

Integrated stratigraphy of the Kronsmoor section (northern Germany), a reference point for the base of the Maastrichtian in the Boreal Realm

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ABSTRACT:

Niebuhr, B., Hampton, M.J., Gallagher, L.T. and Remin, Z. 2011. Integrated stratigraphy of the Kronsmoor section (northern Germany), a reference point for the base of the Maastrichtian in the Boreal Realm. *Acta Geologica Polonica*, **61** (2), 193–214. Warszawa.

Results of detailed multistratigraphic analyses of the Campanian–Maastrichtian boundary section at Kronsmoor in northern Germany are summarised and calibrated with the GSSP at Tercis les Bains, southwest France. Additional markers for the definition of the boundary in the Boreal Realm are proposed, and a detailed carbon isotope curve around the Campanian–Maastrichtian boundary in the chalk facies of the Boreal epicontinental sea is presented. The C isotopic GSSP marker for global correlation is the markedly abrupt decrease of c. 0.7 ‰ $\delta^{13}\text{C}$ directly at the Campanian–Maastrichtian boundary as dated by ammonites. In electronic borehole measurements the Kronsmoor section covers the SP peaks 53 to 64 and the base of the Maastrichtian being situated just below SP peak 60. The first occurrence (FO) of the ammonite *Pachydiscus neubergicus*, which corresponds to biohorizon 1 at Tercis, falls in the upper part of nannofossil Zone UC15, at both localities. Biohorizon 3 is the FO of the ammonite *Diplomoceras cylindraceum*, which first appears in the Upper Campanian of Tercis and at Kronsmoor enters significantly above the FO of *Belemnella lanceolata*, the conventional Boreal belemnite marker for the base of the Maastrichtian Stage. Based on ammonite evidence, the internationally accepted base of the Maastrichtian at Kronsmoor is located between the FOs of *Diplomoceras cylindraceum* (Upper Campanian) and *Pachydiscus neubergicus* (Lower Maastrichtian) c. 11 m above flint layer F 600, at which the first representatives of the belemnite genus *Belemnella*, in particular *Bn. lanceolata* occur. The latter thus is a Late Campanian species, appearing c. 450 ky prior to the ammonite-based boundary. The FOs of *Belemnella pseudobutusa* (*sensu* Schulz) resp. *Belemnella obtusa* (*sensu* Remin) directly at the boundary can be used as the coleoid proxy for the definition of the base of the Maastrichtian in the Boreal Realm. To define the boundary by benthic foraminifera the last occurrence (LO) of *Neoflabellina praereticulata* is suitable. Biohorizon 12, as defined at Tercis, involves the nannofossil *Uniplanarius trifidus*, however, at Kronsmoor this species is rare, occurs only sporadically and also significantly lower in comparison to Tercis. It is possible though to compare and correlate nannofossil events between Kronsmoor and Tercis using cosmopolitan taxa such as *Broinsonia parca constricta* and *Eiffellithus eximius*. The LO of the latter appears to be situated just above the boundary in both sections; it follows from this that the top of nannofossil Zone UC15 is of Early Maastrichtian age.

Key words: Upper Cretaceous; Campanian; Maastrichtian; Stratigraphy; ammonites; Belemnites; Nannofossils; Stable C and O isotopes; Northern Germany.

INTRODUCTION

The sections at Lägerdorf and Krons Moor (Schleswig-Holstein, northern Germany, Text-fig. 1), c. 25 km northwest of Hamburg, comprises the Lower Coniacian to the Lower Maastrichtian in typical North European white chalk facies (Schulz *et al.* 1984). At the Saturn quarry (Krons Moor) the sole continuous Campanian–Maastrichtian boundary succession in northern Germany is accessible; this has been suggested as a possible international reference section for the base of the Maastrichtian (Odin *et al.* 1996). So far, the macrobiostratigraphical subdivision at Krons Moor has been based mainly on a typical Boreal faunal element, belemnites (Schulz 1979); this zonation cannot be correlated in detail to other areas yet. Therefore, a working group was established in order to refine an integrated stratigraphical correlation between the GSSP of the base of the Maastrichtian at Tercis les Bains, southwest France (Odin *et al.* 2001; Odin and Lamaurelle 2001), and Krons Moor. It is assumed here that additional investigations will improve the situation in such a way that Krons Moor could be used with confidence as a reference section for the Boreal Realm. The new stratigraphical data presented herein are based on detailed collecting, lithological analyses, stable C- and O-isotopes, ammonites, belemnites, benthic foraminifera and calcareous nannofossils.

In 2001, the Global boundary Stratotype Section and Point (GSSP) for the base of the Maastrichtian was established at Tercis, SW France, and twelve biohorizons were documented as potential Global boundary Stratotype Points (GSP) on an arithmetic mean at 115.2 m (Odin and Lamaurelle 2001). Four of these can be recognised at Krons Moor:

Ammonites

Biohorizon 1 – FO of *Pachydiscus neubergicus* (~35 ky above the GSSP at Tercis, Lower Maastrichtian).

Biohorizon 3 – FO of *Diplomoceras cylindraceum* (~165 ky below the GSSP at Tercis, Upper Campanian).

Benthic foraminifera

Biohorizon 10 – LO of *Gavelinella clementiana* (~12 ky above the GSSP at Tercis, Lower Maastrichtian).

Calcareous nannofossils

Biohorizon 12 – LO of *Quadrum trifidum* (= *Uniplanarius trifidus* herein) (~750 ky above the GSSP at Tercis, Lower Maastrichtian).

The sequence of nannofossil events at Tercis, as based on Barchi *et al.* (1997) is:

FO of *Ceratholithoides aculeus*

FO and LO of *Uniplanarius gothicus*

FO and LO of *Uniplanarius trifidus*

LO of *Eiffellithus eximius*

LO of *Tranolithus phacelosus* (= *Tranolithus orionatus* herein)

LO of *Broinsonia parca*.

Subsequently, results of nannofloral analyses in a number of independent studies of Tercis material have been presented (Gardin and Monechi 2001; Gardin *et al.* 2001; Melinte and Odin 2001; Salis 2001). Selected samples have also been analysed by Burnett (in Hancock *et al.* 1993). Gardin *et al.* (2001) combined all data from independent analyses and presented a summary of events across the Campanian–Maastrichtian boundary at Tercis, as follows:

LO of *Broinsonia parca constricta* at 166 m

LO of *Amphizygus brooksii brooksii* at 150.5 m

LO of *Broinsonia parca parca* at 142.8 m

LO of *Uniplanarius trifidus* at 135.8 m

LO of *Uniplanarius gothicus* at 129.1 m

LOs of *Eiffellithus eximius*, nannoconids and *Reinhardtites anthophorus* at 89 m.

However, examination of the raw data published in Odin (2001) has revealed anomalous (or “outlier”) occurrences for some of these taxa above their interpreted stratigraphically highest range. The nannoflora recovered from Tercis was said to have Tethyan affinities by Barchi *et al.* (1997). With the exception of *Ce. aculeus* and *Am. br. brooksii*, all of the taxa cited above have also been recorded in the (Boreal) Krons Moor chalk, thus potentially enabling comparison of nannofloral distributions.

LITHOSTRATIGRAPHY AND FOSSIL CONTENT

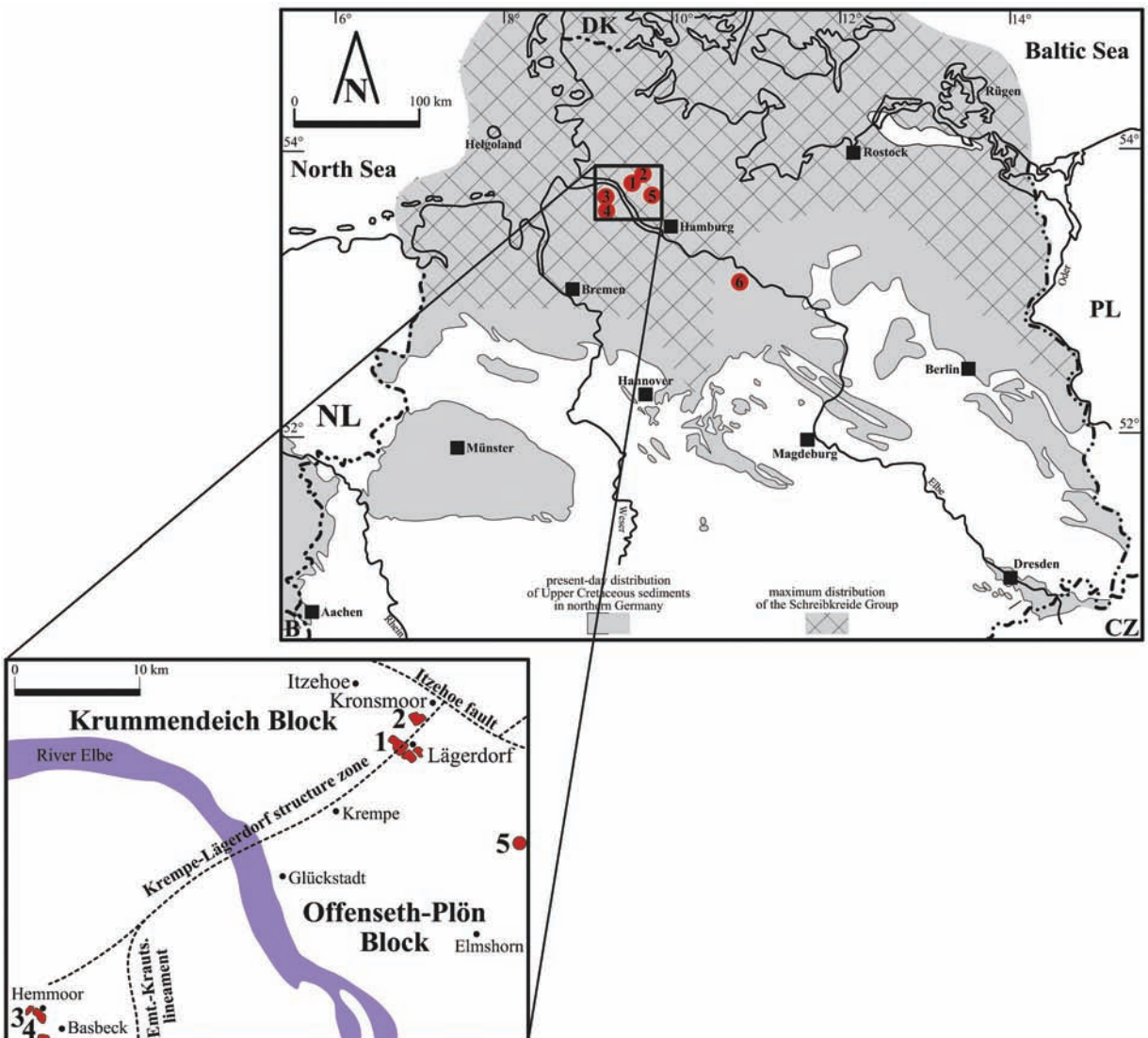
Chalks composed of biomicritic low-magnesium calcite have carbonate contents of >90 %, and a pore volume in excess of 40 % (see Scholz 1973). Traditionally, the “standard section for the Upper Cretaceous white chalk of NW Germany” (Schulz *et al.* 1984) has been subdivided on the basis of marls (M), marly layers (mB), burrowed horizons (G, Gb), flint beds (F) and other lithologically defined horizons. Recently, the more than 1.000 m thick autochthonous northern German chalk facies (Lower Coniacian to Upper Maastrichtian) has been assigned to the Schreibkreide Group and the most complete Lägerdorf–Krons Moor–Hemmoor–Basbeck composite sec-

tion has been subdivided into six formations (Niebuhr 2006; Niebuhr *et al.* 2007).

