Calcareous nannofossils from the upper Campanian–Maastrichtian (Upper Cretaceous) in the Kladorub Formation (Kula tectonic zone, NW Bulgaria)

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Abstract. A detailed investigation into the calcareous nannofossils from the upper Campanian–Maastrichtian deposits of the Kladorub Formation (NW Bulgaria) has been carried out in order to examine their taxonomic content and test the applicability of cosmopolitan zonation schemes for this stratigraphic interval in the country. The Kladorub Formation is composed of silty to fine-sandy marlstones and rare marly limestones, occasionally interbedded with sandstone layers. The recovered nannofloras are abundant, taxonomically diverse and exhibit predominantly moderate preservation, which allowed precise taxonomic identifications and biostratigraphic analysis to be made. As a result, the presence of two previously undocumented, biostratigraphically significant taxa has been recorded (i.e., *Eiffellithus parallelus* and *Ceratolithoides kamptneri*). Consequently, the studied Upper Cretaceous sediments have been assigned to subzone UC15d^{TP} (*pars.*)–subzone UC20d^{TP}; in the uppermost 2 m of the section, the presence of zone NP1 has also been indicated, which is in concordance with previous authors' data. Due to the lack of proper chronostratigraphic framework for the Kladorub Formation, top *Uniplanarius trifidus* and base *Lithraphidites quadratus* have, respectively, been used to approximate the Campanian/Maastrichtian and lower/upper Maastrichtian boundaries. The Cretaceous/Palaeogene boundary, however, could not be drawn with precision, because it falls within a 6.5-m interval of non-exposure. The resulting biostratigraphic framework offers higher stratigraphic resolution than previously used local zonation schemes and allows correlation with coeval sedimentary successions from other parts of the Tethyan and Boreal realms.

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INTRODUCTION

The Upper Cretaceous Series in the Kula tectonic zone (NW Bulgaria; Fig. 1) has long posed a challenge to researchers due to the almost ubiquitous lack of exposures. To date, only a small number of limited outcrops are known, mainly nigh the town of Kula and in the vicinity of Lake Rabisha. Information about the distribution, lithology and stratigraphy of Upper Cretaceous strata has come primarily from subsurface data obtained through numerous exploratory oil-wells drilled between the 1960s and the 1980s. In these boreholes, however,

Upper Cretaceous deposits were drilled almost entirely without core recovery and, in addition, recovered microfossils were largely rare and too poorly preserved to allow precise bio- and/or chronostratigraphic subdivisions (e.g., Valkov, 1977; Monova and Ivanov, 1982; Peycheva and Parvanova, 1989). Thus, age assignments have often been based solely on lithologic comparisons with adjacent boreholes.

In current Bulgarian literature, the Upper Cretaceous in this part of the country is associated with Albian–Cenomanian clay-carbonate deposits transgressively overlain by ‘Turonian–Senonian’ thick, flysch-like successions (V. Tzankov *et al.*, 1960,

Fig. 1. Location of section Kladorub, shown on the tectonic map of Bulgaria (after Ivanov, 1983, 1998, 2017; simplified), with crop and subcrop occurrences of Upper Cretaceous rocks (after Dabovski *et al.*, 2009).

1963; Tz. Tzankov, 1961, 1963a, b, 1964, 1972; Vrablyanski and Popov, 1962; Vaptzarova, 1963, 1965a, b, 1974, 1975a, b, 1976a, b, 1978; Tzankov, 1968; Nachev and Sultanov, 1980; Cheshitev *et al.*, 1989; Nachev and Yanev, 1991; Decheva *et al.*, 1995; Filipov *et al.*, 1995; Haydoutov *et al.*, 1995; Angelov and Dobrev, 2006a, b, c, d, e; Angelov *et al.*, 2006; Dobrev, 2006; Dobrev and Angelov, 2006; Dabovski, 2009; Dabovski *et al.*, 2009; Sinnyovsky, 2009), which laterally transition into Cenomanian–Danian limestone-marlstone sediments towards the Moesian Platform (Dabovski, 2009; Dabovski *et al.*, 2009). V. Tzankov (1972) combined the Albian–Cenomanian clay-carbonate strata into his ‘Rabiša Komplex’ (formalized as the Rabisha Formation by Nikolov and Ruskova, 1993) and described the overlying flysch-like sediments as

‘Kula Komplex’ (formalized as the Kula Formation by Filipov *et al.*, 1995). Additionally, he introduced a third complex (‘Kladorub Komplex’, later formalized as the Kladorub Formation by Filipov *et al.*, 1995) encompassing a ~200-m thick, Maastrichtian in age, succession of grey to grey-greenish silty marlstones exposed in the vicinity of Kladorub Village (Vidin District). Tz. Tzankov (1972) based his age assignments on previously published rare finds of ammonites, inoceramid bivalves and planktonic foraminifera (V. Tzankov *et al.*, 1960; Tz. Tzankov, 1961, 1964, 1972; Vrablyanski and Popov, 1962; V. Tzankov, 1968). However, more recent studies, based on calcareous nannofossils and planktonic foraminifera, have shown that the stratigraphic extent of the Rabisha Formation reaches up to at least the uppermost Turonian (Granchovski, 2013), where-

as the Kladorub Formation embraces the interval from the upper Campanian to the lower Eocene (Sinnyovsky and Petrov, 2000; Sinnyovsky *et al.*, 2002; Sinnyovsky, 2003, 2004, 2007, 2013a, 2015; Stoykova and Ivanov, 2005; Stoykova *et al.*, 2005, 2006; Valchev and Juranov, 2006; Stoykova, 2007). Furthermore, as heeded by Granchovski (2015), the definitions of some of the Upper Cretaceous stage boundaries in the region are outdated and imprecise. Thus, it is apparent that new investigations are needed to better understand the stratigraphy of the Upper Cretaceous sediments in NW Bulgaria.

