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Facies and depositional processes of Lower Cretaceous carbonates, Danish Central Graben

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The Lower Cretaceous Tuxen (lower Hauterivian – upper Barremian) and Sola (upper Barremian – Albian) Formations in the Danish Central Graben (North Sea) constitute one of the oldest chalk successions recorded globally, but have received little attention with regards to sedimentary facies and depositional processes. This study presents the first comprehensive carbonate facies analysis of the succession, retrieved from seven drill cores from the Valdemar and Adda Fields. A total of 50 facies are identified, based on a continuum of six lithologies ranging from chalk to marlstone and tuffaceous siltstone to sandstone that display eight different sedimentary structures or fabrics, and two redox-associated lithological color variations (green and red) in the Adda Field. The eight sedimentary structures record: (i) comprehensive bioturbation of homogeneous sediment during fully oxygenated benthic conditions and low sedimentation rates; (ii) a similar bioturbation process but in heterogeneous sediment with lithological contrasts permitting visible burrows to form, perhaps due to rhythmic alternation between pelagic (clay-poor) and hemipelagic (clay-rich) sedimentation; (iii) pelagic to hemipelagic suspension settling in dysoxic to anoxic bottom-water conditions; (iv) patchy cementation of the shallow sea bed during incipient hardground formation; (v) reworking of bioclasts and chalk intraclasts by bottom or wave-induced currents and cohesive debris flows; (vi) pressure solution during late burial diagenesis; (vii) shear deformation by intense plastic deformation of unlithified sediment from limited lateral displacement; and (viii) silicification during burial diagenesis. The facies distribution indicates that active tectonism took place prior to the onset of anoxia that resulted in deposition of the Munk Marl Bed, which in the Valdemar Field was followed by tectonic waning and repeated anoxia. The Valdemar Field constituted a basinal depocenter and was flanked to the east by an early inversion high in the Adda Field characterized by condensation and bypass. The Fischschiefer Member represents a return to prevailing anoxia, consistent with global records of the early Aptian Oceanic Anoxic Event 1a (OAE-1a).

Keywords: Aptian, Barremian, chalk, marlstone, Sola Formation, Tuxen Formation.

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The Lower Cretaceous Tuxen (lower Hauterivian – upper Barremian) and Sola (upper Barremian – Albian) Formations of the Boreal North Sea Basin constitute one of the oldest chalk successions recorded globally (e.g. Mutterlose & Bottini 2013; van Buchem *et al.* 2018). Previously referred to as the 'Barremian limestones' (e.g. Damtoft *et al.* 1992), this Lower Cretaceous carbonate succession is widespread in the Danish Central Graben (DCG) in the westernmost offshore sector of Denmark (Fig. 1), and comprises a heterogeneous stratigraphy of pelagic white and marly chalk interbedded with marlstone and mudstone (Ineson 1993). The succession was deposited during a time of relatively frequent and pronounced global climatic and carbon-cycle perturbations, culminating with the crisis of the well-known early Aptian Oceanic Anoxic Event 1a (OAE-1a) (e.g. Malkoč *et al.* 2010; Mutterlose & Bottini 2013; Mutterlose *et al.* 2014; Blok *et al.* 2022 and references therein).

Due to a lower economic interest for the succession, the Tuxen and Sola Formations have received less attention than their Upper Cretaceous – Danian counterparts of the Chalk Group characterized by homogeneous, clean white chalk (Surlyk *et al.* 2003).

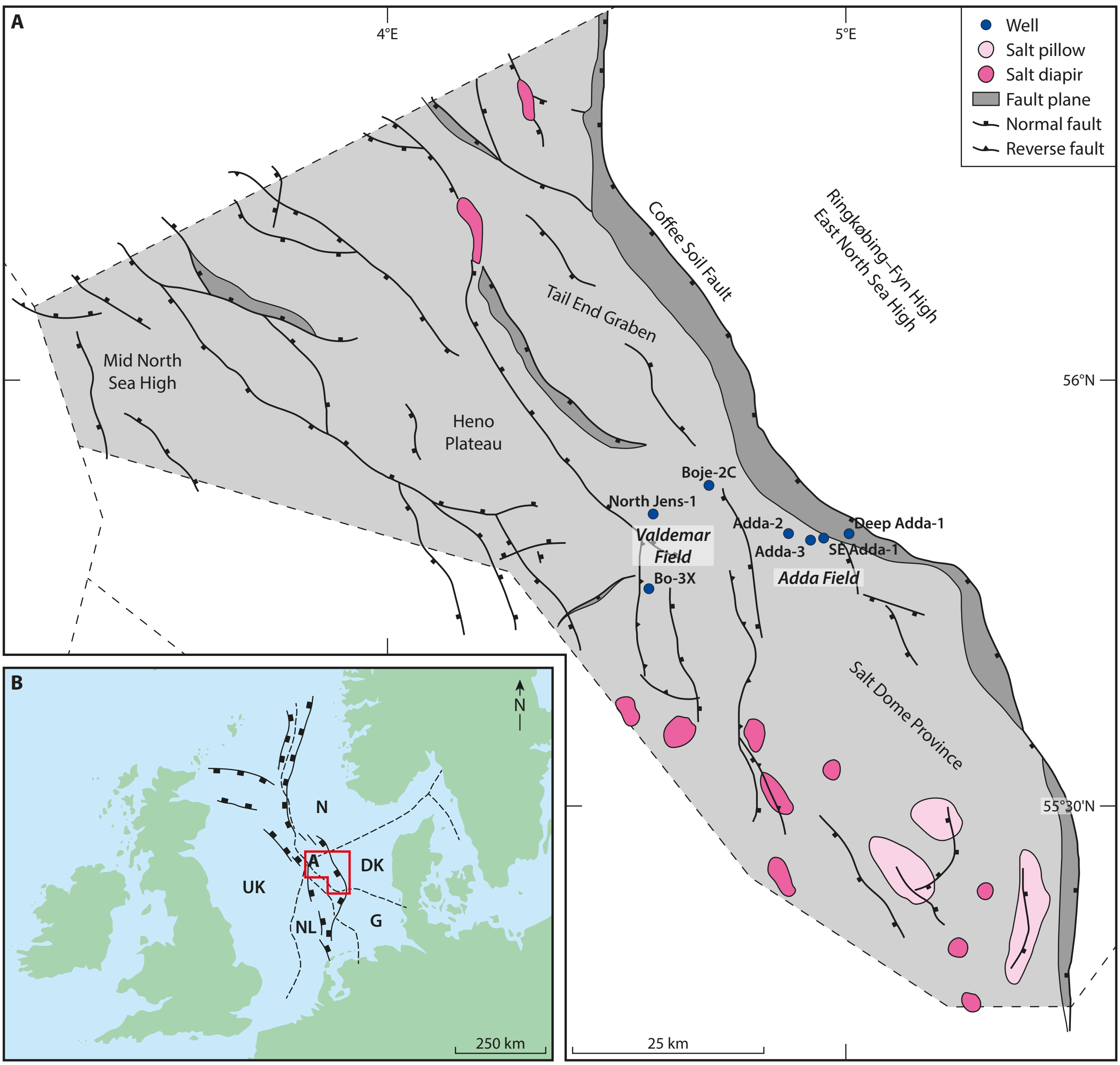

Fig. 1. Simplified maps of the structural configuration (modified from Japsen *et al.*, 2003, Møller & Rasmussen, 2003 and van Buchem *et al.*, 2018) of the DCG (A) in the larger North Sea Basin (B), including the well positions of the seven studied cores from the Valdemar and Adda Fields (A). DK, Denmark; G, Germany; N, Norway; NL, Netherlands; UK, United Kingdom.

Notable exceptions include studies on the general sedimentology (Jensen & Buchardt 1987; Ineson 1993), lithostratigraphy (Jensen *et al.* 1986; van Buchem *et al.* 2018), biostratigraphy (Heilmann-Clausen 1987; Thomsen 1987; Mutterlose & Bottini 2013), stratigraphic architecture and sequence stratigraphy (Vejbæk 1986; Kühnau & Michelsen 1994; Ineson *et al.* 1997; van Buchem *et al.* 2018), as well as reservoir characterization and zonation (Jakobsen *et al.* 2004, 2005). However, no detailed systematic accounts have been given of the sedimentary facies and corresponding depositional processes of the succession.

Thus, the primary objective of this study is to present the first coherent description and interpretation of the full range of carbonate facies of the Tuxen and Sola Formations, based on detailed sedimentological investigations of seven drill cores from the Valdemar and Adda Fields in the Danish Central Graben (Fig. 1A). In combination with a relatively robust lithostratigraphic framework of the cores (e.g. Jensen *et al.* 1986; Ineson 1993; Kühnau & Michelsen 1994; Jakobsen *et al.* 2004; van Buchem *et al.* 2018), this allows new inferences to be drawn for the Early Cretaceous basin development in this area of the DCG.

Regional setting and stratigraphy

Early Cretaceous basin configuration of the Danish Central Graben

In the Early Cretaceous, the North Sea Basin (Fig. 1B) formed part of a regionally extensive, but enclosed, epicontinental sea (Fig. 2) with a general low-gradient ramp physiography dissected centrally by a N–S-trending deeper-water graben system. The basin had relatively narrow connections to the open ocean to the north (Fig. 2A), and progressively to the south during post-Barremian times (Fig. 2B). Prior to the Aptian, however, the southern margin of the basin was closed from Tethyan influence (Tyson & Funnell 1987; Mutterlose 1992; Ineson 1993). Early Cretaceous sedimentation in the DCG is recorded by the Cromer Knoll Group, a marine mudstone-dominated succession up to 1 km thick (Fig. 3). The upper part of the Cromer Knoll Group in the DCG includes chalk-rich intervals within the Tuxen and Sola Formations, representing a gradual change from siliciclastic-dominated to carbonate-dominated sedimentation attributed to an overall sea-level rise that culminated in the Late Cretaceous eustatic highstand (Michelsen *et al.* 1987; Thomsen 1987; Thomsen & Jensen 1989; van Buchem *et al.* 2018).

The DCG consists of a complex series of NNW–SSE-trending half-grabens bounded by the Coffee Soil Fault and Ringkøbing-Fyn High to the east and by the Mid North Sea High to the west (Fig. 1; e.g. Japsen *et al.* 2003). Formation of the DCG commenced during repeated regional rifting and corresponding fault-controlled subsidence, which was initiated in the Callovian and continued into the Ryazanian (Møller & Rasmussen 2003). In the Early Cretaceous, the active rift phase was replaced by regional thermal subsidence centered on the axial graben system of the DCG, although differential subsidence of Late Jurassic half-grabens persisted from the Ryazanian to the mid-Hauterivian (Vejbæk 1986). Subsidence rates were lower than during the Late Jurassic and decreased further in the late Hauterivian with the initiation of uplift along inversion axes, which introduced regional subsidence patterns more characteristic of the Late Cretaceous and controlled the distribution of late Early Cretaceous depocentres (Vejbæk & Andersen 1987).

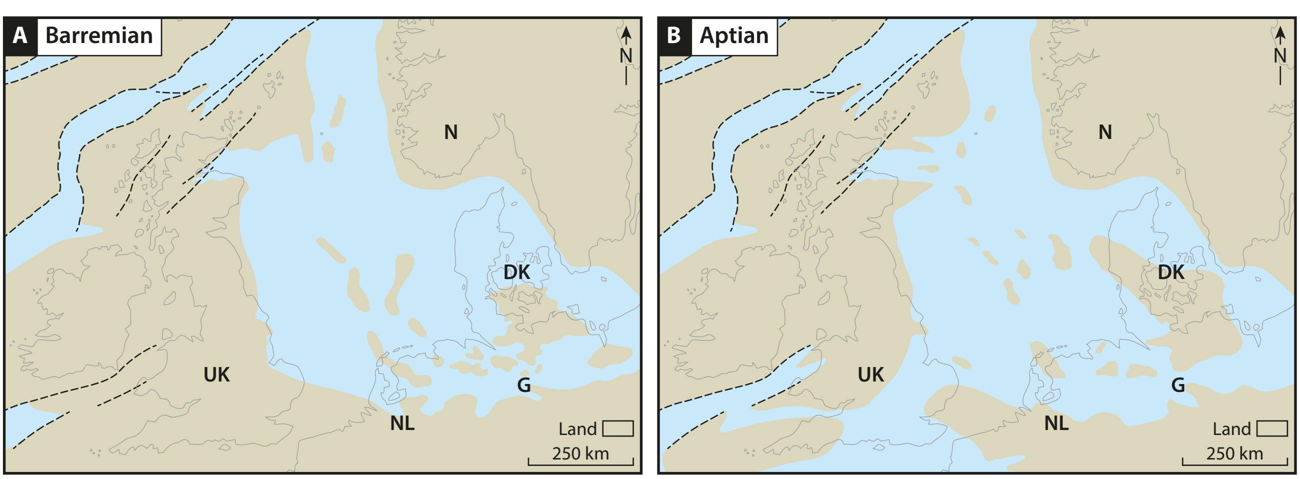

Fig. 2. Simplified Barremian (A) and Aptian (B) palaeogeographic reconstructions of the North Sea Basin (modified from Rückheim *et al.*, 2006). DK, Denmark; G, Germany; N, Norway; NL, Netherlands; UK, United Kingdom.