At the Saturn quarry (Kronsmoor), a total thickness of c. 100 m (= c. 4 my using accumulation rates of 24.5 m/my; compare Ehrmann 1986) is exposed, comprising the *Bt. langei* to *Bn. sumensis* / *Ac. tridens* zones of Schulz (1978, 1979) and Niebuhr (2003). The c. 85 m thick chalk of the Kronsmoor Formation has the lowest carbonate content within the standard section, is nearly flint free, yet shows several marly layers and burrowed horizons (Scholz 1973; Schulz 1978). The isolated flint bed F 600 nearly in the middle of the section (= 0 m level at Kronsmoor) is associated with the FO of the belemnite genus *Belemnella* (Schulz 1979). However, the uppermost c. 5 m of the

underlying *Mi. grimmensis* / *Ca. granulosis* Zone has not yet yielded any belemnites and in the lower part of the *Bn. lanceolata* Zone, these are extremely rare (Schulz 1979; Christensen 2000). There is a distinct acme in belemnite distribution in the Upper Campanian (mid *Mi. grimmensis* / *Ca. granulosis* Zone) between mB 594 and G 595.

25–32 m below F 600, in the *Bt. langei* Zone, calcarenitic chalk rich in inoceramid debris and large-sized siliceous sponges appear; this is referred to as Grobkreide 2 Beds (LCGA = Late Campanian Grobkreide Event in Text-fig. 2 and Table 1), in comparison with the lithologically similar Grobkreide 1 Beds of the Santonian–Campanian boundary interval (Niebuhr 2006; Niebuhr *et al.* 2007). At the top of the



Text-fig. 1. The Cretaceous of northern Germany and adjacent countries, showing the maximum lateral extension of chalk sedimentation (lower Upper Campanian). Location of outcrops and boreholes: 1. Lägerdorf, 2. Kronsmoor, 3. Hemmoor, 4. Basbeck, 5. borehole Offenseth 1, 6. Lüneburg. Tectonic units are according to Baldschuhn *et al.* (2001)

no.	m+/-0.1 m	sampled horizon, +/-0.1 m	macrobiozone	13/12-C	18/16-O
916	47,0	F 633 +3 m	<i>Bn.sumensis</i> / <i>Ac.tridens</i>	1,45	-1,69
915	46,0	F 633 +2 m	" / "	1,55	-1,80
914	45,0	F 633 +1 m	" / "	1,54	-1,61
913	44,0	F 633	" / "	1,63	-1,72
912	43,0	F 632 +1m	" / "	1,51	-1,94
911	42,0	F 632 +0.1 m	" / "	1,55	-1,75
910	41,0	F 630 / 631 +1.2 m	" / "	1,46	-1,88
909	40,0	F 630 / 631 +0.2 m	" / ", EME = Early Ma. Event	1,54	-1,69
908	39,0	F 630 -0.4 m	" / ", EME, base Hemmoor Fm	1,29	-2,07
907	38,0	F 630 -1.5 m	" / ", EME, top Kronsmeer Fm	1,66	-1,76
906	37,0	F 630 -2 m	" / ", EME	1,55	-1,83
905	36,0	mB 628	" / ", EME	1,09	-1,39
904	35,0	mB 628 -1 m	" / ", EME	1,69	-0,85
903	34,0	mB 628 -2 m	" / ", EME	1,39	-1,50
902	33,0	base mB 626	" / ", EME = Early Ma. Event	1,47	-1,47
901	32,0	mB 626 -1 m	" / "	1,16	-1,59
900	31,0	mB 626 -2 m	" / "	1,35	-1,85
899	30,0	mB 626 -3 m, mB 625 -0.4 m	" / "	1,38	-1,94
898	29,0	mB 625 -1.4 m	" / "	1,44	-1,79
897	28,0	mB 623	<i>Bn.sumensis</i> / <i>Ac.tridens</i>	1,42	-1,64
896	27,0	mB 618 +5 m	<i>Bn.obtusa</i>	1,58	-1,53
895	26,0	mB 618 +4 m	"	1,34	-1,74
894	25,0	mB 618 +3 m	"	1,38	-1,63
893	24,0	mB 618 +2 m	"	1,36	-1,81
892	23,0	G 615 +6 m	"	1,40	-1,72
891	22,0	G 615 +5 m	"	1,55	-1,47
890	21,0	G 615 +4 m	<i>Bn.obtusa</i>	1,46	-1,65
889	20,0	G 615 +3 m	", <i>Belemnella</i> sp. F	1,51	-1,64
888	19,0	G 615 +2 m	", "	1,12	-1,71
887	18,0	G 610 +5 m	", <i>Belemnella</i> sp. F	1,54	-1,73
886	17,0	G 610 +4 m	", <i>Belemnella</i> sp. G	1,31	-1,54
885	16,0	G 610 +3 m	", "	1,27	-1,54
884	15,0	G 610 +2 m	", "	1,24	-1,61
883	14,0	G 610 +1 m	", <i>Belemnella</i> sp. G, CMBE = Ca.-Ma. Bound. E.	1,31	-1,87
882	13,0	G 610	", <i>Belemnella</i> sp. I, CMBE	1,26	-1,30
881	12,0	G 610 -1 m	", <i>Bn.</i> sp. I, CMBE	1,22	-1,63
880	11,0	G 610 -2 m	Ca.-Ma. bound., <i>Bn. obtusa</i>, <i>Bn.</i> sp. I, CMBE	1,38	-1,78
879	10,5	F 600 +10.5 m	<i>Bn. obtusa</i> , <i>Belemnella</i> sp. I, CMBE	1,94	-1,69
878	10,0	F 600 +10 m	<i>Belemnella inflata</i> , CMBE	1,78	-1,60
877	9,5	F 600 +9.5 m	", CMBE = Ca.-Ma. Boundary Event	1,90	-1,12
876	9,0	F 600 +9 m	"	1,96	-1,37
875	8,5	F 600 +8.5 m	"	1,84	-1,32
874	8,0	F 600 +8 m	"	1,91	-1,25
873	7,5	F 600 +7.5 m	"	2,03	-1,44
872	7,0	F 600 +7 m	"	1,88	-1,22
871	6,5	F 600 +6.5 m	"	1,92	-1,16
870	6,0	F 600 +6 m	"	1,99	-1,66
869	5,5	F 600 +5.5 m	"	2,05	-1,53
868	5,0	F 600 +5 m	"	1,96	-1,33
867	4,5	F 600 +4.5 m	<i>Belemnella inflata</i>	2,15	-1,29
866	4,0	F 600 +4 m	<i>Belemnella lanceolata</i>	1,89	-1,30
865	3,5	F 600 +3.5 m	"	2,09	-1,23
864	3,0	F 600 +3 m	"	1,98	-1,64
863	2,5	F 600 +2.5 m	"	2,13	-1,65
862	2,0	F 600 +2 m	"	2,12	-1,34
861	1,5	F 600 +1.5 m	"	2,15	-1,62
860	1,0	F 600 +1 m	"	2,11	-1,62
859	0,5	F 600 +0.5 m	"	2,20	-1,43
858	0,0	F 600	<i>Belemnella lanceolata</i>	2,13	-1,69

INTEGRATED STRATIGRAPHY OF THE KRONSMOOR SECTION (GERMANY)

857	-0,5	F 600 -0.5 m	<i>Mi.grimm./Ca.granulosus</i>	2,12	-1,60
856	-1,0	F 600 -1 m	" / "	2,14	-1,39
855	-1,5	F 600 -1.5 m	" / "	2,16	-1,17
854	-2,0	F 600 -2 m	" / "	2,18	-1,72
853	-2,5	F 600 -2.5 m	" / "	2,24	-1,74
852	-3,0	F 600 -3 m	" / "	2,18	-1,62
851	-3,5	F 600 -3.5 m	" / "	2,11	-1,57
850	-4,0	F 600 -4 m	" / "	2,06	-1,71
849	-4,5	F 600 -4.5 m	" / "	2,37	-1,58
848	-5,0	F 600 -5 m	" / "	2,34	-1,59
847	-5,5	F 600 -5.5 m	" / "	2,32	-1,54
846	-6,5	G 595 +1.5 m	" / "	2,02	-2,16
845	-7,5	G 595 +0.5 m	" / "	2,05	-1,90
844	-8,5	G 595 -0.5 m	" / "	2,07	-2,25
843	-9,5	G 595 -1.5 m	" / "	2,06	-2,16
842	-10,5	G 595 -2.5 m	" / "	2,33	-1,95
841	-11,5	G 595 -3.5 m	" / "	2,12	-1,76
840	-12,5	G 595 -4.5 m, mB 594	" / "	1,90	-1,64
839	-13,5	mB 594 -1.5 m	" / "	2,14	-1,93
838	-14,5	mB 594 -2.5 m	" / "	1,95	-2,21
837	-15,5	mB 594 -3.5 m	" / "	1,95	-2,16
836	-16,5	mB 594 -4.5 m, base mB 592	" / "	1,86	-2,08
835	-17,5	mB 592 -1 m	" / "	2,05	-1,73
834	-18,5	mB 592 -2 m	" / "	2,06	-2,12
833	-19,5	mB 592 -3 m	<i>Mi.grimm./Ca.granulosus</i>	2,00	-1,86
832	-20,5	mB 592 -4 m, mB 590	<i>Belemnitella langei</i>	1,99	-1,41
831	-21,5	mB 590 -1 m	"	2,10	-2,12
830	-22,5	mB 590 -2 m	"	2,05	-1,89
829	-23,5	mB 590 -3 m	"	1,85	-1,83
828	-24,5	mB 590 -4 m	" , Grobkreide 2 Beds = LCGE	1,72	-1,95
827	-25,5	mB 589	" , "	2,07	-1,80
826	-26,5	mB 589 -1 m	" , "	1,91	-2,22
825	-27,5	mB 589 -2 m	" , "	2,10	-1,89
824	-28,5	mB 589 -3 m	" , "	2,11	-2,04
823	-29,5	mB 586	" , "	2,08	-2,10
822	-30,5	mB 585 +1 m	" , "	2,05	-2,03
821	-31,5	mB 585	" , Grobkreide 2 Beds = LCGE	1,96	-1,83
820	-32,5	mB 585 -1 m	"	1,78	-2,10
819	-33,5	mB 585 -2 m	"	2,00	-1,97
818	-34,5	mB 585 -3 m	"	2,03	-2,18
817	-35,5	mB 585 -4 m	"	1,83	-2,15
816	-36,5	mB 585 -5 m	"	2,07	-1,80
815	-37,5	mB 585 -6 m	"	2,06	-1,70
814	-38,5	mB 585 -7 m	"	2,05	-1,75
813	-39,5	mB 585 -8 m	"	2,06	-2,01
812	-40,5	mB 585 -9 m	"	2,15	-1,83
811	-41,5	mB 585 -10 m	"	2,28	-1,75
810	-42,5	mB 585 -11 m	"	2,09	-2,09
809	-43,5	mB 585 -12 m	<i>Belemnitella langei</i>	2,01	-1,87

Table 1. Numbers, depths, stratigraphy, and absolute values of stable isotope samples

Kronsmoor Formation, within the *Bn. sumensis* / *Ac. tridens* Zone, between the marly horizons mB 626 to mB 628, macro- and mesofaunal contents (ammonites, inclusive baculites, nautilids, bivalves, brachiopods, echinoids, serpulids, crinoids and more) increase conspicuously. This level (EME = Early Maastrichtian Event in Text-fig. 2 and Table 1) seems to have potential for interregional correlation because the *Bn. sumen-*

sis Zone also appears to be the most fossiliferous unit in the Lower Maastrichtian of the extended type area of the Maastrichtian Stage (Jagt *et al.* 1995; Keutgen *et al.* 2010). Only the topmost 14 m of the section (*Bn. sumensis* / *Ac. tridens* Zone) are part of the Hemmoor Formation with more or less discontinuous nodular flint beds (Niebuhr 2006; Niebuhr *et al.* 2007). This lithological change appears to be isochronous in at least three sec-

tions in northern Germany (F 630 at Krons Moor, Schleswig-Holstein; F 868 at Hemmoor, northern Lower Saxony; and at Lüneburg, eastern Lower Saxony; see Text-fig. 1) (compare Schmid 1955; Schulz *et al.* 1984; Niebuhr 2006; Niebuhr *et al.* 2007). Probably, this change in sedimentary patterns equates with the onset of the Early Maastrichtian Oebisfelde Transgression of proximal sections (Niebuhr 1995).