In the last two decades, several papers involving or dedicated to Upper Cretaceous calcareous nannofossil biostratigraphy in the Kula Zone have emerged (Harkovska *et al.*, 1999; Sinnyovsky and Petrov, 2000; Sinnyovsky *et al.*, 2002; Sinnyovsky, 2003, 2004, 2007, 2011, 2013a, b, 2015; Stoykova, 2007; Stoykova *et al.*, 2010; Granchovski, 2012, 2013, 2015, 2017; Sinnyovsky and Pavlishina, 2014). However, the majority of these (*i.e.*, Sinnyovsky and Petrov, 2000; Sinnyovsky *et al.*, 2002; Sinnyovsky, 2003, 2004, 2007, 2011, 2013a, b, 2015; Sinnyovsky and Pavlishina, 2014) rely on local zonation schemes, which are often based on obsolete/questionable taxonomic identifications. For instance, Sinnyovsky and Pavlishina (2014) used base *Prediscosphaera cretacea* to define the Albian/Cenomanian boundary in a surface exposure of the Rabisha Formation near Tolovichko Vrelo karst spring, but the two specimens they illustrated (Sinnyovsky and Pavlishina, 2014, Fig. 3k, l) are small, circular to subcircular, with narrow inner-rim cycle, which are actually characteristic features of *Prediscosphaera columnata*. The problem with using these local zonations is further exacerbated by the fact that they do not employ qualitative abundances of taxa, which can lead to discrepancies in biostratigraphic correlation, especially close to extinction events (see Thibault, 2016b).

The present paper is an account on the upper Campanian–Maastrichtian calcareous nannofossils from the type section for the Kladorub Formation (Figs 1–3). The aim of this study is to examine in detail their taxonomic diversity and to assess the applicability of cosmopolitan nannofossil zonations, namely Burnett's (1998) UC scheme.

GEOLOGICAL BACKGROUND AND SECTION

In the sense of current geodynamic models, the sediments of the Kladorub Formation are assumed to have been deposited in the upper bathyal zone

(Stoykova *et al.*, 2006) on the continental slope of a deep-water back-arc basin in the western periphery of the Moesian Platform (Dabovski, 2009; Dabovski *et al.*, 2009). In terms of tectonics, its distribution is confined to the limits of Ivanov's (1983, 1998, 2017) Kula Zone (equivalent to the Kula tectonic unit of Dabovski and Zagorchev, 2009; Fig. 1). This para-autochthonous unit is regarded as a part of the South Carpathian orogenic system (Dabovski and Zagorchev, 2009).

Lithologically, the Kladorub Formation has been described as composed of monotonous grey to grey-greenish indistinctly-bedded clayey-calcareous siltstones, interbedded with a limited number of silty marlstones (Sinnyovsky *et al.*, 2002). Their age has been determined as late Campanian (*pars.*)–Ypresian (*pars.*) (Sinnyovsky and Petrov, 2000; Sinnyovsky *et al.*, 2002; Sinnyovsky, 2003, 2004, 2007, 2013a, 2015; Stoykova and Ivanov, 2005; Stoykova *et al.*, 2005, 2006; Valchev and Juranov, 2006; Stoykova, 2007). Sinnyovsky (2004) claimed that the Kladorub Formation contains the most complete succession across the Cretaceous/Palaeogene boundary (KPgB) in Bulgaria. The KPgB itself is marked by a 2-cm dark layer classified as a clayey-calcareous siltstone (Sinnyovsky *et al.*, 2002). In the upper parts of the unit, the Palaeocene-Eocene Thermal Maximum has been recognized (Stoykova and Ivanov, 2005; Stoykova *et al.*, 2005, 2006).

The fossil content of the Kladorub Formation includes ammonites (rare – V. Tzankov *et al.*, 1960; Tz. Tzankov, 1963, 1964b, 1972), inoceramid bivalves (rare – V. Tzankov *et al.*, 1960; Vrablyanski and Popov, 1962; Tz. Tzankov, 1972), foraminifera (V. Tzankov *et al.*, 1960; Vrablyanski and Popov, 1962; Valchev and Juranov, 2006) and calcareous nannoplankton (Sinnyovsky and Petrov, 2000; Sinnyovsky *et al.*, 2000; Sinnyovsky, 2003, 2004, 2007, 2013, 2015; Stoykova and Ivanov, 2005; Stoykova *et al.*, 2005, 2006; this study).