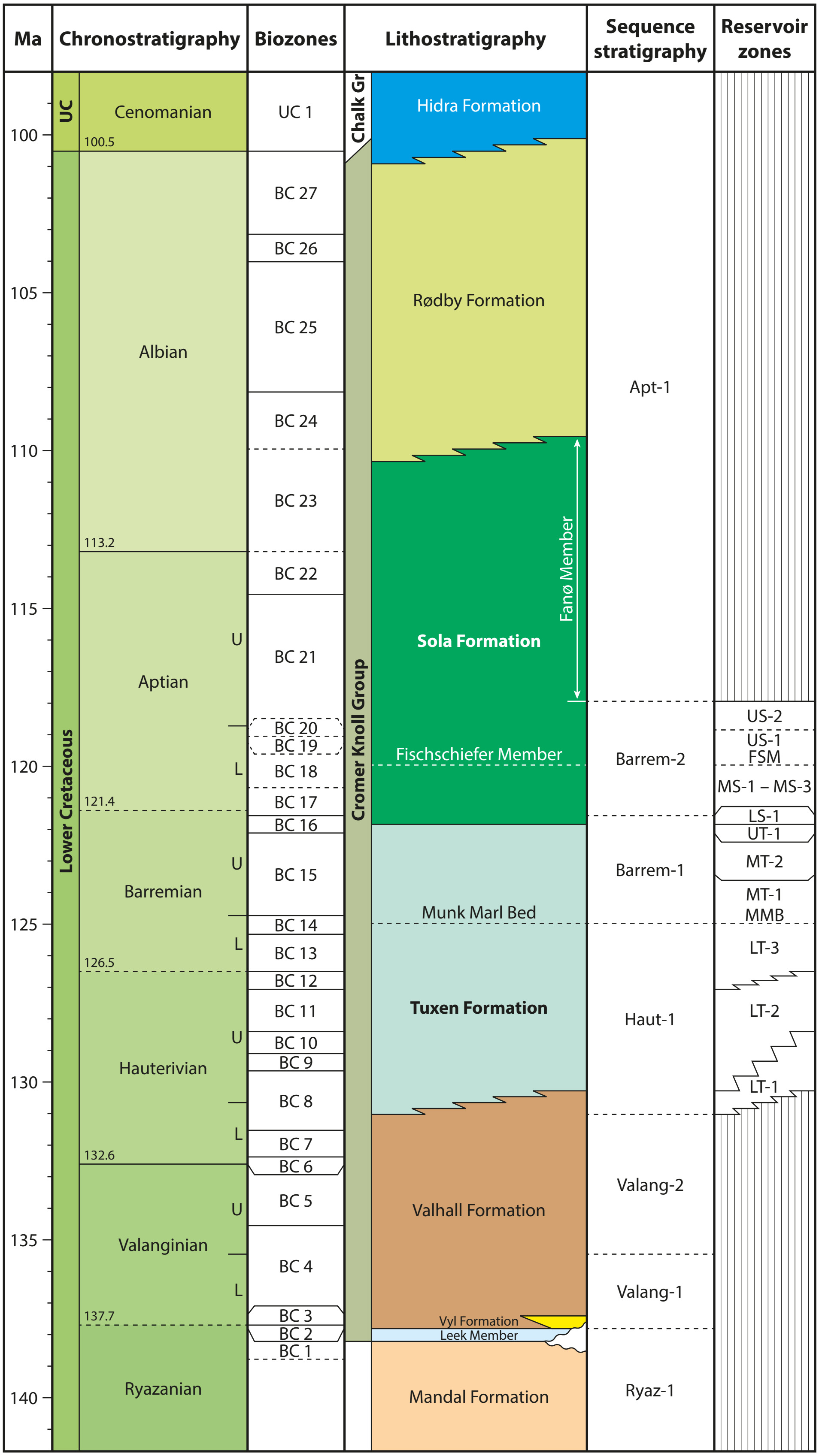

Fig. 3. Stratigraphic chart of the Lower Cretaceous Cromer Knoll Group in the DCG, including the Tuxen and Sola Formations and their depositional sequences and reservoir zones Lower Tuxen-1 (LT-1) to Upper Tuxen-1 (UT-1) and Lower Sola-1 (LS-1) to Upper Sola-2 (US-2). The chart is based on the Geological Time Scale 2020 (GTS2020; Gale *et al.* 2020), and compiled from Ineson (1993), Jakobsen *et al.* (2004) and van Buchem *et al.* (2018). UC, Upper Cretaceous.

The Valdemar and Adda Fields are located in the central part of the Danish Central Graben bounded to the north by the Heno Plateau and Tail End Graben and to the south by the Salt Dome Province (Fig. 1A). The Valdemar Field is situated on the crest of a N–S-elongated inversion ridge (the Jens–Bo Ridge), with the North Jens and Bo areas of this field separated by a saddle point (Jakobsen *et al.* 2004). The Adda Field lies at the north-western end of the Adda–Tyra–Igor ridge system, an inversion structure that was initiated in the late Valanginian – Hauterivian, but is primarily of Late Cretaceous age (Vejbæk & Andersen 1987).

Stratigraphy of the Tuxen and Sola Formations

The Tuxen Formation (lower Hauterivian – upper Barremian) is *c.* 20–80 m (65–260 ft) thick in the DCG (Jensen *et al.* 1986). The formation predominantly consists of white to off-white intensely bioturbated and commonly argillaceous coccolith chalk interbedded with bioturbated to laminated gray to green-gray marlstone (Fig. 4) of inferred pelagic and hemipelagic origin (Ineson 1993). The formation is characterized by two discrete chalk-dominated units separated by an up to 2 m (7 ft) thick unit of dark-gray to black, laminated, organic-rich marlstone of early Barremian age, named the 'Munk Marl Bed' (Jensen *et al.* 1986). The Munk Marl Bed is readily identified in most Lower Cretaceous well sections across the DCG by a clear break in petrophysical log patterns (Ineson 1993; Kühnau & Michelsen 1994), including a characteristic double peak in GR values (Fig. 4). In sequence and reservoir stratigraphic terms, the Tuxen Formation is equivalent to Sub-sequences K34–K36 of Copestake *et al.* (2003) and incorporates the reservoir zones Lower Tuxen-1 to Upper Tuxen-1 of Jakobsen *et al.* (2004) (Figs 3, 4). Whereas the two chalk-dominated, mainly bioturbated units broadly represent transgressive to highstand systems tracts and deposition in relatively well-oxygenated conditions, the laminated and organic-rich Munk Marl Bed has been postulated to record a protracted period of sea-floor anoxia due to sea-level lowstand and resulting basin isolation (Ineson *et al.* 1997; van Buchem *et al.* 2018). The carbonate content of the formation overall increases upwards with the cleanest chalk and best reservoir quality observed in the Upper Tuxen-1 reservoir zone in the top of the succession (Fig. 4; Jakobsen *et al.* 2004).

The Sola Formation (upper Barremian – Albian) is *c.* 20–40 m (65–130 ft) thick in the DCG (Jensen *et al.* 1986). The formation generally displays a laterally and vertically heterogeneous facies development of mainly gray-green to buff marlstone and claystone, dark-gray to black laminated marlstone and claystone (Fig. 4), as well as pale chalk and argillaceous chalk, and local siltstone and sandstone (Jensen & Buchardt 1987; Ineson 1993). Alternating pelagic and hemipelagic processes dominated deposition, with fluctuation of bottom-water oxygen levels and terrestrially derived sediment input (Jensen & Buchardt 1987). The Fischschiefer Member, a prominent laminated, organic-rich marlstone unit up to 2.5 m thick (8 ft), forms a distinctive stratigraphic and petrophysical well-log marker within the Sola Formation (Fig. 4) and time-equivalent formations elsewhere in the North Sea (Ainsworth *et al.* 2000). The uppermost part of the Sola Formation is constituted by the claystone-dominated Fanø Member (Fig. 3; van Buchem *et al.* 2018), previously referred to as the 'Albian shales'. The Sola Formation is equivalent to Sub-sequence K38 and Sequences K40–K50 of Copestake *et al.* (2003) and incorporates the reservoir zones Lower Sola-1 to Upper Sola-2 (Figs 3, 4; cf. Jakobsen *et al.* 2004). The formation has largely been attributed to lowstand and highstand systems tracts, with the base of the Fanø Member demarcating an important sequence boundary (Fig. 3; Ineson *et al.* 1997; van Buchem *et al.* 2018). The Fischschiefer Member corresponds to the globally recorded early Aptian OAE-1a (e.g. Malkoč *et al.* 2010; Mutterlose & Bottini 2013; Mutterlose *et al.* 2014), and has consequently been interpreted to record a maximum flooding surface possibly coinciding with partial oceanographic reconnection southwards with marine Tethyan basins (Malkoč *et al.* 2010; Pauly *et al.* 2013; van Buchem *et al.* 2018).

Material and methods

A total of 287 m (943 ft) of sedimentological logs were measured on drill cores from seven wells, namely the Bo-3X, Boje-2C and North Jens-1 wells of the Valdemar Field, and the Adda-2, Adda-3, Deep Adda-1 and SE Adda-1 wells of the Adda Field (Table 1; Fig. 1A). These wells are distributed across a *c.* 25 km long, roughly W–E-oriented transect (Fig. 1A). Collectively, the studied cores represent *c.* 11 m (35 ft) of the upper part of the Valhall Formation (Ryazanian – lower Hauterivian), 186 m (610 ft) of the entire Tuxen Formation, and *c.* 91 m (298 ft) of most of the Sola Formation with the exception of the upper part of the Upper Sola-2 reservoir zone and the Fanø Member (Table 1; Fig. 5). The cores are in moderate to excellent condition, and generally display a relatively continuous succession, although the uppermost Tuxen and lowermost Sola Formations are generally underrepresented (Fig. 5). Slickensided fractures are recorded locally in most core sections, often concentrated in marlier intervals.

Documentation of structural features in relation to facies and stratigraphy of the North Jens-1 core is presented in Glad *et al.* (2022).

Core description was carefully performed bed-by-bed at a scale of 1:5, and included descriptions of body and trace fossil assemblages and characteristics of bioturbation. The lithology (e.g. chalk, slightly marly chalk, chalky marlstone, etc.) was classified using a Tiffen® Q-13 Color Separation Guide and Gray Scale (Small), and several facies-representative intervals of the cores were treated with light, transparent oil in order to enhance the visual appearance of sedimentary

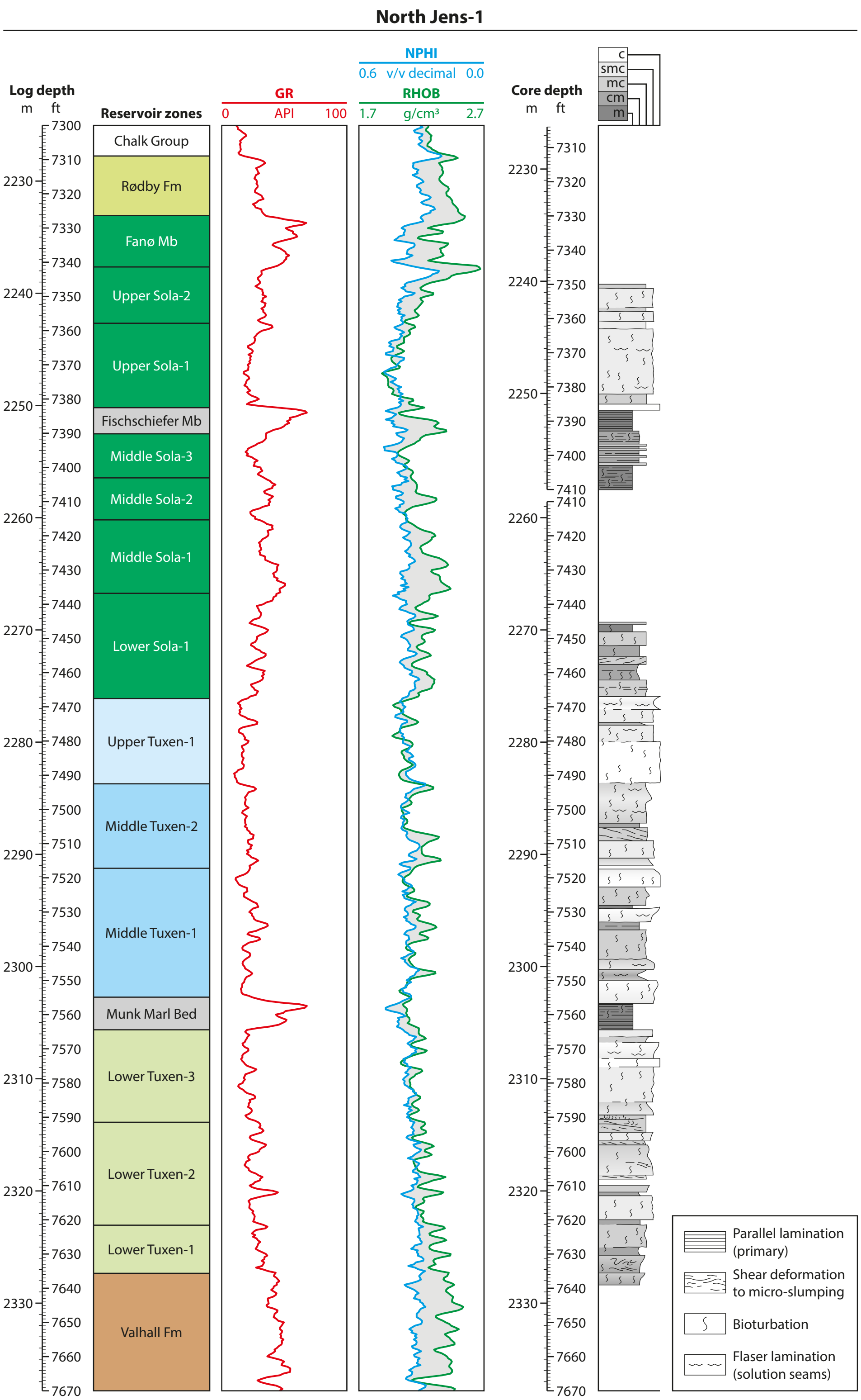

Fig. 4. General stratigraphy of the Cromer Knoll Group exemplified by the North Jens-1 well core, including reservoir zonation (Jakobsen *et al.* 2004), sedimentological log (this study), and petrophysical gamma-ray (GR), neutron porosity (NPHI) and density (RHOB) logs. The minor gap in the depth of the sedimentological log around 7410 ft results from different core:log depth-shifts between the upper core (*c.* 4 ft) and the lower cores (no significant shift). Lithological abbreviations refer to: c, chalk; smc, slightly marly chalk; mc, marly chalk; cm, chalky marlstone; m, marlstone.