BOREHOLE CORRELATION

For correlation with the chalk standard section Lägerdorf–Krons Moor–Hemmoor–Basbeck, borehole Offenseth 1 was selected (Niebuhr 2006; Niebuhr *et al.* 2007). While the Lägerdorf and Krons Moor quarries are situated directly above the Krempe–Lägerdorf structural zone, the Offenseth 1 well was drilled in a tectonically stable position within the central portion of the Offenseth–Plön Block c. 12 km to the southeast (Text-fig. 1). Therefore, deposition there was not influenced by salt intrusions into the Lägerdorf salt structure. Since 1977 the Offenseth 1 has been considered to be the chalk standard borehole because the succession is “basically considerably complete and does not show any local peculiarities in facies and thickness” (Baldschuhn and Jaritz 1977, p. 8). Furthermore, Koch (1977) calibrated his microbiostratigraphic subdivision of the chalk with the self-potential (SP) and resistivity (R) logs of the Offenseth 1 well.

Results in borehole correlation

In electronic borehole measurements the Krons Moor Formation covers the SP peaks 53 to 63 of Baldschuhn and Jaritz (1977). The monotonously low SP values above SP peak 63 correspond to the facies change to flinty chalks of the Hemmoor Formation (Niebuhr 2006; Niebuhr *et al.* 2007). The FO of *Belemnella* is between the SP peaks 58 and 59, and the internationally accepted, ammonite-defined Campanian–Maastrichtian boundary (see below) is just below SP peak 60. The Upper Campanian Grobkreide 2 Beds of the *Bt. langei* Zone at SP peaks 53 and 54 correlate with the upper *Ne. bipunctatum* / *Gt. roemeri* Zone in the spiculitic opoka facies of the Ahlten Formation of the Lehrte West Syncline near Hannover (Niebuhr 2006). This correlation is corroborated by the 4 m-thick overlap in the ranges of two species of benthic foraminifera between –23 and –27 m (Niebuhr *et al.* 1997) and a single find of *Nostoceras* sp. at –37 m in the Krons Moor section (see Text-fig. 3C).

CARBON AND OXYGEN ISOTOPE STRATIGRAPHY

At Krons Moor, 108 samples (nos. 809–916, see Table 1 and Text-fig. 2) were collected in 2002 and 2003 at intervals of 0.5 and 1 m, normalised to the bed numbers used by Schulz (1978). Stable isotope ratios of powdered bulk sediment were measured with a carbonate preparation line (Carbo-Kiel I) connected on-line to a Finnigan Mat 252 mass-spectrometer at the Institut für Geologie und Mineralogie, Universität Erlangen-Nürnberg. All isotopic values are reported in the standard δ -notation relative to V-PDB. Calcite palaeotemperature values were calculated using the equation of Anderson and Arthur (1983): $t(^{\circ}\text{C}) = 16 - 4.14(\delta_{\text{c}} - \delta_{\text{w}}) + 0.13(\delta_{\text{c}} - \delta_{\text{w}})^2$, assuming a $\delta^{18}\text{O}$ value of –1 ‰ for non-glacial Late Cretaceous seawater (e.g. Savin 1977). External precision was checked by multiple analyses of an internal laboratory standard and is better than 0.05 ($\pm 1 \sigma$) for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$.

Results in C and O isotope stratigraphy

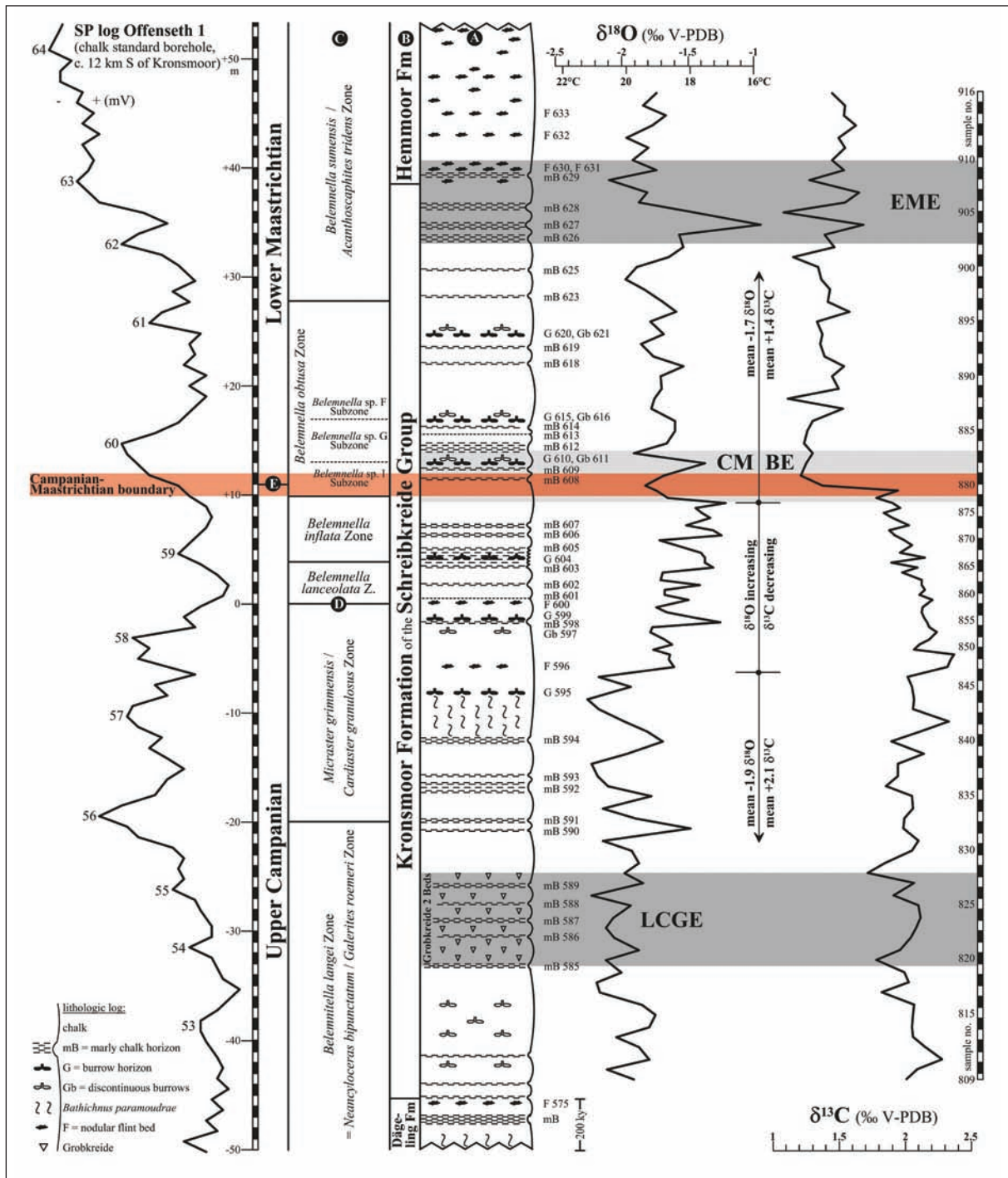
The stable isotope composition of the bulk sediment of Krons Moor ranges from +1.09 to +2.37 ‰ $\delta^{13}\text{C}$ as well as –2.25 to –0.85 ‰ $\delta^{18}\text{O}$, and shows three discrete intervals (Text-fig. 2): in the Upper Campanian *Bt. langei* to mid *Mi. grimmensis* / *Ca. granulosus* zones highest $\delta^{13}\text{C}$ values with a mean of +2.05 ‰ correspond to lowest $\delta^{18}\text{O}$ values with a mean of –1.9 ‰. The uppermost Campanian between –6 and +9.5 m is characterised by gradually increasing $\delta^{18}\text{O}$ and decreasing $\delta^{13}\text{C}$ values. Around the internationally accepted, ammonite-defined Campanian–Maastrichtian boundary (see below), C and O isotope values conspicuously decrease nearly simultaneously with 0.7 ‰ $\delta^{13}\text{C}$ and 0.5 ‰ $\delta^{18}\text{O}$ (CMBE = Campanian–Maastrichtian Boundary Event in Text-fig. 2). This conspicuous negative shift in $\delta^{13}\text{C}$ is very noticeable and appears suitable for global correlation (see Voigt *et al.* 2010). The Lower Maastrichtian at Krons Moor is characterised by low stable isotopic levels with means of +1.4 ‰ $\delta^{13}\text{C}$ and –1.7 ‰ $\delta^{18}\text{O}$.

The general correlation between carbon isotope fluctuations and sea-level changes has been documented by several authors. Positive shifts in marine $\delta^{13}\text{C}$ are generally interpreted to reflect the removal of large amounts of isotopic “light” carbon from the oceans by burial of ^{12}C -rich organic matter and to correlate with a sea-level rise. In contrast, negative shifts have been linked to reduced burial and reworking of organic-rich strata during a sea-level fall (e.g. Schlanger and Jenkyns 1976; Arthur *et al.* 1987; Jenkyns *et al.* 1994; Jarvis *et al.* 2002). Judging from $\delta^{13}\text{C}$ excursions at Krons Moor, a major regression at the Campanian–

Maastrichtian boundary occurred, where values decrease abruptly. During Early Maastrichtian times, $\delta^{13}\text{C}$ values remained low and constant, thus not tracking the inferred sea-level rise which is suggested by the litho- and

biofacies development towards the Early Maastrichtian Event (see Text-fig. 2).

Assuming that bulk sediment of primary low-Mg-calcitic coccoliths is particularly suitable for the re-



Text-fig. 2. Lithology, stable C and O isotopes and SP peaks of the Kronsmoor section. A – lithology (completed after Schulz 1978); B – lithostratigraphy (Niebuhr 2006); C – new macrofossil zonation (arranged after Schulz 1978, 1979; Niebuhr 2003; Remin, present paper); D – traditional Boreal Campanian–Maastrichtian boundary based on belemnites (Schulz 1979); E. internationally accepted ammonite-defined Campanian–Maastrichtian boundary. LCGE = Late Campanian Grobkreide Event; CMBE = Campanian–Maastrichtian Boundary Event, EME = Early Maastrichtian Event

construction of $\delta^{18}\text{O}$ sea-surface palaeotemperatures, 19 to 21°C were reached in the early Late (see Niebuhr and Joachimski 2002; Niebuhr 2005) and late Late Campanian (Text-fig. 2), while the uppermost Campanian *Bn. lanceolata* and *Bn. inflata* zones (*sensu* Remin; see below and Text-fig. 6) are characterised by the lowest palaeotemperatures of c. 18°C, again increasing around the internationally accepted Campanian–Maastrichtian boundary to c. 19.5°C.

AMMONITE STRATIGRAPHY

Ammonites in the M.-G. Schulz Collection are housed at the Geozentrum Hannover (abbreviation: Ma), while those from the K. Esser Collection are part of the Würzburg collection (abbreviation: PIW), in 2007 transferred to the GeoZentrum Nordbayern of the Universität Erlangen–Nürnberg.