So far, the lower boundary of the Kladorub Formation has not been observed; in surface exposures, it is tectonic, with the granodiorites of the Belogradchik pluton (Tz. Tzankov, 1972; Filipov *et al.*, 1995; Sinnyovsky and Petrov, 2000; Sinnyovsky *et al.*, 2000; Sinnyovsky, 2003, 2004, 2007, 2009, 2013a, b, 2015; Angelov and Dobrev, 2006c; this study – Fig. 3). Tz. Tzankov (1972) opined that this lithostratigraphic unit overlies the flysch-like deposits of the Kula Formation and, in some areas of their distributions, the two units may even have lateral relations. The upper boundary is transgressive, with the sandstones and conglomerates of the Staropatitsa Formation (Tz. Tzankov, 1972; Filipov *et al.*, 1995; Sinnyovsky and Petrov, 2000; Sinnyov-

Fig. 2. Sediments from the type section for the Kladorub Formation. The stratigraphic succession is overturned, so upper portions of all images correspond to older strata. *a*) Thin-bedded grey to grey-greenish silty marlstones; *b*) sandstone layer sandwiched between laminated silty to fine-sandy marlstones; *c*) limestone layer with nodules; *d*) cleaved marlstones bracketed by sandstone (above) and marly limestone (below) layers; *e*) deformed sandstone layer at the base of a slump; *f*) slump structure.

sky *et al.*, 2000; Sinnyovsky, 2003, 2004, 2007, 2009, 2013a, 2015; Angelov and Dobrev, 2006c; Stoykova, 2007) or with the Rakevtsi wedge of the Krivodol Formation (Stoykova, 2007).

Of all Upper Cretaceous lithostratigraphic units, the Kladorub Formation has the most limited distribution. It has not been recognized in borehole sec-

tions. According to Tz. Tzankov (1972), it crops out only to the south and southwest of Kladorub Village, Vidin District. Stoykova (2007) mentioned an exposure near Rakovitsa Village, Vidin District, but described the sediments as tectonically overprinted and reported only low in abundance, poorly preserved nannofossil assemblages. It is assumed

Fig. 3. Lithostratigraphy, lithology, calcareous nannofossil biostratigraphy and nannofossil events from section Kladorub. Lithostratigraphy after Filipov *et al.* (1995) and Angelov and Dobrev (2006c); biostratigraphy follows Burnett (1998) and Thibault (2016a).

that the sediments of the Kladorub Formation are also developed to the east and northeast of the Kula Zone within the western parts of the Moesian Platform, where sedimentary rocks with the same lithology and analogous age have been penetrated by numerous boreholes (Stoykova, 2007).

In the present study, the stratotype section for the Kladorub Formation was chosen for investigation because: (1) it presents the most complete, continuous succession of the unit; (2) it is the least-affected by tectonics exposure; (3) nannofossil assemblages are reportedly abundant, taxonomically rich and well preserved. It is located approximately 2.5 km to the southeast of Kladorub Village (Fig. 1; N43°42'30"; E22°39'44") and crops out in the valley of a southern tributary of the Archar River. Here, to the southwest of the exposure, the granodiorites of the Belogradchik pluton are thrust over the Kladorub Formation. The stratigraphic succession is tectonically overturned (Sinnyovsky and Petrov, 2000; Sinnyovsky *et al.*, 2000; Sinnyovsky, 2003, 2004, 2007, 2009, 2013a, 2015; Stoykova, 2007; this study). Sedimentary strata are exposed almost exclusively only in the riverbed, dipping to the SSW at a low angle (15°–45°; in some limited intervals, usually in proximity to slumps, they become steeply inclined to subvertical). For the purposes of the present study, only the lowermost 123 m of the succession were investigated.

The Kladorub Formation is predominantly represented by grey to grey-greenish silty to fine-sandy marlstones and rare marly limestones and sandstones (Figs 2, 3). The marlstones are moderately hard, often crumbly. They are mostly indistinctly to very fine- or medium-bedded (2–3 cm to 15–20 cm), laminated. When weathered, they become light grey. The limestones are hard, compact. They occur as infrequent light-grey beds (8–9 cm to 15–16 cm) or, occasionally, as lenses amongst the marlstones. Some of them contain nodules. Sandstones are also rare. They are grey-beige (rusty-grey when altered) and, with the exception of one 22-cm layer 40 m above the tectonic contact with the Belogradchik pluton, their thicknesses vary narrowly from 3–4 cm to 10–11 cm. Interestingly, slump structures, which have not been mentioned by previous authors, were commonly observed. They occur in the upper half of the studied succession and range from 1 m to 3 m in thickness.

MATERIAL AND METHODS

A total of 164 samples, plus one test sample, have been investigated for their nannofossil content.

They were taken almost exclusively with 0.5-m resolution; in a limited interval in the lower parts of the section where exposure was poor, sampling density was decreased to one sample per 1 m. A distinct, 22-cm thick, resistant to weathering sandstone layer in the lower half of the section was used as a reference point and was conditionally numbered as 100; all sample numbers reflect their position above or below its lower surface in metres.

Calcareous nannofossil assemblages were examined in simple smear-slides, made following the methodology described by Bown and Young (1998). They were viewed at 1250× magnification, using an oil-immersion objective lens (×100) on a Zeiss Axioskop 40 transmitting light-microscope. Micrographs were taken with a ProgRes GT3 digital camera in both cross-polarized light (with and without gypsum plate) and plane-polarized light. All images were uniformly enlarged at 2000× magnification in Photoshop and their contrast was increased by 10–15%. Thereafter, they were sharpened, using the following technique: (1) a copy of the background layer, containing the original image, was made; (2) the copy layer was desaturated, lest original colours be altered, and then a High Pass filter was applied to it with a radius of 3–5 pixels; (3) finally, the blending mode of the copy layer was set to Soft Light, its opacity was lowered to 50–60% and all layers were merged into one. All operations in Photoshop were performed on lossless file formats (*i.e.*, TIFFs) in order to prevent loss of image quality.

