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Calcareous nannofossil and ammonite integrated biostratigraphy across the Jurassic–Cretaceous boundary strata of the Kopanitsa composite section (West Srednogorie Unit, southwest Bulgaria)

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Abstract: Calcareous nannofossil, calpionellid and ammonite occurrences have been directly constrained across the Jurassic–Cretaceous boundary interval in the section of Kopanitsa, SW Bulgaria. This section reveals a continuous and expanded sedimentary record through the Upper Tithonian and Lower Berriasian, besides an excellent calcareous nannofossil and ammonite record. The topmost part of the NJT 16b and the base of NJT 17a nannofossil Subzones correspond to the ammonite Microcanthum/Transitorius Subzone. The major part of the NJT 17a Subzone equates to the Durangites spp. ammonite Zone, whereas the NJT 17b Subzone correlates to the lower part of the B. jacobi ammonite Zone. The NKT nannofossil Zone approximately corresponds to the upper part of the B. jacobi Zone and the NK-1 nannofossil Zone correlates at least to the lowest part of the T. occitanica Zone. The FOs of *Nannoconus globulus minor, N. wintereri, N. kamptneri minor, N. steinmannii minor, N. kamptneri kamptneri* and *N. steinmannii steinmannii* are confirmed as reliable bio-horizons for correlations in the Mediterranean Tethys area. The first occurrence of *Nannoconus wintereri* is regarded as an almost concomitant event with the first occurrence of *Berriasella jacobi*. We suggest it could be the most useful nannofossil proxy for approximating the base of the B. jacobi Zone. Rare, but relatively well preserved calpionellids and calcareous dinoflagellates together with microfacies analysis were used additionally for stratigraphical and palaeoenvironmental interpretations. The investigated sediments are typical for the steep slope of a steepened ramp, with accumulation of hemipelagic and gravitational deposits.

Keywords: Jurassic–Cretaceous boundary, Mediterranean Tethys, southwest Bulgaria, biostratigraphy, calcareous nannofossils, calpionellids, ammonites.

Introduction

The Upper Tithonian–Lower Berriasian succession outcrops near the village of Kopanitsa (southwest Bulgaria, Krayshte area), and has been a subject of studies since 2009. The location offers a continuous and expanded sedimentary record through the Upper Tithonian and Lower Berriasian, as well as pristine calcareous nannofossil and ammonite finds across the section. Our studies have been additionally motivated by the significant advances in nannoplankton, calpionellid and ammonite biostratigraphy calibrated to magnetostratigraphy, published for different Tethyan Jurassic–Cretaceous (J–K) boundary sections (e.g., Casellato 2010; Channel et al. 2010; Lukeneder et al. 2010; Guzhikov et al. 2012; Wimbledon et al. 2013; Frau et al. 2016a,b,c; Hoedemaeker et al. 2016; Michalík et al. 2016; Svobodová & Košťák 2016; Wimbledon 2017a,b). In Bulgaria, Ivanov et al. (2010) presented a comprehensive regional overview of the Upper Tithonian–Lower Berriasian biostratigraphy of the Krayshte area, but with no high-resolution study of the interval. Sinnyovsky (2005) applied the Bralower et al. (1989) nannofossil zonation of the J–K siliciclastic sediments of the Berende section (Pernik District) in the same area.

The purpose of this paper is to work out high-resolution integrated calcareous nannofossil and ammonite biostratigraphies for the continuous Upper Tithonian–Lower Berriasian section at Kopanitsa. This section yields relatively regular ammonite finds and a good calcareous nannofossil record. The direct integration of nannofossil and ammonite data is of crucial importance, allowing precise calibration of the bio-events in both groups and assessing the most reliable ones for correlation. Moreover, there are not many suitable sections known so far across the Mediterranean Tethys, where these two groups of primary biostratigraphic significance can be directly tied together.

Unfortunately, our pilot sampling for magnetostratigraphy (Grabowski & Schnabl, pers. comm.) did not provide reliable results. However, at a late stage (after initial submission of the manuscript), a reconnaissance study for calpionellids and calcareous dinocysts occurrence has been accomplished by

Daniela Reháková. It is added here, thus complementing the ammonites (Vyara Idakieva & Marin Ivanov) and nannofossils (Kristalina Stoykova) data. This study is a contribution to the activities of the Berriasian Working Group (ICS).

Geological setting

The Kopanitsa section is situated ~35 km SW of Sofia in the Krayshte area, Lyubasha–Golo Bardo Tectonic Unit, West Srednogorie Unit (Dabovski & Zagorchev 2009) (Fig. 1). The section consists of four superimposed subsections, from bottom to top: Radibosh (base at 42º33'58.47" N, 22º53'8.63" E), Kopanitsa 1A (base at 42º34'31.45" N, 22º53'18.33" E), Kopanitsa 1B (base at 42º34'34.52" N, 22º53'35.76" E), Kopanitsa 1C (base at 42º34'48.62" N, 22º53'26.75" E). Their combined total thickness is *c.* ~204 m (Fig. 2). Moreover, the studied section is complemented by partial exposure of the same interval at the western end of Kopanitsa village, near the signboard, named here as Kopanitsa 2. It overlaps the middle part of Kopanitsa 1C subsection (Fig. 2).

The bottom of the succession is exposed in the Radibosh subsection, which lies 2.6 km NE of the village of the same name, at the road cutting. The Kopanitsa 1A and Kopanitsa 1B subsections crop out along two gullies, which cut the hill between Radibosh and Kopanitsa. The uppermost Kopanitsa 1C subsection is a road exposure, along the cutting of the rambling road to Kopanitsa (Fig. 1).

The exposed sedimentary succession is characterized by marls and mudstones, intercalated by fine-grained siliciclastic