Results in ammonite stratigraphy

With the exception of scaphitids in the topmost c. 20 m ammonites are rare in the Krons Moor section. Ten species have been recognised to date (Niebuhr 2003), namely *Hypophylloceras velledaeforme*, *Anagaudryceras lueneburgense*, *Saghalinites wrighti*, *Pachydiscus neubergicus* (Text-figs 3D, E), *Menuites cf. wittekindi*, *Diplomoceras cylindraceum* (Text-fig. 3A), *Baculites vertebralis*, *Baculites knorriani*, *Acanthoscaphites tridens* (Text-fig. 3F), and *Hoploscaphites constrictus* (Text-fig. 3B). In addition, a single fragmentary specimen of *Nostoceras* sp. was found at the base of the Krons Moor section (Text-fig. 3C). *Acanthoscaphites tridens* forma trispinosus-trinodosus occurs commonly in the Krons Moor and Hemmoor sections (Birkelund 1982; Niebuhr 2003), where its range is limited to the *Bn. sumensis* Zone. For this reason, this species, together with *Belemnella sumensis*, is considered an index for this zone (compare Text-fig. 6).

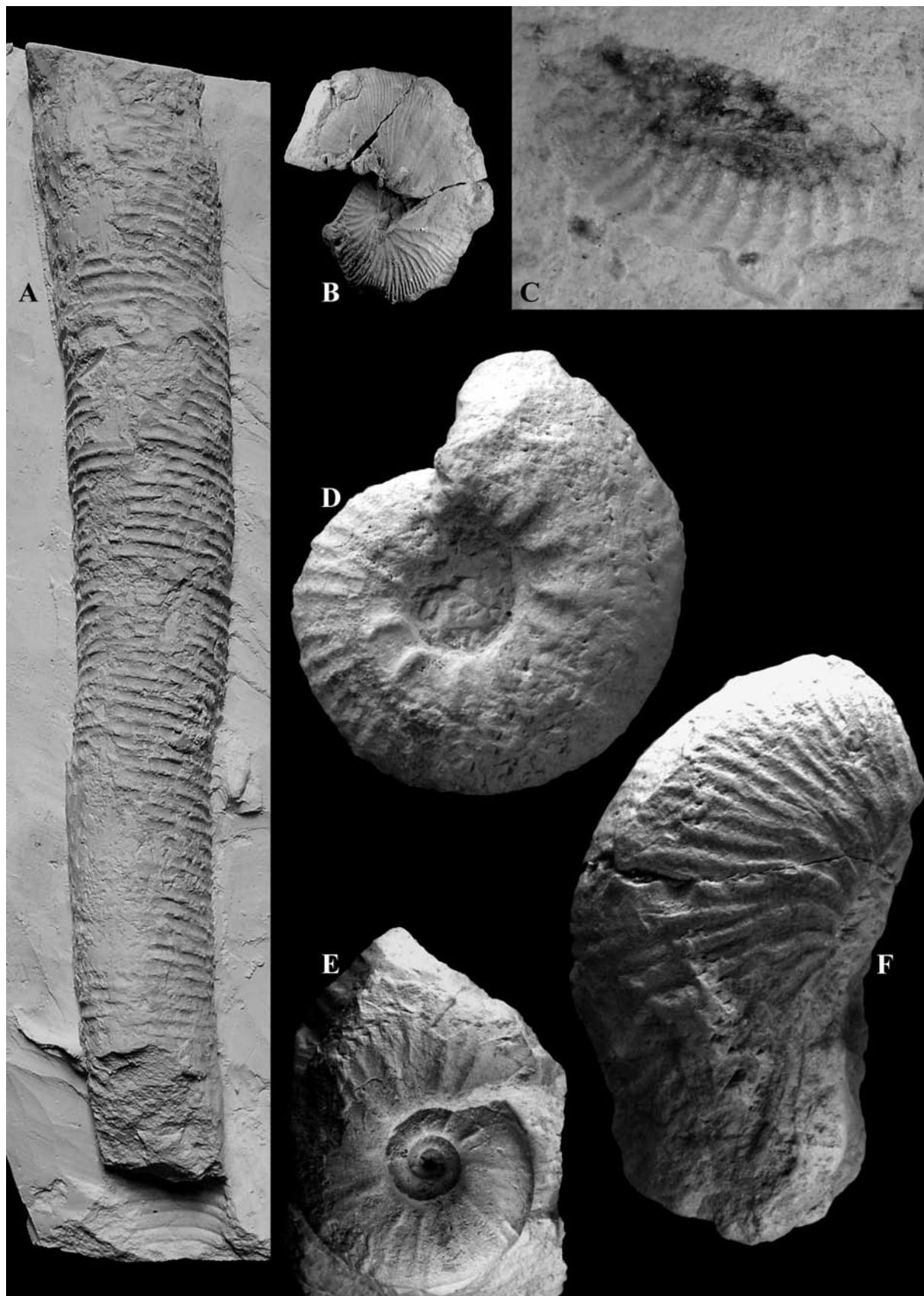
Recently, the Campanian–Maastrichtian boundary at Krons Moor has been placed between the FOs of *Di. cylindraceum* at mB 606 (+7 m, Upper Campanian) and that of the sole *in-situ* find of *Pa. neubergicus* at G 615 (+17 m, Lower Maastrichtian). In view of the fact that the FO of the latter definitely postdates the

GSSP (see Odin and Lamaurelle 2001), this needs to be emended to within the range of the second specimen of *Pa. neubergicus* known from Krons Moor; an *ex-situ* find between G 595 and G 610 (–8 m to +13 m, see Text-fig. 2). At Tercis, the FOs of *Di. cylindraceum* and *Pa. neubergicus* are c. 5 m apart, which corresponds to c. 200 ky (Odin *et al.* 2001, table 1). The internationally accepted Campanian–Maastrichtian boundary at Krons Moor is between +7 m (= FO of *Di. cylindraceum*) and +13 m (= youngest possible FO of *ex-situ Pa. neubergicus*), corresponding to c. 245 ky.

At Krons Moor, the FOs of both *Di. cylindraceum* and *Pa. neubergicus* are significantly higher than that of *Belemnella lanceolata*, the conventional belemnite marker for the base of the Maastrichtian Stage in the Boreal Realm (Schulz 1979). This agrees with Walaszczyk *et al.* (2002, p. 57), who were in favour of the view, based on inoceramid evidence, that “the base of *Belemnella lanceolata lanceolata*, the traditional basal zone of the Maastrichtian in northern Europe, may appear to be stratigraphically much lower” (i.e., than the GSSP at Tercis). However, in Poland *Di. cylindraceum* appears earlier than *Bn. lanceolata* and both species have their FOs below that of *Pa. neubergicus* (see Błaszkiwicz 1980; Machalski 1996). Christensen *et al.* (2000, p. 84) suggest that “the *neubergicus* and *lanceolata* standards for the base of the Maastrichtian Stage are not separated by more than about 0.2 my”, and in the view of Christensen (2001, p. 208) “the FO of *Bn. lanceolata* at Krons Moor virtually corresponds to the Campanian–Maastrichtian Stage boundary at level 115.2 m at Tercis, as defined by a multi-bioevents approach”. However, compared with Tercis, the Campanian–Maastrichtian boundary at Krons Moor is near the base of or within the lowermost *Bn. pseudobtusa* Zone of Schulz (1979) or *Bn. obtusa* Zone (as here defined) at c. +11 m (see Text-fig. 6). Therefore, the FO of the genus *Belemnella* is definitely of Late Campanian age, appearing c. 11 m (= c. 450 ky) earlier.

Hoploscaphites constrictus was not selected to define the GSSP at Tercis, because of the fact that “most commonly the taxon first occurs at a younger level than the stage boundary” as defined by the multi-bioevents approach (Odin *et al.* 2001, p. 827; Machalski and Odin 2001), but this is not true for northern Ger-

Text-fig. 3. Stratigraphically relevant ammonites of the Krons Moor section. A – *Diplomoceras cylindraceum* (Defrance), lateral view, x 0.9, between mB 626 and F 630, K. Esser Collection, PIW2003VII5; B – *Hoploscaphites constrictus* (J. Sowerby), lateral view of a macroconch, x 1, G 604–0.6 m, M.-G. Schulz Collection, Ma13696; C – *Nostoceras* sp., composite mould of a circular whorl section, x 1, F 575 + 9 m; D, E – *Pachydiscus (Pachydiscus) neubergicus* (von Hauer), lateral views, x 1; *ex-situ* between G 595 and G 610, M.-G. Schulz Collection, Ma13688 (D); *in-situ* G 615, K. Esser Collection, PIW2003VII2 (E); F – *Acanthoscaphites (Acanthoscaphites) tridens* (Kner) forma trispinosus-trinodosus, lateral view of a near-complete body chamber of a macroconch, x 1, mB 628 +1 m, M.-G. Schulz Collection, Ma13692



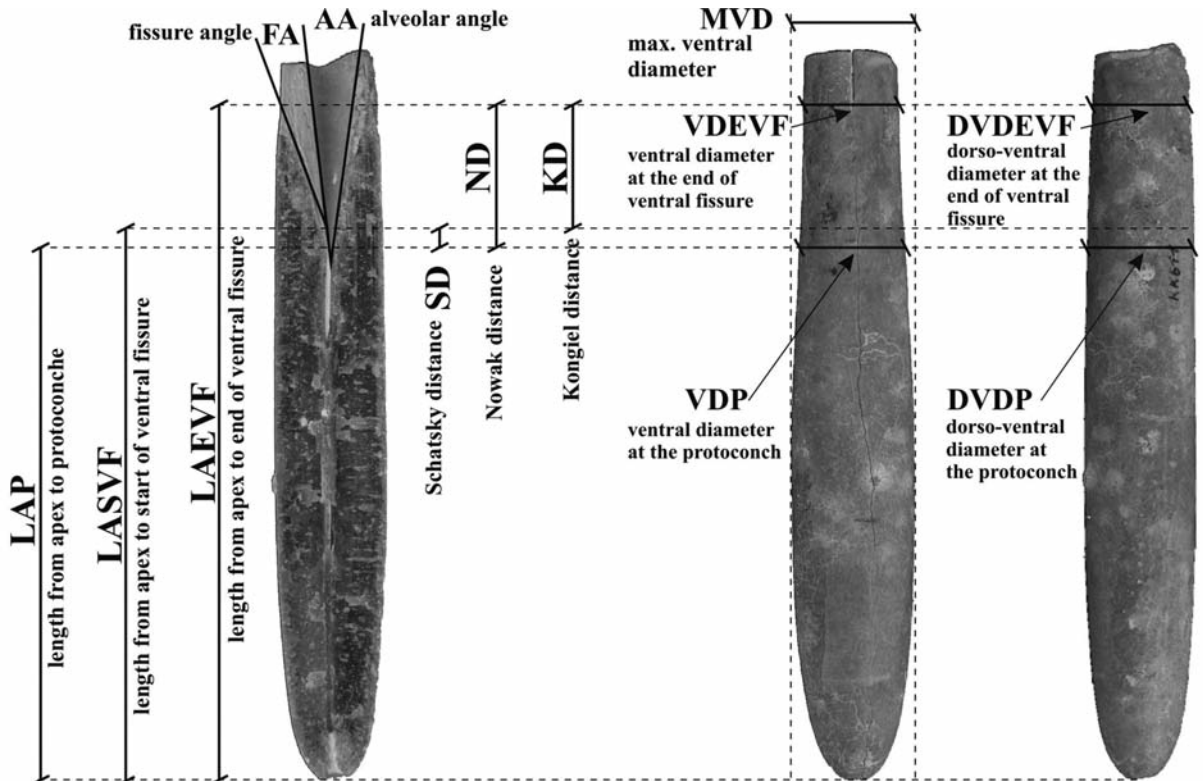
many. At Krons Moor, the lower limit of this species is documented by three specimens from c. + 4 m (= c. 160 ky) above the FO of *Bn. lanceolata*; one of which is the unquestionable macroconch of this species of Text-fig. 3B, well comparable to the type material (Niebuhr 2003). Thus, *Ho. constrictus* is a Late Campanian species, entering at Krons Moor c. 7 m (= c. 285 ky) prior to the internationally accepted Campanian–Maastrichtian boundary.

