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Ryazanian (Berriasian) molluscs and biostratigraphy of the Dutch and Norwegian North Sea area (south of Viking Graben)

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Original Article

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Abstract

Herein, Ryazanian (Berriasian) macrofossils from three well cores in the Central Graben (wells B18-02, L06-02, The Netherlands) and on the Jæren High (well 7/7-2, Norway) in the southern North Sea region are described. Macrofossils are mainly represented by buchiid bivalves (*Buchia volgensis*) and ammonites (*Surites*, *Lynnia* and *Praetollia*?). The genus *Lynnia* is recorded for the first time outside its topotypical area, and its systematic position and stratigraphic ranges are discussed. Additionally, the studied core sections yielded coleoid remains and a single limid bivalve. Based on the stratigraphic ranges of key ammonite genera (*Lynnia, Surites* and *Bojarkia*), the zonation of the Ryazanian stage is reconsidered. Uppermost Volgian to Ryazanian ammonite faunas are quite consistent and diverse but showing a higher degree of similarity throughout the Panboreal Superrealm as compared to those from rest of the Upper Volgian and the Middle Volgian. *Buchia volgensis* is the only species known from the southern North Sea and East Anglia, which is in strong contrast to the high diversity of *Buchia* in East Greenland and the remainder of the Boreal Realm. We hypothesise that such differences in the distribution of ammonites and bivalves in general, and the absence of buchiid species other than *Buchia volgensis* south of East Greenland in particular, are the result of anoxic bottom water conditions in the southern Viking Strait. The unusually wide geographic range of *B. volgensis*, which is known from such distant areas as Mexico and the Crimea, suggests a potential higher tolerance of this species to adverse conditions.

Introduction

Information regarding the temporal and spatial distribution of Ryazanian macrofossils is largely absent for the (southern) North Sea area. No outcrops exist, apart from temporary exposures and quarries in marginal settings (Casey, 1973; Kelly, 1984), and distal deposits occur only offshore. Although a large number of offshore wells have been drilled, continuously cored sections containing macrofossils are exceedingly rare. So far, Birkelund et al. (1983; Denmark) and Abbink et al. (2001b; The Netherlands) have figured ammonites from the latest Jurassic to earliest Cretaceous interval of the region. Herein, we report fossils from two additional wells, namely well B18-02 (The Netherlands) and well 7/7-2 (Norway) (Image 1). Apart from ammonites and a few belemnites, these wells have yielded a high number of bivalves (Buchiidae and one Limidae) exclusively comprising byssally attached suspension feeders. Furthermore, an additional ammonite from well L06-02 (The Netherlands) is described. These findings aid to further improve the record of macrofossils and the correlation of strata within the North Sea region. Throughout this work, ammonite zones (e.g. Icenii Zone) are used in the 'Oppelian' standard chronostratigraphical, hierarchical sense.

Geological setting

During the Triassic and Jurassic, a rift system developed in the present-day North Sea area as a result of the break-up of Pangea (Ziegler, 1982). The development of this rift system can be subdivided into a pre-, syn- and post-rift period (Nøttvedt et al., 1995). Syn-rift conditions influenced the Jurassic sedimentary history up to the earliest Cretaceous. In the Late Jurassic, rifting reached its climax and ceased during the latest Jurassic-earliest Cretaceous transition, resulting in a failed rift (Verreussel et al., 2018, and references therein). The three branches that meet in a triple junction consist of the Viking Graben as the northern branch, the Witch Ground Graben as the western branch and the Central Graben and the Moray Firth Basin as the southern branch. This branch extends in a NW-SE direction from the triple junction to the Salt Dome Province in the Danish offshore. It terminates in the Tail End Graben, but it spreads further south into the German offshore region known as the 'Entenschnabel' and into the Dutch North Sea sector. Well 7/7-2 was drilled on the Jæren High, near the northern end of the East Central Graben. The southern extension of this rift basin, the Dutch Central Graben, where well

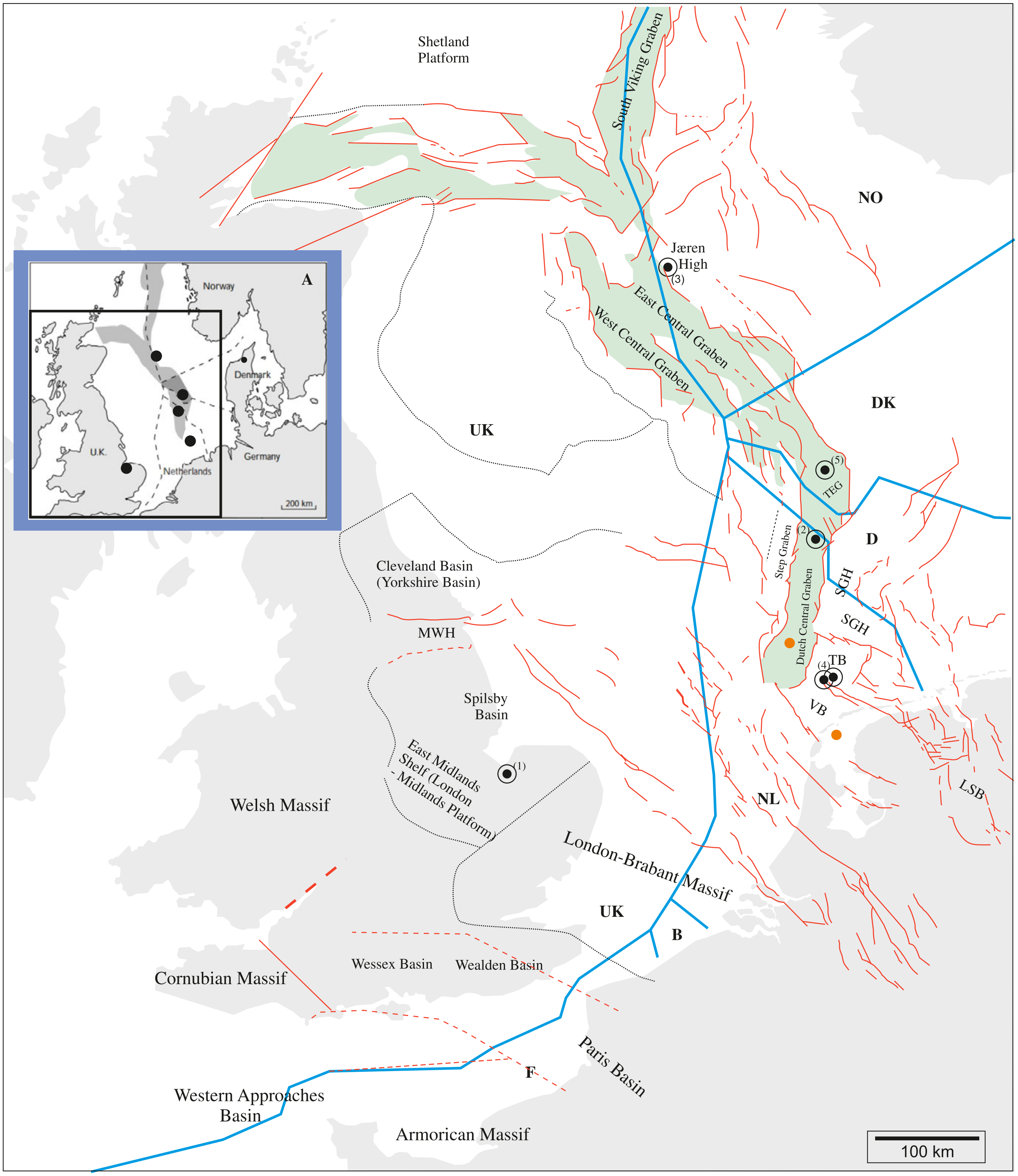

Image 1. Geographical situation. Deep, graben related basins are shaded in green. Red lines indicate faults. Blue lines indicate political sea boundaries. Orange dots indicate Dutch Jurassic volcanos. Black dots indicate the position of the outcrops and wells mentioned or studied herein, where (1) refers to Runcton North and King's Lynn Bypass (UK) (Casey, 1973), (2) to well B18-02 (NAM, NL) (this work), (3) to well 7/7-2 (Statoil, N) (this work), (4) to wells L06-02 and L06-03 (NAM, NL; after Abbink et al., 2001b; this work) and (5) to well E-1 (DK) (Birkelund et al., 1983) (modified from Rawson et al., 1978, Duin et al., 2006 and Hopson et al., 2008). Abbreviations used: B = Belgium, D = Germany, DK = Denmark, F = France, NL = The Netherlands, NO = Norway, UK = United Kingdom. Abbreviations used for the paleo-domains: LSB = Lower Saxony Basin, MWH = Market Weighton High, SGH = Schill Grund High, TB = Terschelling Basin, TEG = Tail End Graben, and VB = Vlieland Basin.

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B18-02 is situated, terminates against the Central Offshore Platform (Image 1). To the south, the Terschelling and Vlieland basins occur (Image 1).

The latest Jurassic to earliest Cretaceous sedimentary succession of the Dutch Central Graben is characterised by organic-rich rocks of the Lutine Formation, which in the past were referred to the Kimmeridge Clay Formation (Munsterman et al., 2012; Verreussel et al., 2018). The Lutine Formation is widespread and in the more distal settings it is characterised by organic-rich, slightly calcareous, greyish-brown fissile mudrocks (Clay Deep Member), while in more proximal settings it has an overall lower organic content (<1%), is more siliciclastic (silts and fine sands) and less dark coloured (Schill Grund Member). A characteristic bundled high gamma ray pattern in the Clay Deep Member distinguishes it from the preceding mudrocks of the Kimmeridge Clay Formation while the overlying mudrocks of the Vlieland Claystone Formation show a low gamma ray pattern.

To the north, the lateral equivalents of the Lutine Formation are the 'hot shales' of the Bo Member (Farsund Formation; Danish sector of the North Sea; Feldthusen Jensen et al., 1986; Michelsen et al., 2003), which have recently also been recorded from the German offshore (Arfai & Lutz, 2018), and the Mandal Formation (Norwegian sector of the North Sea; Hamar et al., 1983). Further north-eastwards lateral equivalents of these black shale formations are the Agardhfjellet Formation (Spitsbergen), Hekkingen Formation (Barents Sea shelf) and Bazhenovo Formation (Western Siberia) (Rogov et al., 2020). The Lutine Formation is equivalent to these 'hot-shale' units, as demonstrated by dinoflagellate cyst stratigraphy (Dybkjær, 1998; Ineson et al., 2003; Verreussel et al., 2018).

The depositional history of the Ryazanian sedimentary succession is influenced both by the intricacy of the basin and platform configuration and also by the presence and deformation of the Zechstein evaporitic series. The plasticity of the salts resulted in the movement and eventual accumulation of sediments, thus influencing both basin configuration, displacement and fault activity (Korstgård et al., 1993; Clark et al., 1999; Arfai et al., 2014; Bouroullec et al., 2018). Surfaced caprocks were eroded and subsequently led to additional erosion of the evaporitic series, locally exposing salts and Permian rocks. Non-deposition and subrosion (subterraneous erosion of salts potentially leading to cavities) could additionally have resulted in irregular distribution of and unconformities in the Ryazanian succession. For example, in the Danish well E-1 (= E-1X or Tyra, Tail End Graben; Birkelund et al., 1983) the top of the 'hot shale unit' is placed in the Kochi Zone, based on the occurrence of the ammonite *Hectoroceras* cf. *kochi*, while the upper part of the Ryazanian is missing, and an erosional surface separates the uppermost lower Ryazanian deposits from lower Valanginian deposits (Andsbjerg & Dybkjær, 2003, p. 291).

The 'end-Jurassic to earliest Cretaceous rifting phase' was followed by what is known as 'the Cretaceous transgression', essentially indicating the base of the Valanginian post-rift sequence (tectono-stratigraphic mega-sequence TMS-4, see Verreussel et al., 2018), when subsidence was no longer limited towards the graben area but influenced the whole region (Jeremiah et al., 2010; Verreussel et al., 2018, fig. 4). This resulted in contrasting lithologies, creating an important marker horizon in the North Sea area, which is often characterised by a significant unconformity variously termed the 'base Cretaceous', 'late Cimmerian' or 'northern North Sea' unconformity (see Kyrkjebø et al., 2004 and references therein). Recently, new information regarding the 'base Cretaceous unconformity' (BCU) in the Danish Central Graben (North Jens-1 borehole) has been published by Ineson et al. (2022). These authors dated the BCU as latest Ryazanian (Peregrinoceras albidum Zone), but the evidence provided seems controversial. Although the presence of a few ammonites below the unconformity is noted, only two incompletely preserved ammonites were figured. Apparently, these ammonites came from the lower part of the Albidum Zone but were referred to *Praetollia* (Ineson et al., 2022, figs 12A, B), an ammonite genus indicative for the Praetollia maynci – Hectoroceras kochi Zones (early Ryazanian). The authors resolved this conundrum by assuming reworking of the macrofossils. In our opinion, insufficient preservation prevents the precise identification of these specimens. The well-developed and forwards projected ribs of the specimen from their fig. 12B strongly resemble those of the ammonite genus *Bojarkia*, but we cannot prove this suggestion because the inner whorls are poorly visible. However, the latter genus is characteristic for the latest Ryazanian, broadly indicating the Stenomphala to early Albidum zones.