Relative abundances of the species were estimated semi-quantitatively over four traverses (three central and one random to avoid overlooking rarer taxa) for each slide and the data are presented as a range-chart (see [Table A1](#) in the Appendix). On the chart, abundances are indicated as follows: C = common (1–10 specimens/field of view); F = frequent (one specimen/2–50 fields of view); R = rare (one specimen/51–100 fields of view); VR = very rare (one specimen/traverse); P = present (one specimen/sample); and questionable (? = identification uncertain). Species occurrences interpreted as a result of reworking are indicated with an asterisk (*).

A qualitative estimate of calcareous nannofossil preservation was also made for each sample. It is indicated on the range-chart in [Table A1](#) as: moderate (M = virtually all specimens are identifiable, although the appearance of certain taxa and/or features has been modified by secondary calcite dissolution and/or overgrowth); poor (P = depleted assemblage due to calcite dissolution and/or taxonomic identification of a considerable portion of specimens is thwarted by calcite dissolution or secondary over-

growth); very poor (VP = much of the assemblage is dissolved and/or the majority of specimens are difficult or even impossible to identify). Most of the investigated samples are characterized by moderate preservation.

Taxonomic concepts follow those of Perch-Nielsen (1985) and Burnett (1998), although some more recent works have also been taken into account (Lees and Bown, 2005; Lees, 2007; Shamrock and Watkins, 2009; Thibault, 2010a, b). Full taxonomic descriptions, with authorship, of all taxa mentioned in the text and figures can be found online on *Nannotax3* at <http://www.mikrotax.org/Nannotax3/index.php?dir=Mesozoic>. Burnett's (1998) UC zonation scheme, as supplemented by Thibault (2016a), was applied for biostratigraphic subdivision of the studied sedimentary succession.

Sample material and slides are housed at the Department of Palaeontology, Stratigraphy and Sedimentology of the Geological Institute "Str. Dimitrov" (Bulgarian Academy of Sciences).

RESULTS

A total of 137 species have been identified. Nanofossil preservation varies from very poor to moderate, the latter state being predominant. Small coccoliths (e.g., *Biscutum constans*, *Corollithion? madagaskarensis*, *Prediscosphaera stoveri* and small *Staurolithites* and *Zeugrhabdotus* species) and holococcoliths (*Calculites*, *Lucianorhabdus*, *Octolithus* and *Russelia*, as well as *Lanternithus* in the lowermost Palaeogene) are reasonably well and consistently represented in samples and, in comparison to other species, no excessive concentration of solution-resistant taxa (i.e., *Watznaueria barnesiae* and *Micula staurophora*) was observed. This suggests that, altogether, diagenesis has probably not impacted too deleteriously the assemblages. Per-sample species richness varies between 54 and 97 but most often stays between 70 and 80. Significant and some rarely or never previously reported from the Upper Cretaceous of Bulgaria taxa are illustrated in Figs 4–18. Table A1 shows the semi-quantitative calcareous nanofossil data; the low-latitude part of Burnett's (1998) UC zonation scheme (UC^{TP}), as supplemented by Thibault (2016a) for zone UC16, has been applied to this. On Table A1, stratigraphical ranges of biostratigraphically significant taxa are highlighted, and a summary of the bioevents detected is provided on the right-hand side.

The calcareous nanofossil assemblages are dominated by *Prediscosphaera cretacea* (Fig. 10w, x), *Watznaueria barnesiae* (Fig. 12j), *Micula stauro-*

phora (Figs 16h, 17k–m), *Cribrosphaerella ehrenbergii* (Fig. 9j, k) and *Biscutum constans* (Figs 9y, 10a). Of these, *Prediscosphaera cretacea* is ubiquitously the most abundant (when common, it is represented by 5–8 specimens/field of view, and its abundance never drops below one specimen/2 fields of view), whereas *Watznaueria barnesiae* (1–3 specimens/field of view to one specimen/2–6 fields of view) and *Micula staurophora* (1–2 specimens/field of view to 1 specimen/2–12 fields of view) have somewhat subordinate presence, in comparison. *Prediscosphaera microrhabdulina* (Fig. 11h, i, k) and *Prediscosphaera stoveri* (Fig. 11m, n) are also considerable constituents of the assemblages throughout the studied succession.

The lowermost 10 m of the section proved to be somewhat problematic. Tectonic overprint of the sediments, coupled with very poor exposure, hindered sampling of this interval. At ~2 m above the tectonic boundary with the granodiorites, one test sample was taken from indistinctly-bedded, poorly exposed, fragmented marls. The recovered nanofossils were poorly preserved, with low species richness (29 species). Despite that, reliably identifiable specimens of *Uniplanarius trifidus* and *Eiffellithus eximius* were observed. These two taxa, in the absence of *Eiffellithus parallelus*, indicate subzone UC15d^{TP}, which is consistent with data from the 4 m immediately above the covered interval. However, these marls are herein considered subcrop occurrence and, thus, the test sample is not recorded in Table A1.

The first reliably identifiable specimens of *Eiffellithus parallelus* (Fig. 7j–o) were noted in sample Kl-74 (at 14 m), which draws the boundary between subzones UC15d^{TP} and UC15e^{TP}. The last consistently occurring specimens of *Reinhardtites anthophorus* (Fig. 5c–g) were observed in the same sample; up-section, this species was present in only one sample, Kl-77, very rare in abundance. According to Burnett (1998), top *Reinhardtites anthophorus* indeed falls within UC15e^{TP} at low palaeolatitudes. The consecutive tops of *Lucianorhabdus quadridus* (at 18 m; Fig. 14b, c), *Rucinolithus* spp. (at 18.5 m), *Prediscosphaera arkhangelskyi* (at 34 m; Fig. 10u, v), *Corollithion? madagaskarensis* (at 34.5 m; Fig. 8r–u) and *Staurolithites imbricatus* (at 36.5 m; Fig. 5p, q) were also recorded within subzone UC15e^{TP}.