Table 1. Depth, well stratigraphic thickness (including core gaps) and logged thickness (excluding core gaps) of studied core intervals, including the Valhall, Tuxen and Sola Formations

	Depth				Well stratigraphic thickness				Logged core thickness			
	Valhall Fm	Tuxen Fm	Sola Fm	Total	Valhall Fm	Tuxen Fm	Sola Fm	Total	Valhall Fm	Tuxen Fm	Sola Fm	Total
Valdemar Field												
Bo-3X	–	2580.13–2546.60 m	–	2580.13–2546.60 m	–	33.53 m	–	33.53 m	–	26.68 m	–	26.68 m
	–	8465 ft 0 in – 8355 ft 0 in	–	8465 ft 0 in – 8355 ft 0 in	–	110 ft 0 in	–	110 ft 0 in	–	87 ft 7 in	–	87 ft 7 in
Boje-2C	2623.41–2616.40 m	2616.40–2556.36 m	2556.36–2544.17 m	2623.41–2544.17 m	7.01 m	60.05 m	12.19 m	79.25 m	6.96 m	55.99 m	12.15 m	75.10 m
	8607 ft 0 in – 8584 ft 0 in	8584 ft 0 in – 8387 ft 0 in	8387 ft 0 in – 8347 ft 0 in	8607 ft 0 in – 8347 ft 0 in	23 ft 0 in	197 ft 0 in	40 ft 0 in	260 ft 0 in	22 ft 10 in	183 ft 9 in	39 ft 11 in	246 ft 6 in
North Jens-1	2328.37–2326.54 m	2326.54–2275.94 m	2275.94–2240.28 m	2328.37–2240.28 m	1.83 m	50.60 m	35.66 m	88.09 m	1.83 m	48.22 m	35.55 m	85.60 m
	7639 ft 0 in – 7633 ft 0 in	7633 ft 0 in – 7467 ft 0 in	7467 ft 0 in – 7350 ft 0 in	7639 ft 0 in – 7350 ft 0 in	6 ft 0 in	166 ft 0 in	117 ft 0 in	289 ft 0 in	6 ft 0 in	158 ft 2 in	116 ft 8 in	280 ft 10 in
Adda Field												
Adda-2	–	2393.59–2370.73 m	2370.73–2362.20 m	2393.59–2362.20 m	–	22.86 m	8.53 m	31.39 m	–	17.89 m	7.70 m	25.59 m
	–	7853 ft 0 in – 7778 ft 0 in	7778 ft 0 in – 7750 ft 0 in	7853 ft 0 in – 7750 ft 0 in	–	75 ft 0 in	28 ft 0 in	103 ft 0 in	–	58 ft 9 in	25 ft 3 in	84 ft 0 in
Adda-3	2404.90–2402.94 m	2402.94–2377.29 m	2377.29–2363.42 m	2404.90–2363.42 m	1.96 m	25.65 m	13.87 m	41.48 m	1.91 m	20.78 m	13.87 m	36.56 m
	7890 ft 1 in – 7883 ft 8 in	7883 ft 8 in – 7799 ft 6 in	7799 ft 6 in – 7754 ft 0 in	7890 ft 1 in – 7754 ft 0 in	6 ft 5 in	84 ft 2 in	45 ft 6 in	136 ft 1 in	6 ft 3 in	68 ft 2 in	45 ft 6 in	119 ft 11 in
Deep Adda-1	–	2450.52–2446.02 m	–	2450.52–2446.02 m	–	4.50 m	–	4.50 m	–	4.29 m	–	4.29 m
	–	8039 ft 9 in – 8025 ft 0 in	–	8039 ft 9 in – 8025 ft 0 in	–	14 ft 9 in	–	14 ft 9 in	–	14 ft 1 in	–	14 ft 1 in
SE Adda-1	–	2413.25–2396.24 m	2396.24–2374.39 m	2413.25–2374.39 m	–	17.02 m	21.84 m	38.86 m	–	12.12 m	21.44 m	33.56 m
	–	7917 ft 6 in – 7861 ft 8 in	7861 ft 8 in – 7790 ft 0 in	7917 ft 6 in – 7790 ft 0 in	–	55 ft 10 in	71 ft 8 in	127 ft 6 in	–	39 ft 9 in	70 ft 4 in	110 ft 1 in
				TOTAL	10.80 m	214.21 m	92.09 m	317.10 m	10.70 m	185.97 m	90.71 m	287.38 m
					35 ft 5 in	702 ft 9 in	302 ft 2 in	1040 ft 4 in	35 ft 1 in	610 ft 3 in	297 ft 8 in	943 ft 0 in

structures, and subsequently photographed using a fixed-position camera with precisely calibrated white and color balances.

In order to validate that the classification of lithologies was accurately determined by using the color (i.e. grayscale) of the sediments, a total of 246 geochemical data points were acquired from the Boje-2C core by X-ray fluorescence (XRF) on powdered samples using an Innov-x Olympus DELTA Premium 6000 Handheld XRF Analyzer with a 4W X-ray Rh tube in a stationary setup in combination with Innov-x DELTA PC software. The $CaCO_3$ content was estimated using a calibration of the Ca concentration measured by the XRF to reference powders (Ullmann 2013). Concurrently, lithological grayscale values were measured of the powdered samples using a conventional flatbed scanner.

The core depths are reported in imperial units, which were directly transcribed during core description and subsequently converted to metric units, with both units employed throughout this manuscript in order to preserve accurate relationships to the primary drilling data.

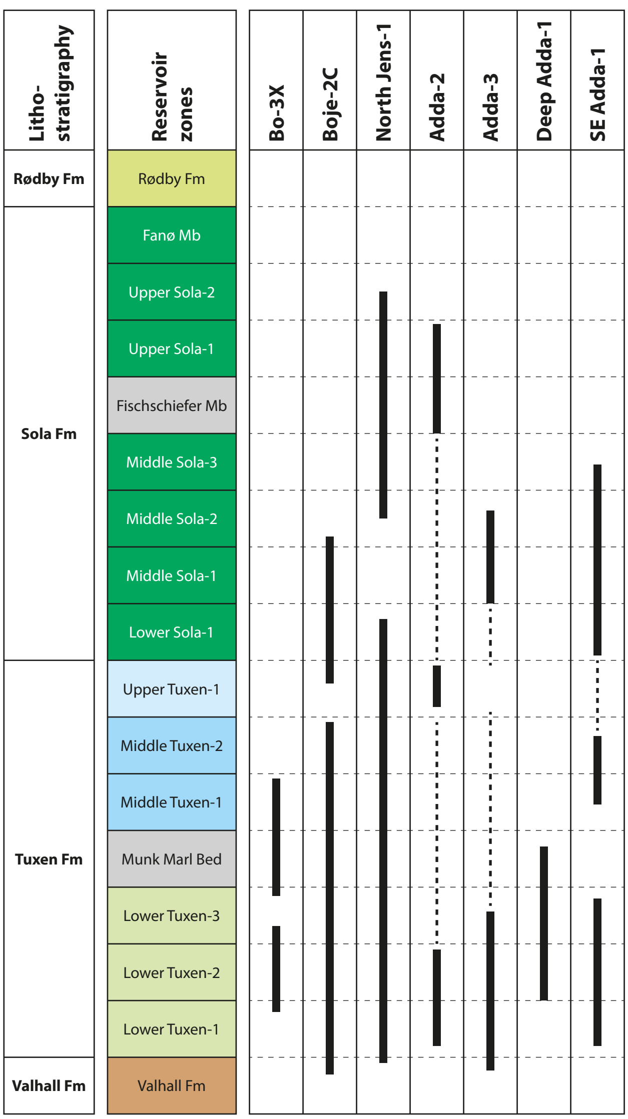

Fig. 5. Range and distribution of lithostratigraphic units, reservoir zones and hiati (dashed lines) in each of the seven well cores (black bars) investigated in this study.

Facies

Classification and definition

A total of 50 facies are defined and annotated according to: (i) six lithologies; (ii) eight different sedimentary structures (or fabrics); and (iii) two lithological color variations. First, the lithologies (1–6) include chalk (1), slightly marly chalk (2), marly chalk (3), chalky marlstone (4), marlstone (5; including shaly, silty and sandy marlstone and mudstone) and tuffaceous siltstone to sandstone (6), with the total thickness, proportion and number of units of each lithology varying between the studied cores (Table 2). Lithologies 1–5 constitute a color continuum from white (chalk) to dark-gray and black (marlstone), which correlates with a high and low carbonate content, respectively, and correspondingly low and high content of detrital mud, pyrite and/or organic matter. The exception is the Munk Marl Bed, which is anomalously dark compared to lithologies of similar carbonate content (Fig. 6), probably largely due to its high organic-matter content. Second, sedimentary structures (a–e and x–z) include homogeneous bioturbation (a), mottled bioturbation (b), parallel lamination (c), nodular fabric (d), matrix-rich conglomerate (e), flaser lamination (x), shear deformation structures (y) and silicified fabric (z) (Figs 7, 8). Third, lithological color variations include green (*g*) and red (*r*) redox-associated nuances of slightly marly chalk to marlstone (lithologies 2–5). This color-differentiated group of facies is confined to the Adda-2, Adda-3 and SE Adda-1 cores. In some cases, this facies classification and annotation results in a particular carbonate being described by three facies labels; for example, a facies of marly chalk (lithology 3) that is both biomottled (sedimentary structure b) and red-colored (color *r*) is referred to as 'F3b*r*' (Fig. 7).

Facies defined by sedimentary structures a–e are 'classical' facies, representing fabrics that either relate to depositional processes directly (e.g. grading, lamination etc.) or to processes within the surficial sediment that are directly linked to the depositional interface (i.e. bioturbation, early diagenetic nodular cementation etc.). Facies comprising sedimentary structures x–z, in contrast, represent subsequent modifications of the depositional fabric under progressive burial by processes controlled by basin morphology or tectonics and the burial history. Facies that comprise sedimentary structures x–z thus constitute a heterogeneous group of fabrics formed in the shallow subsurface due to gravitational instability (i.e. shear-deformed fabrics), and fabrics that are of later, diagenetic origin (i.e. solution seams and silicified fabrics). It should be noted that deformation bands (*sensu lato* hairline fractures; Wennberg *et al.* 2013) are recorded in a range of facies (Glad *et al.* 2022). Given their facies-crossing nature and probable compactional origin (Wennberg *et al.* 2013), however, deformation bands are not considered here as a criterion for facies differentiation, though their abundance in certain facies is noted.

Recurring facies arrangements of the eight different sedimentary structures allow identification of fundamentally different depositional processes, which are thus outlined in detail below.