Studied wells

Well B18-02 (54° 05′ 35.4′′ N, 04° 47′ 48.6′′ E; Central Graben, Dutch offshore)

B18-02 is the type well of the Lutine Formation (Munsterman et al., 2012), comprising the interval from 2225 to 2315 (± 0.2) m. The well was drilled at the northern limit of the Dutch offshore in the Central Graben (Image 1). The cored interval is approximately 18 m thick, from 2242 to 2259.9 m (90% recovery). Additionally, the description of the formation is based on wireline readings and sidewall-cores. Based on dinoflagellate cyst biostratigraphy, Herngreen et al. (2000, p. 28) concluded that deposition took place during the Icenii/Stenomphala to Stenomphala/Albidum zones for the cored part (Image 2).

Well L06-02 (53° 48′ 53.70′′ N, 04° 59′ 20.00′′ E; Terschelling Basin, Dutch offshore)

In L06-02, the cored interval is from 2227.00 to 2510.10 m with some minor non-recovered intervals. The upper Volgian to lower Ryazanian occurs between 2227.27 and 2263.40 m. Ammonites were first mentioned in an unpublished report (GAPS, 1991) indicating a late Ryazanian age for the interval from 2245.00 to 2263.40 m, based on the occurrence of abundant *Tollia*, *Bojarkia*, *Peregrinoceras* and indeterminable craspeditids. However, these ammonites turned out to be misidentified. Subsequently, based on determinations of the ammonites by Callomon, Abbink et al. (2001b) indicated a late Volgian to early Ryazanian age for the same interval. In addition, the upper part of the core yielded only a single ammonite specimen, herein figured and described as *Praetollia* cf. *contigua* Spath, 1952 (Pl. 3, Fig. 5), indicating the Kochi Zone. The upper 15 m shows conspicuously few macrofossil remains. Occasionally, non-buchiid bivalves occur at 2228.65–66, 2251.45–47, 2255.23–24 and 2260.19–20 m. The studied interval consists mainly of heavily bioturbated glauconitic sandstone with sponge spicules (Scruff Formation), except for the upper part (2227.00–2227.27 m), which is a dark grey silty to very fine-grained micaceous sandstone without any apparent bioturbation or macrofossils. These are lowermost Valanginian deposits (based on dinoflagellate cysts biostratigraphy; pers. com. R. Verreussel, TNO), while the preceding glauconitic rocks can be dated as latest early Ryazanian (Kochi Chron). Hence, the upper Ryazanian appears to be absent in this borehole.

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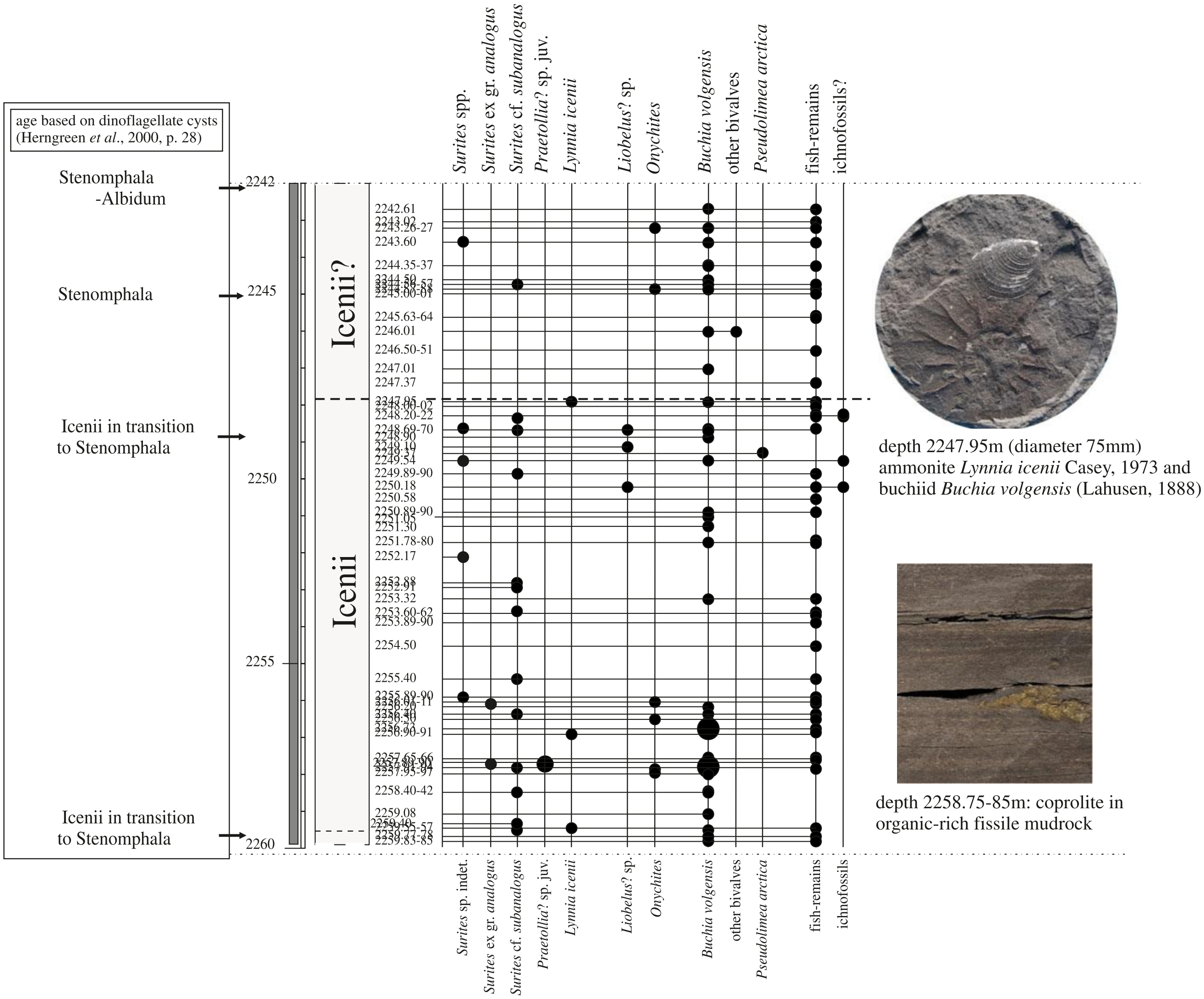

Image 2. Schematic representation of macrofossil distribution of B18-02 and ammonite zonation based on occurrences of *Lynnia* (delicate ribbed *Lynnia icenii* with *Buchia volgensis* seen in upper right photograph from 2247.95 m). Lower right photograph (depth 2258.75–85 m) shows coprolite in organic-rich fissile mudrock. To the left conditional zonation as applied by Herngreen et al., 2000.

Well 7/7-2 (57° 29′ 4.16′′ N, 2° 18′ 17.59′′ E; Brynhild field, Jæren High, Norwegian offshore)

At the Jæren High, the combination of Jurassic uplift and rotation, and subsequent erosion resulted in the exposure of salt along elongated ridges. The dissolution of these salts due to exposure at the surface eventually created accommodation space for Upper Jurassic deposits (Høiland et al., 1993).

In well 7/7-2, 4.5 m of dark coloured shales was cored (90% recovery of interval 3242–3246.96 m; see NPD Factpages) in a relatively thin development of the Mandal Formation, showing the typical 'hot shale' signature of this formation. The deposits consist of very dark brown, grey to black coloured mudrocks. Macrofossils are represented by ammonites of the genus *Surites* (Pl. 4, Figs 1–5) and the species *Lynnia icenii* (Pl. 4, Fig. 6). They are stored in the Ole Bruun Christensen collection (formerly known as Statoil collection). In addition, the studied interval yielded *Buchia volgensis*, belemnite remains of *Acroteuthis* sp. juv. and *Onychites*, and fish remains (J. Hurum pers. comm. 2019). Unfortunately, the whole collection is simply recorded as derived from the interval of 3201.0–3246.96 m (Åsgard Formation, as indicated by Nerdal et al., 1992, tab. 2.1.1), without further detail regarding the position of the individual fossils in the core.

Macrofossils

Ammonites and buchiid bivalves are the most commonly encountered macrofaunal elements (Image 2). Sporadically, belemnites, other bivalves and isolated fish remains (scales, bones; Pl. 1, Figs 8, 13) occur (see also Koevoets et al., 2018). Hitherto, only a few latest Jurassic to earliest Cretaceous ammonites from the North Sea have been reported (Casey, 1973; Birkelund et al., 1983; Abbink et al., 2001b; Jeremiah et al., 2010; Ineson et al., 2022). Only five specimens of *Buchia* are recorded from the east Midlands Shelf (eastern England) (Kelly, 1983, p. 289) and a few more specimens from on- and offshore Denmark (Sorgenfrei & Buch, 1964). It should be noted that all the studied fossils except

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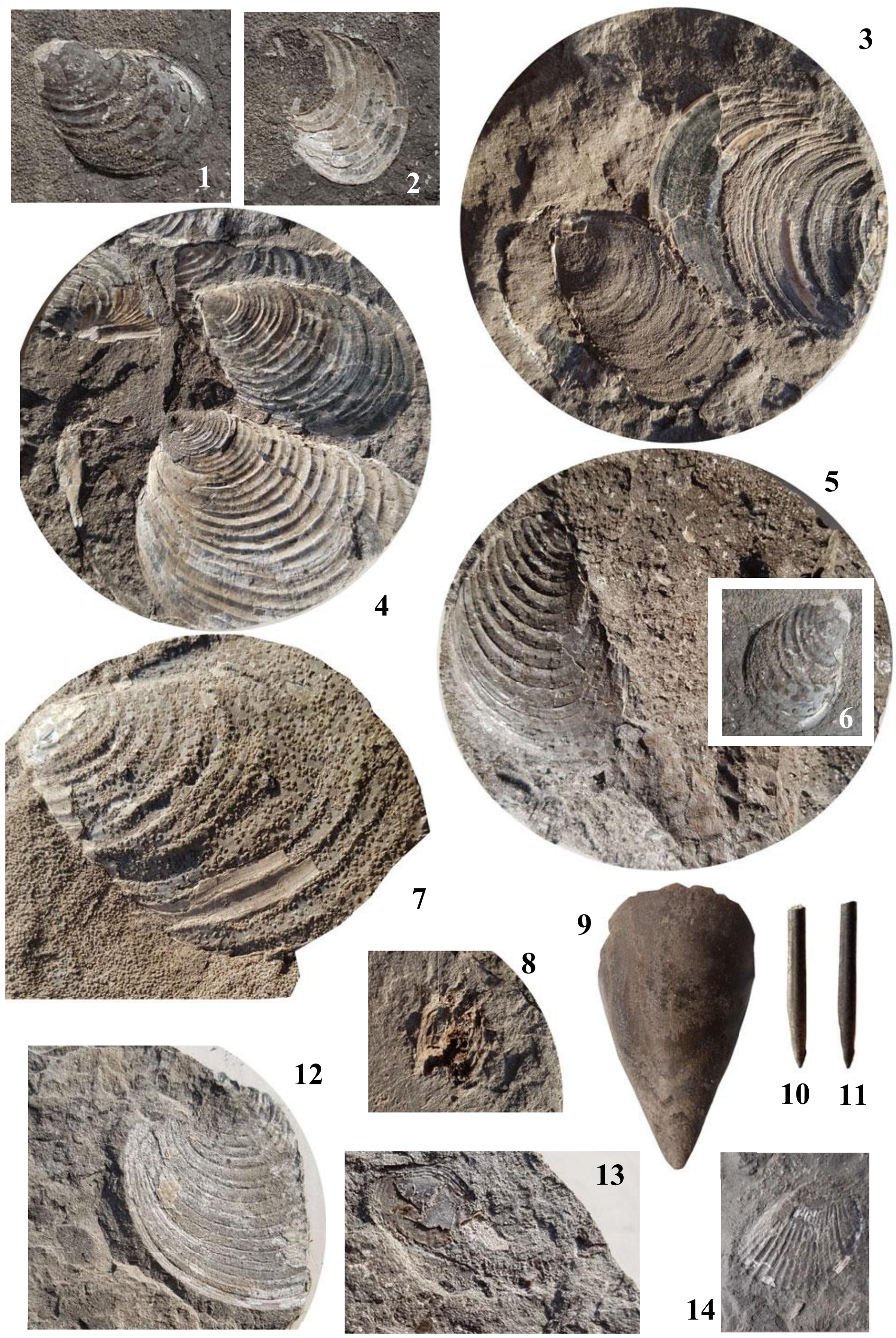

Plate 1. Fossils from well B18-02; all natural size, core diametre = 7 cm)
Figs 1–2. *Buchia volgensis* (Lahusen, 1888), cast and left valve – 2243.60 m
Fig. 3. *Buchia volgensis* (Lahusen, 1888), left and right valves – 2244.35 m
Fig. 4. *Buchia volgensis* (Lahusen, 1888) – 2256.73 m
Fig. 5. *Buchia volgensis* (Lahusen, 1888) – 2258.40 m
Fig. 6. *Buchia volgensis* (Lahusen, 1888) – 2257.95 m
Fig. 7. *Buchia volgensis* (Lahusen, 1888) – 2258.42 m
Fig. 8. Fish-remain – 2245.63 m
Fig. 9. Apical part of *Liobelus*? sp. – 2249.10 m
Fig. 10. Juvenile belemnite (lateral) – 2250.18 m
Fig. 11. *Ibid*. ventral or dorsal view
Fig. 12. *Buchia volgensis* (Lahusen, 1888) – 2259.83 m
Fig. 13. Fish-remain – 2256.50 m
Fig. 14. *Pseudolimea* cf. *arctica* (Zakharov, 1966) – 2249.37 m

