous benthic chalk fossils (e.g. Surlyk 1972; Lauridsen & Surlyk 2008): adaptations such as a split pedicle in brachiopods, thick and heavy lower valves in bivalves and brachiopods, or spines on valves to avoid sinking into the chalk mud as developed in bivalves and serpulids. Soft chalk was still a relatively new substrate in the Early Cretaceous, which could explain the relatively low diversity of benthic fauna in the Lower Cretaceous deposits compared with the Upper Cretaceous.

Stratigraphic ties between the Vinding-1 well and the Danish Central Graben

The alternation of chalk-rich and marl-rich intervals in the studied Vinding-1 core section reflects the interplay between pelagic carbonate supply and land-derived siliciclastic input under a regime of changing relative sea level. Climatic changes, such as variations in temperature, precipitation and humidity may also have affected the amount of run-off to the basin. Two scenarios can be envisaged, as depicted in Fig. 10. During lowstands, land-derived siliciclastic sediments prograde basin-wards, distal structural highs may experience submarine erosion or be emergent (*e.g.* Adda High and Ringkøbing–Fyn High), and pelagic carbonate productivity in shelf situations (such as in the Danish Basin) may be inhibited by turbidity or excessive nutrient supply. The late Barremian (BC15) provides a potential example of this scenario when an unconformity developed at the Vinding-1 location and on the Adda High (Fig. 10). During relative sea-level highstands, siliciclastic sediments are sequestered landwards, and pelagic carbonate production dominates in distal basin settings, particularly if structurally elevated and hence sheltered from siliciclastic input. The early Aptian (BC20) chalks in the Vinding-1 section exemplify such a scenario with the deposition of slightly marly chalk in Vinding-1 (Fig. 10).

The studied core section from the Vinding-1 well in the Danish Basin can be compared with the better-known and stratigraphically expanded Hauterivian–Aptian succession in the Danish Central Graben (Jensen & Buchardt 1987; Ineson 1993; Jakobsen *et al.* 2004, 2005; Mutterlose & Bottini 2013; van Buchem *et al.* 2017). The latter succession is referred to the Tuxen and Sola Formations (Jensen *et al.* 1986) and is best represented by the intensively cored and well-studied North Jens-1 well where the equivalent Hauterivian–Aptian section is about 260 ft (80 m) thick (Fig. 11). The Tuxen Formation comprises a heterogenous layered succession of chalks and argillaceous chalks interbedded with greenish grey to dark grey marlstones. The formation ranges in age from late Hauterivian (BC9) to late Barremian (BC16) and is subdivided into two discrete chalk units by the lower Barremian (BC14) Munk Marl Bed, about 2 m thick interval of finely laminated dark grey – black organic-rich chalky marlstones.

The succeeding Sola Formation is marlstone dominated overall but includes a basal marly chalk and chalky marlstone unit of late Barremian age (BC16) and a discrete chalk unit of early Aptian age (BC19–21) higher in the formation (Fig. 11). A discrete organic-rich marker bed, the lower Aptian (BC18) Fischschiefer Member immediately underlies the upper chalk packet and is the North Sea representative of the OAE 1a (*e.g.* Malkoc *et al.* 2010).

The conformable Hauterivian–Aptian succession in North Jens-1 and Adda-2 is subdivided into three depositional sequences (Haut-1, Barrem-1, Barrem-2 on Fig. 11); this sequence stratigraphic subdivision is modified from the preliminary subdivision of Ineson (1993) and more recent subdivisions by Jakobsen *et al.* (2004, 2005) and van Buchem *et al.* (2017). Using the detailed biostratigraphic constraints of the Central Graben and Danish Basin well sections, the Haut-1 sequence of the Danish Central Graben is correlated with Sequence A of the Vinding-1 well whilst the Barrem-2 sequence is correlated with Sequence B. The Barrem-1 sequence of the North Jens-1 well comprising the upper Tuxen Formation and lowermost Sola Formation, representing most of the Barremian stage, is partly present in Adda-2 as burrowed massive to laminated marly chalk, and entirely absent in the Vinding-1 well; this period is represented by the hiatal surface separating Sequences A and B. Resumption of sedimentation in the Aptian at the Vinding-1 location post-dated deposition of the Fischschiefer Member in the Central Graben which is generally interpreted to represent a transgressive peak, and to include the maximum flooding surface (e.g. van Buchem *et al.* 2017). The inferred transgressive systems tract (TST) of Sequence B in Vinding-1 appears to be anomalous in a regional context, therefore, though the succeeding highstand chalks in Vinding-1 correlate well with the Aptian reservoir chalks of the Sola Formation (Fig. 11), referred to the highstand system tract by van Buchem *et al.* (2017).

Conclusions

The renewed focus on Lower Cretaceous carbonate reservoirs has emphasised the need for more predictive models and a refined depositional and paleogeographic understanding of these complex layered heterogenous chalk-marl reservoirs in Denmark. One of the things to be studied is the relative roles of pelagic and benthic carbonate production. The study of Vinding-1 has increased our understanding of the Early Cretaceous shallow shelf system and the role of benthic carbonate production in the Danish Basin by studying vintage wells in the core storage at GEUS. Apparently, the Danish Basin was during late Hauterivian to early Aptian dominated by siliciclastic deposition but had a pelagic-dominated carbonate component demonstrated by the presence of chalks. But the area was not a benthic carbonate platform since macrofossils are relatively rare with only belemnites commonly encountered. The scarcity of benthic macrofossils could be due to the lack of specialised boreal chalk fauna. They commonly occur on the soft chalk substrate in the Late Cretaceous, but since the chalk sediment was a relatively new substrate in the Early Cretaceous, morphological adaptations among the macrofauna had not yet evolved.

A revised biostratigraphy of the Vinding-1 is presented based on calcareous nannofossils and foraminifera. The new ages are confirmed by previously unpublished studies of ostracods from the core. Four lithofacies describe the spectrum from marlstone to slightly marly chalk, characterising four depositional units recording two discrete transgressive–regressive cycles. Unit 1 dated as late Hauterivian to early Barremian (BC11 to 12) was deposited during a relative sea-level rise and is truncated by an erosional surface recording a relative fall in sea level and the development of a hiatus accounting for much of the Barremian stage (BC13 to 17). The lower part of unit 2 comprises a marly chalk and is dated as early Aptian (BC18–19) but contains reworked nannofossils from the early Barremian which were deposited during the initial onlap of the eroded surface topping unit 1. The upper part of unit 2 shows a gradual change from chalky marl to marly chalk representing a sea-level rise. Unit 3 (BC 20) is of early Aptian age and the presence of slightly marly chalk is indicative of pelagic chalk accumulation with a limited supply of siliciclastic material. It probably represents the highest relative sea level recorded in the studied section. Unit 4 (BC20) is also of early Aptian age and contains more marly facies compared to unit 3. It records a gradual shift to a progressive shallowing of the basin associated with basin-ward progradation of siliciclastic facies.

The study provides a depositional record that permits sequence stratigraphic correlation to the Valdemar and Adda Fields in the Central Graben and a sequence stratigraphic model is developed.

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