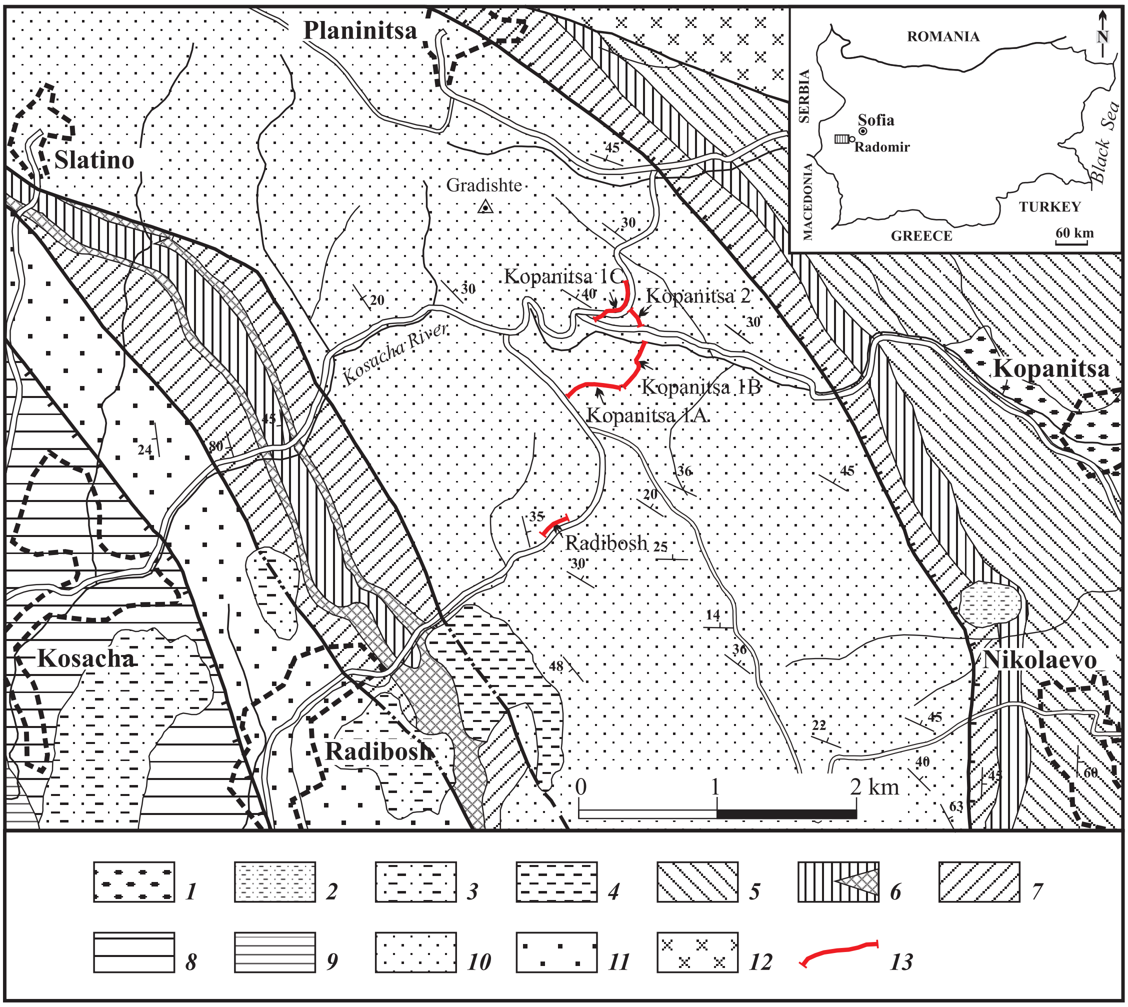

Fig. 1. Geological map of the studied area (modified from Milovanov et al. 2006), with location of the subsections of the Kopanitsa composite section. *1* — alluvial deposits (Quaternary, Holocene); *2* — alluvial and alluvial-prolluvial deposits (Upper Romanian–Lower Pleistocene); *3* — prolluvial-delluvial and alluvial-prolluvial deposits (Romanian–Lower Pleistocene); *4* — lake-fluvial sediments (Neogene, Upper Dacian–Lower Romanian); *5* — variegated molasse formation (Middle–Upper Oligocene); *6* — bitumen formation (Middle Oligocene); *7* — conglomerate-sandstone formation (Middle Oligocene); *8* — flyshoid formation (Campanian–Maastrichtian); *9* — conglomerate-sandstone formation (Campanian); *10* — Gorochevo Mb of the Kostel Fm (Tithonian–Berriasian); *11* — Bobovo Mb of the Kostel Fm (Kimmeridgian–Berriasian); *12* — Propalnitsa Fm, Cherna Gora Group (Devonian–Carboniferous, Fammenian–Tournaisian); *13* — measured subsection.

turbidites. In the past, these beds have been referred to as "Berriasian post-flysch" or the "Kostel Formation" by various researchers (e.g., Nachev & Nikolov 1968). Later on, Sapunov et al. (1985) separated two members within the Kostel Formation (Fm.) — the Bobovo Member and Gorochevo members. The studied succession belongs to the Bobovo Member. In general, the beds dip at 30º–35º to the NE with an angle 30º–45º (Fig. 1). Occasionally, the rhythmic turbidites are interrupted by conglomerate. As a matter of fact, a huge body displaying a thickness greater than 8 m characterized by poorly sorted conglomerate, which pinches out laterally, is observed in the middle part of the Kopanitsa 1C subsection.

Material and methods

The Kopanitsa section was measured bed by bed, and a systematic sampling was performed in order to analyse the nannofossil and ammonite contents. A total of 126 samples were collected for calcareous nannofossils. Sampling resolution varies between few centimetres and two metres, depending on lithology. Marly claystones and marlstones and occasionally siltstones were chosen for nannofossil analyses. All samples were processed and fixed on smear-slides using the standard preparation technique of Bown & Young (1998). Zeiss polarized light microscope *Axioskop 40Pol* with *ProgRes®*