The last consistent occurrence of *Eiffellithus eximius* (Fig. 7c–g) was detected in sample Kl-98 (at 38 m). Up-section, this taxon is present very sporadically (observed in only eight samples at 40 m, 43.5 m, 59 m, 89 m, 108 m, 110.5 m, 112 m, 112.5 m and 123 m), generally very low in abundance and

Fig. 4. Calcareous nannofossils from section Kladorub (Chiastozygaceae). Scale bar applies to all images. Abbreviations: XPL – cross-polarized light; PPL – plane-polarized light.

Fig. 5. Calcareous nannofossils from section Kladorub (Chiastozygaceae). Scale bar applies to all images. Abbreviations: XPL – cross-polarized light; PPL – plane-polarized light; GP – gypsum plate.

Fig. 6. Calcareous nannofossils from section Kladorub (Chiastozygaceae). Scale bar applies to all images. Abbreviations: XPL – cross-polarized light; PPL – plane-polarized light; GP – gypsum plate.

Fig. 7. Calcareous nannofossils from section Kladorub (Chiastozygaceae, Eiffellithaceae). Scale bar applies to all images. Abbreviations: XPL – cross-polarized light; PPL – plane-polarized light; GP – gypsum plate.

Fig. 8. Calcareous nannofossils from section Kladorub (Eiffellithaceae, Stephanolithiaceae). Scale bar applies to all images. Abbreviations: XPL – cross-polarized light; PPL – plane-polarized light; GP – gypsum plate.

Fig. 9. Calcareous nannofossils from section Kladorub (Stephanolithiaceae, Axopodorhabdaceae, Biscutaceae). Scale bar applies to all images. Abbreviations: XPL – cross-polarized light; PPL – plane-polarized light.

Fig. 10. Calcareous nannofossils from section Kladorub (Biscutaceae, Prediscosphaeraceae). Scale bar applies to all images. Abbreviations: XPL – cross-polarized light; PPL – plane-polarized light; GP – gypsum plate.

Fig. 11. Calcareous nannofossils from section Kladorub (Prediscosphaeraceae, Cretarhabdaceae). Scale bar applies to all images. Abbreviations: XPL – cross-polarized light; GP – gypsum plate.

Fig. 12. Calcareous nannofossils from section Kladorub (Watznaueriaceae, Arkhangelskiellaceae). Scale bar applies to all images. Abbreviations: XPL – cross-polarized light; PPL – plane-polarized light; GP – gypsum plate.

Fig. 13. Calcareous nannofossils from section Kladorub (Arkhangelskiellaceae, Kamptneriaceae, heterococcoliths incertae sedis, holococcoliths). Scale bar applies to all images. Abbreviations: XPL – cross-polarized light; PPL – plane-polarized light; GP – gypsum plate.

Fig. 14. Calcareous nannofossils from section Kladorub (holococcoliths, nannoliths incertae sedis, nannoliths – Braarudosphaeraceae, Microrhabdulaceae). Scale bar applies to all images. Abbreviations: XPL – cross-polarized light; PPL – plane-polarized light; GP – gypsum plate.

Fig. 15. Calcareous nannofossils from section Kladorub (nannoliths – Microrhabdulaceae). Scale bar applies to all images. Abbreviations: XPL – cross-polarized light; PPL – plane-polarized light; GP – gypsum plate.

Fig. 16. Calcareous nannofossils from section Kladorub (nannoliths – Polycyclolithaceae). All images are uniformly enlarged at $\times 2000$ and taken in cross-polarized light.

Fig. 17. Calcareous nannofossils from section Kladorub (nannoliths – Polycyclolithaceae, incertae sedis). Scale bar applies to all images. Abbreviations: XPL – cross-polarized light; PPL – plane-polarized light; GP – gypsum plate.

Fig. 18. Calcareous nannofossils from section Kladorub (nannoliths – Polycyclolithaceae, *Ceratolithoides*). Scale bar applies to all images. Abbreviations: XPL – cross-polarized light; PPL – plane-polarized light; GP – gypsum plate.

poorly preserved, which is why these occurrences are likely to be the result of reworking. The latter assumption is further supported by the presence of slump structures in the upper half of the studied succession. Therefore, the boundary between zones UC15 and UC16 is placed at 38 m. Two metres above the boundary, top *Amphizygus brooksii* (Fig. 4h) was detected.

Top *Uniplanarius trifidus* (Fig. 18e–j) was noted in sample Kl-116 (at 56 m), followed by base *Prediscosphaera mgayae* (at 58 m; Fig. 11f, g), top *Broinsonia parca* subsp. *parca* (at 61 m; Fig. 13a–e) and top *Broinsonia parca* subsp. *constricta* (at 62.5 m; Fig. 13f). The latter event defines top UC16/base UC17. Recently, Thibault (2016a) commented that top *Uniplanarius trifidus* appears to be a highly useful biostratigraphic marker for the Campanian/Maastrichtian boundary in the Tethyan realm and used it to subdivide Burnett's (1998) zone UC16 into two subzones: UC16a^{TP} and UC16b^{TP}. This new subdivision for the Tethyan province has been applied in the present study. Thus, both base *Prediscosphaera mgayae* and top *Broinsonia parca* subsp. *parca* fall within UC16b^{TP}.