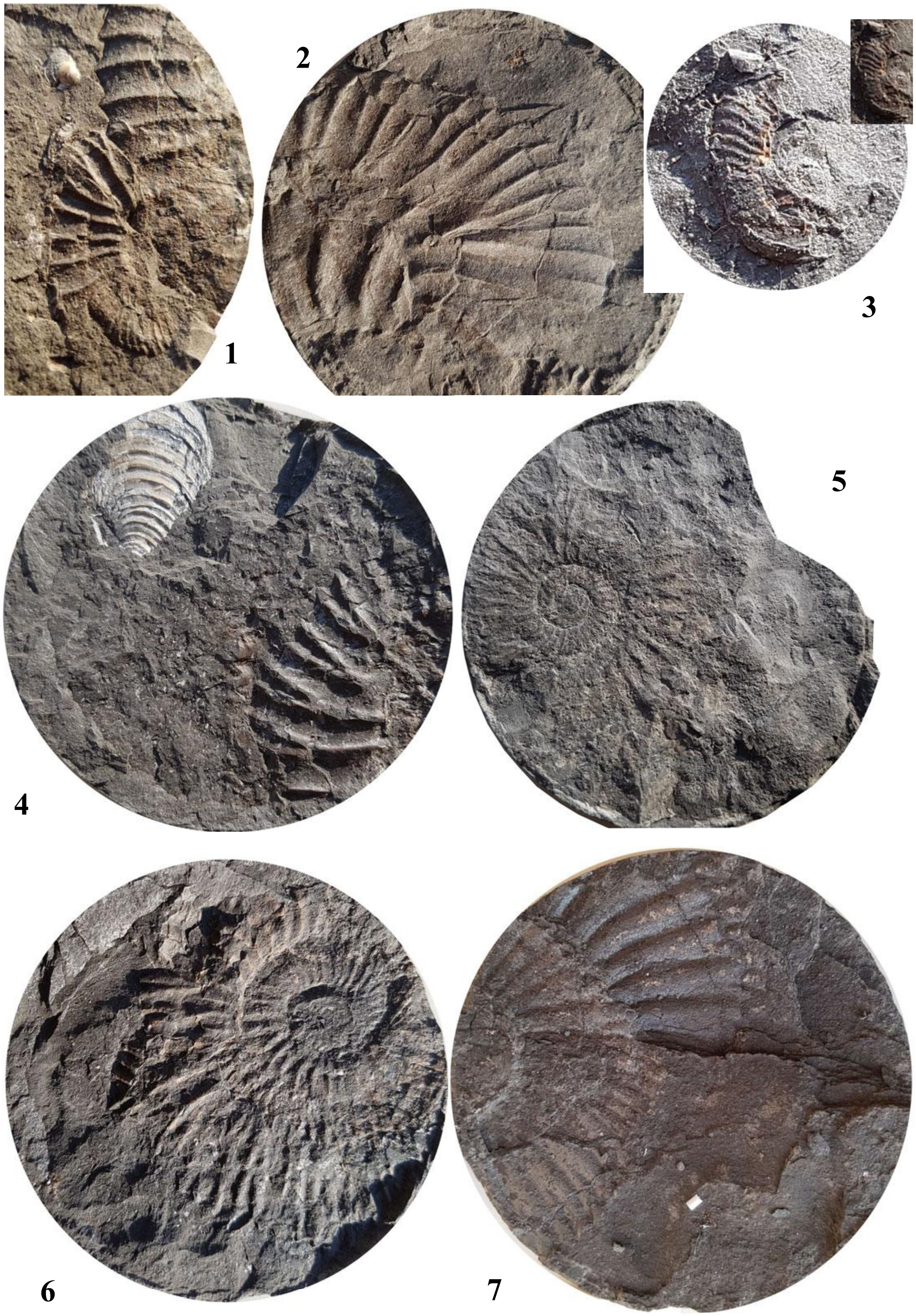

Plate 2. Fossils from well B18-02; all natural size, unless stated otherwise, core diametre = 7 cm)
Fig. 1. *Surites* sp. (cf. *subanalogus* Shul'gina, 1972) – 2244.56 m
Fig. 2. *Surites* sp. (cf. *subanalogus* Shul'gina, 1972) – 2248.22 m
Fig. 3. *Surites* sp. juvenile (and 2,5x enlarged) – 2249.54 m
Fig. 4. *Surites* cf. *subanalogus* Shul'gina, 1972 and *B. volgensis* (Lahusen, 1888) – 2256.40 m
Fig. 5. *Surites* sp. – 2255.90 m
Fig. 6. *Surites* sp. (ex gr. *analogus* (Bogoslowsky, 1896)) – 2256.08 m
Fig. 7. *Surites* sp. (cf. *subanalogus* Shul'gina, 1972) – 2252.90 m

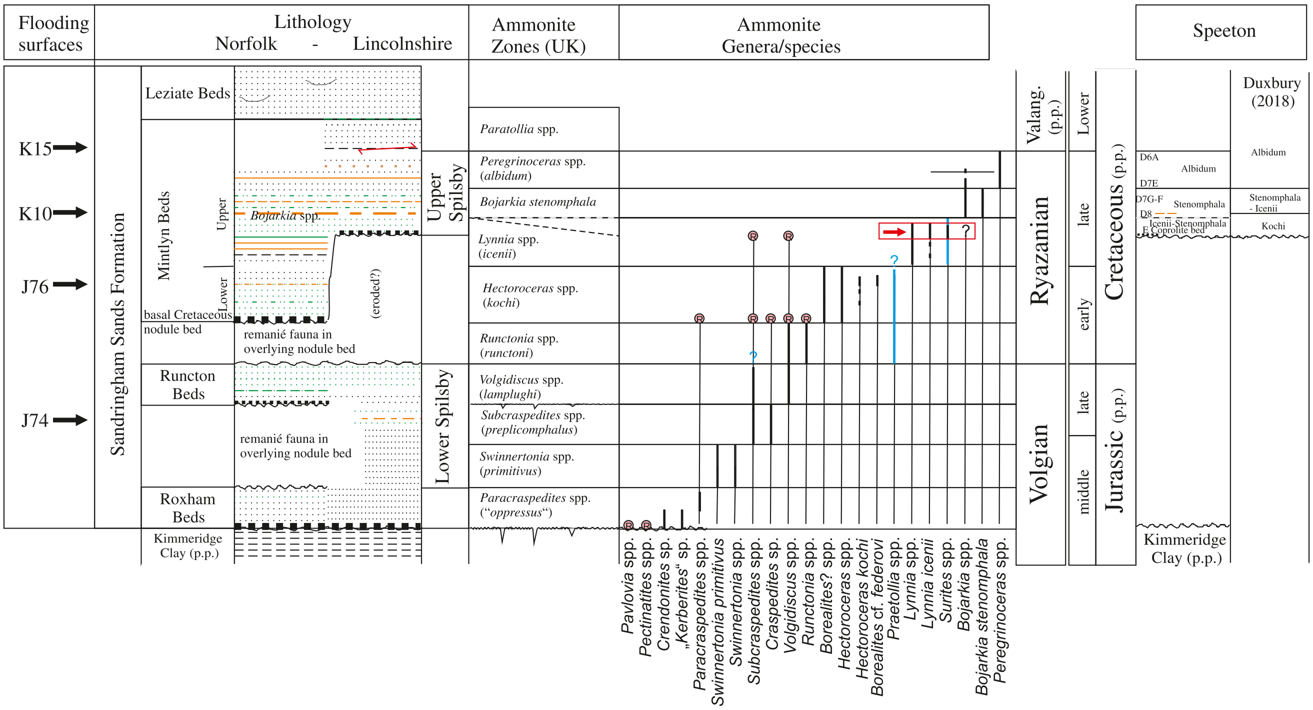

Image 3. Schematic representation of lithology/lithostratigraphy versus biochronostratigraphy (UK), modified after Casey (1973), Gallois (1984) and Cope (2020). Left column: J74, J76, K10 and K15 are the maximum flooding surface of Partington et al. (1993). In the lithological column, thick black points indicate nodule-rich levels, small points indicate dominantly sandy lithology, while dashed stripes indicate dominantly clayey lithology. Note position of flooding surface K10 (Stenomphala) which is in our opinion characterised by abundant *Bojarkia* but does not represent the first occurrence of that genus. However, the index species *Bojarkia stenomphala* seems to occur from K10 on, but not below! In addition, the range of *Bojarkia* and *Surites* does not overlap, as erroneously indicated in Casey (1973), and thus omitted in this figure. These are factors complicating the actual extent of the preceding Icenii Zone (see text; indicated by red arrow and red box). Ranges of ammonites are indicated by thick black line (in blue additional data from cores mentioned herein), uncertain ranges are indicated by dashed lines, while reworked specimens are indicated by pink dot with encircled the letter 'R'. Our interpretation of the correlation towards Speeton (UK) versus (Duxbury, 2018, fig. 2) is shown in the rightmost column.

the belemnites are preserved as flattened moulds (in some cases with the remains of part of the shell). Therefore, the original size and outline are distorted by compaction.

Ammonites

Casey (1973) introduced seven new ammonite zones applied to the North Sea area, based on temporary outcrops, railway cuttings and quarries from the East Midlands in the Spilsby Sandstone and Sandringham Sands formations (Hopson et al., 2008, and references therein). These lithologies show signs of intense winnowing and reworking. Typically, sets of clayey to sandy chamosite, glauconite and limonite rich sediments occur, separated by beds consisting of gravel and phosphatic nodules, including *in situ* and redeposited macrofossils (Casey & Gallois, 1973; Casey, 1973; Gallois, 1984). Several of these levels yielded latest Jurassic to earliest Cretaceous ammonites (Image 3). Correlation of NW European Ryazanian ammonite zones with those of other Boreal areas, as proposed by Casey (1973) and subsequently widely accepted (Casey et al., 1977, 1987; Marek, 1984; Shul'gina, 1985; Mesezhnikov, 1988, p. 55), was based on the constrained ranges of several genera, such as *Hectoroceras*, *Surites*, *Bojarkia* and *Peregrinoceras*. The succession of these genera can be traced throughout the Panboreal Superrealm (*sensu* Westermann, 2000, p. 52), despite a certain amount of provincialism at the species level. The most challenging problem regarding the zonal succession as proposed by Casey (1973) relates to the apparent lack of expanded sequences and the overall rarity of macrofossils from boreholes (e.g. ammonites were figured and described only once so far by Abbink et al., 2001b). Moreover, the sections in which the ammonite zones were established are no longer exposed, and after the initial publication of Casey (1973) no additional Ryazanian ammonites were figured or described from East England.

Class Cephalopoda Cuvier, 1795
Subclass Ammonoidea Zittel, 1884
Order Ammonitida Agassiz, 1847
Suborder Ammonitina Hyatt, 1889
Superfamily Perisphinctoidea Steinmann, 1890
Family Craspeditidae Spath, 1924
Subfamily Subcraspeditinae Rogov, 2014
Genus *Praetollia* Spath, 1952
Praetollia cf. *contigua* Spath, 1952
Pl. 3, Fig. 5

Material. One specimen from L06-02 (depth 2242.40 cm), from glauconitic sandstones of the Scruff Formation.

Description. The specimen is represented by a fragment of the outer whorl (body chamber?), with a relatively wide umbilicus. It shows the typical ribbing of *Praetollia*, which consists of slightly curved primary ribs accompanied in the upper flanks by intercalated secondaries. Primaries and secondaries are weakly connected, and the ribbing is unclear on the mid-flanks. High rib ratio (~3.5) suggests proximity of this specimen to *P. contigua*, especially with specimens from the Kochi Zone of the lower reaches of the Lena River (Rogov et al., 2011, pl. V, figs 1, 2, 8). When compared to *P. contigua* from the Maynci Zone of East Greenland (Spath, 1952, pl. I, fig. 2; pl. II, fig. 1; pl. III, fig. 1; pl. IV, fig. 2), our specimen shows slightly more distant ribs.