Table 2. Lithological distribution in cores

	Lithology 1	Lithology 2	Lithology 3	Lithology 4	Lithology 5	Lithology 6	TOTAL
	Chalk	Slightly marly chalk	Marly chalk	Chalky marlstone	Marlstone	Tuff	All lithologies
Bo-3X							
Units (N)	3	51	34	37	28	1	154
Cumulative thickness (m)	0.41	19.36	3.52	2.17	1.20	0.02	26.68
Content (%)	1.54	72.56	13.19	8.13	4.50	0.07	100.00
Boje-2C							
Units (N)	1	115	137	118	66	1	438
Cumulative thickness (m)	0.15	31.64	24.39	12.04	6.87	0.01	75.10
Content (%)	0.20	42.13	32.48	16.03	9.15	0.01	100.00
North Jens-1							
Units (N)	17	65	90	49	24	0	245
Cumulative thickness (m)	8.56	24.69	35.30	10.02	7.03	0.00	85.60
Content (%)	10.00	28.84	41.24	11.71	8.21	0.00	100.00
Adda-2							
Units (N)	7	37	60	29	18	0	151
Cumulative thickness (m)	0.92	4.07	13.89	2.60	4.11	0.00	25.59
Content (%)	3.60	15.90	54.28	10.16	16.06	0.00	100.00
Adda-3							
Units (N)	2	12	30	35	11	0	90
Cumulative thickness (m)	1.16	2.39	8.40	4.34	20.27	0.00	36.56
Content (%)	3.17	6.54	22.98	11.87	55.44	0.00	100.00
Deep Adda-1							
Units (N)	12	0	10	0	4	1	27
Cumulative thickness (m)	2.11	0.00	0.56	0.00	1.41	0.21	4.29
Content (%)	49.18	0.00	13.05	0.00	32.87	4.90	100.00
SE Adda-1							
Units (N)	2	15	19	18	4	0	58
Cumulative thickness (m)	3.40	1.84	4.40	5.56	18.36	0.00	33.56
Content (%)	10.13	5.48	13.11	16.57	54.71	0.00	100.00
TOTAL							
Units (N)	44	295	380	286	155	3	1163
Cumulative thickness (m)	16.71	83.99	90.46	36.73	59.25	0.24	287.38
Content (%)	5.81	29.23	31.48	12.78	20.62	0.08	100.00

Homogenously bioturbated facies

Description

A total of 12 homogeneously bioturbated facies are recognized (Fig. 7). Facies units are common and generally a few decimeters thick, but range between 1–200 cm (0.5 in – 6 ft 5 in). The facies are characterized by intense bioturbation with a relatively structureless fabric, faint biomottling (often only recognizable on clean, polished surfaces), and lack of physical sedimentary structures. The facies are commonly recognized in intervals displaying little lithological variation of either chalk (F1a), slightly marly chalk (F2a, F2a*g* and F2a*r*), marly chalk (F3a, F3a*g* and F3a*r*), chalky marlstone (F4a, F4a*g* and F4a*r*) or marlstone (F5a and Fa*r*) (Figs 7–9). The bioturbated fabric is predominantly devoid of recognizable trace fossils, but conspicuous burrows occur sporadically in low numbers and limited diversity, dominated by *Chondrites* and *Planolites* with rare *Nereites*, *Palaeophycus*, *Teichichnus*, *Thalassinoides* and *Zoophycos*. The facies units also commonly display deformation bands, and less commonly indistinct parallel lamination, shear banding, chalk nodules, pyrite, and sporadic sand-grade chalk clasts, as well

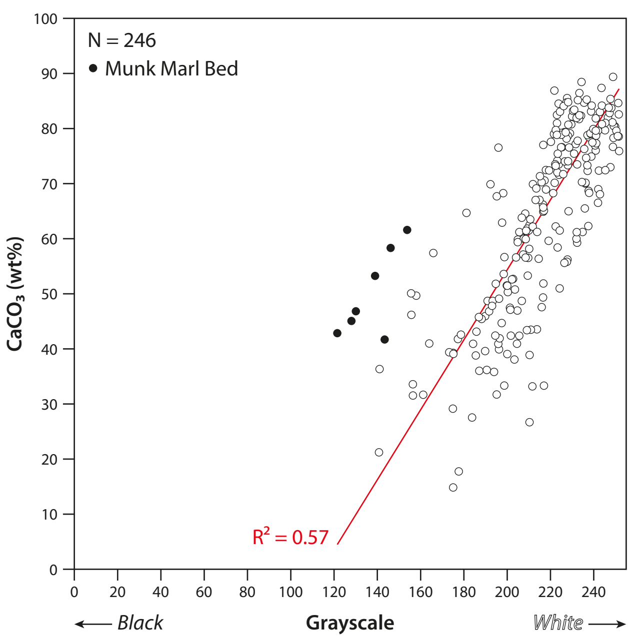

Fig. 6. Cross-plot of grayscale and XRF-determined carbonate ($CaCO_3$) percentage (wt%) of 246 samples in the Boje-2C core, showing that white (i.e. chalk-dominated) and dark-gray to black (i.e. marlstone-dominated) facies correlate with higher and lower carbonate percentage, respectively (except for the seven samples of the Munk Marl Bed, being anomalously dark compared to lithologies of similar carbonate content). The grayscale unit corresponds to a subdivision of the white–black spectrum into 256 shades.

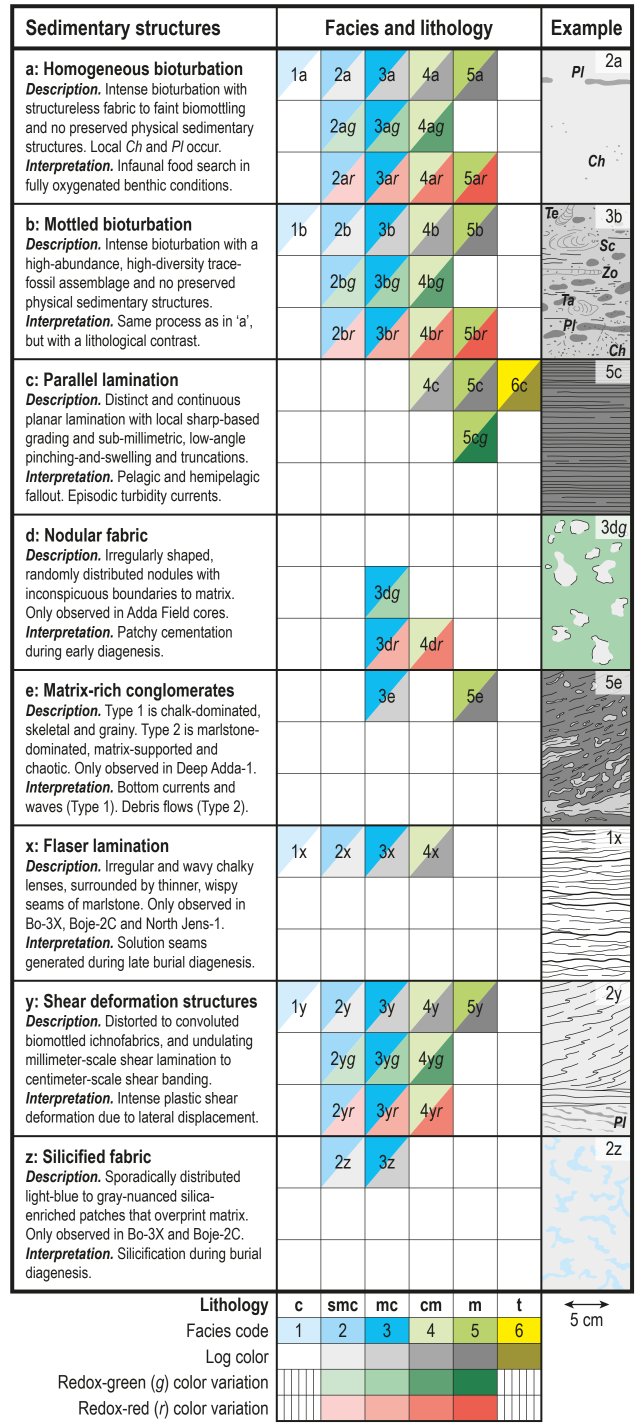

Fig. 7. Summary and representative line drawings of facies, annotated according to the six lithologies (1–6), eight different sedimentary structures (a–e and x–z), and two redox-associated color variations (green and red; *g* and *r*). Lithological abbreviations refer to: c, chalk (lithology 1); smc, slightly marly chalk (lithology 2); mc, marly chalk (lithology 3); cm, chalky marlstone (lithology 4); m, marlstone (lithology 5); t, tuff (lithology 6). Trace-fossil abbreviations refer to: *Ch*, *Chondrites*; *Pl*, *Planolites*; *Sc*, *Scolicia*; *Ta*, *Taenidium*; *Te*, *Teichichnus*; *Zo*, *Zoophycos*.

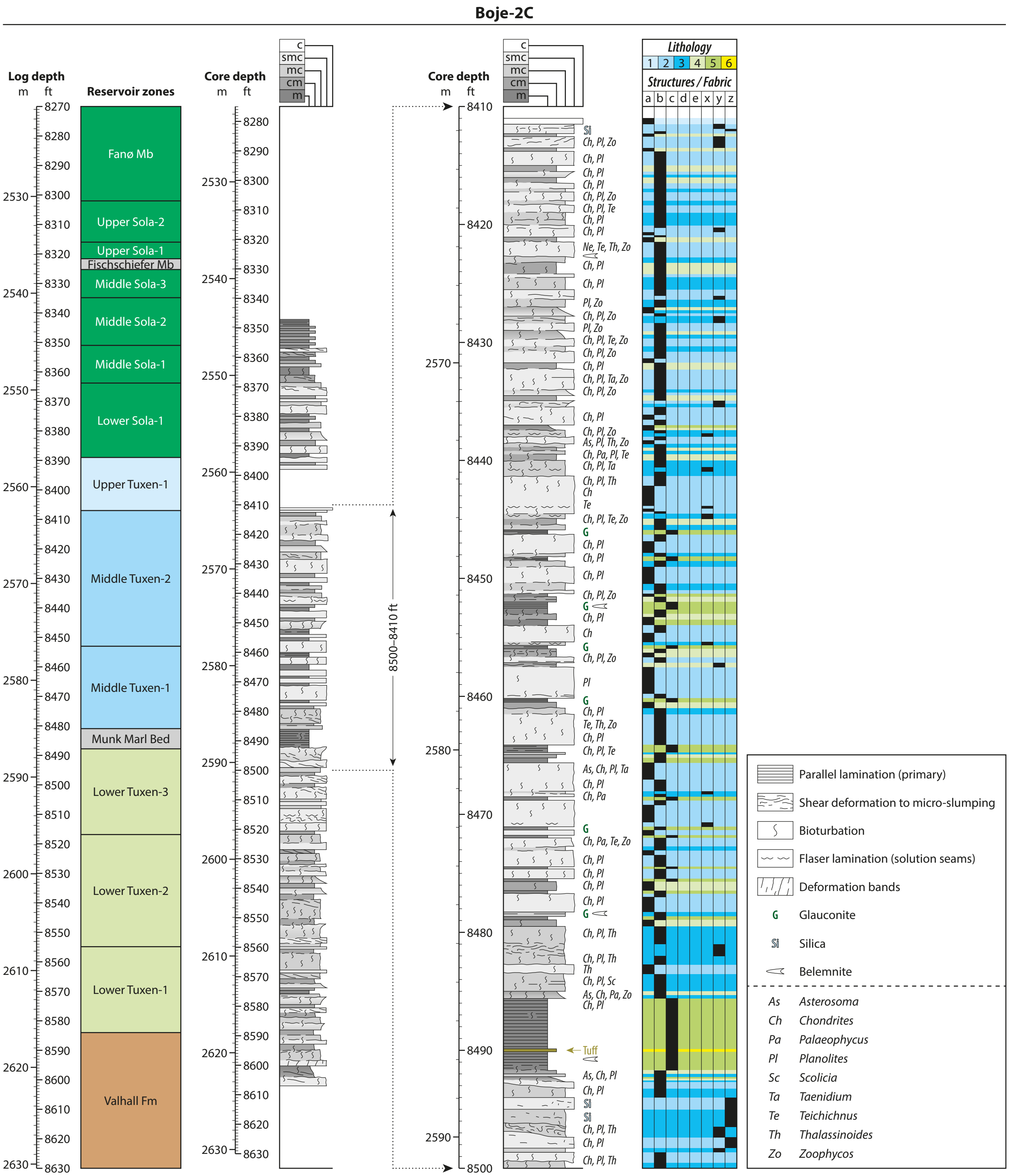

Fig. 8. Representative sedimentological log and accompanying reservoir zonation of the Tuxen and Sola Formations in the Boje-2C core, including detailed inset log of a heterolithic interval in the Tuxen Formation with corresponding facies plot of lithologies (chalk to marlstone, 1–5, and tuff, 6) and sedimentary structures (a–e and x–z), which highlights their stratigraphic distribution. Note the core:log depth-shift of *c.* 5 ft. Lithological abbreviations refer to: c, chalk; smc, slightly marly chalk; mc, marly chalk; cm, chalky marlstone; m, marlstone.

as belemnites, bivalves (including inoceramid shell fragments), crinoid stalks and rare ammonites. Lower boundaries of homogeneously bioturbated facies units are gradational, whereas upper boundaries are generally biomottled to irregular but may also be sharp (Fig. 9). Homogeneously bioturbated facies units are commonly interbedded with biomottled and shear-deformed facies units and subordinate flaser-laminated facies units (Fig. 9). Alternatively, the facies are either: (i) stacked as consecutive units of differing lithologies (e.g. F5a overlain by F3a and F4a); or (ii) forming bioturbated facies successions with lower biomottled and commonly marly divisions (e.g. F3b) cleaning upwards into chalkier and homogeneously bioturbated divisions (e.g. F2a).

Interpretation

The general lack of physical sedimentary structures and the completely bioturbated fabric indicate fully oxygenated benthic conditions and low sedimentation rates, which allowed the infauna to continuously exploit the sea bed in search for food, resulting in thorough obliteration of physical sedimentary structures. The subtle biomottling and the rarity of visible trace fossils probably reflects the homogeneity of the sediment and the resultant lack of color contrasts to define the biogenic structures. The destruction of the physical sedimentary structures inhibits precise determination of the precursor depositional process of the sediments, but low sedimentation rates are probably consistent with tranquil background deposition from pelagic (chalk to marly chalk) and hemipelagic (chalky marlstone and marlstone) fallout, although the episodic incursion of low-density turbidity currents and/or mudflows cannot be ruled out, as indicated by localized, dispersed sand-grade chalk clasts (e.g. Anderskouv & Surlyk 2011). The resulting units of such episodic flows would, however, probably be too thin to be preserved from subsequent bioturbation.