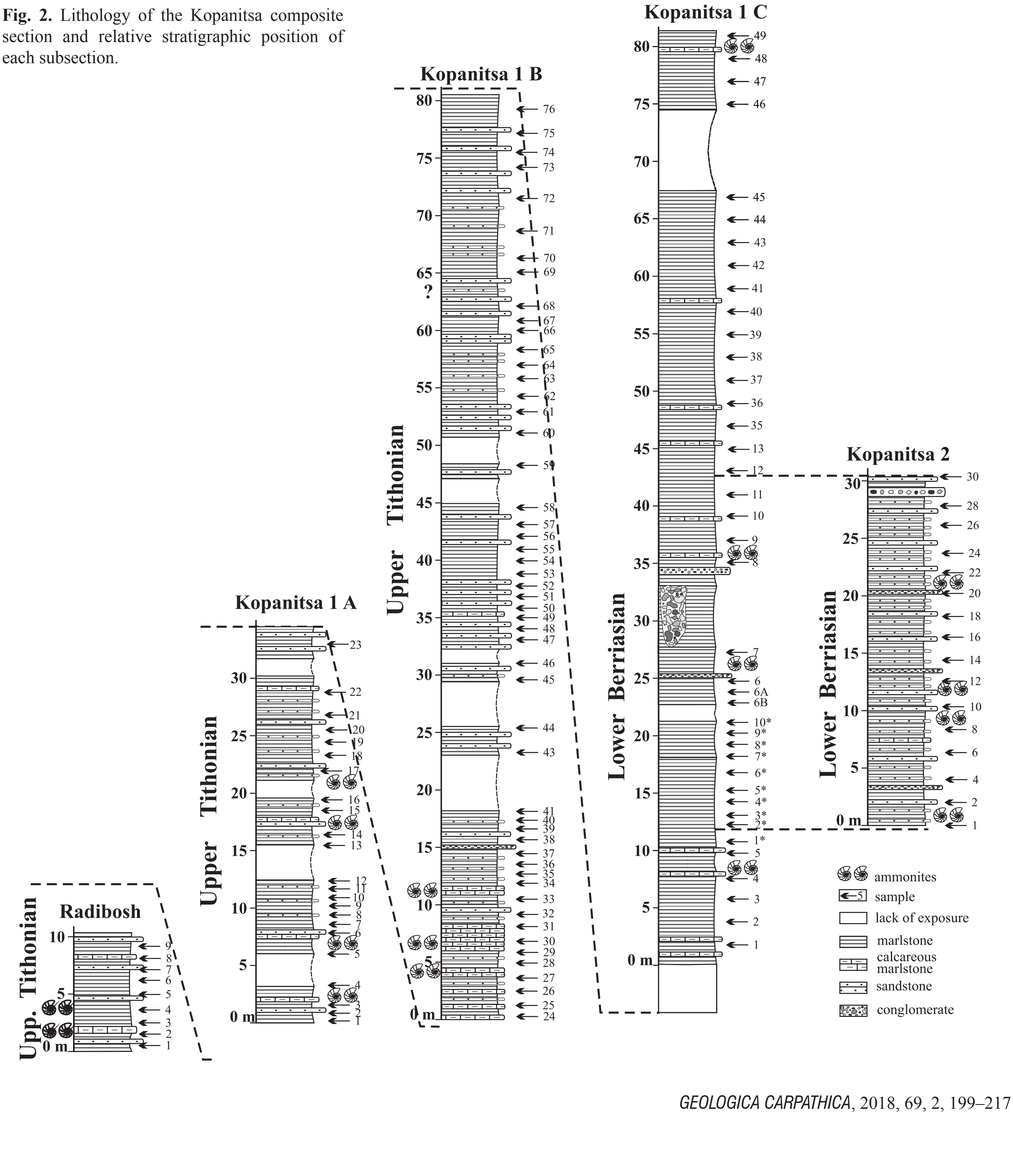

Fig. 2. Lithology of the Kopanitsa composite section and relative stratigraphic position of each subsection.

Capture Pro digital camera was used for nannofossil study. Observations and micropalaeontological identifications were carried out with an immersion objective (100×) at magnification of 1000×.

The set of the smear-slides is stored at the Department of Palaeontology and Stratigraphy, Geological Institute BAS, Sofia, as item (Rdb/Kpnc). The ammonite specimens are stored at the Museum of Palaeontology, Sofia University, under the № MP-SU K_1 10483 to MP-SU K_1 10498.

Finds of ammonites were restricted to several ammonite-bearing levels, usually related to higher carbonate content in the sediments. More than 170 ammonite specimens were collected, 76 of them were identified and used for the biostratigraphy. It is noteworthy that long intervals lack ammonites and the zonal boundaries are not precisely fixed.

A total of 23 samples (mainly marlstones) from the Radibosh, Kopanitsa 1A, 1B and 1C subsections were studied for calpionellids and calcareous dinocysts content. Thin-sections were prepared in the laboratory of the Department of Geology and Palaeontology of Comenius University in Bratislava. Several thin-sections (5 pieces maximum) were produced from each sample, due to the rarity of the microfossils. The calpionellid zonation (Reháková & Michalík 1997; Lakova & Petrova 2013), cysts succession (Lakova et al. 1999; Reháková 2000a, b) and revised Dunham classification of microfacies (Embry & Klovan 1971) were applied.

For calcareous nannofossil biostratigraphy, we adopted the scheme of Casellato (2010) as a reference biostratigraphic zonation within the Upper Tithonian and Lower Berriasian interval. Some of the nannofossil bio-events, pointed out by Bralower et al. (1989), are also considered. For the ammonite study we use the standard ammonite zonation for the Upper Tithonian (Geyssant 1997; Zeiss 2003) and Lower Berriasian (Reboulet et al. 2014) in the Mediterranean Realm.

Results

The big advantage of the Kopanitsa section is its expanded, more or less continuous record, enabling easy and reliable recognition of the successive bio-events amongst the nannofossil and ammonite groups. In the samples inspected, calcareous nannofossils were common to abundant and moderately to well preserved. In total, 56 nannofossil taxa were recognized. Their stratigraphic occurrence is plotted on Figs. 3–7. The complete list of the recognized species is provided in *Appendix A*. Concerning ammonites, 35 ammonite taxa were identified. Most of the specimens are preserved as moulds, but ornamentation is discernible, allowing taxonomic determination. The ammonite bearing levels and vertical distribution of the recovered species are displayed in the same figures. The list of the identified ammonite species is provided in *Appendix B*. The samples selected for thin section preparation contained rare, but relatively well preserved calpionellids and calcareous dinoflagellates, which were used in microfacies analysis of the studied sediments (*Appendix C*).

Nannofossil biostratigraphy

The studied interval falls within the Upper Tithonian and Lower Berriasian, corresponding to the following nannofossil zones: NJT 16 Zone (pars), NJT 17 Zone, NKT Zone and NK-1 Zone (pars). The base of the succession (Radibosh subsection) is assigned to the Upper Tithonian NJT 16 and NJT 17 Zones — respectively topmost NJT 16b and basal NJT 17a Subzones (Fig. 3). The presence of the NJT 16b Subzone is proved by the occurrence of *Nannoconus infans* in all lowermost samples investigated, Rdb 1 to Rdb 5. The NJT 16/NJT 17 zonal boundary is placed at the first occurrence (FO) of *Nannoconus globulus minor* in sample Rdb 6 (Fig. 3). The latter bio-event is concomitant with the FO of *Umbria granulosa minor* in the same sample. The calcareous nannofossil assemblages from the basal part of the Kopanitsa section (NJT 16b Subzone) are dominated by the representatives of *Watznaueria, Cyclagelosphaera* and *Conusphaera,* though the first primitive nannoconids are recorded there — *Nannoconus infans* (Fig. 8/1*), N. puer* (Figs. 9/2–3), *N. compressus* (Figs. 8/2, 9/1). The Upper Tithonian NJT 17 Zone is divided into NJT 17a and NJT 17b subzones, although the lower one, NJT 17a, is significantly thicker and longer than the upper NJT 17b. The NJT 17a Subzone encompasses the Kopanitsa 1A and 1B subsections. Within this subzone, further successive FOs were registered: *Umbria granulosa granulosa*, *Retecapsa surirella, Cruciellipsis cuvillieri, Acadialithus* spp*., Lithraphidites* spp*., Rhagodiscus asper, Retecapsa octofenestrata* (Kopanitsa 1A — Fig. 4, Figs. 8, 9); *Polycostella senaria, Polycostella parvistellatus, Nannoconus globulus globulus, Hexalithus strictus* and *Nannoconus erbae* (Kopanitsa 1B — Fig. 5, Figs. 8, 9). This interval clearly shows the accelerating diversification and speciation of nannofossil assemblages, manifested by the appearance of several new genera and species — *Retecapsa, Assipetra, Acadialithus, Cruciellipsis, Lithraphidites*. The total range of the representatives of the newly published genus *Acadialithus* Howe, 2017 is restricted to the Upper Tithonian and Lower Berriasian NJT 17–NKT nannofossil zones. The FO of *Nannoconus wintereri* (Fig. 8/6–7), marking the NJT 17a/NJT 17b subzonal boundary, is recorded in sample 3 of Kopanitsa 1C (Fig. 6) and in sample 1 of Kopanitsa 2 (Fig. 7). This bio-horizon virtually coincides with the base of the local acme of *Polycostella senaria* — an apparent event registered in NJT 17b Subzone. Moreover, in this subzone, the FOs of *Nannoconus colomii* and *N.* sp. aff. *bucheri* (Fig. 9/19–20) are recognized in sample 6* of Kopanitsa 1C (Fig. 6). The NJT 17b/NKT zonal boundary is placed at the FO of *Nannoconus steinmannii minor* (Fig. 9/23–26), observed in sample 6B of Kopanitsa 1C (Fig. 6) and in sample 12 of Kopanitsa 2 (Fig. 7). It is noteworthy that the FO of *Nannoconus kamptneri minor* (Fig. 9/21–22) is in the same sample, 6B, from Kopanitsa 1C, but slightly lower (sample 11) in Kopanitsa 2. Finally, the NKT/NK-1 zonal boundary is drawn at the FO of *Nannoconus steinmannii steinmannii* (Fig. 9/29–30) in the topmost sample 49 of Kopanitsa 1C (Fig. 6), together with *Nannoconus*