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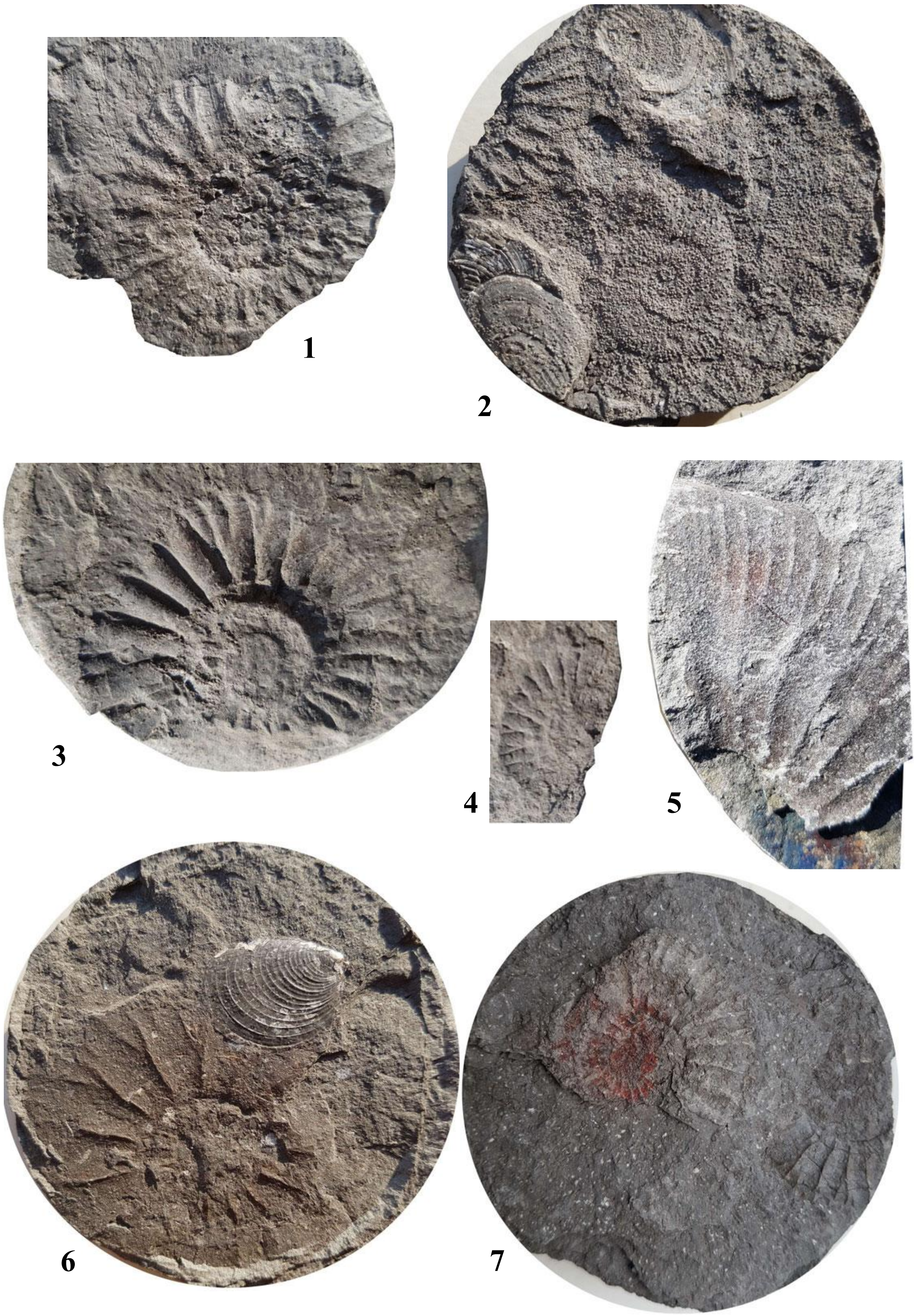

Plate 3. Fossils from well B18-02; unless indicated otherwise) (all natural size, core diametre (cd) = 7 cm, unless indicated otherwise)
Fig. 1. *Lynnia icenii* Casey, 1973 – 2256.91 m
Fig. 2. *Surites* sp. (ex gr. *analogus* (Bogoslowsky, 1896)), *Praetollia*? sp. juv. (2 specimens), and *Buchia volgensis* (Lahusen, 1888) – 2257.93 m
Fig. 3. *Lynnia icenii* Casey, 1973 – 2259.55 m
Fig. 4. *Surites* sp. (cf. *subanalogus* Shul'gina, 1972) – 2259.78 m
Fig. 5. *Praetollia* cf. *contigua* Spath, 1952 – 2242.40 m (L06-02; Kochi Zone)
Fig. 6. *Lynnia icenii* Casey, 1973 and *Buchia volgensis* (Lahusen, 1888) – 2247.95 m (cd =75 mm)
Fig. 7. *Surites* sp. (cf. *subanalogus* Shul'gina, 1972) – 2257.90 m

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Remarks. The figured specimen was not mentioned by Abbink et al. (2001b). The remaining core, which was not investigated by these authors, did not yield any ammonites. The specimen points to the Kochi Zone, as follows from its stratigraphic position above the first *Hectoroceras* occurrences and from its overall morphology, most closely resembling those *Praetollia* recorded from the Kochi Zone.

Praetollia? sp. juv.
Pl. 3, Fig. 2

Materials. Two specimens from core B18-02 (depth 2257.93 m).

Description. The small-sized (diametre approximately 28.6 and 19.7 mm) juvenile specimens show densely ribbed whorls with a narrow umbilicus. The very fine ribbing of these ammonites distinguishes them from other co-occurring craspeditids. Although the early whorls of *Borealites* and *Lynnia* are covered by relatively densely spaced ribs, their ribbing is more prominent and coarser when compared to that seen in *Praetollia*.

Remarks. Until recently, the youngest records of the ammonite genus *Praetollia* were reported from the Kochi Zone (cf. Abbink et al., 2001b, p. 285; Rogov et al., 2011; Igolnikov, 2019, p. 42–43, 121). However, the occurrence of *Lynnia* below and above our record of *Praetollia* suggests *Praetollia* to range into at least the lower part of the Icenii Zone.

Subfamily Craspeditinae Spath, 1924

Herein, the subfamily Suritinae Sazonova, 1971 is considered a synonym of Craspeditinae. Suritinae is distinguished from the Tolliinae in the sense of Shul'gina (1985), who emphasised differences in septal suture ontogeny between Tolliinae (*Bojarkia*, *Tollia*, *Neotollia* and *Virgatoptychites*) and the rest of the early craspeditids. All other Volgian and Ryazanian genera were ascribed to the Craspeditinae by Shul'gina; at present some of these genera are re-assigned to Subcraspeditinae and Garniericeratinae.

Genus *Lynnia* Casey, 1973

1973 *Surites* (*Lynnia*) subgen. nov. – Casey, p. 254.
1977 *Lynnia* Casey – Casey et al., p. 23.
1983 *Lynnia* Casey – Gallois, p. 322.
1985 *Lynnia* Casey – Shul'gina, p. 133, 156.
1996 *Surites* (*Lynnia*) Casey – Callomon in Wright et al., p. 25.

Type species. *Surites* (*Lynnia*) *icenii* Casey, 1973 (by original designation).

Diagnosis. Craspeditid ammonites, characterised by very strong and widely spaced triplicate ribs covering the terminal body chamber and perhaps part of the phragmocone, a sculptural feature that is unique for the Ryazanian craspeditids.

Remarks. The genus *Lynnia* is an insufficiently known taxon. Its original diagnosis was published in a relatively short form along with the diagnosis as a new subgenus (Casey, 1973, p. 254), and only one species has been referred to *Lynnia* (*L. icenii*). A few years after erecting the (sub)genus *Surites* (*Lynnia*), its rank has been elevated to the genus level by Casey et al. (1977), but without any explanation, which was subsequently followed by Gallois (1983), Shul'gina (1985, p. 156) and Klein (2006). Only Shul'gina (1985, p. 156) noted that '*Lynnia* . . . is a separate genus, as by character of its sculptural development it differs from *Surites*'. Unfortunately, when describing *Lynnia*, Casey (1973) did not provide any data about the development of its sculpture; however, in the figure of the holotype of *L. icenii* part of the inner whorls is visible; these are covered by relatively weak, dense and thin ribs (Casey, 1973, pl. 8, fig. 5). Perhaps Callomon (in Wright et al., 1996) based his diagnosis of this (sub)genus on the aforementioned figure. He considered this taxon as microconch, but the provided diagnosis is very short: 'ribs fine at first, later coarse and trifurcating high on side' (Callomon in Wright et al., 1996, p. 25).

Lynnia icenii is the only valid species ascribed to the genus *Lynnia*, although Casey (1973, p. 254) wrote: 'This subgenus is represented by a number of species in the interval between the *kochi* and *stenomphalus* Zones in England'. In this paper, *Lynnia* is considered a separate genus following Casey et al. (1977 and subsequent contributions). However, an emended diagnosis of the genus *Lynnia* or the species *L. icenii* can only be given after re-studying of the collection of Casey, and for now all occurrences herein mentioned are ascribed to a single variable species, *L. icenii*. Outside NW Europe similar craspeditids are unknown. Only some coarsely ribbed *Surites* from the Russian platform sometimes show the presence of triplicate ribs (Sazonova, 1971, pl. XX, fig. 3), and the same is true for some Siberian *Surites* (Rogov et al., 2011, pl. V, fig. 6), but nevertheless biplicate ribs predominate in *Surites*, while in addition the ribs in *Lynnia* are more widely spaced. Herein, specimens of *Lynnia* are reported for the first time from outside their type area.

Lynnia icenii (Casey, 1973)
Text-Fig. 2; Pl. 3, Figs 1, 3, 6; Pl. 4, Fig. 6.

1973 *Surites* (*Lynnia*) *icenii* sp. nov. – Casey, p. 254, pl. 8, figs 4–5; figs 6 l-m.
1996 *Surites* (*Lynnia*) *icenii* Casey – Callomon in Wright et al., p. 25, figs 15.3a-c [= Casey, 1973].
2006 *Lynnia icenii* Casey – Klein, p. 39.

Holotype. *Surites* (*Lynnia*) *icenii* Casey, 1973, p. 254, pl. 8, fig. 5 (holotype by original designation); coll. no. GSM Ce 5298, Mintlyn Beds, Icenii Zone, bed 12, North Sea gas pipe-line trench, Manor Farm, North Runcton, near King's Lynn, Norfolk.

Materials. 3 specimens from well B18-02, Clay Deep member, Lutine Formation, depth 2247.95 to 2259.91 m; one specimen (coll. no. NHM 93S001/famm5020b) in Christensen collection, from Statoil well 7/7-2, Åsgard Formation, depth 3242.00–3246.96 m.

Description. Both B18-02 and 7/7-2 yielded small-sized (diametre 5.2–5.6 cm) craspeditid ammonites, characterised by very strong and widely spaced triplicate ribs (9–12 primaries per half of the whorl) covering the terminal body chamber and part of the phragmocone. The ribbing of the inner whorls is poorly visible and its character is unclear. The umbilicus is moderately wide. At least one specimen (Pl. 3, Fig. 6) shows some kind of widening of the umbilicus near the body chamber, giving evidence of the 'eccentric umbilicus' as mentioned by Casey (1973). Although all our specimens are preserved as crushed moulds, their ribbing is very clear. Some of our specimens (Pl. 3, Fig. 6; Pl. 4, Fig. 7) show the typical *Lynnia* ribbing, while other (Pl. 3, Figs 1, 3) recorded below the typical specimen in the core B18-02 are characterised by a ribbing pattern intermediate between those of *Lynnia* and *Surites*. These poorly preserved ammonites with intermediate sculpture should possibly be referred to a new species of *Lynnia*, but for the moment we prefer to include them in *L. icenii*.

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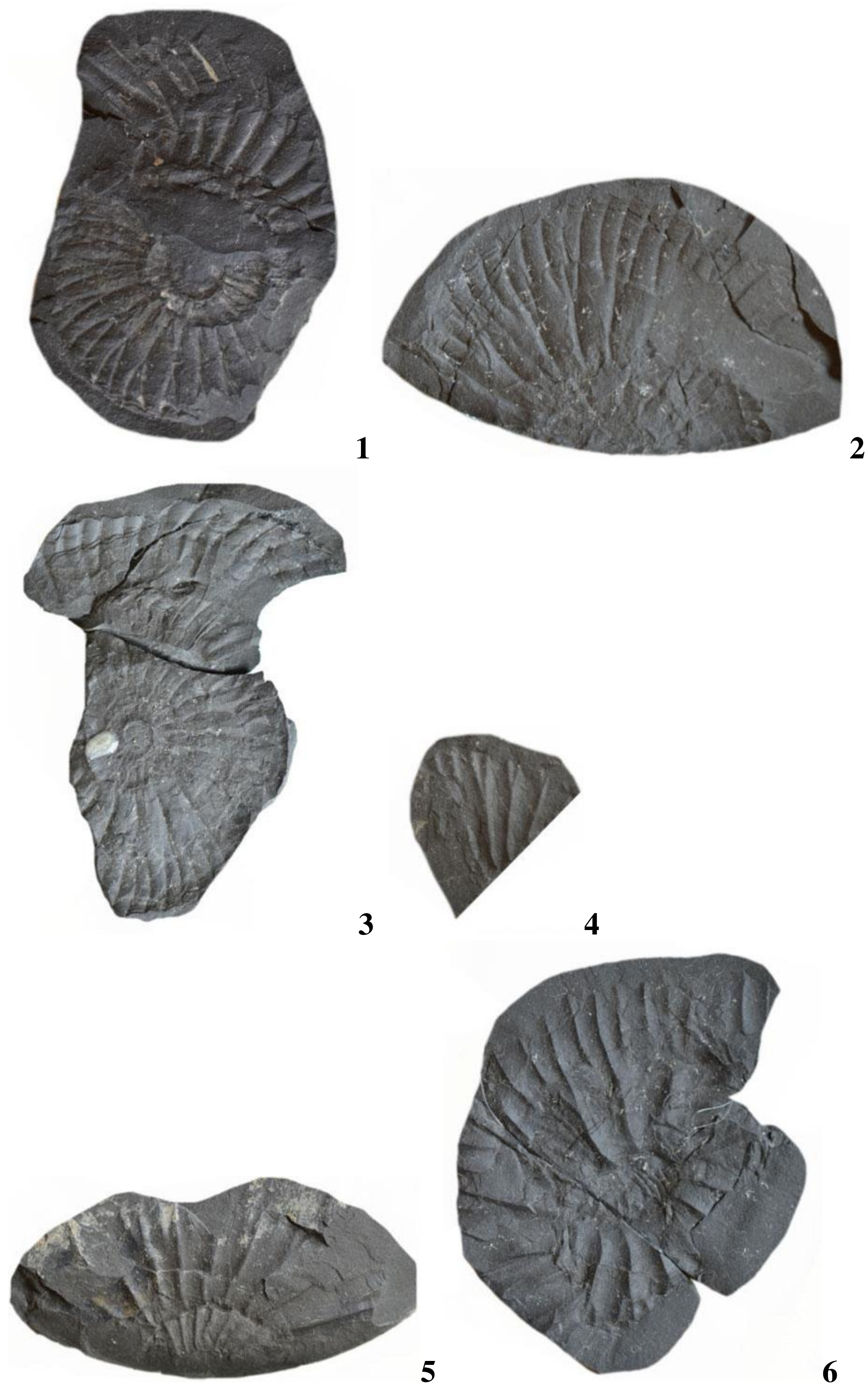

Plate 4. Fossils from well 7/7-2 Mandal Formation, 3242-3246.96 m (all natural size)
Fig. 1. *Surites subanalogus* Shul'gina, 1972
Fig. 2. *Surites* aff. *poreckoensis* Sazonov, 1951
Fig. 3. *Surites* aff. *poreckoensis* Sazonov, 1951
Fig. 4. *Surites* sp.
Fig. 5. *Surites* sp.
Fig. 6. *Lynnia icenii* Casey, 1973

Genus *Surites* Sazonov, 1951
Surites aff. *poreckoensis* Sazonov, 1951
Pl. 4, Figs 2–3

Material. Two specimens from Statoil well 7/7-2.