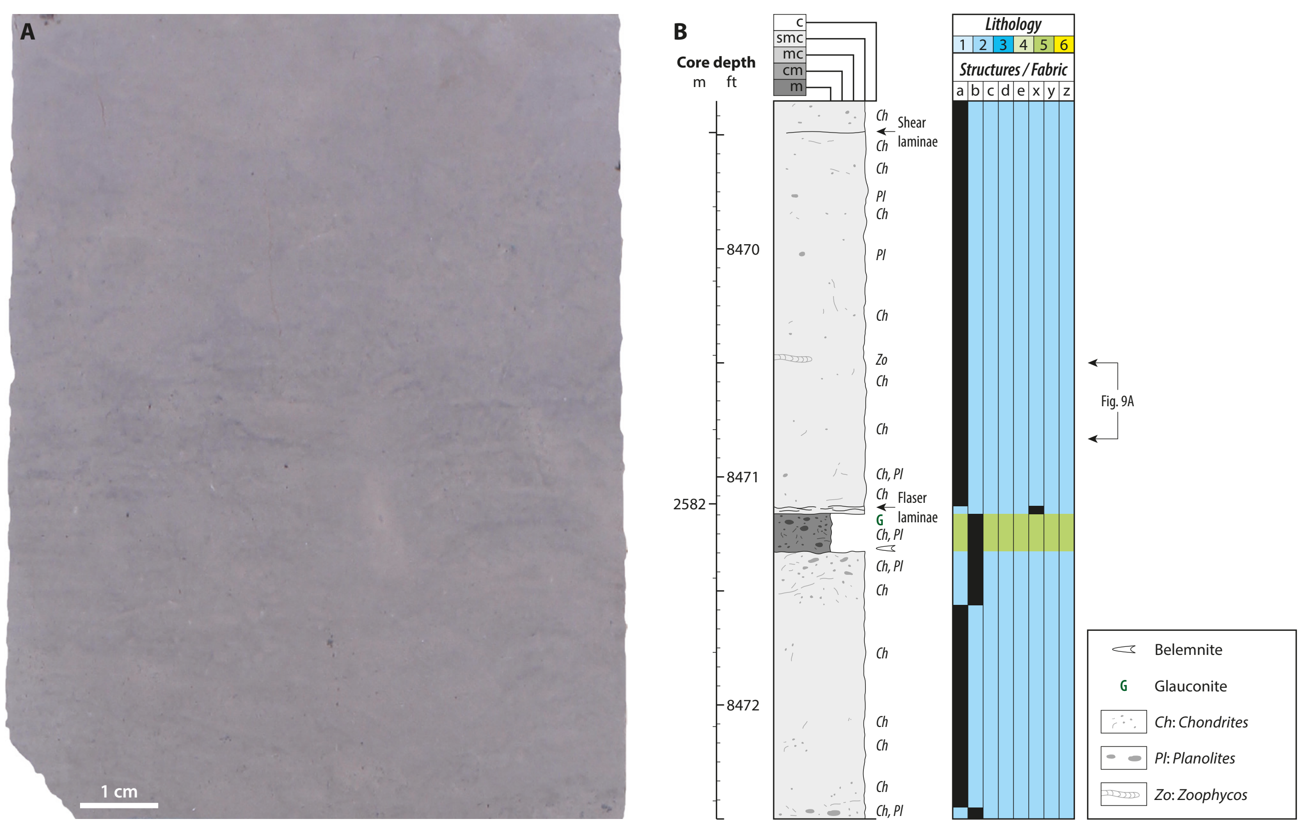

Fig. 9. Representative photograph (A) and detailed log (B) of homogeneous bioturbation (sedimentary structure a) in the Boje-2C core. The photograph shows completely homogenized slightly marly chalk (F2a) devoid of visible trace fossils, except some inconspicuous *Chondrites*. The photographed interval (A) has been treated with light oil for visual enhancement of sedimentary structures and corresponds to the middle part of the log, indicated to the right of the facies plot (B). Lithological abbreviations refer to: c, chalk (lithology 1); smc, slightly marly chalk (lithology 2); mc, marly chalk (lithology 3); cm, chalky marlstone (lithology 4); m, marlstone (lithology 5). Tuff corresponds to lithology 6.

Biomottled facies

Description

A total of 12 biomottled facies are recognized (Fig. 7). Facies units are dominant and generally a few decimeters thick, but range between 1–240 cm (0.5 in – 7 ft 11 in). The facies are characterized by a fully bioturbated fabric with a generally high-abundance, moderate to high-diversity trace-fossil assemblage and lack of physical sedimentary structures. The facies consist of slightly marly chalk (F2b, F2b*g* and F2b*r*), marly chalk (F3b, F3b*g* and F3b*r*), chalky marlstone (F4b, F4b*g* and F4b*r*), and locally chalk (F1b) and marlstone (F5b and F5b*r*), with the latter commonly being glauconitic in thin beds (Figs 7, 8, 10). Mottled bioturbation generally occurs in heterolithic intervals where it may form stacks of consecutive facies units of differing lithologies (e.g. F3b overlain

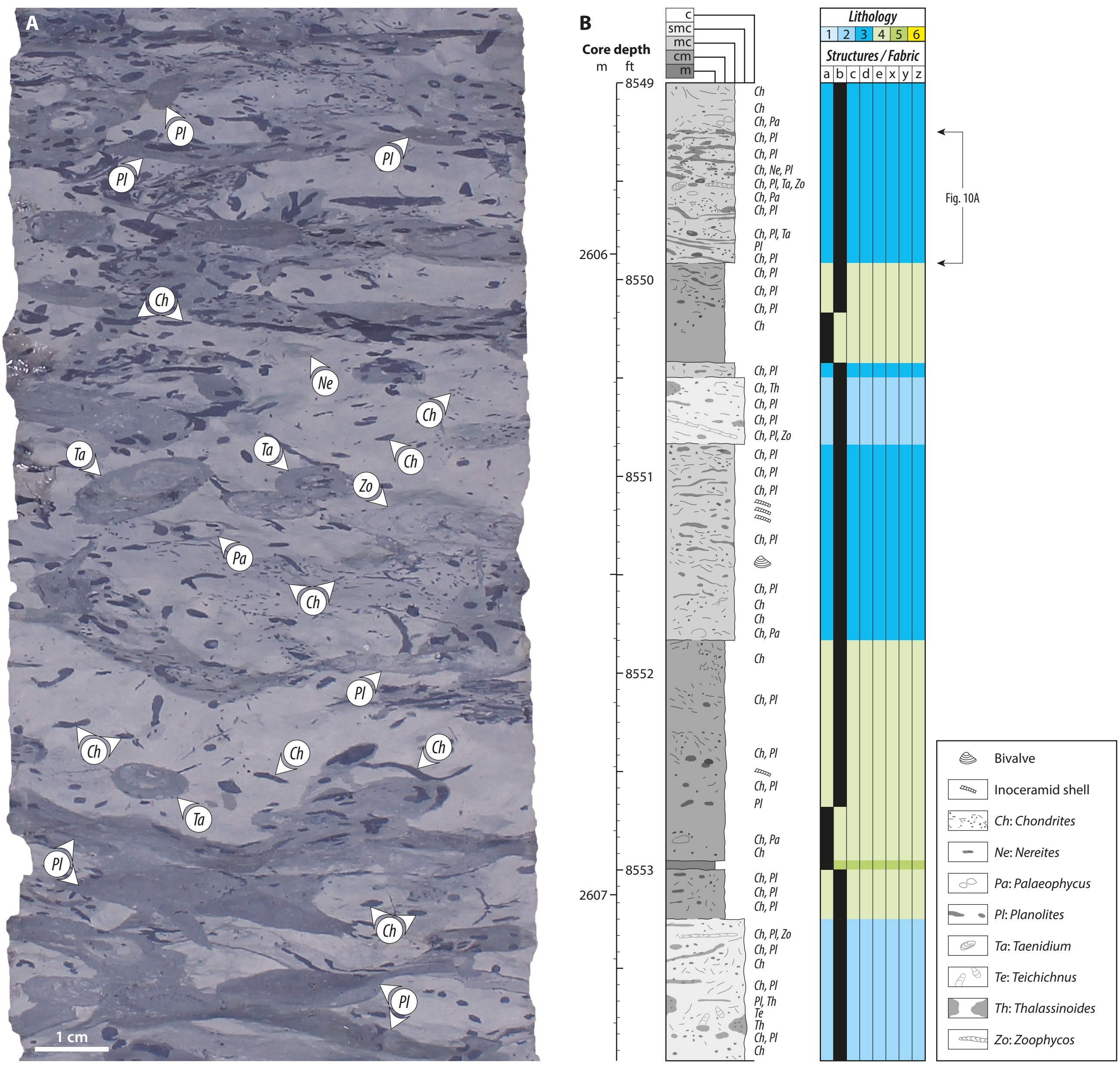

Fig. 10. Representative photograph (A) and detailed log (B) of mottled bioturbation (sedimentary structure b) in the Boje-2C core. The photograph shows thoroughly biomottled marly chalk (F3b), constituting a relatively high-abundance and moderate to high-diversity trace-fossil assemblage. The photographed interval (A) has been treated with light oil for visual enhancement of sedimentary structures and corresponds to the upper part of the log, indicated to the right of the facies plot (B). Lithological abbreviations refer to: c, chalk (lithology 1); smc, slightly marly chalk (lithology 2); mc, marly chalk (lithology 3); cm, chalky marlstone (lithology 4); m, marlstone (lithology 5). Tuff corresponds to lithology 6.

by F2b and F4b) up to 2.6 m (8 ft 6 in) thick. Trace fossils are generally clearly differentiated from the surrounding matrix, with chalk-dominated (i.e. chalk to marly chalk) units generally exhibiting the largest diversity of trace fossils. Trace-fossil assemblages are overwhelmingly dominated by *Chondrites* and *Planolites*, which are commonly the only ichnogenera present in a unit. Other trace fossils include common *Thalassinoides*, *Teichichnus*, *Scolicia* and *Zoophycos*, with lesser *Asterosoma*, *Palaeophycus*, *Taenidium*, *Nereites* and *Phycosiphon*, and very rare *Cosmorhaphe* (Figs 7, 8, 10). Larger burrows (e.g. *Planolites*, *Taenidium* or *Thalassinoides*) are typically exploited by smaller burrows (e.g. *Chondrites* and/or *Teichichnus*) (Fig. 10). Locally, biomottled facies units display relict parallel lamination, floating very coarse sand-grade to granule-sized chalk clasts, or slight inclination of the ichnofabric. Additional facies variations include: (i) local chalk nodules in the Adda-2, Adda-3 and SE Adda-1 cores, where the units may also consecutively shift between redox-associated green (*g*) and red (*r*) colors; and/or (ii) rare occurrences of bivalves (including inoceramid shell fragments), belemnites and ammonites, shear deformation structures (including shear lamination, shear banding and/or inclination and contortion of the ichnofabric), deformation bands, patchy silicified fabrics or flaser lamination, and pyrite nodules/- or cement. The boundaries of biomottled facies units are generally gradational to irregular or bioturbated, but rare cases of sheared to erosional or sharp boundaries do occur. The units are commonly interbedded with homogeneously bioturbated, parallel-laminated and shear-deformed facies units (Fig. 10), and more rarely silicified facies units.

Interpretation

Similar to homogeneous bioturbation, the thoroughly bioturbated fabric and general lack of physical sedimentary structures indicate fully oxygenated benthic conditions and dominantly low sedimentation rates compatible with pelagic (chalk to marly chalk) and hemipelagic (chalky marlstone and marlstone) fallout. However, the clearly distinguishable trace fossils probably reflect sufficient lithological contrasts in the burrowed sediments for well-defined burrows to be formed, and hence availability of heterolithic sediments. This suggests that dominantly pelagic (clay-poor) and hemipelagic (clay-rich) sedimentation may have alternated relatively rhythmically, perhaps due to recurring periods of heightened and lowered carbonate production and/or siliciclastic input, with the sediments subsequently mixed during bioturbation. The range of ichnogenera and the rarity of benthic fossils further indicate a relatively rich infauna and a restricted shelly epifauna, which suggests a high nutrient flux to the sea floor (Dayton & Oliver 1977; Bambach 1993; McKinney & Hageman 2006; Anderskouv & Surlyk 2011). In addition, the locally occurring chalk clasts may indicate episodic deposition from low-density turbidity currents (e.g. Anderskouv & Surlyk 2011).

Parallel-laminated facies

Description

Four parallel-laminated facies are recognized (Fig. 7). Facies units are generally a few centimeters thick, but range between 1–240 cm (0.5 in – 8 ft). The facies are predominantly characterized by relatively distinct and continuous planar lamination in clean to shaly and sandy marlstone (F5c and F5c*g*) and chalky marlstone (F4c), identified by sub-millimetric and millimetric variations between pale and dark laminae (Figs 7, 8, 11; Jensen & Buchardt 1987; Thomsen 1989a, b). In the Munk Marl Bed, the fine lamination is superimposed upon centimeter- to decimeter-scale diffuse banding defined by bulk color variations in the marlstone. Rare variations of the lamination include: (i) minute low-angle pinch-and-swell architecture, which may be associated with sub-millimetric truncations; or (ii) sets (3–10 mm thick) of three to five, sharp-based and graded or inversely graded laminae, for example by marlstone grading into marly chalk. In the Bo-3X core, a peculiar example of lamination (2553.5 m; 8377 ft 9 in) displays onlap against a small-scale (2 mm throw) fault scarp. Parallel-laminated facies units are commonly glauconitic and devoid of trace fossils, although small *Chondrites* and *Planolites*, typically confined to the top of the units, may occur (Figs 8, 11), as well as rare, isolated *Asterosoma*, *Teichichnus*, *Thalassinoides* or *Zoophycos*. Alternatively, the parallel-laminated facies units exhibit subtle shearing to contortion or small-scale overturning of the laminae, as well as scattered pyrite cement and/or nodules, siderite and rare chalk nodules, ammonites, belemnites, bivalves (including inoceramid shell fragments) and fish remains. Unit boundaries are predominantly sharp, with subordinate lower transitional and upper erosional boundaries, and the facies units are mainly interbedded with biomottled facies units and subordinately shear-deformed facies units (Figs 8, 11).