Nostoceras hyatti, whose LO defines biohorizon 2 in the boundary definition of the GSSP at Tercis (Odin and Lamaurelle 2001, fig. 8), is not known from Krons Moor, nor from elsewhere in northern Germany. This contrasts with Odin (2001, p. 814), who showed the LO of this species to equate the FO of *Belemnella lanceolata*. The composite mould of *Nostoceras* sp. (Text-fig. 3C), from the *Bt. langei* Zone of Krons Moor (c. 37 m below the FO of *Bn. lanceolata* at F 575 +9 m), shows the same coarse ribbing than the time equivalent nostoceratid ammonites from the spiculitic opoka facies of the Ahlten Formation near Hannover (Niebuhr 2004a), and appears best referred to *No. (Didymoceras) postremum* (Błaszkiwicz, 1980). At Tercis, this species co-occurs with *No. polyplacum* in the Polyplacum 2 Zone below the FO of *No. hyatti* (Küchler and Odin 2001).

BELEMNITE STRATIGRAPHY

All measured belemnites from the M.-G. Schulz Collection have been deposited in the collection of the Geologisch-Paläontologisches Institut und Museum of the Universität Hamburg. For the present paper, belemnites of the genus *Belemnella* (*sensu* Schulz 1979) have been restudied using a new taxonomic and methodological approach (Remin 2008, 2011). Of the entire lot of >800 specimens, only a fraction has been described in detail and precisely located. A total of 377 specimens, all properly labelled and originating from the three lower *Belemnella* zones as recognised by Schulz (1979), i.e., the *Bn. lanceolata*, *Bn. pseudobtusa* and *Bn. obtusa* zones, were subjected to further analyses.

For taxonomic descriptions, a unified and objective biometric procedure has lately been proposed. In order to resolve classificatory problems of belemnites, a powerful tool, the artificial neural networks (AANs; in particular the self-organising Kohonen networks) have been implemented (Remin 2008, 2011). AANs is software or system that is able to “learn” on the basis of a previously collected input data set. The unsupervised self-organising Kohonen algorithm used in the present study has allowed an analysis of the structure of the data input set (the biometric features of the



Text-fig. 4. Terminology and measurements of external and internal features of a belemnite guard (Remin 2008, 2011); two other features, not illustrated here, are: LABVF = length from apex to posteriormost part of ventral fissure; RDBSVF = relative distance of posterior of ventral fissure

guard, consequently the guards), divides it into coherent clusters as well as detecting novelties. In the taxonomic description fifteen direct measurements were used. Additionally, fourteen ratios based on raw data were calculated and used in the Kohonen networks analyses. The primary biometric features are summarised in Text-fig. 4; used ratios are as follows: SD/LAP, ND/LAP, SD/ND, SD/KD, KD/ND, LAP/LASVF, LAP/LAEVF, LASVF/LAEVF, VDP/DVDP, VDEVF/DVDEVF, VDP/MVD, VDEVF/VDP, DVDEVF/DVDP and DVDP/LAP (compare Remin 2011).

Results in belemnite stratigraphy

The exploration of artificial neural networks (the Kohonen network) allows to distinguish nine morphological groups within the genus *Belemnella* (*Bn.*) from Krons Moor, which are understood to be distinct species (Remin 2011). Taxa recognised (Text-fig. 5) are characterised by intraspecific cohesion and statistically significant differences between them. These differences are also emphasised by the different stratigraphic intervals occupied by various species. It is of note that some of the species recognised by Schulz (1979) have turned out to be polymorphic; consequently, the concept of some of his taxa has changed markedly (Remin 2011), as well as their stratigraphic ranges. This holds also true for the subgenera *Belemnella* (*Bn.*) and *Pachybelemnella* (*Pb.*) of Schulz (1979). This subgeneric subdivision is different from the one which results from the new procedure, which is why no subgeneric taxa are used in the present paper.

Belemnella lanceolata (von Schlotheim, 1813) *sensu* Remin (2011) includes specimens that were previously classified by Schulz (1979) as *Bn. (Bn.) lanceolata*, *Bn. (Bn.) longissima*, *Bn. (Pb.) desnensis* and most species covered by his wide concept of *Belemnella (Pb.) inflata* (see Text-fig. 5F).

Belemnella longissima Schulz, 1979 *sensu* Remin (2011) includes the holotype (see Text-fig. 5A) and the majority of individuals of this species distinguished by Schulz (1979). Single specimens of three other species recognized by Schulz (1979), *Bn. (Bn.) lanceolata*, *Bn. (Pb.) inflata* and *Bn. (Pb.) desnensis*, are also included in this species.

Belemnella inflata (Arkhangelsky, 1912) *sensu* Remin (2011) consists almost exclusively of individuals of *Bn. (Pb.) inflata sensu* Schulz (1979). Single specimens were previously assigned by Schulz (1979) to *Bn. (Pb.) desnensis*. Representatives of *Bn. inflata sensu* Remin (2011) are consistent with the original diagnosis of this species (see Text-fig. 5F).

Belemnella spp. A and C of Remin (2011) include specimens previously referred by Schulz (1979) almost exclusively to his wide concept of *Bn. (Pb.) inflata* (see Text-fig. 5B, E).

Belemnella sp. I of Remin (2011) includes representatives of three species, assigned previously by Schulz (1979) to *Bn. (Pb.) inflata*, *Bn. (Pb.) pseudobtusa* and *Bn. (Pb.) obtusa* (see Text-fig. 5H).

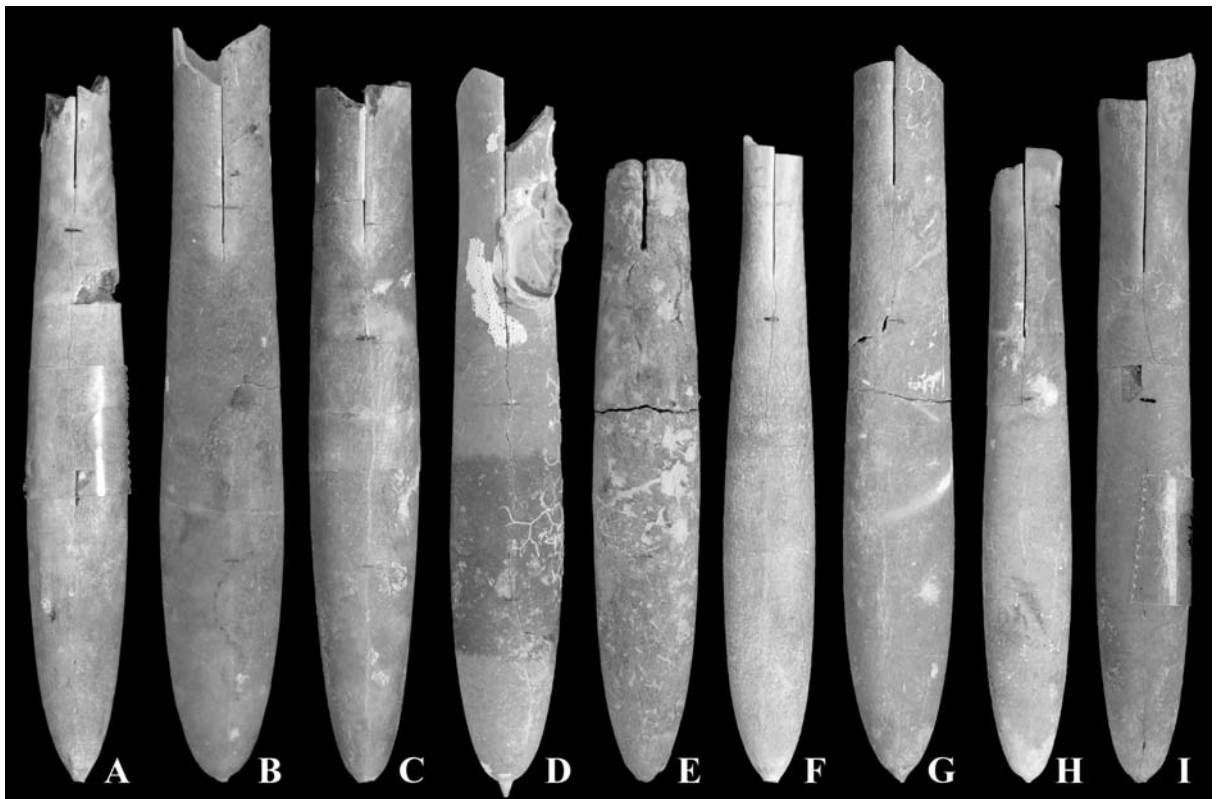
Belemnella obtusa Schulz, 1979 (*sensu* Remin 2011) includes most representatives of *Bn. (Pb.) obtusa* of Schulz (1979); however, single specimens here assigned to this species were earlier assigned to *Bn. (Pb.) inflata* and *Bn. (Pb.) pseudobtusa*. *Bn. obtusa sensu* Remin (2011) includes also the holotypes of *Bn. (Pb.) obtusa* (see Text-fig. 5I) and *Bn. (Pb.) pseudobtusa*.

Belemnella spp. F and G of Remin (2011) include exclusively representatives of the widely understood *Bn. (Pb.) obtusa* of Schulz (1979) (see Text-fig. 5C, D).

These re-examinations have allowed to distinguish five intervals based on the genus *Belemnella* at Krons Moor, all defined by their lower boundaries. The Upper Campanian is represented by the new *Bn. lanceolata* and *Bn. inflata* zones, while the Lower Maastrichtian is represented by the *Bn. obtusa* Zone which can be further subdivided into three subzones (*Belemnella* sp. I, *Belemnella* sp. G and *Belemnella* sp. F; see Text-fig. 6). Above +20 m no data are available, which means that the *Bn. sumensis* Zone above +28 m can be left as defined by Schulz (1979).

The Upper Campanian *Bn. lanceolata* interval Zone: The base of this zone is defined by the FO of the index taxon *Belemnella lanceolata* and/or the near-isochronous FO of *Belemnella longissima*, while the upper boundary of this zone is defined by the FO of the *Belemnella inflata sensu* Remin (2011). The lower boundary equates with flint layer F 600 (= 0 m level); the upper being drawn at the G 604 level (+4 m). The new *Bn. lanceolata* Zone corresponds to the lower part of the *Bn. lanceolata* Zone *sensu* Schulz (1979).

The Upper Campanian *Bn. inflata* interval Zone: The base of this zone is defined by the FO of the index taxon *Belemnella inflata sensu* Remin (2011) and/or the isochronous FOs of *Belemnella* sp. A and *Belemnella* sp. C. *Belemnella longissima* is also known from this zone, the upper boundary of which is defined by the FO of *Belemnella* sp. I and/or near-isochronous FO of *Belemnella obtusa sensu* Remin (2011). However, in the Krons Moor section there is an interval between +9 m and +11 m without belemnite record. Thus, this boundary is drawn at the +10 m level between the last *Bn. inflata* and the first *Belemnella* sp.



Text-fig. 5. The nine species of the genus *Belemnella* recognised in the Kronsmoor section (compare Remin 2011). A – *Belemnella longissima* Schulz, holotype, KK 408, mB 606 +0.6 m, described and figured as *Belemnella (Belemnella) longissima* by Schulz (1979: 98, pl. 2, figs. 3, 4); B – *Belemnella* sp. A, KK 704, mB 606 +2.2 m, described as *Belemnella (Pachybelemnella) inflata* (Archangelsky) by Schulz (1979: 107); C. *Belemnella* sp. G, KM 511, G 620 – 6 to 7 m, described as *Belemnella (Pachybelemnella) obtusa* by Schulz (1979: 114); D – *Belemnella* sp. F, KM 829, G 615 +2.5 m, described as *Belemnella (Pachybelemnella) obtusa* by Schulz (1979: 114); E – *Belemnella* sp. C, KK 521, mB 607 ±0.3 m, described as *Belemnella (Pachybelemnella) inflata* (Archangelsky) by Schulz (1979: 107); F – *Belemnella lanceolata* (von Schlothheim), KK 007, G 604 +0.7 m, described as *Belemnella (Pachybelemnella) inflata* (Archangelsky) by Schulz (1979:107); G – *Belemnella inflata* (Archangelsky), KK 010, mB 605 -0.3 m, described as *Belemnella (Pachybelemnella) inflata* (Archangelsky) by Schulz (1979: 107); H – *Belemnella* sp. I, KM 312, G 615 –0.25 m; described as *Belemnella (Pachybelemnella) obtusa* by Schulz (1979: 114); I. *Belemnella obtusa* Schulz, holotype, KN 810, G 620, described and figured as *Belemnella (Pachybelemnella) obtusa* by Schulz (1979: 114, pl. 9, figs. 3, 4)

I or *Bn. obtusa* (all *sensu* Remin 2011). The new *Bn. inflata* Zone corresponds to the upper part of the *Bn. lanceolata* Zone *sensu* Schulz (1979) between +4 m and +10 m at Kronsmoor.