Remarks. The studied ammonites are represented by partially preserved moulds (~52 mm in maximum visible diametre), with badly preserved inner whorls. Both the outer whorl and the visible part of the inner whorl are covered by relatively dense, inclined forwards, triplicate ribs, with a little addition of single and biplicate ribs.

Remarks. This binomen is herein used for *Surites* specimen showing frequent triplicate ribs. Although the occurrence of triplicate ribs is known in the outer whorls of diverse *Surites*, these ammonites usually show the transition from mainly biplicate to mixed biplicate-triplicate ribbing additionally to a bigger diametre. *Surites poreckoensis* specimens from the Russian Platform (Sazonov, 1951, pl. 1, fig. 2; Sazonova, 1971, pl. V, figs 1–2) differ from the figured specimen by having coarser ribs in their inner whorls, and later appearance of the triplicate ribbing. The style of ribbing in *S.* aff. *poreckoensis* resembles those of the

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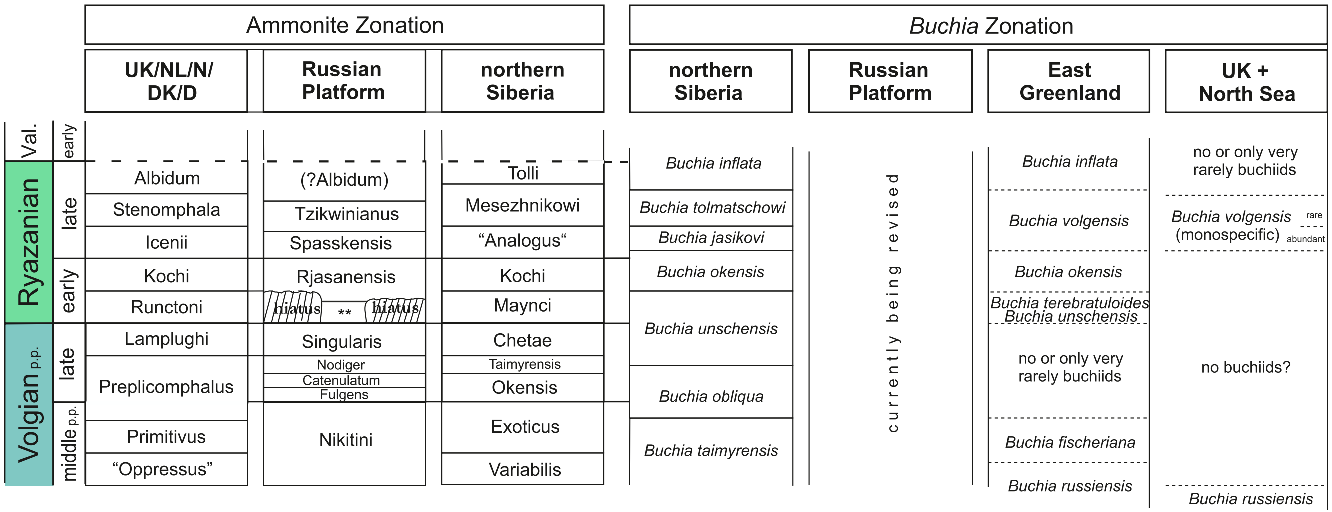

Image 4. Correlation of ammonite zonation (modified after Rogov et al., 2011; Kiselev et al., 2018; Cope, 2020) and *Buchia* zonation (modified after Kelly, 1990; Rogov et al., 2020) for northern Siberia, Russian Platform (not represented, momentarily being revised), East Greenland and North Sea areas. Note: asterisk indicated pre-Rjasanensis beds containing a *Buchia–Shulginites* association and possibly being the source of the ammonite *Chetaites chetae*.

subcraspeditid genus *Borealites*, but the latter is characterised by weaker ribs with early appearance of branches and with a rib ratio of 3–4.

Surites ex gr. *subanalogus* Shul'gina, 1972
Pl. 2, Figs 1–7; Pl. 3, Figs 2, 4, 7

Materials. 14 specimens from well B18-02: 2244.56 m (Pl. 2, Fig. 1), 2248.22 m (Pl. 2, Fig. 2), 2248.70 m, 2249.90 m (Pl. 3, Fig. 7), 2252.88 m, 2252.90 m (Pl. 2, Fig. 7), 2253.60 m, 2255.40 m, 2256.08 m (Pl. 2, Fig. 6; *S.* ex gr. *analogus*), 2256.40 m (Pl. 2, Fig. 4), 2257.93 m (Pl. 3, Fig. 2; *S.* ex gr. *analogus*), 2258.40 m, 2259.40 m, 2259.78 m (Pl. 3, Fig. 4) and one specimen from well 7/7-2 (Pl. 4, Fig. 1).

Diagnosis. Relatively small-sized ammonites (with a diametre mainly between 40 and 75 mm) with semi-evolute shells. The umbilicus varies from relatively narrow to relatively wide. The ribbing is represented by strong and relative frequent ribs (15–20 primaries per half of the whorl) inclined towards the aperture. In the inner whorls, all ribs are biplicate but on the body chamber and last part of the phragmocone, more or less commonly triplicate ribs appear.

Remarks. Species of *Surites* are predominantly known from the late Ryazanian but do occur from the latest early Ryazanian onward and disappear in the Stenomphala Zone. A less densely ribbed juvenile specimen (Pl. 2, Fig. 3) is relatively similar to *Praetollia*? sp. juv. (Pl. 3, Fig. 2). In addition, several indeterminable specimens are figured (Pl. 2, Fig. 5; Pl. 4, Figs 4–5). Both the type of ribbing and the size of these ammonites are in agreement with *S. subanalogus* of the type area (Igolnikov, 2006). However, these ammonites are determined in open nomenclature, due to their preservation (crushed moulds) besides the rare occurrence of outer whorls.

Belemnites

The investigated cored rocks from the wells B18-02 and 7/7-2 yielded only a few belemnites. This seems in line with other records from the North Sea area, where belemnites findings seem mainly confined to shallow and condensed deposits (Pinckney & Rawson, 1974; Swinnerton & Kent, 1981, p. 60–63; Jeremiah et al., 2010, p. 210). In addition, Sorgenfrei & Buch (1964) mention specimens from northern Denmark (core E-1). The Norwegian core 2/1-9 (East Central Graben; Gyda Field, NPD Factpages), yielding Ryazanian rocks, shows relatively frequent cross-sections of cylindroteuthid species. Swientek (2002) mentions relatively common belemnites and buchiids throughout the Volgian–Ryazanian succession from core 13/1-U-2 (southern Norway). However, few belemnite species have been identified hitherto from the latest Jurassic-earliest Cretaceous of the North Sea. Compared to the Russian Platform (e.g. Saks & Nal'nyaeva, 1975; Sazonova, 1977; Urman et al., 2019), belemnites appear almost absent in the North Sea area, which could be due to a lack of outcrops and limited availability of cored material. Additionally, their distribution appears to be controlled by their swimming capacity (Zakharov et al., 2014; Mutterlose et al., 2020). In general, rostrum remains are more often concentrated in the more proximal (glauconitic) facies, for example, by winnowing, while in more distal mudrock facies belemnites are more isolated and arm hooks are more striking (e.g. Hammer et al., 2013; Koevoets et al., 2018).

Phylum Mollusca Cuvier, 1795
Subclass Coleoidea Bather, 1888
Order Belemnitida Zittel, 1895
Family Cylindroteuthididae Stolley, 1919
Genus *Liobelus* Dzyuba, 2004
Liobelus? sp. indet.
Pl. 1, Fig. 9

Material. An apical part of a belemnite rostrum occurs at 2249.10 m. In addition, two juvenile specimens (Pl. 1, Figs 10–11), most probably belonging to the same genus, were retrieved (see Fig. 2). Also few micro-*Onychites* or belemnite hooks occur in the core B18-02. The core 7/7-2 yielded belemnite hooks and a juvenile *Acroteuthis* (or *Liobelus*).

Remarks. Pickney & Rawson (1974) mention belemnites from the Lincolnshire area. Their 'Assemblage 2' represents the early – early late Ryazanian, yielding rare *Liobelus* ex gr. *lateralis* (Phillips,

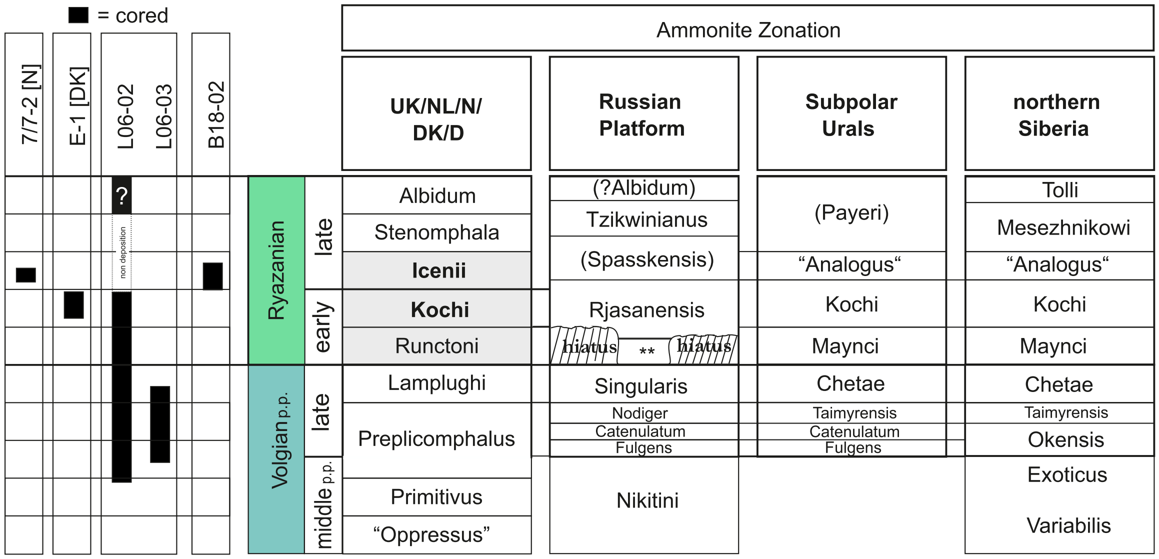

Image 5. Extension of cores investigated and mentioned herein versus Panboreal correlation of late Volgian-Ryazanian (Jurassic-Cretaceous) ammonite zones. Modified after: Rogov et al., 2015, 2020; Kiselev et al., 2018. Note: asterisk indicated pre-Rjasanensis beds containing a *Buchia–Shulginites* association and possibly being the source of the ammonite *Chetaites chetae*.

1835). The subsequent 'Assemblage 3' is most probably of latest Ryazanian age and younger.

Buchiids.

The genus *Buchia* is restricted to the northern hemisphere (Panboreal Superrealm), but sometimes migrated southwards into northern margins of the Tethyan and Pacific Realms, in which these bivalves cooccurred with Tethyan and Pacific ammonites respectively (cf. Zakharov & Rogov, 2003, 2020). Because of its ubiquitous presence and a high rate of evolution buchiids are relatively good guide fossils, but some differences in their assemblages can be observed in the distal to proximal trends within a basin (Zakharov, 1987) and between the different paleogeographic subdivisions. Nonetheless, a rather uniform zonation can be established (Zakharov, 1981, 1987; Grey, 2009; Zakharov & Rogov, 2020 and refs. therein; Image 4).

Buchiids produced planktotrophic larvae, so-called veliger, and were thus feeding in the water column as part of the zooplankton. The planktotrophic larvae allowed buchiids to disperse over wide geographic areas. Furthermore, they were able to tolerate a variety of environments (eurybiontic). However, eventually during maturity they needed a (hard) substrate to settle, as they were byssally attached filter feeders. Yet, buchiid bivalves are known from nearly all sedimentary marine facies, from black shales and limestones to conglomerates and tuffites.

During the late Volgian, buchiid bivalves appear to have been absent from the North Sea area. All known Ryazanian *Buchia* records from NW Europe so far are represented by very few occurrences of a single species (*Buchia volgensis*), including those from the east coast of the UK (Casey, 1973; Kelly, 1983, 1984, 1990). Few *B. volgensis* were mentioned from the Upper Spilsby Sandstone in Donington (Lincolnshire), apparently from the Stenomphala Zone (Casey, 1973; Kelly, 1984, 1990). Additional specimens of *B. volgensis* were figured from a deep borehole drilled in northern Denmark (Sorgenfrei & Buch, 1964, figs. 72, 86 as *Buchia fischeriana*). Previously reported findings of *B.* cf. *volgensis* from northern Germany (Pavlow, 1896; Harbort, 1905) were erroneously determined and represent Valanginian *Buchia* (Kelly, 1990).