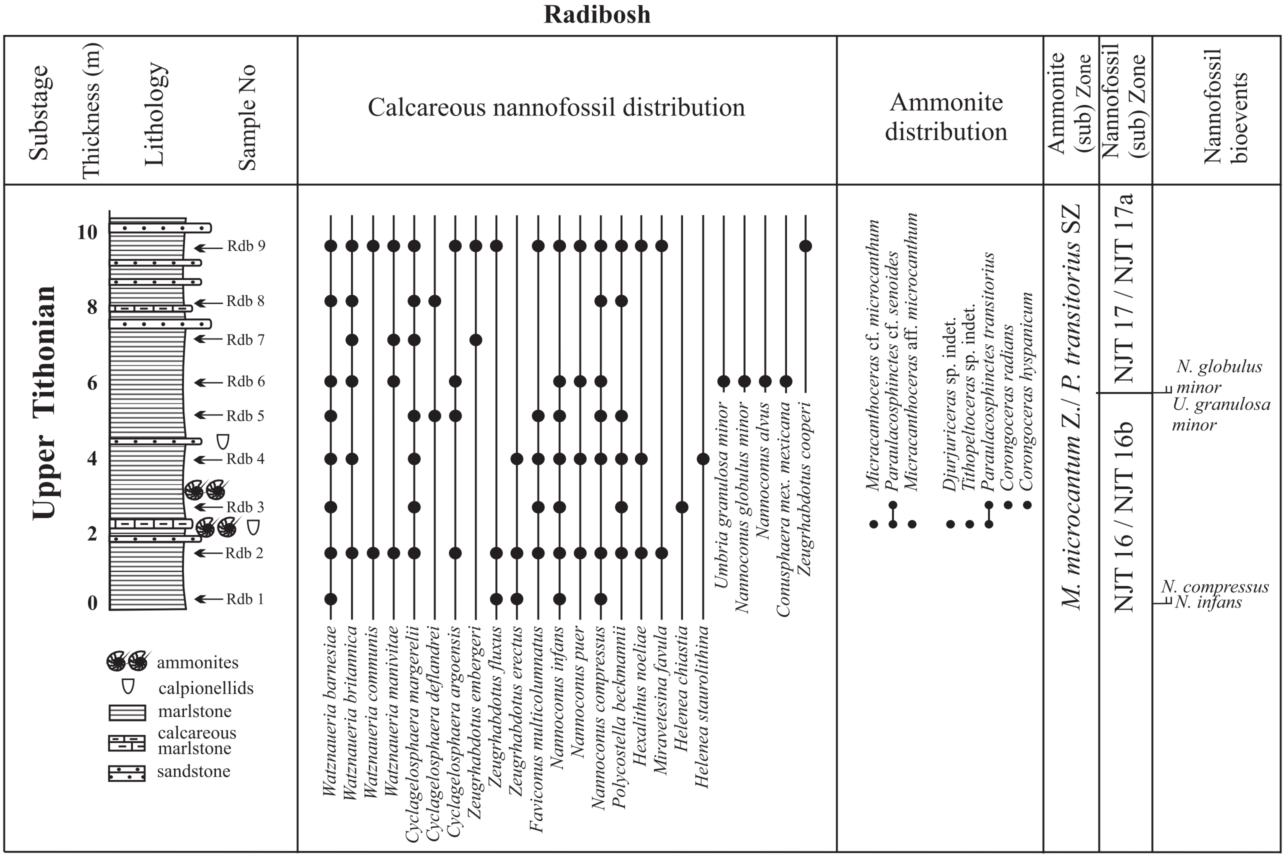

Fig. 3. Distribution of the calcareous nannofossil and ammonite species in the Radibosh subsection.

kamptneri kamptneri (Fig. 9/27–28). This is the last biohorizon detected within the studied section.

Ammonite biostratigraphy

The presence of the Upper Tithonian Micracanthoceras microcanthum Zone with its upper P. transitorius Subzone is proved in the Radibosh subsection. Moreover, the last Tithonian ammonite zone — Durangites spp. Zone, is unequivocally identified, encompassing the subsections Kopanitsa 1A and 1B. Finally, the Lower Berriasian part of the Berriasella jacobi Zone is recognized in the Kopanitsa 1C and Kopanitsa 2. The boundary between Microcanthum and Durangites spp. ammonite Zones falls within an interval with no exposure, between the outcrops of Radibosh and Kopanitsa 1A. The same applies to the boundary between Durangites spp. and Berriasella jacobi Zones: it is not possible to precisely locate it due to the lack of exposures. It lies above the top of the Kopanitsa 1B and below the base of Kopanitsa 1C subsections, within a 15 m-thick concealed interval (Fig. 2). The latter conclusion is fully corroborated by the additionally acquired calpionellids data from the topmost part of Kopanitsa 1B subsections — samples 1B-1 to 1B-8 (Fig. 5), indicating the highest part of the Tithonian, near the J–K boundary (see comments below).

Upper Tithonian ammonite fauna has been recovered from the Radibosh, Kopanitsa 1A and Kopanitsa 1B subsections. In the lower part of Radibosh, an abundant association was found. It comprises *Micracanthoceras* cf. *microcanthum* (Fig. 10/6), *M.* aff. *microcanthum* (Fig. 10/5), *Paraulacosphinctes transitorius* (Fig. 10/1), *P.* cf. *senoides*, *Corongoceras radians* (Fig. 10/4), *C. hyspanicum*, *Tithopeltoceras* sp. indet., *Djurjuriceras* sp. indet., allowing us to assign this interval to the P. transitorius Subzone of the M. microcanthum Zone (Fig. 3).