The upper boundary of UC17 was drawn at 71.5 m by the last occurrence of *Tranolithus orionatus* (Fig. 5w–y). In the frame of this biostratigraphic unit, three nannofossil events were detected: (1) the concomitant tops of *Uniplanarius gothicus* (Fig. 17s–w) and *Uniplanarius sissinghii* (Figs 17x, y, 18a–d) 50 cm above base UC17; (2) top *Acuturris scotus* (Fig. 13u) at 70 m. Top *Reinhardtites levis* (Fig. 5h–l), which defines the upper boundary of UC18, was noted at 75.5 m.

The first reliably identifiable specimens of *Lithraphidites quadratus* (Fig. 15a–j), the base of which marks top UC19/base UC20, was observed in sample Kl-156 (at 96 m). The interval between top *Reinhardtites levis* and base *Lithraphidites quadratus* (i.e., zone UC19) contains the following five nannofossil events (from oldest to youngest):

- 1) top *Lucianorhabdus cayeuxii* (Fig. 14a) at 85.5 m;
- 2) top *Zeugrhabdotus bicrescenticus* (Fig. 6a, b) at 87 m;
- 3) base *Lithraphidites praequadratus* (Fig. 15f–j) at 92.5 m;
- 4) base *Arkhangelskiella maastrichtiensis* (Fig. 12v–y) at 94 m;
- 5) base *Nephrolithus frequens* (Fig. 9p–r) at 94.5 m.

The consecutive bases of *Micula murus* (Fig. 16k–t), *Ceratolithoides kamptneri* (Fig. 18p–v) and *Micula prinsii* (Figs 16u–y, 17a–g) define the bases of subzones UC20b^{TP}, UC20c^{TP} and UC20d^{TP} at

108 m, 109 m and 113 m, respectively. The last consistently occurring specimens of *Calculites obscurus* (Fig. 13v, w) and *Prediscosphaera mgayae* were noted within UC20a^{TP} in samples Kl-159 (at 99 m) and Kl-160.5 (at 100.5 m). However, it is uncertain whether these reflect their true tops or not, since they were observed in samples taken immediately above a 3-m interval of slumped sediments, where reworking is apparent. Base *Cribrosphaerella daniae* was detected in subzone UC20c^{TP} at 111 m.

In the uppermost 2 m of the studied succession, *Cyclagelosphaera alta* (Fig. 12a–e) is present, which, in the absence of *Crucioplacolithus intermedius*, indicates Martini's (1971) lowermost Danian zone NP1. Due to recent massive landslide processes, the Cretaceous/Palaeogene boundary falls within a 6.5-m interval of non-exposure, buried under a thick layer of soil, and efforts to uncover it have so far been futile. Nevertheless, attempts at removing the soil cover are in progress so that the Cretaceous/Palaeogene boundary can be better constrained.

DISCUSSION

Correlation with local nannofossil zonation schemes for the upper Campanian–Maastrichtian interval

A complete nannofossil zonation scheme for the Upper Cretaceous of Bulgaria was developed by Sinnyovsky (2007, 2013a, 2015). In the upper Campanian (*pars.*)–Maastrichtian interval, Sinnyovsky (2013a, 2015) recognized a total of five zones and six subzones (Fig. 19), mostly based on nannofossil datums also employed by the CC zonation of Sissingh (1977), as modified by Perch-Nielsen (1985), and the UC scheme of Burnett (1998). One of these events, base *Lithraphidites praequadratus*, used by Sinnyovsky (2007, 2013a, 2015) to demarcate the lower boundary of his *Lithraphidites praequadratus* Subzone in the uppermost lower Maastrichtian, is strikingly unreliable because it has been demonstrated to be highly diachronous within the Campanian–Maastrichtian interval in both Bulgaria and elsewhere. Ivanov *et al.* (2007) reported this species from the upper Campanian in the Kraishte Zone (SW Bulgaria) in association with *Eiffellithus eximius* and *Uniplanarius trifidus*. Pérez-Rodríguez *et al.* (2012, Table 3) documented a reasonably consistent stratigraphical range for *Lithraphidites praequadratus* from the upper Campanian UC15e^{TP} to the upper upper Maastrichtian UC20d^{TP} at Zumaia (northern Spain). In the Danish Basin, Thibault *et al.* (2012a) observed its base in the lowermost