Phylum Mollusca Cuvier, 1795
Class Bivalvia Linnaeus, 1758
Order Pectinida Gray, 1854
Family Buchiidae Cox, 1953
Genus *Buchia* Rouillier, 1845
Buchia volgensis (Lahusen, 1888)
Pl. 1, Figs 1–7, 12; Pl. 2, Figs 1, 4; Pl. 3, Figs 2, 6

*1888 *Aucella volgensis* – Lahusen, p. 16, pl. III, figs 1-17.
1896 *Aucella volgensis* Lahusen – Pavlow, p. 549, pl. 27, fig. 1.
1896 *Aucella volgensis* var. *radiolata* – Pavlow, p. 549, pl. 27, fig. 2.
1905 *Aucella volgensis* Lahusen – Woods, p. 69–70, pl. X, figs 1–2 [= Pavlow, 1896].
1964 *Buchia fischeri* (d'Orbigny) – Sorgenfrei & Buch, p. 131, pl. 7, fig. 72; pl. 8, fig.86.
1978 *Buchia volgensis* (Lahusen) – Birkelund et al., p. 56, pl. 4, figs 1–2; pl. 5, figs 4–6.
1978 *Buchia volgensis* (Lahusen) – Surlyk, pl. 4, fig. 8; pl. 6, figs 1–5.
1981 *Buchia volgensis* (Lahusen) – Håkansson et al., p. 26, pl. 5, figs 4–5.
1981 *Buchia volgensis* (Lahusen) – Zakharov, p. 125, pl. XXXVII, figs 5–7; pl. XXXVIII, figs 1–3; pl. XXXIX, figs 1–4; pl. XL, figs 1–2 (cum syn.).
1981 *Buchia volgensis* (Lahusen) – Zakharov et al., p. 264, pl. I, fig. 5.
1982 *Buchia volgensis* (Lahusen) – Surlyk & Zakharov, p. 740, pl. 75, fig. 2 (cum syn.).
1984 *Buchia (Buchia) volgensis* (Lahusen) – Kelly, p. 58, pl. 10, figs 1,3,4,7,8 (cum syn).
1986 *Buchia* cf. *volgensis* (Lahusen) – Århus et al., p. 23 (cum syn).
1986 *Buchia volgensis* (Lahusen) – Braduchan et al., p. 119, pl. XXXIX, figs 7–10.
1987 *Buchia volgensis* (Lahusen) – Zakharov, p. 146.
1989 *Buchia volgensis* (Lahusen) – Paraketsov & Paraketsova, p. 22, pl. XI, figs 1–3.

1990 *Buchia* cf. *volgensis* (Lahusen) – Århus et al., p. 177, fig. 7D (cum syn).
1990 *Buchia volgensis* (Lahusen) – Kelly, p. 138, pl. II, figs 2a-c.
1990 *Buchia volgensis* (Lahusen) – Vyachkileva et al., p. 66, pl. 27, figs. 1–3, 5, 13–14; pl. 28, figs 1,3,5,9.
1993 *Buchia volgensis* (Lahusen) – Sha & Fürsich, p. 536, figs 3n-o.
2009 *Buchia* cf. *volgensis* (Lahusen) – Marinov et al., pl. II, fig. 17.
2011 *Buchia volgensis* (Lahusen) – Rogov et al., pl. 2, fig. 7, pl. 3, fig. 1.
2014 *Buchia volgensis* (Lahusen) – Urman et al., pl. 3, figs 1–3.
2017 *Buchia volgensis* (Lahusen) – Rogov et al., figs 6.2–3, 10.
2019 *Buchia volgensis* (Lahusen) – Kosenko et al., p. 555.
2019 *Buchia volgensis* (Lahusen) – Urman et al., pl. I, fig. 10–11
2020 *Buchia volgensis* (Lahusen) – Schneider et al., p. 12, figs 11G-H (cum syn.).

Syntypes. 17 specimens, some of which were figured by Lahusen, 1888, pl. III, fig. 1–17; Lectotype: Lahusen, 1888, pl. III, figs 3–5, indicated by Glazunova (1973, p. 35), re-figured in Zakharov, 1981, pl. XL, fig. 1.

Materials. At least 40 specimens from well B18-02, Clay Deep Member, Lutine Formation, Central Graben, Dutch offshore, mainly represented by right valves. All from the late Ryazanian (Icenii Zone).

Description. The shells are uncommonly large (length up to 62 mm, see Pl. 1, Figs 1, 3, 4, 7), high, slightly oblique, moderately convex and slightly inequilateral. Right valves are characterised by inversion of the ontogeny (well visible in Pl. 1, Figs 1, 3, 7). In outline, the right valves are close to an isosceles triangle, elongated in height (Pl. 1, Figs 1, 5, 7). The apical angle is close to 90°. The sculpture on the shell is commonly represented by thick lamellar concentric ribs (Pl. 1, Figs 2. 7). Small concentric smoothed folds are clearly visible on the nuclei (Pl. 1, Figs 1, 3, 4, 5, 12).

Results and discussion

Ammonite stratigraphy

Based on the occurrence of ammonites (*Lynnia* and common *Surites*), and *Buchia volgensis*, a Ryazanian age can be assigned to the studied core sections. A more specific age is based on the occurrence of *Lynnia icenii* indicating the Icenii Zone, and thus marking the base of the late Ryazanian. The Icenii Zone was introduced by Casey (1973) based on ammonite findings in temporary outcrops near 'The Wash', an inlet at the border between Norfolk and Lincolnshire at the east coast of the UK (Image 1). The Icenii Zone is best known from exposures in the vicinity of North Runcton and King's Lynn (Casey & Gallois, 1973; Casey, 1973), where it consists of only a few decimetres of glauconitic sands and clay with clay ironstone and seams of phosphatic nodules (Image 3).

Lynnia is the characteristic ammonite genus of this zone. *Surites* and *Bojarkia* were also reported but were not figured and are generally less common (Casey, 1973, p. 210). The co-occurrence of *Lynnia* and *Bojarkia* has been reported from a condensed 5 cm thick nodule bed only (Casey, 1973, p. 200). Subsequently, Casey et al. (1987, 1988) indicated the co-occurrence of *Lynnia*, *Surites* and *Bojarkia* throughout the Icenii Zone. However, in the remainder of the Panboreal Superrealm *Surites* and *Bojarkia* do not co-occur and are only known from different, succeeding ammonite zones (Shul'gina, 1985, p. 21–22; Baraboshkin, 2004, p. 53). Hence, the ammonite assemblage of the Icenii Zone in its type area remains controversial. There are three options, regarding the range and occurrence of *Lynnia*: (1) *Lynnia* is restricted to the Icenii Zone. (2) *Lynnia* occurs in the Icenii Zone and also at the base of the Stenomphala Zone. (3) *Lynnia* is represented as reworked phosphatic casts at the base of the succeeding Stenomphala Zone. Casey (1973, p. 200, 210) mentions *Bojarkia* sp. from a 5 cm thick level (bed 6 at King's Lynn Bypass) with black rolled phosphatic nodules, resting on an irregular surface of the bed below, a condensed bed (bed 5) of 10 cm with pale, sandy, clay ironstones with semi-phosphatised knobs on the upper surface yielding *Lynnia* sp. nov. From this, it is clear that these *Bojarkia* co-occurred with *Lynnia* in the condensed level. It is well possible that bed 6 yields taxa characteristic for both the Icenii Zone and the succeeding Stenomphala Zone, which would explain the presence of *Bojarkia* in this bed. Actually, Casey (1973, p. 200) mentions almost 5 m of strata above bed 6 without ammonites. The two condensed beds are part of the Upper Spilsby Sandstone (Mid-Spilsby Nodule Bed) (see Casey, 1973, p. 201). Casey (1973, p. 254) further noted that 'This subgenus is represented by a number of species in the interval between the Kochi and Stenomphala Zones in England'. However, to date only the type species *Surites* (*Lynnia*) *icenii* is figured and described.

Casey, 1973 and Casey et al. (1987, fig. 4; 1988, p. 81) correlate the Icenii Zone with the Analogus Zone, taking into account its stratigraphic position (above the Kochi Zone, which is widely traced throughout the Boreal regions) and findings of unfigured *Surites* in this zone, and we follow the same correlation.

In summary, well B18-02 yielded an exceptionally rich but monospecific buchiid fauna (*B. volgensis*), combined with frequent Boreal ammonites, mainly *Surites*, possibly *Praetollia*, and few endemic *Lynnia*, but very few belemnites. In northern Siberia, similar abundances of *B. volgensis* occur above the Kochi Zone, at the base of the Analogus Zone (Zakharov, 1981, fig. 79; Zakharov, 1990, figs 2–3). *Surites* occurs in abundance in northern and western Siberia (e.g. Shul'gina, 1975, 1985; Vyachkileva et al., 1990; Igolnikov, 2019), the Russian Platform (e.g. Sazonova, 1977; Mitta, 2017), East Greenland (Alsen, 2006), Spitsbergen (Ershova, 1983) and Franz-Josef Land (Dibner & Shulgina, 1998).

Recapitulation of the ammonite zonal succession of the Volgian/Ryazanian boundary and the Ryazanian of NW Europe and its Panboreal correlation

Some comments should be provided concerning ammonite zonal succession applied in this paper for the Ryazanian, and its correlation with other Boreal key successions yielding ammonites (Image 5), primarily with those of European Russia, which is the type area of the Ryazanian stage, and of Northern Siberia, where a continuous succession of Boreal ammonite stages occurs. The Ryazanian Stage was initially proposed by Sazonov (1951) without detailed characterisation, but a few years later Sazonov (1953) provided details concerning the faunal composition and geographic distribution including the type region, the Pericaspian area and the Northern Caucasus. Outside Russia this stage name was first applied by Casey (1962) as 'Riasan Beds' and by Casey (1963) as Ryazanian for a sedimentary succession in Norfolk and Lincolnshire (UK). Casey considered the Ryazanian as the first stage of the Cretaceous, and, in Lincolnshire, drew

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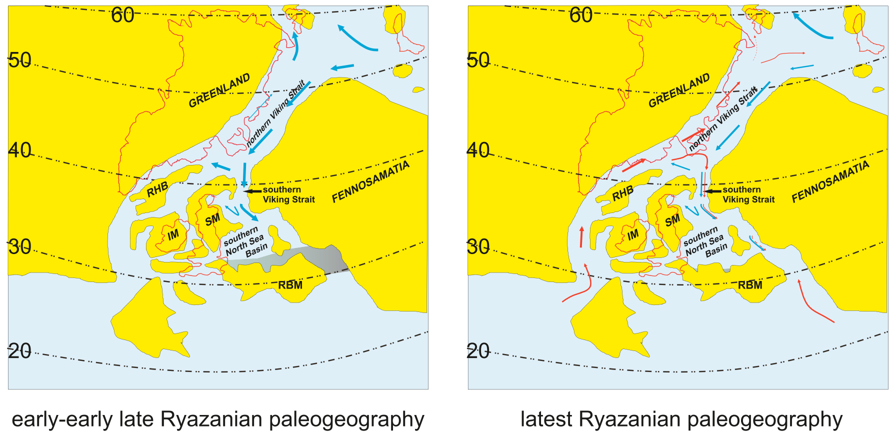

Image 6. Paleogeographic reconstruction of North Sea area modified after Abbink et al. (2001a, fig. 15). Left part early – early late Ryazanian, right figure latest Ryazanian (- earliest Valanginian?). Legenda: northern Viking Strait = Greenland Norwegian Seaway, IM = Irish Massif, RBM = Rhenisch-Bohemian Massif, RHB = Rockall-Hatton Bank, and SM = Scottish Massif. Red arrows indicate warm (Tethyan influenced) water currents, blue arrows indicate relative cold water currents; the thicker the arrow, the bigger the influence.

its base at the top of Lower Spilsby Sandstone. The Ryazanian Stage became widely used for Boreal regions after the publication of the seminal paper by Casey (1973) comprising the description of ammonites and zonal succession of the upper Volgian and Ryazanian deposits of eastern England, as well as its correlation with other Boreal successions. Unfortunately, several important ammonite taxa mentioned by Casey remain unfigured, and later only minor additions concerning the English succession were published in cooperation with Soviet scientists (Casey et al., 1977, 1987, 1988).

The Lamplughi Zone is the uppermost unit of the Volgian Stage (Images 3–5) introduced by Casey (1973) and is characterised by a very specific ammonite assemblage that consists of *Volgidiscus* and *Subcraspedites*, genera that disappear at the Volgian/Ryazanian boundary. The genus *Volgidiscus* occurs in coeval strata of the Russian Platform, Subpolar Urals and Northern Siberia (Kiselev et al., 2018; Rogov, 2020, 2021). Furthermore, on the Russian Platform and in the Subpolar Urals other Boreal taxa, such as *Shulginites* and *Chetaites chetae* (especially common east of the Subpolar Urals) occur, providing direct correlation of the English Lamplughi Zone with the Russian Singularis and Chetae zones.

Subsequently, Casey et al. (1987, 1988) and Hoedemaeker & Herngreen (2003) introduced one more unit above the Lamplughi Zone but below the base of the Ryazanian in NW Europe. The first authors proposed the 'beds with *Subcraspedites claxbiensis*' on the base of the occurrence of their index species in re-deposited pebbles from the basal Albian. However, Casey (1973) and later Casey et al. (1988) also mentioned this species from the Preplicomphalus Zone and a younger age (occurrence in the Lamplughi Zone) of this taxon cannot be negated. Hoedemaeker & Herngreen (2003) indicated an assemblage with '*Subcraspedites* spp.' above the Lamplughi Zone in the North Sea region, following Casey et al. (1987) and additionally based on the ammonite data published by Abbink et al. (2001b; but see reinterpretation of several species by Kiselev et al., 2018, p. 220).