Rare occurrences of parallel lamination are recorded in tuffaceous siltstone to sandstone (F6c) within the Munk Marl Bed (Table 2), which in the Deep Adda-1 core forms a sharp-based graded bed with diffuse and spaced horizontal lamination defined by the concentration of coarse silt-grade grains.

Interpretation

The predominance of the distinctly planar lamination in fine-grained marlstone (F5c) devoid of textural variations, cross-cutting relations and bioturbation indicates that the bulk of parallel-laminated facies reflects deposition in tranquil conditions from pelagic to hemipelagic suspension settling in dysoxic to anoxic bottom-water conditions (Jensen & Buchardt 1987; Ineson 1993). In the Munk Marl Bed, Thomsen (1989a, b) related the deposition to seasonal production variability and blooms of calcareous nannofossils resulting in the alternation of pale (calcareous nannofossil-rich) and dark (clay-rich) laminae. In comparison, the local presence of lamina truncations and grading probably reflects episodic sea-bed erosion and penecontemporaneous deposition from low-density turbidity currents. This notion is supported by the minute pinch-and-swell architecture of some laminae, which roughly mimics experimentally produced ripples formed from carbonate mud sediment that has flocculated into coarse silt to sand-sized particles capable of producing current ripples and associated cross-lamination comparable to those of siliciclastic deposits (Schieber *et al*. 2007, 2013; Ghadeer & Macquaker 2011). The localized examples of lamina disruption and small-scale draped scarps are attributed to minor slope creep.

The sharp-based tuffaceous siltstone to sandstone bed in the Munk Marl Bed of the Deep Adda-1 core is interpreted as a turbidite, with the lamination conforming to the T_b division of Bouma (1962).

Nodular facies

Description

Three nodular facies are recognized (Fig. 7). Facies units are decimeter-thick, ranging between 17–30 cm (6.5–12 in), and occur in the four Adda Field cores (Ta-

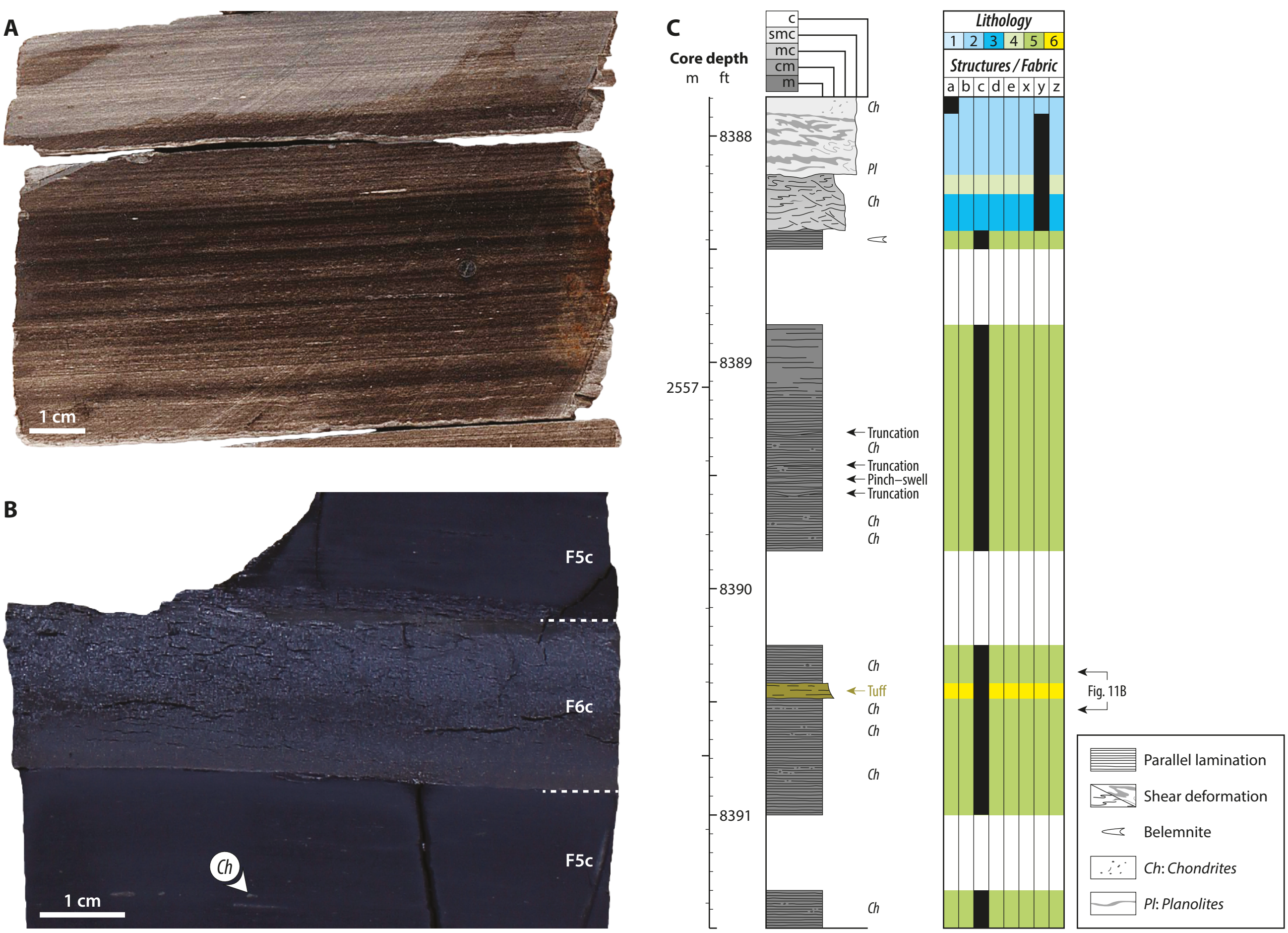

Fig. 11. Representative photographs (A, B) and detailed log (C) of parallel lamination (sedimentary structure c) in the Munk Marl Bed of the North Jens-1 (A; 2304.49–2304.41 m) and Bo-3X (B, C) cores. The photographs show distinctly laminated marlstone (A; F5c) and weakly graded tuff (B; F6c) with solitary *Chondrites* (*Ch*). The photographed interval in (B) has been treated with light oil for visual enhancement of sedimentary structures and corresponds to the lower part of the log, indicated to the right of the facies plot (C). Lithological abbreviations refer to: c, chalk (lithology 1); smc, slightly marly chalk (lithology 2); mc, marly chalk (lithology 3); cm, chalky marlstone (lithology 4); m, marlstone (lithology 5). Tuff corresponds to lithology 6.

ble 1). The facies are characterized by centimeter-scale chalk nodules floating in a matrix of redox-associated green-colored (F3d*g*) and red-colored (F3d*r*) marly chalk and red-colored chalky marlstone (F4d*r*) (Figs 7, 12). The nodules are generally randomly distributed, devoid of prevalent orientations, and irregularly shaped with inconspicuous to gradual boundaries to the surrounding matrix (Fig. 12). Nodular facies units are locally associated with faint sub-vertical deformation bands, biomottling, and rare bivalves and pyrite nodules. Unit boundaries are generally transitional to irregular, with the exception of upper boundaries in the Deep Adda-1 core that form conspicuous firmgrounds to hardgrounds. Nodular facies units are generally interbedded with biomottled and shear-deformed facies units.

Interpretation
The nodular fabric conforms to an early stage in the process that eventually leads to the formation of incipient hardgrounds. The nodules formed during relatively prolonged periods of sediment starvation

Fig. 12. Representative photograph of nodular fabric (sedimentary structure d) in the Adda-3 core (2387.19–2386.99 m), showing various irregular shapes and indistinct boundaries of chalk nodules in dominantly red (F3d*r*) and green (F3d*g*) marly chalk. The interval has been treated with light oil for visual enhancement of sedimentary structures.

and early diagenesis resulting in patchy cementation of the shallow sea bed (Kennedy & Garrison 1975). This interpretation is consistent with the position of the units below firmgrounds and hardgrounds in the Deep Adda-1 core.

Matrix-rich conglomerate facies

Description
Two matrix-rich conglomerate facies are recognized (Fig. 7). Facies units are generally a few decimeters thick, but range between 1–38 cm (0.5–15 in). The facies occur only in the Deep Adda-1 core, where they constitute chalk-dominated and marlstone-dominated conglomerates (Figs 7, 13).

The chalk-dominated conglomerates (F3e) comprise centimeter-thick (1–15 cm; *c.* 0.5–6 in) beds in the lower Tuxen Formation below the Munk Marl Bed, which are primarily characterized by matrix-supported granule to pebble-sized, skeletal wackestone chalk clasts randomly floating in a matrix of marly chalk of skeletal wackestone grading into packstone and locally grainstone. The clasts are commonly accompanied by inoceramid, belemnite and more rarely ammonite shell fragments. The chalk-dominated conglomerates generally occur immediately above firmground to hardground surfaces and are interbedded with biomottled and nodular facies units, with the lower boundaries being sharp or irregular to erosional, whereas the upper boundaries are transitional.

The marlstone-dominated conglomerates (F5e) are represented by three decimeter-thick (10–38 cm; 4–15 in) beds in the Munk Marl Bed, which are primarily characterized by chaotic fabrics devoid of conspicuous sedimentary structures or textures, but with granule to cobble-sized chalk and marlstone clasts randomly dispersed in a structureless marlstone matrix (Figs 7, 13). Whereas the lower and upper beds are predominantly matrix-supported (Fig. 13), the middle bed is clast-supported. In addition, the middle and upper beds exhibit a low-angle oblique fabric defined primarily by the orientation of elongate clasts (Fig. 13). The clasts are predominantly characterized by being either: (i) nodular to spherical in shape with local bioerosion and glauconitic impregnation of the margins; or (ii) plastically deformed with lenticular and elongated to contorted shapes that may be associated with slight convolution of streaked-out marlstone matrix (Fig. 13). The marlstone-dominated conglomerates have sharp boundaries and are interbedded with parallel-laminated facies units.

Interpretation
The general occurrence of the chalk-dominated conglomerates (F3e) above irregular and erosional

firmground to hardground surfaces, and the absence of physical sedimentary structures in a skeletal and grainy fabric, collectively indicate that this facies represents reworking of locally derived bioclasts and chalk intraclasts by relatively intense bottom or wave-induced currents. The heterogeneous fabric of the facies units further suggests that they were subsequently subjected to intense biogenic reworking in concert with pelagic ooze fallout.

In contrast, the chaotic fabric and structureless, mud-grade matrix of the marlstone-dominated conglomerates (F5e) suggest that this facies represents gravity flows. The random distribution and plastic deformation of the clasts indicate that deposition was associated with freezing of the flows, and that these possessed a shear strength sufficiently large for the matrix to prohibit sorting and cause small-scale shearing. Such non-Newtonian flow conditions are well-documented features of cohesive debris flows (Postma 1986; Mulder & Alexander 2001), which were likely to have developed from nearby mass wastage.

Flaser-laminated facies

Description

Four flaser-laminated facies are recognized (Fig. 7). Facies units are generally a few centimeters thick, ranging between 1–13 cm (0.5–5 in), and occur in the three Valdemar Field cores (Table 1). The facies constitute irregular and wavy lenses of predominantly chalk (F1x) and slightly marly chalk (F2x), and subordinately marly chalk (F3x) and chalky marlstone (F4x), surrounded by thinner, wispy seams of marlstone (Figs 7, 14). The facies generally occur as isolated beds, and are only rarely stacked as consecutive units of differ-

Fig. 13. Representative photograph of matrix-rich conglomerate (sedimentary structure e) in the Deep Adda-1 core (2446.25–2446.05 m), showing a marlstone-dominated (F5e), relatively chaotic and low-angle oblique fabric that contains dispersed granule to cobble-sized, plastically deformed chalk clasts with lenticular and elongated to contorted shapes and slight lamina convolutions.