Bulgaria (after Sinnyovsky, 2007, 2013a, 2015)			Section Kladorub (present study) UC zones after Burnett (1998) and Thibault (2016a) NP zones after Martini (1971) and Stoykova (2007)		
Danian (<i>pars.</i>)			NP1 (<i>pars.</i>)	base <i>Cyclagelosphaera alta</i> non-reworked Cretaceous taxa	Danian (<i>pars.</i>)
up. Maastrichtian	top <i>Micula prinsii</i> ▼	<i>Micula prinsii</i> Zone	UC20d ^{TP}	▲ base <i>Micula prinsii</i>	up. Maastrichtian
	base <i>Micula prinsii</i> ▲		UC20c ^{TP}	▲ base <i>Ceratolithoides kamptneri</i>	
	base <i>Micula murus</i> ▲	<i>Micula murus</i> Zone	UC20b ^{TP}	▲ base <i>Micula murus</i>	
	base <i>Nephrolithus frequens</i> ▲	<i>Lithraphidites quadratus</i> Zone	UC20a ^{TP}	▼ ?top <i>Prediscosphaera mgayae</i> ▲ base <i>Lithraphidites quadratus</i>	
lower Maastrichtian	base <i>Lithraphidites praequadratus</i> ▲	<i>L. praequadratus</i> Subzone	UC19	▲ base <i>Nephrolithus frequens</i> ▲ base <i>Arkhangelskiella maastrichtiensis</i> ▲ base <i>Lithraphidites praequadratus</i>	lower Maastrichtian
	base <i>Ark. maastrichtiana</i> (common) top <i>Reinhardtites levis</i> (+ top <i>L. cayeuxii</i>)	<i>A. maastrichtiana</i> Subzone		▼ top <i>Zeugrhabdus bicrescenticus</i> ▼ top <i>Lucianorhabdus cayexii</i>	
		<i>R. levis</i> Subzone	UC18	▼ top <i>Reinhardtites levis</i>	
			UC17	▼ top <i>Tranolithus orionatus</i> ▼ top <i>Acuturris scotus</i>	
	top <i>Broinsonia parca constricta</i> ▼	<i>B. parca constricta</i> Subzone	UC16b ^{TP}	▼ top <i>U. gothicus</i> , <i>U. sissinghii</i> ▼ top <i>Broinsonia parca constricta</i> ▲ base <i>Prediscosphaera mgayae</i> ▼ top <i>Uniplanarius trifidus</i>	
	top <i>Uniplanarius trifidus</i> ▼ (+ top <i>U. gothicus</i> , top <i>U. sissinghii</i>)	<i>Luciano. arcuatus</i> Subzone	UC16a ^{TP}	▼ top <i>Amphizygus brooksii</i> ▼ top <i>Eiffellithus eximius</i>	
upper Campanian (<i>pars.</i>)	top <i>Reinhardtites anthophorus</i> ▼	<i>Uniplanarius sissinghii</i> Subzone (<i>pars.</i>)	UC15e ^{TP}	▼ top <i>Staurolithes imbricatus</i> ▼ top <i>Prediscosphaera arkhangelskyi</i>	upper Campanian (<i>pars.</i>)
	top <i>Lucianorhabdus quadrifidus</i> ▼			▼ top <i>Lucianorhabdus quadrifidus</i> ▼ base <i>Eiffellithus parallelus</i> top <i>Reinhardtites anthophorus</i>	
	top <i>Eiffellithus eximius</i> ▼		UC15d ^{TP} (<i>pars.</i>)	U. <i>trifidus</i> , E. <i>eximius</i> (present)	

Fig. 19. Comparison of nannofossil datums at Kladorub (this study) with the local zonation scheme for Bulgaria of Sinnyovsky (2007, 2013a, 2015).

Maastrichtian, within subzone UC16d^{BP}, whereas, in the Indian Ocean (ODP Hole 762C), it was detected in the Maastrichtian UC19 (Thibault *et al.*, 2012b). In the present study, the first reliably identifiable specimens of *Lithraphidites praequadratus* were noted in UC19. This seems to be a real signal since this taxon is characterized by a consistent stratigraphical range up-section and rapidly becomes a considerable constituent of the upper Maastrichtian assemblages, taxonomic concepts were meticulously applied, and there are no deleterious changes in preservation to explain any possible loss of *Lithraphidites praequadratus* in lower samples. Interestingly, according to Sinnyovsky (2007, 2013a, 2015), base *Lithraphidites praequadratus* also post-dates base common *Arkhangelskiella maastrichtiensis*, which is not the case in section Kladorub. In the present study, the first rare representatives of *Arkhangelskiella maastrichtiensis* (*sensu* Burnett, 1997) were noted 1.5 m above base *Lithraphidites praequadratus*, in the upper part of UC19, and the former taxon does not become com-

mon until mid-UC20a^{TP}. At Zumaia, base *Arkhangelskiella maastrichtiensis* has also been recorded within UC19, well above base *Lithraphidites praequadratus* (Pérez-Rodríguez *et al.*, 2012). In the Danish Basin, Thibault *et al.* (2012a) also reported the first occurrence of *Arkhangelskiella cymbiformis* var. W (*sensu* Thibault, 2010a; equivalent to *Arkhangelskiella maastrichtiensis*) in the upper part of UC19 and above base *Lithraphidites praequadratus*.

Regarding secondary nannofossil events, many discrepancies between section Kladorub and Sinnyovsky's (2007, 2013a, 2015) zonation were found (see Fig. 19). For instance, (1) the tops of *Reinhardtites anthophorus* and *Lucianorhabdus quadrifidus* pre-date top *Eiffellithus eximius*; (2) the tops of *Uniplanarius gothicus* and *Uniplanarius sissinghii* not only do not coincide with top *Uniplanarius trifidus* but even post-date top *Broinsonia parca* subsp. *constricta*; (3) top *Lucianorhabdus cayeuxii* was detected above top *Reinhardtites levis*; (4) base *Nephrolithus frequens* predates base *Lithraphidites*

quadratus; (5) top *Zeugrhabdotus bicrescenticus* was noted within zone UC19 in Kladorub, whereas Sinnyovsky (2007, 2013a, 2015) described it as consistently present to end-Cretaceous. Of the secondary datums recognized in the present study, the tops of *Acuturris scotus* (in UC17) and *Zeugrhabdotus bicrescenticus* (in UC19) are worthy of note. Recently, Pérez-Rodríguez *et al.* (2012) opined that these events may prove to have wide low-latitude stratigraphic and correlative value. In the tropical Indian Ocean, top *Acuturris scotus* approximates the top of *Tranolithus orionatus* (Lees, 2002). At Zumaia, top *Acuturris scotus* lies immediately above top *Tranolithus orionatus* (Pérez-Rodríguez *et al.*, 2012) and, in Kladorub, the former biohorizon was also detected in very close proximity to the latter, albeit below. In the tropical Pacific Ocean, top *Zeugrhabdotus bicrescenticus* lies above top *Tranolithus orionatus* (Lees and Bown, 2005) and, in the tropical South Atlantic, it falls in the lower part of UC19 right above top *Reinhardtites levis* (Thibault, 2016a). The same observation has been made in the Zagros Basin (Iran) in the eastern Tethys (Razmjooei *et al.*, 2018). However, these bioevents are not well documented in Bulgarian sections and further investigations are needed to test their stratigraphic utility.