The Lower Maastrichtian *Bn. obtusa* interval Zone: The FO of the index taxon *Belemnella obtusa* (*sensu* Remin 2011) and the near-isochronous FO of *Belemnella* sp. I at the base of this zone are the belemnite biohorizons which are here proposed for the definition of the base of the Maastrichtian Stage. The upper boundary of this zone is defined by the FO of the successive *Belemnella sumensis* (*sensu* Schulz 1979). The *Bn. obtusa* Zone, as here defined, corresponds to the *Bn. pseudobtusa* and *Bn. obtusa* zones of Schulz (1979), between +10 m and +28 m at Kronsmoor. *Belemnella obtusa* (*sensu* Remin 2011) definitely is present in the interval between +10 and

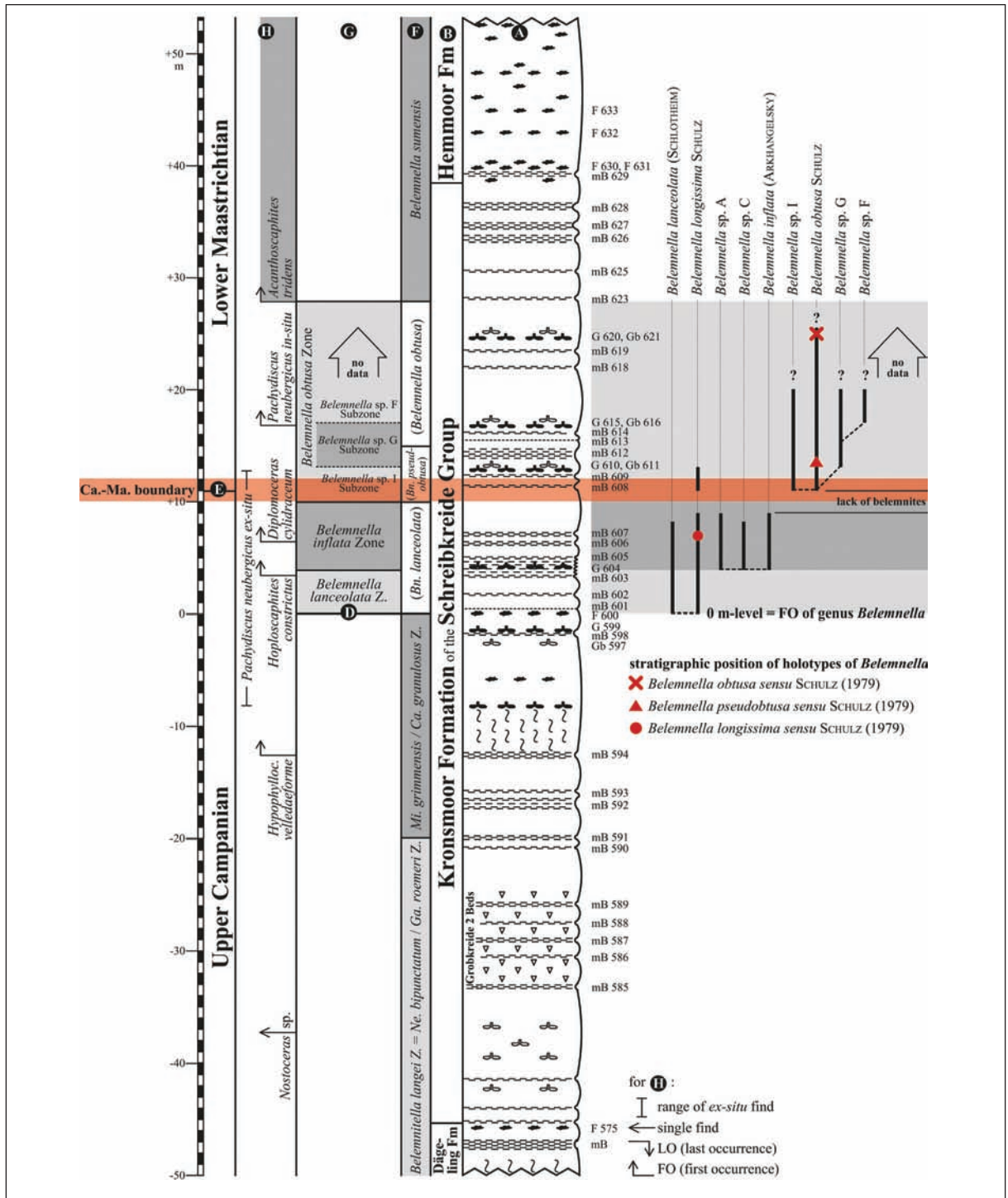
+25 m, because the holotype originates from the G 620 level (see Text-figs 5I, 6); however, for higher levels of the section, there are no belemnite data.

The new *Bn. obtusa* Zone can be subdivided into three subzones. The lower *Belemnella* sp. I Subzone corresponds to the major portion of the *Bn. pseudobtusa* Zone of Schulz (1979), between +10 m and +13 m at Kronsmoor. The upper boundary of this subzone is defined by the FO of the successive *Belemnella* sp. G. At the top of this zone *Belemnella longissima* disappears.

The middle *Belemnella* sp. G Subzone is defined by the FO of the index taxon. *Belemnella* sp. I and *Belemnella obtusa* co-occur. Its upper boundary is defined by the FO of the successive *Belemnella* sp. F. The *Belemnella* sp. G Subzone corresponds to the uppermost part of the *Bn. pseudobtusa* and lowermost

Bn. obtusa zones of Schulz (1979), between +13 m and +17 m at Kronsmoor. The upper *Belemnella* sp. F Subzone is defined by the FO of the index taxon.

Belemnella sp. G, *Belemnella* sp. I and *Belemnella obtusa* co-occur in this subzone, whose upper boundary cannot be precisely defined due to a lack of belemnite



Text-fig. 6. Proposed definition of the belemnite zonation of the genus *Belemnella* for the Campanian–Maastrichtian boundary interval and its comparison to conventional zones of Schulz (1979) at Kronsmoor. For columns A, B, D, E see Text-fig. 2; F – traditional macrofossil stratigraphy (Schulz 1978); G. new *Belemnella* stratigraphy (Remin, present paper); H. ammonite stratigraphy (Niebuhr 2003). Grey areas define the new macrofossil zonation proposed herein; see column C of Text-figs 2, 7

data starting at the +20 to +21 m level. The *Belemnella* sp. F Subzone corresponds to at least the middle part of the *Bn. obtusa* Zone of Schulz (1979) and covers the interval between +17m to and unknown horizon higher up in the Krons Moor section.

The Lower Maastrichtian *Bn. sumensis* / *Ac. tridens* concurrent range Zone: The base of this zone is defined by the FO of *Belemnella sumensis* of Schulz (1979) and the near-isochronous FO of *Acanthoscaphites tridens* forma trispinosus-trinodosus of Niebuhr (2003). It covers the interval above +28 m at Krons Moor and enables the correlation to the Hemmoor section c. 35 km to the southwest (see Text-fig. 1). Its upper boundary is marked by the FO of the successive *Belemnella cimbrica* of Schulz (1979).

BENTHIC FORAMINIFERAL STRATIGRAPHY

Biohorizon 10 for the definition of the base of the Maastrichtian at Tercis (Odin and Lamaurelle 2001, fig. 8) involves the LO of *Gavelinella clementiana* c. 12 ky above the Campanian–Maastrichtian boundary. However, at Krons Moor this species disappears in the lower *Mi. grimmensis* / *Ca. granulosus* Zone c. 16.5 m (Schönfeld 1990; = c. 670 ky) below the FO of *Bn. lanceolata* and c. 1.2 my below the ammonite-based Campanian–Maastrichtian boundary, respectively. For the definition of the Campanian–Maastrichtian boundary as defined by benthic foraminifera in the chalk facies of northern Germany the FO of *Neoflabellina reticulata* (Upper Campanian) and the LO of *Neoflabellina praereticulata* (Lower Maastrichtian) are suitable: these species have a c. 12 m thick overlap in their ranges at Krons Moor, from the base of the *Bn. lanceolata* Zone to the top of the *Belemnella* sp. I Subzone of the *Bn. obtusa* Zone (see Text-fig. 7; compare Weiss in Niebuhr 2004b).

The LO of *Neoflabellina rugosa* is clearly situated in the upper *Bt. langei* Zone (Schönfeld 1990) and, therefore, not suitable as a foraminiferal Campanian–Maastrichtian boundary marker in boreholes in northern Germany (see Koch 1977). The c. 4 m thick overlap of *Nf. rugosa* and *Bolivinooides delicatulus regularis* at the top of the Grobkreide 2 Beds 23–27 m below the FO of *Bn. lanceolata* at Krons Moor equates with the *Ne. bipunctatum* / *Gt. roemeri* Zone of the spiculitic opoka facies of the Ahlten Formation near Hannover (Niebuhr et al. 1997; Niebuhr 2006).

Further stratigraphically relevant benthic foraminiferal events for correlation with the chalk succession in England are *Gavellinella monterelensis* and *Angulogavelinella bettenstedt*. *Ga. monterelensis* is a Late Cam-

panian marker in English boreholes (Bailey in Wood et al. 1994); however, it extends into the Early Maastrichtian *Belemnella* sp. F Subzone of the *Bn. obtusa* Zone at Krons Moor, c. 18 m above the FO of *Bn. lanceolata* (Schönfeld 1990) and c. 7 m above the internationally accepted Campanian–Maastrichtian boundary. In contrast, *An. bettenstedti* is characteristic of the Lower Maastrichtian benthic foraminifera Zone B6i of Swiecicki (1980; Bailey in Wood et al. 1994). According to Schönfeld (1990), it appears at Krons Moor between –18.7 m (basal *Mi. grimmensis* / *Ca. granulosus* Zone) and +33.5 m (lower *Bn. sumensis* / *Ac. tridens* Zone).

NANNOFOSSIL STRATIGRAPHY

Standard calcareous nannofossil smear slides were prepared from the same samples used for stable C and O isotope analyses using the technique outlined in Bown and Young (1998). Nannofossil assemblages were logged semi-quantitatively from two traverses of the slide. The data generated in the present study have been combined and interpreted along with the dataset generated from the Krons Moor section by Burnett (in Hancock et al. 1993). The UC nannofossil zonation of Burnett et al. (1998) has been applied. This scheme builds on previously published schemes (principally Roth 1978; Sissingh 1977, 1978; Perch-Nielsen 1979, 1983, 1985) in an attempt to provide a globally applicable zonation that also respects endemic, shelfal and oceanic variations. This zonation also attempts to calibrate the nannofossil stratigraphy with macrofossil zonation and stage boundaries.