The Kopanitsa 1A subsection yields a rich and diverse ammonite association dominated by *Durangites*, and also comprising representatives of *Durangites*, *Protacanthodiscus* and *Neoperisphinctes* (Fig. 4). This fauna has been collected from three successive levels and includes *Durangites singularis* (Fig. 10/2)*, D. acanthicus, D. astilerensis* (Fig. 10/3)*, D.* cf. *vulgaris, D.* cf. *gigantis, D.* aff. *astilerensis, D.* aff. *fusicostatus, "Durangites"* sp., *Protacanthodiscus* aff. *andreaei* (Fig. 10/7), *Protacanthodiscus* sp., *Neoperisphinctes falloti* (Fig. 10/8), as well as *Corongoceras* sp., *Himalayites* sp. and *Berriasella* aff. *tithonica*. Some of the listed species were previously published by Ivanov et al. (2010). A similar faunal association was gathered at the base of Kopanitsa 1B subsection, represented by *Protacanthodiscus andreaei, Protacanthodiscus* sp. juv., *Protacanthodiscus* sp. indet., *Corongoceras* cf. *mendozanum*, *C.* cf. *minor*, *Corongoceras* sp., *Durangites* aff. *fusicostatus, Berriasella* cf. *tithonica* (Fig. 5). The upper part of the Kopanitsa 1B subsection yields

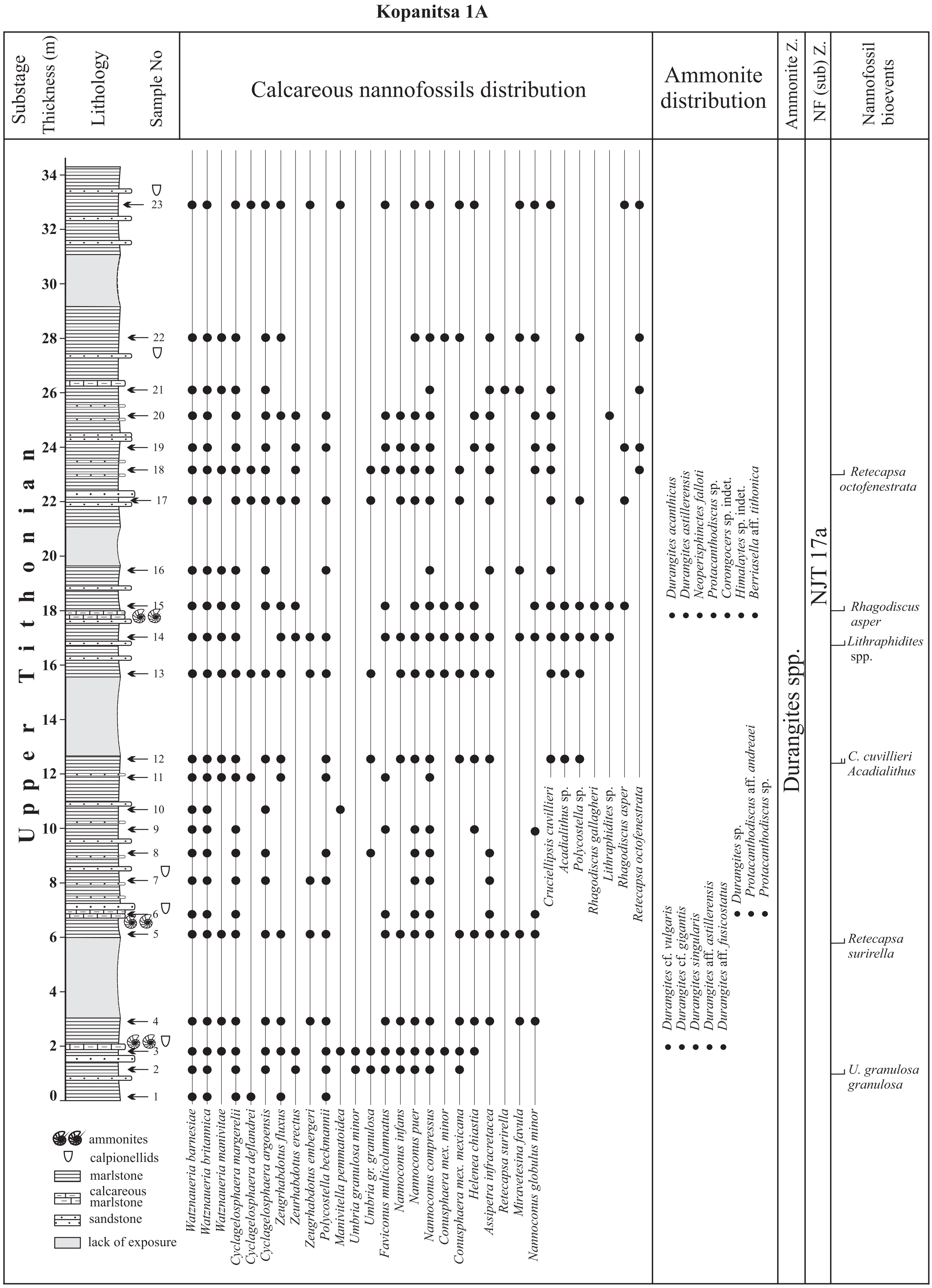

Fig. 4. Distribution of the calcareous nannofossil and ammonite species in the Kopanitsa 1A subsection.