The Campanian/Maastrichtian and lower/upper Maastrichtian boundaries in section Kladorub

The Campanian/Maastrichtian boundary

The Campanian/Maastrichtian boundary is nowadays officially defined as lying at 115.2 m on platform IV of the geological site at Tercis les Bains (Landes, France), the GSSP having been ratified in 2001 (Odin and Lamaurelle, 2001). This level corresponds to the arithmetic mean of 12 biohorizons including ammonites, dinoflagellate cysts, planktonic and benthic foraminifera, inoceramid bivalves and calcareous nannofossils, the first occurrence of ammonite *Pachydiscus neubergicus* being the primary criterion. In nannofossil terms, the Campanian/Maastrichtian boundary at Tercis has been shown to lie between the tops of *Eiffellithus eximius* (below) and *Uniplanarius trifidus* (above) (Gardin *et al.*, 2001), the latter having been chosen as one of the aforementioned 12 biohorizons (Odin and Lamaurelle, 2001). Prior to this ratification, the boundary was correlated with top *Broinsonia parca* subsp. *constricta* in the UC zonation of Burnett (1998). Pérez-Rodríguez *et al.* (2012) also heeded that there is evidence of top *Uniplanarius trifidus* lying above

top *Broinsonia parca* subsp. *constricta*, as exemplified by the CC scheme of Sissingh (1977), as modified by Perch-Nielsen (1985), and Burnett's (1998) UC zonation, and so they deemed the use of top *Uniplanarius trifidus* as an indicator for the Campanian/Maastrichtian boundary outside of Tercis questionable. However, based on comparisons of four of the main reference sites for the Campanian/Maastrichtian boundary (*i.e.*, Tercis les Bains, Gubbio, DSDP Site 525a and ODP Site 762c), Thibault (2016a) demonstrated that top *Uniplanarius trifidus* is an excellent biostratigraphic marker for the Campanian/Maastrichtian boundary in the Tethyan realm. Due to the lack of proper chronostratigraphic framework for section Kladorub, this event has been used to draw the boundary in the present study (at 56 m).

The lower/upper Maastrichtian boundary

There is still no formal agreement for the placement of a lower/upper Maastrichtian boundary. Paul and Lamolda (2007) highlighted base *Lithraphidites quadratus* as a potential marker for the lower/upper Maastrichtian boundary at Zumaia. Since Zumaia is a candidate substage-boundary stratotype for the lower/upper Maastrichtian boundary, Pérez-Rodríguez *et al.* (2012) proposed the following defining criteria: (1) the C31r/C31n magnetic reversal; (2) the base of calcareous nannofossil *Lithraphidites quadratus*; and (3) the base of the planktonic foraminifer *Racemiguembelina fruticosa*. In regards to calcareous nannoplankton, they also commented that *Lithraphidites quadratus* has a wide geographical distribution and the proximity of its base to the base of C31n makes it an acceptable candidate for defining the substage boundary, at least at low to mid latitudes. At Gubbio, the first occurrence of *Lithraphidites quadratus* has also been shown to lie very close to the base of Chron C31n and has been used to draw the lower/upper Maastrichtian boundary (Gardin *et al.*, 2012). The same nannofossil biohorizon has also been used as a marker for the base of the upper Maastrichtian in the Danish Basin (Thibault *et al.*, 2012a, b) and in the Zagros Basin, Iran (Razmjooei *et al.*, 2014, 2018). Thus, again due to the lack of proper chronostratigraphic framework for section Kladorub, the lower/upper Maastrichtian boundary in the present study has been placed at the base of *Lithraphidites quadratus* at 96 m.

CONCLUSIONS

New calcareous nannofossil data from the upper Campanian–Maastrichtian portion of the Kladorub

Formation in NW Bulgaria have allowed detailed biostratigraphic framework to be erected. This zonation offers higher stratigraphic resolution than previously used local zonation schemes. Since it relies on well-established, traceable on a global scale bioevents, it facilitates further correlation with coeval sedimentary successions in other parts of the world, both in the Tethyan and the Boreal realm. Due to the lack of proper chronostratigraphic framework for the Kladorub Formation, top *Uniplanarius trifidus* and base *Lithraphidites quadratus* have been used to approximate the Campanian/Maastrichtian and lower/upper Maastrichtian boundaries, respectively, based on published data from elsewhere. The uppermost Maastrichtian–lowermost Danian strata are completely buried under a thick soil cover as a result of recent landslide processes, and thus further investigations are needed to place precisely the position of the Cretaceous/Palaeogene boundary in the section.

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APPENDIX

Table A1. Calcareous nannofossil stratigraphic range-chart, section Kladorub. (This table is available online in an over-sized format at https://www.geologica-balkanica.eu/sites/default/files/supplementary/05_Granchevski_Geol_Balc_48-1_2019_Appendix.pdf.)

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