Results in nannofossil stratigraphy

The distribution of stratigraphically significant taxa recorded from the Krons Moor section identified in the combined dataset is as follows:

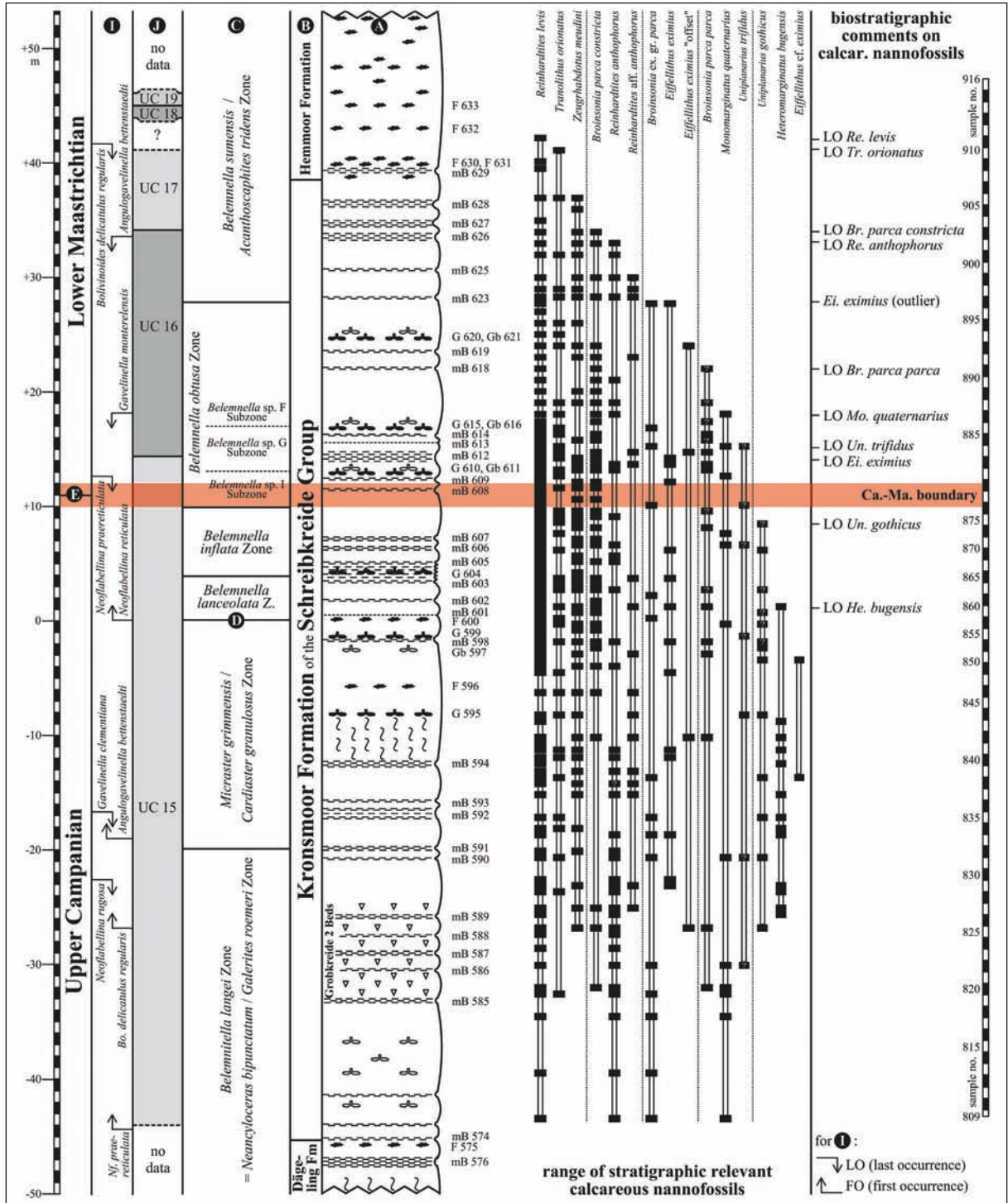
- LO of *Reinhardtites levis* at +44 m
- LO of *Tranolithus orionatus* at +41 m
- LO of *Broinsonia parca constricta* at +34 m
- LO of *Reinhardtites anthophorus* at +33 m
- LO of *Eiffellithus eximius* (“outlier”) at +24 m
- LO of *Broinsonia parca parca* at +22 m
- LO of *Monomarginatus quaternarius* at +18 m
- LO of *Uniplanarius trifidus* at +15 m
- LO of *Eiffellithus eximius* at +14 m
- LO of *Uniplanarius gothicus* at +8.5 m
- LO of *Heteromarginatus bugensis* at +1 m

The UC zonal interpretation of the Krons Moor data is plotted in Text-fig. 7 along with the distribution of stratigraphically important taxa.

INTEGRATED STRATIGRAPHY OF THE KRONSMOOR SECTION (GERMANY)

The UC zonal framework of Burnett *et al.* (1998) holds for this dataset; however, there are some discrepancies with the recognition of subzonal criteria and the calibration with the macrofossil stratigraphy and chronostratigraphy (see Voigt *et al.* 2010, fig. 3). Varia-

tions in the relative positions of subzonal markers in the Upper Campanian and Lower Maastrichtian are discussed in Fritsen *et al.* (1998) and Sheldon (2008), therefore UC subzones have not been applied to this dataset. The calibration between nannofossil events, macrofos-



Text-fig. 7. Calcareous nannofossils of the Kronsmoor section. For columns A-E see Text-fig. 2; I – benthic foraminiferal events (after Schönfeld 1990; Weiss in Niebuhr 2004b); J – new nannofossil zonation, proposed herein

sil stage boundary definition and chronostratigraphy in Burnett *et al.* (1998) is currently being revised (Jackie A. Lees, *pers. comm.* 2010). For example, the zonal scheme of Burnett *et al.* (1998) suggests *Broinsonia parca constricta* and *Pachydiscus neubergicus* to be mutually exclusive taxa, despite data published by Burnett (*in* Hancock *et al.* 1993) which identifies an overlap in the range of these taxa. Such an overlap at Tercis is also supported by Gardin *et al.* (2001). At Krons Moor, matrix samples of both specimens of *Pachydiscus neubergicus* (see Text-fig. 3D, E) and bulk sediment samples between –32 m (Upper Campanian) and +33 m (Lower Maastrichtian) contain *Broinsonia parca constricta*, *Reinhardtites anthophorus* and *Reinhardtites levis*, confirming this interpretation.

At Krons Moor, the LO of *Eiffellithus eximius* is at +14 m, within the *Bn. obtusa* Zone of Remin (the present paper). Therefore, the Campanian–Maastrichtian boundary as defined in the Krons Moor section lies close to the top of nannofossil Zone UC15. However, the zonal scheme of Burnett *et al.* (1998) suggests that this is an intra-Late Campanian event (intra-*Mi. grimmensis* / *Ca. granulatus* Zone; see Voigt *et al.* 2010). The “anomalously” high occurrence of *Ei. eximius* in the Krons Moor section has previously been discussed (Schönfeld and Burnett 1991; Burnett *et al.* 1992) where sporadic occurrences in material younger than its usual LO were interpreted as rendering this taxon unreliable in Boreal settings. In addition, specimens of *Reinhardtites anthophorus* are also recorded high. Similarly, high occurrences of *Ei. eximius* and *Re. anthophorus* are recorded from Denmark (Sheldon 2008), the North Sea Central Graben Chalks (Hampton and Gallagher *in* Fritsen *et al.* 1998; Hampton and Gallagher *in prep.*) and Norfolk (Trunch borehole and Norfolk coastal sections, Hampton and Gallagher *in prep.*). Examples of specimens informally referred to *Ei. eximius* “off-set” and *Eiffellithus* sp. 2 are also known from Central Graben data sets (Gallagher and Hampton *in prep.*). The morphological variation of eiffellithids has recently been discussed in detail by Shamrock and Watkins (2009) and new species concepts described for members of the *Ei. eximius*-plexus based on minor morphological variations. Interrogation of the published raw datasets from Tercis in Odin (2001) also reveals stratigraphically high occurrences of these taxa (Text-fig. 8), which appear to have been discounted in the final interpretations.

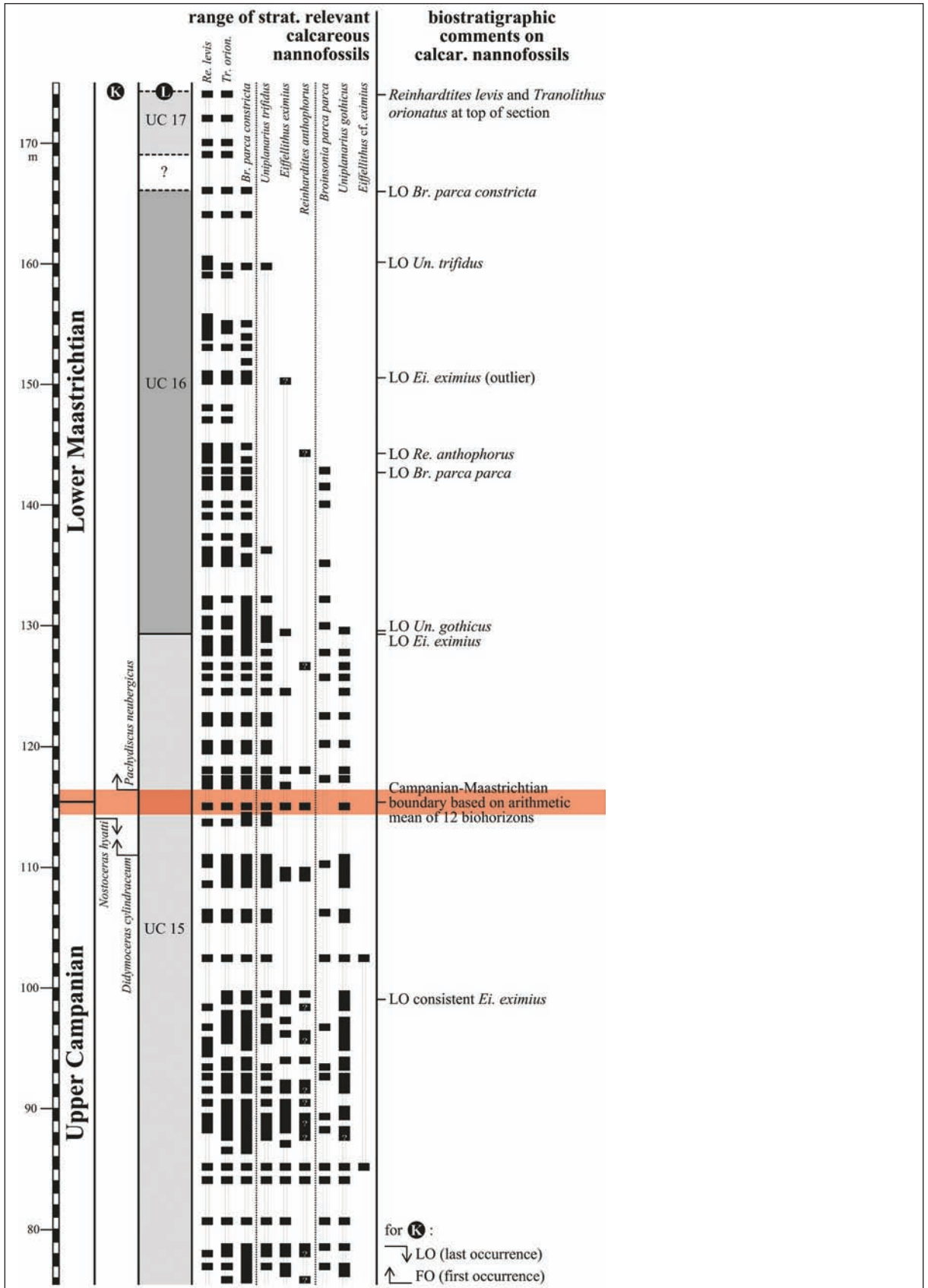
The sporadic occurrence of a species towards the top of its range may be due to a number of factors in-

cluding reworking, time spent analysing the sample, variations in sedimentation rate (either diluting or concentrating the flora), sampling interval, preparation techniques or diagenetic / taphonomic effects. Therefore, an interpreted last occurrence of a species may variably represent a point between its true extinction event and the last consistent occurrence. Thus stratigraphic precision may be difficult when using sporadic occurrences. Alternatively, the LOs of *Eiffellithus eximius* and *Reinhardtites anthophorus* in the Burnett *et al.* (1998) scheme may represent its last “consistent” occurrence. However, deterministic interpretations alone suggest a degree of repeatability in the high occurrences of these taxa in the Krons Moor and Tercis datasets, which may not, in fact, be “anomalous” in Boreal sections. Further work using ranking and scaling techniques on datasets from a number of Boreal sections is ongoing in order to ascertain a ranked sequence of events and their reliability in Boreal settings.