Kopanitsa 1B

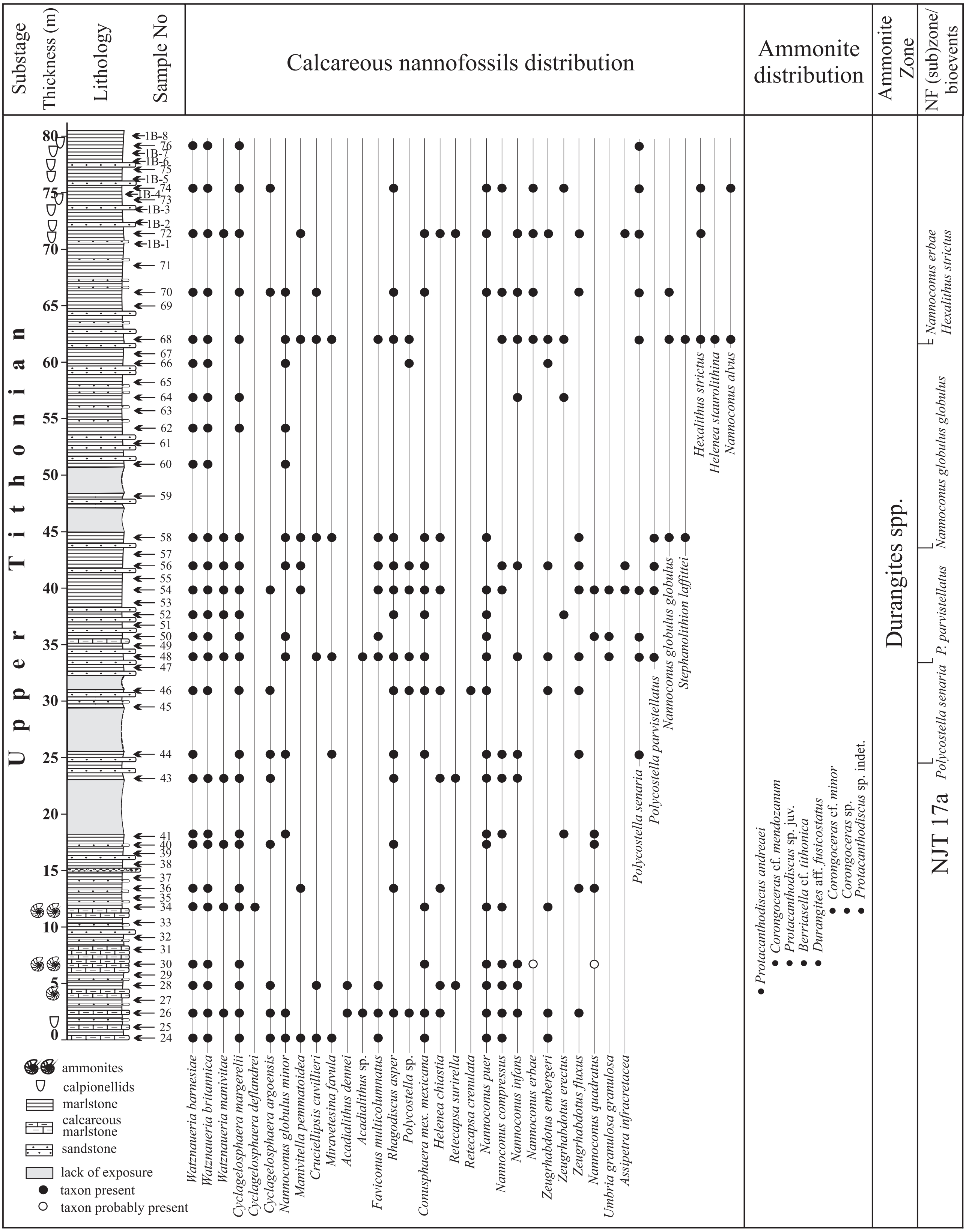

Fig. 5. Distribution of the calcareous nannofossil and ammonite species in the Kopanitsa 1B subsection.

abundant lytoceratids and phylloceratids, but no stratigraphically diagnostic taxa were found. Both the Kopanitsa 1A and Kopanitsa 1B subsections are assigned to the Durangites spp. Zone.

Up sequence, in the Kopanitsa 1C and Kopanitsa 2 sections, typical Lower Berriasian ammonite taxa were recovered. The Kopanitsa 2 succession repeats the lower and middle parts of Kopanitsa 1C (Fig. 2). The ammonites in the latter were collected from four successive levels (Fig. 6): *Pseudosubplanites* cf. *combesi*, *P*. aff. *hegarati* (Fig. 10/9), *Delphinella* cf. *crimensis* (Fig. 10/14), *D*. cf. *delphinensis*, and *Spiticeras* sp. from the lower part; *Berriasella jacobi* (Fig. 10/10), *B*. cf. *jacobi*, *Spiticeras* sp., *Pseudosubplanites grandis, P. ponticus* (Fig. 10/11)*, P. lorioli*, *Berriasella* cf. *subcalisto*, *B*. cf. *jauberti*, *Dalmasiceras (Elenaella)* cf. *cularense* and *Spiticeras* sp. from the uppermost part. The entire interval of Kopanitsa 1C corresponds to the Lower Berriasian part of the B. jacobi Zone. The first occurrence of *Pseudosubplanites grandis* in the middle part of Kopanitsa 1C indicates the presence of the upper part of this Zone (= Grandis Subzone, Vašíček et al. 2013). Interestingly, this important ammonite bio-horizon is bracketed by the nannofossil FOs of *N. steinmannii minor* and *N. kamptneri minor* (Fig. 6).

From the Kopanitsa 2 subsection the following taxa were identified, from four successive levels (Fig. 7): *B. jacobi* and *Subalpinites* aff. *aristidis* (Ivanov et al., 2010); *Pseudosubplanites subrichteri*; *B. oxicostata* (Fig. 10/13) and *Fauriella shipkovensis*, *Delphinella janus*, *Dalmasiceras* sp. (already published, Ivanov et al. 2010); *F. shipkovensis* (Fig. 10/16)*, Dalmasiceras (E.)* cf. *cularense* (Fig. 10/15) and *D. gigas* (Fig. 10/12). The sequence indicates the B. jacobi Zone.

Microfacies, calpionellid and calcareous dinoflagellate biostratigraphy

The microfacies analysis reveals that the investigated sediments are typical for the steep slope of a steepened ramp, with accumulation of hemipelagic and gravitational sediments (Flügel 2004). Examples of gravity-flow deposits in the Upper Jurassic–Lower Cretaceous sequences have been documented by Matyszkiewicz & Slomka (1994), Schlagintweit & Gawlick (2007), Auer et al. (2009), Bucur et al. (2010), Guzhikov et al. (2012), Kukoč et al. (2012), Wimbledon et al. (2013), Petrova et al. (2012). The position of calpionellids sampling is marked on the respective subsection (Figs. 3–6).

The samples Rdb 3, Rdb 4 from the Radibosh subsection show bioturbated, graded silty limestone with calcisilt laminated pebbles of cm size, incorporated in fine calcisilt matrix with small rounded micrite pebbles. The coarser clastics are passing into fine grained ones. They contain quartz, muscovite, rare glauconite, feldspars, also pebbles of micrite sediment, seldom cysts of *Colomisphaera lapidosa* (Fig. 11/1), *Colomisphaera fortis,* probably algae microproblematicum of *Muranella* sp., sponge spicules, crinoids, aptychi and foraminiferal fragments. The age we suppose to be Late Tithonian on the basis of the presence of *Colomisphaera fortis*, the index species for the Fortis Zone (Ivanova *in* Lakova et al. 1999; Reháková 2000a).

In the Kopanitsa 1A subsection, the samples Kpnc 1A-3 and Kpnc 1A-6 represent a carbonate breccia with silty matrix. It contains bioclasts (crinoids, echinoids, aptychi, *Laevaptychus* sp., bivalves, bryozoans, brachiopods, *Lenticulina* sp., *Trocholina* sp., *Andersenolina alpina*, *Nautiloculina bronnimanni*, *Charentia* sp., *Haplophragmium* sp.), microencrusters *Crescientella moronensis*, *Koskinobullina socialis*, worm tubes, *Terebella lapilloides, Mercierella* sp., and extraclasts (fragments of pelbiomicrosparite limestones with rare ostracods/or sponge spicules/or *Cadosina semiradiata fusca*/ or *Saccocoma* sp.). The matrix contains a rich clastic admixture. Sample Kpnc 1A-7 (7a,b,c,d thin-sections) is composed of fine grained siltstones, the matrix is slightly silicified. Bioclasts are very rare. Loricae of calpionellids were identified: *Tintinnopsella carpathica*, *Crassicollaria massutiniana* (Fig. 11/6), *Crassicollaria intermedia* (Fig. 11/7), *Calpionella alpina*, *Calpionella elliptalpina* (Fig. 11/5)*,* cysts of *Colomisphaera carpathica, Cadosina semiradiata semiradiata, Cadosina semiradiata fusca* (Fig. 11/3), foraminifera (*Spirillina* sp., *Lenticulina* sp.), also planktonic *Saccocoma* sp., ostracods, bivalves. The matrix contains rich framboidal pyrite, plants fragments and silty clastics. The calpionellid association mentioned above is typical for the Late Tithonian Intermedia Subzone of the standard Crassicollaria Zone.