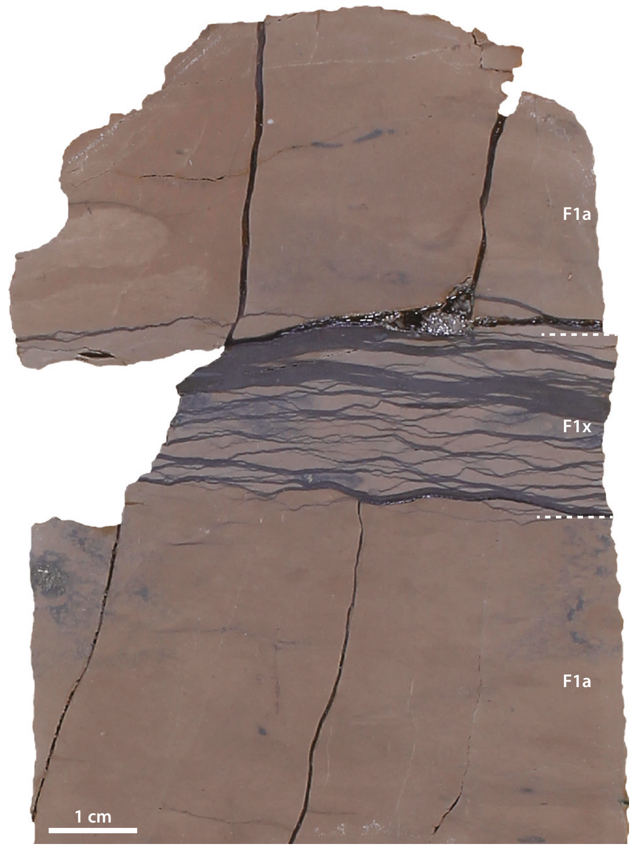

Fig. 14. Representative photograph of flaser lamination (sedimentary structure x) in the Bo-3X core (2568.83–2568.73 m), showing irregular and wavy lenses of chalk (F1x) surrounded by thinner wispy seams of marlstone. The flaser-laminated unit is intercalated between two homogeneously bioturbated chalk facies units (F1a). The interval has been treated with light oil for visual enhancement of sedimentary structures.

ing lithologies (e.g. F4x overlain by F3x). Boundaries are generally sharp and irregular conforming to the shape of the marlstone seams, and the facies units are generally interbedded with homogeneously bioturbated and biomottled facies units, and more rarely with shear-deformed facies units.

Interpretation

Flaser lamination in chalk generally represents solution seams generated during late burial diagenesis in response to mechanical compaction and pressure dissolution of the carbonate, as outlined by Garrison & Kennedy (1977). Following the interpretation of these authors, the dissolution mainly affected the coccolith-rich chalk matrix, and was probably most intense in the most argillaceous parts of the primary sediment.

Shear-deformed facies

Description

A total of 11 shear-deformed (*sensu lato* Anderskouv & Surlyk 2011) facies are recognized (Fig. 7). Facies units are generally a few decimeters thick, but range between 1–90 cm (0.5 in – 2 ft 10 in). The facies exhibit a relatively wide range of sedimentary structures in chalk (F1y), slightly marly chalk (F2y, F2y*g* and F2y*r*), marly chalk (F3y, F3y*g* and F3y*r*) and chalky marlstone (F4y, F4y*g* and F4y*r*), and more rarely in marlstone (F5y) (Figs 7, 8, 15). The sedimentary structures represent two common end-members, which typically co-occur within a single facies unit.

The first end-member displays a distorted to convoluted biomottled ichnofabric recognized by horizontal to inclined strain of relatively poorly preserved burrows and locally overturned relict lamination (Fig. 15). Individual burrows may display contorted to folded morphologies, although trace fossils can commonly be identified as *Chondrites* and *Planolites* with subordinate *Palaeophycus*, *Phycosiphon*, *Teichichnus*, *Thalassinoides* and *Zoophycos*. Locally, oblique imbrication of strained *Planolites* burrows mimic centimeter-scale thrusts above basal shear planes. Such micro-thrusted ichnofabrics may occur several times within a single facies unit and display opposing directions of displacement. Fine pebble-sized chalk clasts are locally present.

The second end-member is predominantly characterized by horizontal to sub-horizontal lamination and banding that deviates from primary parallel lamination by exhibiting minor undulations to significant pinching-and-swelling organized as either millimeter-scale (shear lamination) or centimeter-scale (shear banding) lamina sets (Fig. 15). Coarse sand-grade chalk clasts and/or cross-cutting relationships are locally present.

Shear-deformed facies units are commonly associated with irregular or conjugate deformation bands, and locally contain belemnites, bivalves (including inoceramid shell fragments), and silicified intervals, and more rarely pyrite (Fig. 15). Facies units are predominantly interbedded with biomottled facies units, and subordinately with homogeneously bioturbated, parallel-laminated, flaser-laminated or silicified facies units (Fig. 15). Alternatively, shear-deformed facies form stacks of consecutive units of differing lithologies (e.g. F2y*r* overlain by F4y*r* and F3y*r*) up to 2.5 m (8 ft 2 in) thick. Lower boundaries of the facies units are generally sharp, erosional or irregular, whereas upper boundaries are bioturbated, irregular or transitional. In some cases, lower erosional boundaries contain rip-up clasts and incipient rip-up clasts, the former generally recognized by base-detached, irregularly shaped clasts (some with unidirectional or bidirectional double tails), and the latter characterized by base-attached, angular clasts situated immediately above similarly shaped cavities.

Interpretation

The shear-deformed ichnofabrics and shear lamination/- and banding end-member configurations are strikingly similar to shear deformation or 'shredded' structures previously reported in Upper Cretaceous chalk (Kennedy 1980; Nygaard *et al.* 1983; Anderskouv & Surlyk 2011). Correspondingly, the configurations reported here were probably formed from plastic shear deformation of relatively unlithified sediment, including moderately intense deformation of biomottled sediment (first end-member configuration), and highly intense deformation of sediment where the precursor sedimentary structures are virtually indeterminable (second end-member configuration).

As emphasized by Anderskouv & Surlyk (2011), it is typically difficult to determine in core whether shear-deformed units occur *in situ* or allochthonously, for example as part of larger slumps or structurally deformed intervals of the succession. Indeed, a core section through a succession of thin recumbent folds with large aspect ratios would probably exhibit numerous laminae and only few fold hinges, thereby prohibiting recognition of the formative process of the shear deformation (Anderskouv & Surlyk 2011). However, the generally limited unit thickness, common interbedding with undisturbed facies (for example biomottled facies units) and lack of marked erosion surfaces collectively indicate that most of the deformation took place *in situ* as episodic events. Considering that only few of the observed shear-deformed facies units occur in association with deposits formed from events conspicuously capable of producing shear deformation (e.g. overriding slumps or debris flows; cf. Anderskouv & Surlyk 2011), the general deformation is inferred to have been governed by relatively limited lateral displacement. The common co-occurrence of the different configurations within a single facies unit indicates that the different shear deformation styles acted penecontemporaneously, or that the unit was repeatedly deformed through different shear events. For example, basal shear planes beneath micro-thrusted *Planolites* ichnofabrics probably record highly intense ductile deformation that acted as minor 'décollement' surfaces bounding intervals that experienced less intense deformation.

Consequently, most of the shear deformation structures are suggestive of minor sediment creep at or close to the sediment surface. However, some beds that display shear-deformed, shredded ichnofabrics and folded lamination (such as in the North Jens-1 core; Fig. 4) probably record rare events when slope creep and *in situ* deformation resulted in failure and limited mass transport in the form of disconnected slumps transitional to debris flows (Anderskouv & Surlyk 2011).

Silicified facies

Description

Two silicified facies are recognized (Fig. 7). Facies units are generally a few decimeters thick, but range between 5–42 cm (2–16.5 in), and occur in the Bo-3X and Boje-2C cores. The facies are characterized by sporadically distributed light-blue to gray-nuanced silica-enriched patches that overprint the prevailing lithology of slightly marly chalk (F2z) and marly chalk (F3z) (Figs 7, 8, 16). The silica patches are generally irregularly shaped with indistinct boundaries, but may also mimic precursor sedimentary structures, such as shear deformation structures and biomottling

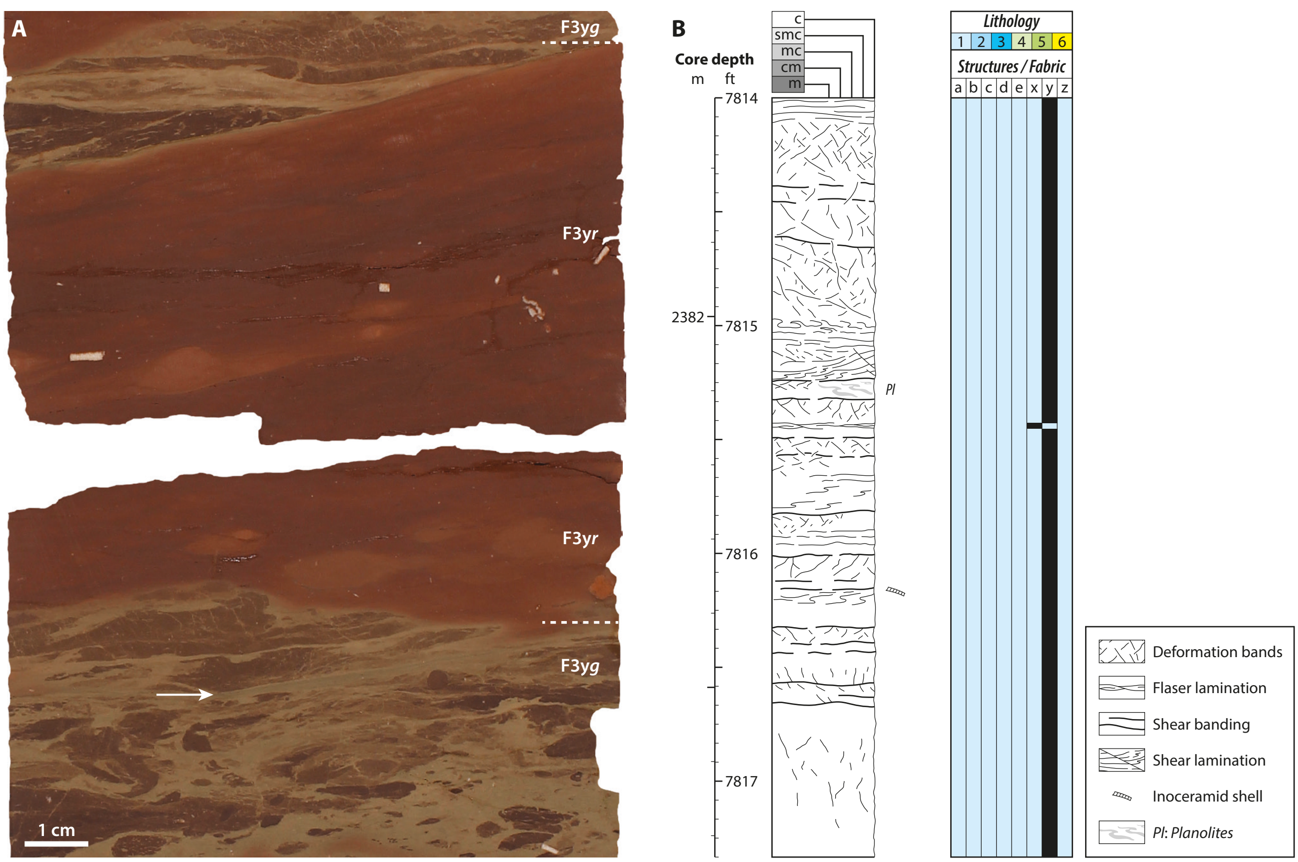

Fig. 15. Representative photograph (A) and detailed log (B) of shear deformation structures (sedimentary structure y) in the SE Adda-1 (2505.21–2505.08 m) and Adda-3 cores, respectively. The photograph shows a distorted to convoluted biomottled ichnofabric (first end-member configuration) recognized by horizontal to inclined strain and contortion of relatively poorly preserved burrows (most likely *Chondrites* and *Planolites*) in green (F3yg) and red (F3yr) marly chalk, with a single occurrence of shear lamination (second end-member configuration) indicated by the white arrow. The floating, white, angular grains are inoceramid shell fragments. The photographed interval has been treated with light oil for visual enhancement of sedimentary structures. Lithological abbreviations refer to: c, chalk (lithology 1); smc, slightly marly chalk (lithology 2); mc, marly chalk (lithology 3); cm, chalky marlstone (lithology 4); m, marlstone (lithology 5). Tuff corresponds to lithology 6.

with local relict *Chondrites* and *Planolites* (Fig. 16). Correspondingly, silicified facies units are predominantly interbedded with biomottled and shear-deformed facies units, as well as homogeneously bioturbated facies units, and exhibit transitional boundaries. Rarely, silicified facies form stacks of consecutive units of differing lithologies (e.g. F3z overlain by F2z) up to 0.7 m (2 ft 5 in) thick.

Interpretation

The overprinting of the silica on precursor sedimentary structures testifies to a post-depositional origin of these facies, namely precipitation of a stable silica phase during burial diagenesis. The silica was most likely sourced by dissolved, biogenic, amorphous silica (Clayton 1986; Madsen & Stemmerik 2010). The diffuse precipitation and lack of flint nodules may represent a lack of body (e.g. echinoids) and trace (e.g. *Thalassinoides*) fossils.