The base of the Ryazanian was defined by Casey (1973) as to coincide with the transition from beds with *Volgidiscus* to *Praetollia* (*Runctonia*), that is, at the boundary of the Lamplughi and Runctoni zones. Casey regarded these genera as members of a single lineage *Swinnertonia* – *Subcraspedites* – *Volgidiscus* – *Runctonia* – *Hectoroceras*, providing a solid background for both the subdivision and the correlation of the late Volgian and early Ryazanian throughout the Boreal areas. At first, Casey designated *Runctonia* as a separate genus, but later, based on the opinion of Shul'gina, considered it a subgenus of *Praetollia* (Casey et al., 1977), and additionally figured *Praetollia* (*Runctonia*) from the Subpolar Urals (loc. cit., pl. II, fig. 3). Here, *P.* (*Runctonia*) co-occurs with *Chetaites sibiricus*, a typical lowermost Ryazanian species. The ammonite assemblage of the Runctoni Zone of NW Europe also includes *Praesurites* (considered a junior synonym of *Praetollia* by Igolnikov, 2019), an ammonite genus whose first occurrence marks the base of the Ryazanian in the Subpolar Urals (Casey et al., 1988). The lower and upper boundaries of the Runctoni Zone can be traced throughout the Boreal areas, defined by first and last occurrences of distinct common and short-ranging ammonite genera. In addition to the last occurrences of *Volgidiscus* and *Subcraspedites*, the lower boundary of this zone is marked by the first occurrence of *Praetollia*, while the upper boundary coincides with the appearance of *Hectoroceras*.

The genus *Shulginites* first appears in the latest Volgian and typically occurs in the lowermost zone of the Ryazanian in Western Siberia, in the Subpolar Urals and on the Russian Platform (cf. Mitta, 2017, p. 143–144; the upper part, bed 5b, of section A along the Unzha river were it yields *Shulginites* and *Praesurites*, herein considered as a typical earliest Ryazanian taxa). However, in the Subpolar Urals, the uppermost occurrence of this genus is in the lower part of the overlying Kochi Zone (Mesezhnikov et al., 1983). *Shulginites* appears to be restricted to the uppermost upper Volgian, lower part of the Rjasanensis Zone and the Kochi Zone, while *Hectoroceras* seems to be confined to the Kochi and the Transfigurabilis zones (*sensu* Baraboshkin, 2004). Mesezhnikov et al. (1983, pl. VI, fig. 4) figured a typical *Shulginites* characterised by weak ribbing from the lower (but not basal) part of the Ryazanian. The underlying bed contains *Riasanites* and *Garniericeras*. However, this bed is thought to contain a reworked and re-deposited assemblage (Sasonova & Sasonov, 1984). Based on this record and the re-interpretation of *Hectoroceras* from the Subpolar Urals figured in Mesezhnikov et al. (1983, pl. V, fig. 3) as *Shulginites* (see Mitta, 2019), Mitta considers *Shulginites* as synonym of *Hectoroceras*. At present, we consider *Shulginites* and *Hectoroceras* as separate genera, but transitional morphologies from one genus to another as well as a potential co-occurrence of the two genera should be further investigated. Both on the Russian Platform and in the Subpolar Urals, the range of *Shulginites* seems to be similar. The oldest findings of this genus co-occur with *Volgidiscus* (Kiselev et al., 2018, pl. II, fig. 7). Above *Shulginites* is recorded from the lowermost

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Ryazanian pre-Rjasanensis beds (Kiselev et al., 2018, pl. VI, fig. 8), as well as from the Rjasanensis Zone in association with *Hectoroceras* (Mesezhnikov et al., 1979, pl. I, fig. 5).

The Kochi Zone is defined as the range zone of the genus *Hectoroceras* s.str. and is among the best correlated intervals within the Ryazanian. *Hectoroceras* is characterised by a wide geographical range and its remarkable morphologic features permit to determine even fragmentary and/or crushed specimens. The additional components of the ammonite assemblages in this zone vary and include *Borealites* in NW Europe, *Surites, Pseudocraspedites* and *Runctonia* in Northern Siberia, and Submediterranean taxa in the corresponding interval on the Russian Platform, which is traditionally referred to as the Rjasanensis Zone (Mitta, 2019, 2021).

The index species of the overlying Icenii Zone in NW Europe is an endemic species, which previously was only known from its type locality and a few adjacent sections, and *L. icenii* is the only ammonite species figured from this zone. As a result, the correlation of this zone with other regions was mainly based on the positions of the underlying and overlying units. Casey et al. (1977, 1987, 1988) mentioned also '*Surites* ex gr. *spasskensis*' and *Bojarkia* from this zone. However, as has been emphasised above, *Bojarkia* was only mentioned from a condensed level at the boundary with the overlying zone from Lincolnshire, and the *in situ* co-existence of *Surites* and *Bojarkia* still cannot be confirmed. By its relative position, this zone corresponds to the 'Analogus' Zone of Northern Siberia as well as the Spasskensis and the lower part of Tzikwinianus zones of the Russian Platform.

The Siberian 'Analogus Zone' is mentioned in quotes, as the index species is taxonomically instable and needs revision. At least some ammonites referred by Shul'gina to *S. analogus* were later described as the new species *S. subanalogus* (Shul'gina, 1972), and few specimens were figured as '*S.* ex gr. *analogus*'. Also, it should be noted that *S. analogus* is an insufficiently known species as after its first description by Bogoslowsky (1896) it was not figured again from the type region. Moreover each specimen figured by him was proposed as lectotype subsequently by Sazonova (1971, p. 45 – Bogoslowsky, 1896, pl. III, fig. 6, indicated as a variety *loc. cit.* p. 67) and Shul'gina (1972, p. 153 – Bogoslowsky, 1896, pl. III, fig. 5), while another specimen figured by Bogoslowsky was referred to *S. subanalogus*.

The 'Analogus Zone' of northern Siberia is at its base defined by the highest appearance datum of *Hectoroceras* and in its top by the first appearance datum of *Bojarkia* and disappearance of *Surites* (Alekseev, 1984; Baraboshkin, 2004). It is well-traceable throughout the Panboreal Superrealm. This zone has been introduced by Shul'gina (*in* Sachs & Shul'gina, 1962) as 'Paracraspedites analogus subzone'. Subsequently, she provided some information about the ammonite assemblage of this unit (*in* Saks and Shul'gina 1962), which included various '*Paracraspedites*' (i.e. *Surites*), among others *P. analogus* subsp. nov. Subsequently, this taxon was described as *Surites subanalogus* sp. nov. (Shul'gina, 1972), while *S. analogus* was mentioned and described in open nomenclature only (i.e. *Surites* ex gr. *analogus*, loc. cit., pl. XIII, figs 1–2; Igolnikov, 2019, pl. XIII, fig. 2) and any evidence for the presence of *S. analogus* outside the Russian Platform is still missing. Moreover, to emphasise the difference between *S. analogus* from the Russian Platform and *S.* ex gr. *analogus* we added 'Shul'gina, 1972' as an author of the latter binomen, though strictly speaking it was not introduced as a new species (group).

The Stenomphala Zone of Casey (1973) is characterised by a mix of ammonites which includes both *Bojarkia* and *Surites* (at least in the lower part). Casey et al. (1977, p. 23) re-assigned '*Bojarkia*' *tealli* (Casey) to the genus *Surites* (Casey, 1973 considered *Bojarkia* as a subgenus of *Surites*) and additionally mentioned a finding of an unfigured *Surites* aff. *caseyi* (Sazonova) close to the top of this zone (bed 12, Stenomphala Zone of Mintlyn Wood section). Later, the same authors (Casey et al., 1988) restricted the ranges of *Surites* s.str. and *Lynnia* to the Icenii Zone, while only *Bojarkia* was shown from the Stenomphala Zone. Thus, the co-existence of *Surites* and *Bojarkia* still should be further clarified and cannot be proven. Roughly, this interval corresponds at least partially to the Tzikwinianus Zone of the Russian Platform (a condensed sequence). As a result, the precise ranges of the ammonites are unclear in this zone, but it yields *Surites*, *Bojarkia* and *Peregrinoceras* (in its upper part only). Because it is based on the range of the genus *Bojarkia*, this zone corresponds to the lower part of the expanded Mesezhnikowi Zone of Northern Siberia.

The assemblage of the Albidum Zone, also defined by Casey (1973), contains *Peregrinoceras* spp. with the addition of *Bojarkia* in the lower part of this zone. This can be concluded from data presented in Casey, 1973, although later Casey et al. (1987, 1988) show the range of *Bojarkia* covering the whole of that zone. Such co-occurrence of *Peregrinoceras* and *Bojarkia* was also mentioned from the Tzikwinianus Zone of the Russian Platform. Eventually, the occurrence of *P.* aff. *albidum* (Casey et al., 1977, p. 32, pl. I, fig. 1) in the latter region leads to the establishment of the '*P. albidum* beds' (Casey et al., 1988) and *P. albidum* Zone (Baraboshkin in Rogov et al., 2015). However, although the *Peregrinoceras*-bearing interval can be recognised in the topmost part of the Russian Platform, its direct comparison with the Albidum Zone of England remains doubtful and needs further clarification. Apparently, the total range of the genus *Peregrinoceras* in the Russian Platform exceeds its range in NW Europe. On the Russian Platform, the oldest findings of *Peregrinoceras* co-occur with *Surites* and *Riasanites* (Mesezhnikov, 1984; Casey et al., 1988). Currently, the occurrence of an assemblage consisting of *Peregrinoceras* or of *Peregrinoceras* with additionally *Bojarkia* is confirmed for condensed sections of the Middle Volga area only (Rogov et al., 2015). But information concerning the ammonite ranges in the uppermost Ryazanian is limited. Hence, correlation of the Albidum Zone with other Boreal successions is only possible through indirect evidence based on finding of *Bojarkia* in its lower part.

The overlying part of the Lower Cretaceous succession in England was referred by Casey to the *Paratollia* beds or *Paratollia* horizon (Casey, 1973; Casey et al., 1987, 1988) but is separated by a minor fault in the Lincolnshire area. This unit is characterised by the occurrence of *Paratollia*, *Delphinites* (= *Pseudogarnieria* ('*Proleopoldia*') of Casey, 1973), *Propolyptychites* and *Menjaites* (Casey, 1973; Casey et al., 1977). The presence of *Peregrinoceras* in this zone has been shown by Casey et al. (1988, fig. 4) but was not mentioned elsewhere, and there is no evidence to corroborate. Approximately this unit corresponds to the Undulatoplicatilis Zone of the Russian Platform, which also yields a *Delphinites – Menjaites* assemblage. In Siberia, it can be correlated with the Tolli Zone, as a rich assemblage with *Tollia* has been found in the Undulatoplicatilis Zone of the Russian Platform (Bogomolov et al., 2011). However, the age of the top of the *Paratollia* unit and its correlation with other Boreal succession is unclear.

Depositional setting

The bituminous mudrocks (Clay Deep Member) of the Lutine Formation were likely deposited under the influence of

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'temporarily stagnated circulation, at least in the deeper parts of the graben, which resulted in partially dysaerobic basin-floor conditions. In the relatively shallower settings, mixing prevailed with normal basin-floor ventilation (Schill Grund Member)' (Munsterman et al., 2012, p. 585–586).

The core B18-02 yields benthic-nektonic cephalopods, fish remains and their waste products (pyritised coprolite; Image 2). *Buchia* bivalves occur throughout the core (Image 2), sometimes in abundance. Buchiids lived as epifauna, byssally attached suspension feeders (Zakharov, 1981, fig. 78; Fürsich, 1984, fig. 26; Hryniewicz et al., 2014). The single limid bivalve recorded, *Pseudolimea* cf. *arctica* (Zakharov, 1966) (Pl. 1, Fig. 14) was also a byssally attached suspension feeder. All these fossils indicate oxic-marine waters, eventually above an ephemeral oxygen-restricted zone just above the water/sediment interface but never in or reaching the photic zone as vegetative cysts of prasinophytes are very few only. Buchiids, like all non-chemosymbiotic bivalve taxa, required some oxygen to thrive, thus their (abundant) occurrence excludes anoxic conditions. However, anoxic or dysoxic conditions prevailed in the sediment as the presence of infauna, indicated by bioturbation, appears to be absent but for some minor perpendicular structures between 2248.20 and 2250.18 m (Image 2).

Paleo(bio)geography

The investigated and cited boreholes were all located in an area south of 40°N paleo-latitude (Mutterlose et al., 2003). The North Sea area was connected through the southern Viking Graben to the Greenland-Norwegian seaway (Image 6). From the middle Volgian towards the late Ryazanian, alternating dysoxic to anoxic bottom conditions prevailed in the southern Viking Graben as suggested by trace element concentrations and foraminiferal assemblages (Mutterlose et al., 2003). North of the southern Viking Graben and certainly in the basins bordering the Arctic Ocean buchiids were diverse and abundant, but they were apparently rare in the North Sea area and totally absent during the late Volgian (Image 4). Very few Ryazanian occurrences of *Buchia* are recorded in NW Europe. More common and diverse, buchiid faunas are encountered along the Norwegian coast (Lofoten Islands, Birkelund et al., 1978; Zakharov et al., 1981; Århus et al., 1990), the Barents Sea (Smelror et al., 2001, fig. 5), the east coast of Greenland (Håkansson et al., 1981; Surlyk & Zakharov, 1982), Svalbard (Frebold, 1930; Sokolov & Bodylevski, 1931; Ershova, 1983) and on the Russian Platform (part of the East European Province) (Sazonova, 1975; Zakharov, 1987; Urman et al., 2019; Fig. 4). Only in the uppermost Volgian Singularis Zone buchiids are missing on the Russian Platform (Kiselev et al., 2018, p. 231), as well as in contemporary strata of the Subpolar Urals (Dzyuba et al., 2018). All in all, compared to the before mentioned areas and especially northern Siberia and Canada (see Zakharov, 1987, p. 144–145; Grey, 2009, fig. 5.2), the West European Province or Boreal-Atlantic Province appears to lack any or any diversified buchiid fauna.