Thin-sections of the Kpnc 1A-22 sample show sandy carbonate turbidite and carbonate breccia (Kpnc 1A-23). The first contains rare fragments of microencruster *Crescientella moronensis* and micrite mudstone pebbles. The matrix is rich in clastic admixure, consisting of quartz, muscovite, biotite and fragments of feldspars. Carbonate breccia has silty matrix. It contains bioclasts (crinoids, bivalves, bryozoans, brachiopods, *Crescientella moronensis*, corals, crustose coralline red algae with reproductive bodies (sporangia), *Haplophragmium* sp., miliolid foraminifera, worm tubes, tubes of *Carpathocancer triangulatus* and extraclasts (fragments of pelbiomicrosparite limestones with rare ostracods/or sponges/or saccocoma limestones). The Late Tithonian ammonite association, identified below (Kpnc 1A-14, 15, 17), is practically the same as that observed in the Le Chouet section (Wimbledon et al. 2013), where it coincides with the onset of the Colomi Subzone of the Standard Crassicollaria Zone.

The samples from the topmost part of the Kopanitsa 1B subsection (1B-1 to 1B-8, Fig. 5) consist predominantly of carbonate breccia, with possible redeposition of calpionellid loricae (1B-5, 1B-8) or fine grained siltstones. The samples 1B-4 and 1B-7 are silty limestones; therefore it can be assumed that some of loricae are *in situ*. The calpionellid association in the sample 1B-7 consists of small loricae of *Calpionella alpina*, implying that, stratigraphically, this is the highest part of the Upper Tithonian, near the Jurassic–Cretaceous boundary. However, the low quantity, bad preservation and irregular pattern of the calpionellid distribution make it impossible to accurately place the onset of the calpionellid zone and

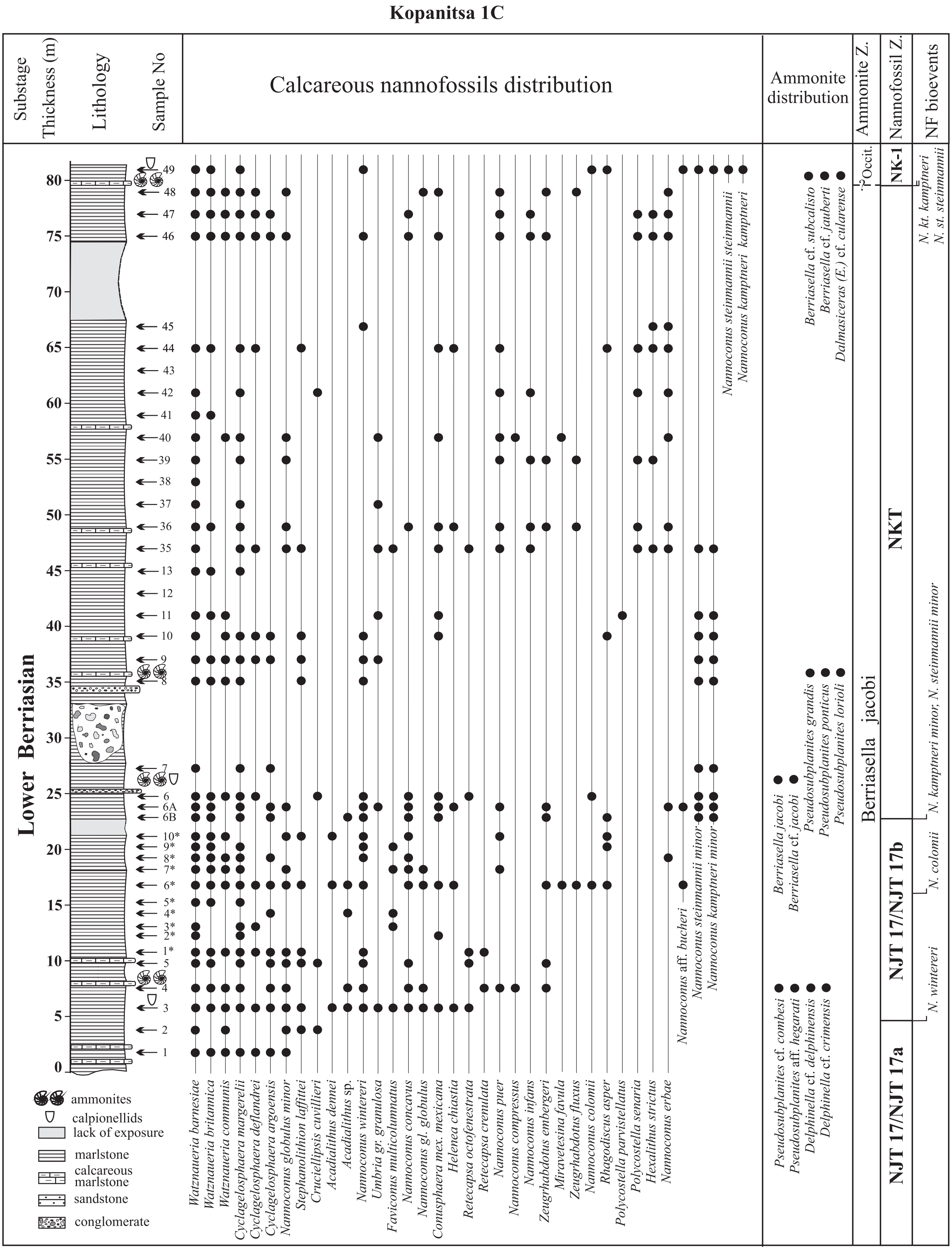

Fig. 6. Distribution of the calcareous nannofossil and ammonite species in the Kopanitsa 1C subsection.