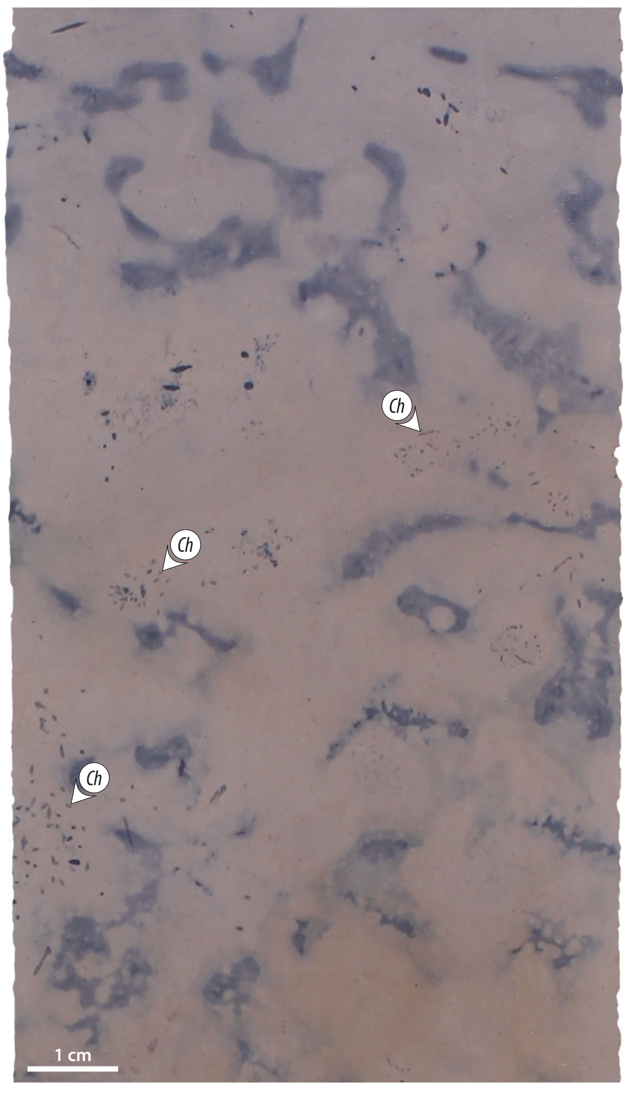

Fig. 16. Representative photograph of silicified fabric (sedimentary structure z) in the Bo-3X core (2558.15–2558.03 m), showing sporadically distributed, irregularly shaped light-blue silica-enriched patches that overprint the prevailing slightly marly chalk lithology (F2z). The interval has been treated with light oil for visual enhancement of sedimentary structures. *Ch*, *Chondrites*.

Facies distribution and implications for basin development

The facies distribution and stratigraphic development of the Tuxen and Sola Formations in the seven investigated cores generally conform to previous observations of the succession (Jensen & Buchardt 1987; Ineson 1993; Jakobsen *et al.* 2004). The Tuxen Formation predominantly comprises intensely bioturbated marly chalk and chalk, punctuated by parallel-laminated marlstone of the Munk Marl Bed, whereas the Sola Formation is significantly more marly and displays relatively thick parallel-laminated and bioturbated marlstone units, particularly in the Fischschiefer Member (Figs 4, 8, 17). However, a vertical and lateral variability in the distribution of facies is recorded throughout the study area, with important implications for understanding the Early Cretaceous basin evolution of the DCG. These are primarily observed in the Tuxen Formation, and include: (i) abundant shear-deformed facies units below the Munk Marl Bed (but a general absence above) (Figs 8, 17A); (ii) abundant thin, parallel-laminated marlstone facies units above the Munk Marl Bed (but a general absence below) (Figs 8, 17A); (iii) redox-associated green and red lithological color variations and associated nodular fabrics confined to the Adda Field (Fig. 17B); and (iv) matrix-rich conglomerates confined to the Deep Adda-1 core.

The general dominance of intense bioturbation in the Tuxen Formation indicates a continuously well-oxygenated depositional setting, with the alternation of the chalk- and marlstone-dominated facies reflecting the relative sediment flux from pelagic and terrestrial sources, respectively. In contrast, the Munk Marl Bed records a period of persistent sea-floor anoxia, postulated to have been caused, at least in part, by lowstand conditions (Jensen & Buchardt 1987; Ineson *et al.* 1997; van Buchem *et al.* 2018). In this scenario, the low relative sea-level may have led to isolation of the basin contributing to restricted ocean ventilation and/or potential lowering of the oxygen minimum zone to the seafloor. The predominance of shear-deformed facies units below the Munk Marl Bed (Figs 8, 17A), probably indicates that active tectonism took place prior to the onset of anoxic conditions in the basin. This is compatible with inferences from seismic observations

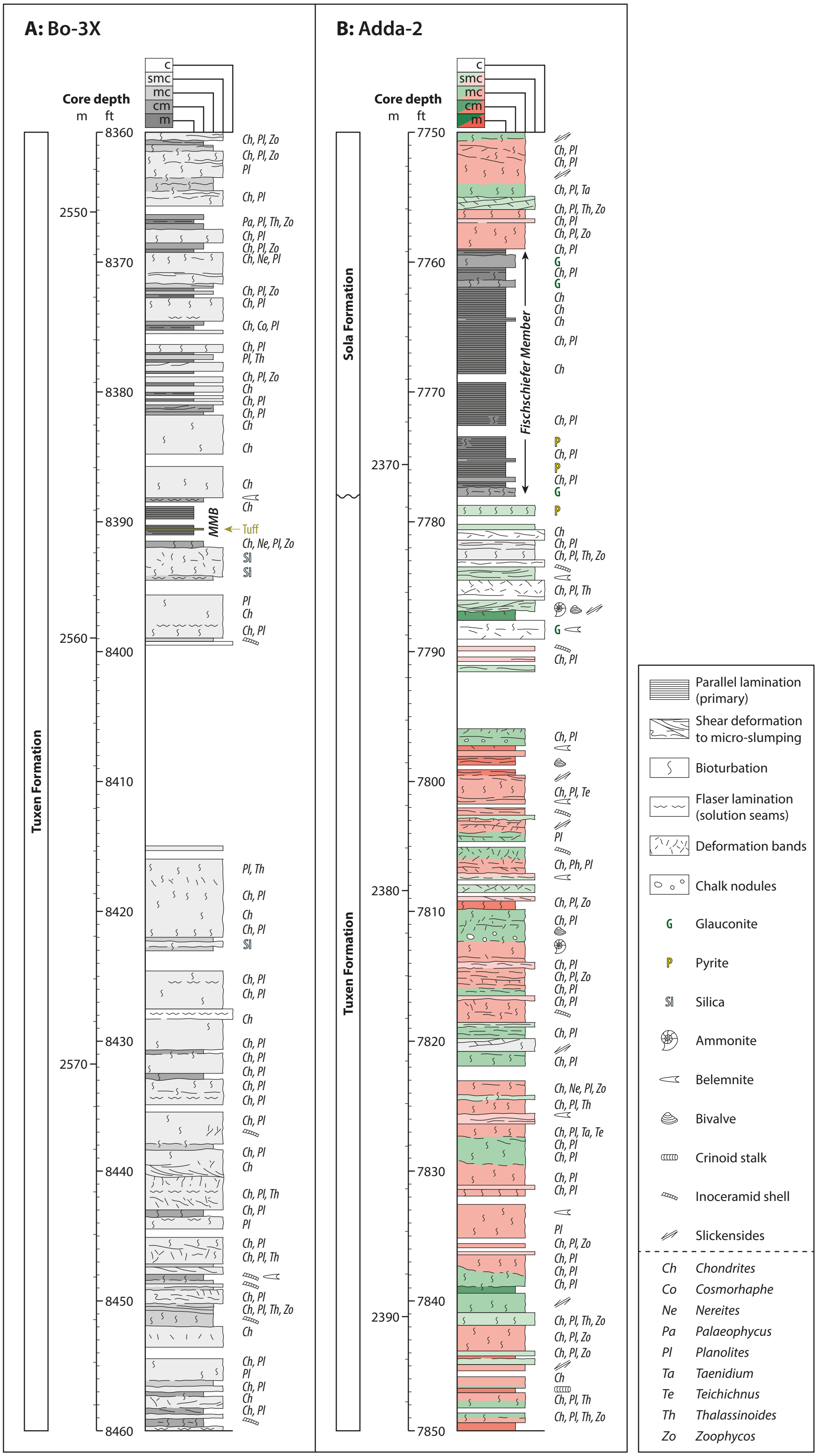

Fig. 17. Representative sedimentological logs of the Bo-3X (A) and Adda-2 (B) cores highlighting the most important characteristics of the vertical and lateral variability in the distribution of facies (see Fig. 1A for well positions). Notable facies-distribution characteristics include an upward increase in the marlstone content passing from the Tuxen Formation to the Sola Formation, exemplified here by the Fischschiefer Member (B); the presence of redox-associated green and red lithological color variations and nodular fabrics in the Adda Field (B), while these are absent in the Valdemar Field (A); abundant shear-deformed facies units below the Munk Marl Bed (MMB) in the Tuxen Formation (A); and abundant thin, parallel-laminated marlstone facies units above the Munk Marl Bed in the Valdemar Field (A). Lithological abbreviations refer to: c, chalk; smc, slightly marly chalk; mc, marly chalk; cm, chalky marlstone; m, marlstone.

of the initiation of inversion in the Adda Field in the late Valanginian – Hauterivian (Vejbæk & Andersen 1987). In the Valdemar Field, the general absence of shear-deformed facies units above the Munk Marl Bed suggests subsequent waning of gravitational instability (and hence tectonism) in that area. In addition, the abundant thin, parallel-laminated marlstone facies units above the Munk Marl Bed in the Valdemar Field reflect recurring episodes of anoxia.

Inversion and tectonic instability of the Adda Field area during the Hauterivian–Barremian is also supported by the thin and incomplete stratigraphic record in this area (Jensen & Buchardt 1987; van Buchem *et al.* 2018) when compared with the Valdemar Field cores (Figs 5, 17). The dominance of green and red redox-associated lithological color variations and the common occurrence of nodular fabrics in the Adda Field cores also indicate that this area was subject to condensation and perhaps sediment bypass. This facies evidence supports the bathymetric model of van Buchem *et al.* (2018) proposing that the Adda Field constituted a plateau at the eastern basin margin of the DCG in the Barremian, separated from the basinal depocenter of the Valdemar Field area. This model is compatible with the presence of matrix-rich conglomerates in the Munk Marl Bed of the Deep Adda-1 core, which suggest that steady pelagic and hemipelagic background sedimentation was occasionally interrupted by deposition from gravity-flow events, most likely sourced from the adjacent Coffee Soil Fault (Fig. 1A; Jensen & Buchardt 1987).

The relatively thick parallel-laminated marlstone facies units in the Fischschiefer Member (Figs 4, 8, 17B) represent a return to prevailing anoxic conditions during the early Aptian, consistent with global records of the OAE-1a (e.g. Mutterlose & Bottini 2013; Blok *et al.* 2022 and references therein).

Conclusions

Comprehensive carbonate facies analysis of cored sections of the Lower Cretaceous Tuxen and Sola Formations from seven wells in the Valdemar (Bo-3X, Boje-2C and North Jens-1) and Adda (Adda-2, Adda-3, Deep Adda-1 and SE Adda-1) Fields of the Danish Central Graben (DCG) has permitted: (i) the first detailed account of the range of lithologies, sedimentary structures and depositional processes in the succession; and (ii) new insights into the Early Cretaceous basin evolution of the DCG, drawn from the documentation of vertical and lateral variability in the distribution of facies.

- A total of 50 facies are defined by: (i) lithology, ranging from chalk to marlstone and tuffaceous siltstone to sandstone; (ii) eight different sedimentary structures (or fabrics); and (iii) two (green and red) redox-associated lithological color variations (confined to the Adda-2, Adda-3 and SE Adda-1 cores) of slightly marly chalk to marlstone.
- Homogeneous bioturbation represents fully oxygenated benthic conditions and low sedimentation rates, allowing the infauna to obliterate physical sedimentary structures.
- Mottled bioturbation records the same process as homogeneous bioturbation, but lithological contrasts in the burrowed sediments ensured that biogenic structures are well-defined, possibly reflecting a relatively rhythmic alternation between pelagic (clay-poor) and hemipelagic (clay-rich) sedimentation.
- Parallel lamination is predominantly recorded in marlstone within and above the Munk Marl Bed in the Tuxen Formation, and is common in the Sola Formation marlstones, and reflects deposition in tranquil conditions from pelagic to hemipelagic suspension settling in dysoxic to anoxic bottom-water conditions.
- Nodular fabrics are confined to the Adda Field cores, and represent patchy cementation of the shallow sea bed during early diagenesis as a precursor to the development of incipient and mature hardgrounds.
- Matrix-rich conglomerates are confined to the Deep Adda-1 core, and record: (i) reworking of locally derived bioclasts and chalk intraclasts by relatively intense bottom or wave-induced currents; and (ii) cohesive debris flows indicative of mass wastage, probably at the eastern margin of the graben.
- Flaser lamination represents solution seams generated during late burial diagenesis in response to mechanical compaction and pressure dissolution of clay-rich carbonate.
- Shear deformation structures are mainly recorded in the lower Tuxen Formation, below the Munk Marl Bed, and represent moderate to intense plastic shear deformation of relatively unlithified sediment, predominantly involving limited lateral displacement.
- Silicified fabrics reflect burial diagenesis.
- The vertical and lateral distribution of facies record that: (i) active tectonism, probably related to early inversion, created localized sediment instability prior to the onset of anoxic conditions that resulted in deposition of the Munk Marl Bed, which in the Valdemar Field was followed by tectonic waning and repeated episodes of anoxia in the basin; and (ii) the Valdemar Field area constituted the primary basinal depocenter in this part of the DCG and during the Barremian was flanked to the east

in the Adda Field area by an early inversion high characterized by condensation and bypass.

- The Fischschiefer Member represents a return to prevailing anoxic conditions during the early Aptian consistent with global records of the Oceanic Anoxic Event 1a (OAE-1a).

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