The absence of a diverse buchiid fauna in this region is in contrast with the similarity between the ammonite faunas of West European Province and those of other Boreal areas. Since the latest late Volgian and throughout the Ryazanian, Boreal ammonites were mainly represented by the same genera and closely allied species throughout the Panboreal Superrealm. Although in the West European Province some endemic ammonite taxa are known (e.g. *Lynnia*), the other ammonites here are belonging to genera and species which occur in other Boreal regions (e.g. *Hectoroceras kochi*, *Peregrinoceras* spp., *Surites* spp., and *Bojarkia* spp.). This faunal homogeneity appears at least since the latest Volgian, when *Volgidiscus lamplughi* and *V. pulcher* dispersed through this huge area, from NW Europe to the Barents Sea shelf, the Russian Platform, the Subpolar Urals and Northern Siberia (Rogov, 2020).

The low diversity of buchiid bivalves and their overall rarity in the West European Province during the Ryazanian cannot be explained by paleogeographic restrictions alone. In contrast to ammonites, bivalves strongly depend on the configuration of the paleo-currents and the presence of a proper substrate for juvenile settling. Taking into account the common presence of TOC-enriched oxygen-depleted bottom settings throughout the Greenland-Norwegian seaway (northern Viking Graben; Image 6) during the Volgian and Ryazanian (Mutterlose et al., 2003), southward migrations of bivalves were recurrently hampered, in the southern Viking Graben. Especially during the late(st) Volgian, when oxygen depletion was highest.

The abundant occurrence of *B. volgensis* in the late Ryazanian of the region under discussion points to higher tolerance of this species to normally unfavourable environments, an opportunistic taxon, which is further evidenced by its wide geographic range outside the Panboreal Superrealm, as it is known from Submediterranean regions, like the Crimea, Mangyshlak and Mexico (see Zakharov, 2015).

During the latest Jurassic-earliest Cretaceous, the (low)lands bordering the mid-latitudinal West European Province (marine realm) were characterised by a warm and arid climate (Hallam et al., 1991; Abbink, 1998; Turner, 2018). The relatively shallow basins that occurred at high to mid northern latitudes were all connected to the Arctic area while some east-west connections, having been closed during latest Volgian to early Ryazanian at mid-latitudes, started to open in the late(st) Ryazanian (Image 6). These basins share the accumulation of organic-rich mudstones, for example, the hot and warm shales of the North Sea area, the Bazhenov facies of the Siberian Basin, with onset of deposition in the Kimmeridgian, accumulating rapidly in the Volgian and waning in the Ryazanian (Rogov et al., 2020, fig. 2).

According to Sinclair (1994, p. 195), the approximate top (at least Icenii age) of the highly organic, condensed shales of the 'hot shale' facies can be considered the uppermost maximum flooding surface which developed prior to a subsequent increase in clastic input. This level is based on the last occurrence of abundant amorphous organic matter (Stenomphala Zone, according to Fraser et al., 2003, p. 165), but more recently placed in the Albidum Zone (Verreussel et al., 2018, figs 2, 15), that is, latest Ryazanian and possibly into the earliest Valanginian. It is regarded as the first indication of the occurrence of micro-fossils with Cretaceous (i.e. Valanginian) affinity, hence 'Cretaceous flooding'.

It coincides with the influx of Tethyan taxa at high latitudes, indicated in the latest Ryazanian and earliest Valanginian (Möller et al., 2015). Previously, this event was believed to have happened earlier in the Ryazanian (Mutterlose et al., 2003; Alsen & Mutterlose, 2009; Pauly et al., 2012, 2013). From that time on, more calcareous, low organic, sediments occur temporarily.

In the late Ryazanian, the North Sea area was bordered to the south, stretching into parts of France, Belgium, the Netherlands, Germany and Poland, by continental to very shallow marine

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Wealden facies, restricting eventual connections to the south, south-west and east (Image 6). Marine influence on the continental Wealden facies increased and became dominant in the latest Ryazanian to earliest Valanginian, as large parts of the Wealden deposits were overlain by fully marine sediments, especially in the Lower Saxony Basin to the south-east and the Vomb Trough, the western most extension of the Polish Strait, to the east. Farther to the east, fully marine conditions were already established in Kochi Zone-time or slightly earlier, when Tethyan ammonites occur on the Russian Platform (Mitta, 2017; Grabowski et al., 2021). Contemporaneous sediments were then still marginally marine to continental towards the North West European Province, with only occasional flooding surfaces evidencing marine influence (Schneider et al., 2018, fig. 2).

Connections to the southeast along the Polish Strait, lows superimposed on the Sorgenfrei-Tornquist Zone (see e.g. maps envisaged by Kelly, 1990, p. 144), connecting either the Russian Plain and/or the Tethys with the West European province, were established around the transition from the early to the late Valanginian, perhaps as early as the latest Ryazanian-earliest Valanginian. A further possible connection towards the south is south of the Market Weighton High (Image 1) during the earliest Ryazanian (see Abbink, 1998, p. 136; Abbink et al., 2001a, fig. 15) but was definitely closed during the late Ryazanian when Wealden facies was deposited.

Marginal or proximal marine facies often include abundant continentally derived organic matter, in part as pollen and spores. A climate shift was postulated based on a sudden decline in the abundance of *Classopollis* (Abbink, 1998; Abbink et al., 2001a, 2006, fig. 6). This so-called Kochi climate shift occurs in the Kochi Zone just below J76. It is also called the Kochi flooding of Partington et al. (1993) and marks the transition from a warm and arid climate (cf. Hallam et al., 1991; Turner, 2018) to a tropical wet climate. The sudden decrease in *Classopollis* in favour of Gleicheniaceae is well recorded on the Russian Platform (Fedorova & Gryazeva, 1984, tab. 1, p. 154) as well as in the Laptev Sea (northern Siberia) (Kashirtsev et al., 2018, fig. 2; approximately between their members 12 and 13). In the Ryazanian sediments of the Laptev Sea, though *Classopollis* is overall sparsely represented, but fern spores indicating tropical wet conditions increase in abundance. Nevertheless, Lindström & Ekström (2011) and Schneider et al. (2018, fig. 2) indicate *Classopollis* to diminish already in the top of the Lamplughi Zone in the Cherty Freshwater Beds. Hoedemaeker (1999) and Hoedemaeker & Herngreen (2003, 2004) date these Purbeckian cherty beds between the Lamplughi and Runctoni flooding surfaces though.

Based on paleogeographic reconstructions, a marine passage has been inferred between the Shetland area and the south of Greenland (Laughton, 1975, p. 179, fig. 3; Ziegler, 1988; Roberts et al., 1999, figs 14–15). However, recent research does not provide strong evidence for this NE Atlantic rift system, at least not before the Early Cretaceous (Stoker et al., 2017, p. 57–58). The latter age is demonstrated, as throughout the Viking Graben, up to the Norwegian-Greenland seaway Tethyan calcareous microfossils (*Nannoconus*) have been observed. They occur regularly in the late(st) Ryazanian to the earliest Valanginian at high latitudes, 55ºN palaeolatitude (Århus et al., 1986; Jeremiah, 2001; Pauly et al., 2013; Möller et al., 2015) but probably not before the Albidum Chron (Jeremiah, 2001; Möller et al., 2015, fig. 3).

In the latter context, it should be noted that for instance in North-East Greenland the underlying organic-rich mudstones of the Bernbjerg Formation are generally indicated to be Volgian or older (Alsgaard et al., 2003; Piasecki et al., 2004). However, these beds were considered to be of Late Jurassic-earliest Cretaceous age by Pauly et al. (2012, 2013) and are coeval to the Upper Jurassic source rock of the mid-Norwegian shelf and the Barents Sea (Alsgaard et al., 2003). Apparently, the top of the Bernbjerg Formation can be strongly diachronous partially being as young as the Ryazanian. Recent biostratigraphical research (Piasecki et al., 2020) revealed two different formations, that is, the Bernbjerg Formation of Oxfordian-Kimmeridgian age and the Stratumbjerg Formation of latest Hauterivian-Albian age, which are virtually impossible to separate from a lithological point of view. However, the latter formation is much younger as compared to the strata dealt with herein.

Thus, either there is a significant hiatus, or *Nannoconus* are not preserved in the organic-rich facies, or indeed not present. If so, it is likely to assume that the (sudden) *Nannoconus* influx arrived with what is commonly referred to as the 'Stenomphala flooding' (K10 of Partington et al. (1993) and or 'Paratollia flooding' (K15 of Partington et al. (1993), that is, that is after the Icenii Chron. Along the northeast coast of Greenland, the Ryazanian-Valanginian deposits yield additionally Tethyan cephalopods (belemnites like *Pseudobelus* and *Duvalia*; Alsen & Mutterlose, 2009; Mutterlose et al., 2020) and brachiopods (e.g. *Pygope*; Ager & Walley, 1977; Sandy, 1991; Harper et al., 2005), along with relatively frequent ammonites of oceanic type, such as *Lytoceras* and *Ptychophylloceras* (Alsen, 2006), which invaded this area from the south (Mutterlose et al., 2020). All in all, the arrival of these typical Tethyan micro- and macrofossils can only be explained by a connection between the Tethys and the Boreal via the so-called Atlantic route (Image 6).

Swientek (2002), Mutterlose et al. (2003), Alsen (2006), Pauly et al. (2012, 2013) and Möller et al. (2015) argued that high meridional temperature gradients and cool-cold climatic conditions in high latitudes caused the formation of (cold) deep water in the South Anyui Gulf (Arctic) in the late Ryazanian-Valanginian and palaeoceanographic changes, reflected in a counter-balanced ocean current system in the Greenland-Norwegian Seaway and allowed Tethyan biota to spread as far north as North-East Greenland during the late Ryazanian and early Valanginian. Simultaneously, with incoming Tethyan waters, the accumulation of calcareous sediments at high latitudes relates to an important influx of calcareous nannofossils into the Greenland-Norwegian Seaway, exhibiting an influx of Tethyan and low-to-mid latitudinal taxa, synchronous with observed influxes of Tethyan ammonite and belemnite species (Pauly et al., 2013). However, the northward extension of this warm-water fauna was mainly restricted to East Greenland and adjacent areas of the Greenland-Norwegian seaway. North of this area only a single record of *Lytoceras* is known to date from the Valanginian of Spitsbergen (Frebold & Stoll, 1937, p. 52). During the (late) Valanginian, the Tethyan influence became stronger and caused the occurrence of a specific 'warm-water foraminiferal assemblage' in the Russian part of the Barents Sea shelf (Basov & Vasilenko, 1999).

These influxes suggest the occurrence of northward flowing warmer, less saline surface currents in the Norwegian-Greenland seaway (northern Viking Graben), which allowed Tethyan nekton and plankton to spread even as far north as North-East Greenland at 55°N palaeolatitude (Pauly et al., 2013; Möller et al., 2015; Mutterlose et al., 2020) and further north-east, but also suggest these surface currents to flow south-ward through the (southern

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extension of the) Viking Graben, to approximately 35–40°N, 'piggy backing' the normal colder north-south currents, enabled – to some extent – the exchange of cephalopods and bivalves (Image 6). Perhaps connections with a strong north-south component (Image 6) existed already temporarily, because of the general similarity between some ammonite assemblages described from the West European Province and other Boreal provinces. However, during these times, the southern connections, as envisaged by Kelly (1990, p. 144), were seriously hampered.

Conclusions

This work contributes to the stratigraphy of the Ryazanian (Berriasian) in general, and to the early and late Ryazanian Kochi and Icenii zones in particular. Key macrofossils, especially ammonites (*Lynnia*, *Surites*) and buchiids (*Buchia volgensis*), are for the first time mentioned from the offshore of the Netherlands (cores B18-02 and L06-02) and Norway (core 7/7-2). Their abundances, paleo(bio)geography and depositional context are further discussed. This work is summarised as follows.

1. The monospecific abundance of *Buchia volgensis* is explained by higher tolerance of this species to fluctuating oxygen levels, but probably to a lesser degree temperature. In all probably it is an opportunistic taxon.
2. Ammonite assemblages have typical Boreal composition with common *Surites* and few *Lynnia*. *Lynnia* is for the first time reported outside its type locality. The finding of a potentially juvenile *Praetollia* indicates the last occurrence of this taxon in the lower part of the Icenii Zone.
3. Dispersal of the herein mentioned Boreal macrofossils strongly favours arrival through the Viking Graben. Nonetheless, the provincial character is a pristine feature, based on the low diversity and relative abundance of endemic taxa, and is thought to relate to the oxygen-depletion in the relative shallow and narrow Viking Graben, apart from southern restrictions due to low sea-levels.
4. During the latest Volgian-earliest Ryazanian (pre-Kochi time) isolation of the North Sea Basin towards the south was at its peak. Therefore, the presence of *Volgidiscus* (indicating the Lamplughi Zone) in the North Sea area on the one hand, and on the other on the Russian Platform, in the Subpolar Urals and northern Siberia, must indicate a connection between these areas via the southern Viking Strait.
5. No buchiids are known from the Late Volgian to Ryazanian in the Lower Saxony Basin and Polish Strait, further strengthening the arrival of Boreal macrofossils through the southern Viking Strait. In the latest Ryazanian, only a shallow water connection existed in the south-eastern part of the West-European Province.
6. The initial Tethyan influx of nannoplankton (from literature data) postdates the Icenii Zone and is related to the Stenomphala flooding (K10) that includes latest Ryazanian (Stenomphala-Albidum zones) but possibly also earliest Valanginian sediments.

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