The Krons Moor sequence places *Reinhardtites anthophorus* morphotypes above *Broinsonia parca parca* and *Eiffellithus eximius*. This is consistent with the observations in Fritsen *et al.* (1998) from the North Sea Central Graben chalks and specimens of *Re. anthophorus* are not used to define Zone UC15 herein. The LO of *E. eximius* is used to pick top Zone UC15 and at both Tercis and Krons Moor this event is either above or near the level of the Campanian–Maastrichtian boundary. Therefore, this boundary lies at, or within, Zone UC15. This is contrary to data from published sections from the northern Tethyan Realm (Navarra, Spain; Nagoryanŭ, Ukraine; Neuberg, Austria; Bjala, Bulgaria), where the local FOs of *Pachydiscus neubergicus* and, therefore, the base of the Maastrichtian are situated in Zone UC16 or younger (Wagreich *et al.* 2003). The evidence presented herein also suggests that *Ei. eximius* ranges into the *Bn. obtusa* Zone (contrary to the intra *Mi. grimmensis* / *Ca. granulatus* Zone implied by Burnett *et al.* 1998). The interpreted LO of *Ei. eximius* at Krons Moor (+14 m) occurs close to the proposed Campanian–Maastrichtian boundary in this section (Text-fig. 7). At Tercis, the raw data suggest regular, conspicuous occurrences of *Ei. eximius* at, and below, 118 m, with rare and sporadic occurrences up to 129 m (Text-fig. 8). On this evidence the top of Zone UC15 also occurs close to the GSSP of the base of the Maastrichtian at Tercis (arithmetic mean at 115.2 m).

The LO of *Broinsonia parca constricta* at Krons Moor (+34 m) is an intra-Early Maastrichtian event

INTEGRATED STRATIGRAPHY OF THE KRONSMOOR SECTION (GERMANY)



and defines the top of Zone UC16. At Krons Moor this occurs within the lowermost *Bn. sumensis* / *Ac. tridens* Zone. According to these data there is a >23 m thick overlap in the ranges of *Br. parca constricta* and *Pachydiscus neubergicus* at Krons Moor which compares with a c. 50 m overlap recorded at Tercis (see Text-fig. 8). Within Zone UC16 the LO of *Broinsonia parca parca* at +22 m occurs within the (intra Early Maastrichtian) *Bn. obtusa* Zone, significantly higher than the *Mi. grimmensis* / *Ca. granulatus* event implied by Burnett *et al.* (1998). There is overlap in the occurrence of this taxon with the recorded range of *Pachydiscus neubergicus* at Krons Moor. The raw data from Tercis reveal similarities in the distributions of these taxa with reliable occurrences identified within the range of *Pa. neubergicus*. These taxa have previously been interpreted as mutually exclusive by Burnett *et al.* (1998). The LO of *Reinhardtites anthophorus* at +33 m suggests that this event is an intra Zone UC16 event, supporting observations made by Sheldon (2008) and Gallagher and Hampton (*in Fritsen et al.* 1998).

The LO of *Tranolithus orionatus* at +41 m is taken as evidence for Zone UC17 at this depth within the *Bn. sumensis* / *Ac. tridens* Zone. At Tercis this event occurs at the top of the studied section and therefore the top of this zone cannot be determined. In the Maastrichtian of the North Sea Central Graben this event is rarely recognised above the highest stratigraphic occurrence of *Br. parca constricta*. This may be due to a regional hiatus or the relatively thin development of the zone in that area.

The LO of *Reinhardtites levis* at +42 m is an intra-Early Maastrichtian event although within the *Bn. sumensis* / *Ac. tridens* Zone and corresponds to a level close to the lithostratigraphic boundary between the Hen Moor and Krons Moor formations. This event defines the top of Zone UC18 at this depth. The LO of *Re. levis* is believed to lie above the exposed quarry section at Tercis.

In addition, there are a number of events that are not possible to compare, primarily because they are not recognised in both sections, or, show variations in their relative stratigraphic positions. The LO of *Monomarginatus quaternarius* occurs within the *Bn. obtusa* Zone at Krons Moor, however, this Boreal / high-latitude marker species was not recorded at Tercis. The same is true for *Heteromarginatus bugensis*, its LO is situated at +1 m at Krons Moor within the Upper Campanian *Bn. lanceolata* Zone.

The LO of *Uniplanarius trifidus* and *Un. gothicus* are recorded at Krons Moor at +15 m and +8.5 m, respectively. They are recorded only rarely and sporad-

ically, and, significantly lower in comparison to their record at Tercis. These taxa are not considered useful markers in Boreal sediments due to their Tethyan affinities and also display variations in their range according to position on the shelf or in oceanic settings. Despite the suggestion that *Un. trifidus* is biohorizon 12 and serves as the nearest nannofossil proxy for the Campanian–Maastrichtian boundary (Gardin *et al.* 2001), it is not recommended that it be used to help determine placement of this boundary due to latitudinal and palaeoenvironmental controls on its distribution. The last consistent occurrence of *Ei. eximius* was not recorded in the Krons Moor samples and this event may occur in samples older than those studied. Consistent *Ei. eximius* are recorded in the Tercis datasets.

With the exception of endemic taxa (such as *Uniplanarius* spp., *Monomarginatus quaternarius*) it is possible to compare and correlate nannofossil events between Krons Moor and Tercis using cosmopolitan taxa such as *Broinsonia parca constricta* and *Eiffelolithus eximius*. The LO of *Ei. eximius* appears to be located close to the boundary in both sections (although there are some younger “outliers”). The presence of Boreal / high-latitude taxa such as *Mo. quaternarius* and *He. bugensis* in the Krons Moor data, while absent from the Tercis dataset may suggest that Tercis was outside of the influence of Boreal nannofossil taxa at this time.

The raw data from the Krons Moor and Tercis sections imply differences in the calibration between the nannofossil events, macrofossil zonation and stage boundary positions as illustrated in Burnett *et al.* (1998). Further work is needed to determine whether this is due to miscalibration or extended ranges of some stratigraphically significant taxa in Boreal shelfal settings.

CONCLUSIONS

Results of detailed multistratigraphic analyses of the Campanian–Maastrichtian boundary section at Krons Moor (northern Germany) are summarised and calibrated with the GSSP at Tercis les Bains (south-west France). Further markers for the definition of the boundary in the Boreal Realm are proposed. All data were defined with respect to the traditional subdivision and bed numbers of the “standard section for the Upper Cretaceous white chalk of NW Germany” (Schulz 1978; Schulz *et al.* 1984). A detailed carbon isotope curve around the Campanian–Maastrichtian boundary in chalk facies of the Boreal epicontinental sea, without any sedimentary gaps, is presented. The C isotopic GSSP marker for global correlation is the

markedly abrupt decrease of c. 0.7 ‰ $\delta^{13}\text{C}$ directly at the ammonite-defined Campanian–Maastrichtian boundary. The Upper Campanian shows an arithmetic mean of c. 2.1 ‰ $\delta^{13}\text{C}$ and the Lower Maastrichtian a mean of c. +1.4 ‰ $\delta^{13}\text{C}$. In electronic borehole measurements the Krons Moor section covers the SP peaks 53 to 64 of Baldschuhn and Jaritz (1977) and the base of the Maastrichtian is located just below SP peak 60. The FO of the ammonite *Pachydiscus neubergicus*, biohorizon 1 out of twelve such horizons for the definition of the base of the Maastrichtian at Tercis, is situated in the upper part of the nannofossil Zone UC15. This holds true for both Tercis and Krons Moor. Both localities document the oldest (local) appearance of *Pachydiscus neubergicus* of the northern Tethyan Realm (Spain, Ukraine, Austria, Bulgaria; see Wagreich *et al.* 2003). Biohorizon 3 is the FO of the ammonite *Diplomoceras cylindraceum*, appearing in the Upper Campanian of Tercis and, in Krons Moor, significantly above the FO of *Belemnella lanceolata*, the conventional Boreal belemnite marker for the base of the Maastrichtian Stage (compare Schulz 1979). On ammonite evidence, the internationally accepted base of the Maastrichtian Stage is recorded at Krons Moor between the FOs of *Di. cylindraceum* (Upper Campanian) and *Pa. neubergicus* (Lower Maastrichtian) c. 11 m above the flint layer F 600. The ammonite *Hoploscaphites constrictus* was not selected to locate the level of the GSSP at Tercis; however, at Krons Moor, its lower limit is well documented in the Upper Campanian, appearing c. 285 ky below the boundary.

Associated with flint layer F 600 is the FO of the belemnite genus *Belemnella*, in particular *Bn. lanceolata* (see Schulz 1978). This is an Upper Campanian species, appearing c. 450 ky prior to the ammonite-defined boundary. The FO of *Belemnella pseudobtusa* (*sensu* Schulz 1979) and *Belemnella obtusa* (*sensu* Remin 2011) directly at the boundary can be used as the belemnite marker for the definition of the base of the Maastrichtian Stage in the Boreal Realm.

Biohorizon 10 at Tercis is the LO of the benthic foraminifer *Gavelinella clementiana* c. 12 ky above the Campanian–Maastrichtian boundary. However, at Krons Moor, this species disappears within the Upper Campanian *Mi. grimmensis* / *Ca. granulosus* Zone (Schönfeld 1990) c. 1.2 my below the ammonite-defined Campanian–Maastrichtian boundary. For the definition of the boundary by benthic foraminifera in the chalk facies of northern Germany the LO of *Neoflabellina praereticulata* is suitable. This species disappears in the lower part of the Early Maastrichtian *Bn. obtusa* Zone (newly defined herein), close to the boundary.

Biohorizon 12 is *Uniplanarius trifidus*; however, this nannofossil is rare at Krons Moor and occurs only sporadically and significantly lower in comparison to Tercis. Despite the suggestion that this is the nearest nannofossil proxy for the Campanian–Maastrichtian boundary, it is not recommended that it be used to help determine the position of the boundary due to latitudinal and palaeoenvironmental controls on its distribution. It is possible to compare and correlate nannofossil events between Krons Moor and Tercis using cosmopolitan taxa such as *Broinsonia parca constricta* and *Eiffellithus eximius*. The last occurrence of *Ei. eximius* appears to be located just above the boundary in both sections and, therefore, the top of nannofossil Zone UC15 is of Early Maastrichtian age. The presence of Boreal / high-latitude taxa such as *Monomarginatus. quaternarius* and *Heteromarginatus bugensis* in the Krons Moor data, while absent from the Tercis dataset, may suggest that Tercis was outside of the influence of Boreal nannofossil taxa at this time.

Acknowledgements

We thank J.W.M. Jagt (Natuurhistorisch Museum Maastricht) and M. Machalski (Polska Akademia Nauk, Instytut Paleobiologii, Warszawa) for constructive reviews. W. Weiss (BGR, Hannover) and K. Esser (Ellerau) is thanked for joint fieldwork and J.A. Lees (Dept. Earth Sciences, University College London) for discussion of the calcareous nannofossils. One of the authors (Z.R.) acknowledges the Polish Ministry of Science and Higher Education for the financial support during belemnite study (grant no. 2 P04D 020 27).

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