Kopanitsa 2

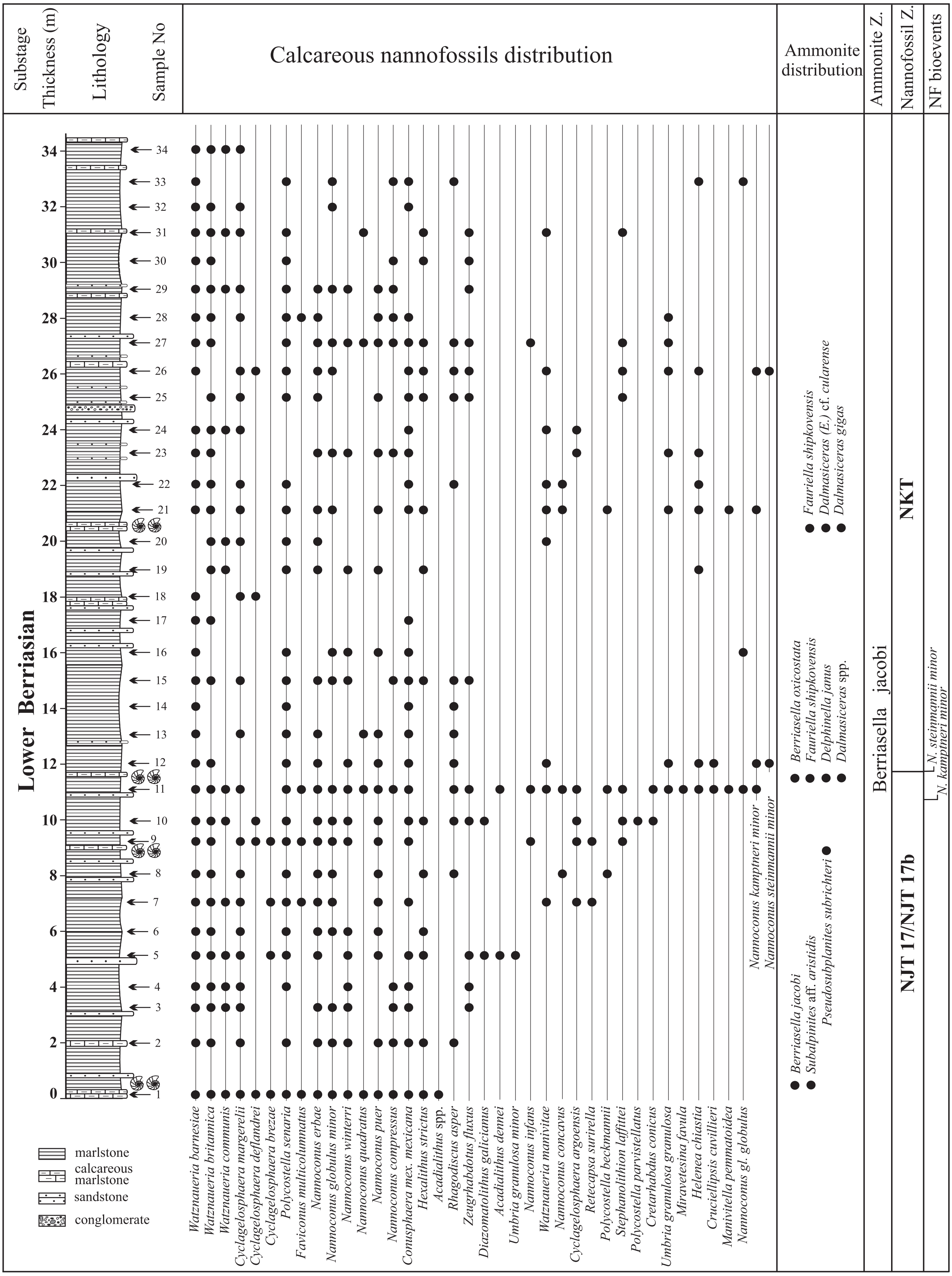

Fig. 7. Distribution of the calcareous nannofossil and ammonite species in the Kopanitsa 2 subsection.

subzone, similarly like in the Crimean Theodosia section (Bakhmutov et al. 2016; Bakhmutov et al. in press).

In the Kopanitsa 1C subsection the sample Kpnc 1C-3 (4 thin sections prepared) shows silty marly limestone, containing loricae of *Calpionella alpina,* rare *Tintinnopsella carpathica* and ?*Remaniella* sp., *Lorenziella hungarica*, accompanied by spores of *Globochaete alpina,* cysts of *Colomisphaera lapidosa*, *Stomiosphaera* sp. Two ghosts, resembling tests of planktonic foraminifera and fragments of ostracods and aptychi were identified. The recorded calpionellid association indicates the Alpina Subzone of the standard Calpionella Zone. Thus, the J–K boundary is somewhere below this level. The overlying sample Kpnc 1C-7 (thin sections 7a, b, c, d), situated above the turbiditic layer, belongs to bioturbated biomicrite limestone, with slightly silicified matrix and bioclasts. As a result of bioturbation, many clastics are concentrated into nests. *Calpionella alpina, Remaniella ferasini, Remaniella catalanoi, Remaniella colomi, Remaniella borzai, Tintinnopsella carpathica, Tintinnopsella doliphormis, Lorenziella hungarica,* cysts of *Colomisphaera carpathica, Cadosina* sp., *Cadosina semiradiata fusca,* bivalves, ostracods, and silty clasts were observed in the matrix. Calpionellid association consists of species, typical for the higher part of the Ferasini Subzone (very close to the onset of the Elliptica Subzone) of the standard Calpionella Zone. These results are in good agreement with the ammonite data — upper part of the B. jacobi Zone. Similar calpionellid and ammonite correlations have recently been documented in the Río Argos section (Hoedemaeker et al. 2016), as well as in the Les Combes section (Frau et al. 2016c). The topmost sample for the entire succession, Kpnc 1C-48, is a coarse grained siltstone, rich in pyrite and clastic admixture. Lenses like fragments of silty limestone occur. *Calpionella alpina*, *Calpionella elliptica*, *Tintinnopsella carpathica* penetrated by pyrite were observed. That implies the Elliptica Subzone of the Calpionella Zone.

In conclusion, the recorded calpionellids in the Kopanitsa composite section belong to the Late Tithonian (Intermedia Subzone) and to Early Berriasian (higher part of the Alpina Subzone, Ferasini Subzone and Elliptica Subzone). It is impossible to place accurately the onset of the successive calpionellid subzones, but those mentioned above represent the intervals of calpionellid radiation and diversification, which together with diversified nannofossil and ammonite associations could be related to sea-level fluctuations (Reháková 2000b; Hoedemaeker et al. 2016). The additional incorporation of the calpionellids allows us to identify more precisely the relative position of the J–K boundary according to the formal decision of ISCS's Berriasian working group to choose the Alpina Subzone's base as the primary marker for the boundary.

Calibration of nannofossil, calpionellid and ammonite data

As a result of the current integrated biostratigraphic investigations, calcareous nannofossil bio-horizons and zones are tied to the ammonite zones and calpionellid record. The topmost part of NJT 16b and the base of NJT 17a nannofossil subzones correspond to the Microcanthum/Transitorius ammonite Subzone and Colomisphaera fortis calcareous dinocyst Zone (Fig. 3). The main part of the volume of the NJT 17a Subzone, however, equates to the Durangites spp. Zone (Figs. 4, 5). The lower part of latter corresponds to the Intermedia Subzone of Crassicollaria standard calpionellid Zone, whereas its upper part correlates to the Colomi Subzone. The NJT 17b Subzone correlates to the lower part of the B. jacobi Zone, since the FO of *Nannoconus wintereri* is concomitant with the FO of *Berriasella jacobi*, and the FOs of *N. steinmannii minor* and *N. kamptneri minor* are close to the FO of *Pseudosubplanites grandis* (Fig. 6). The NJT 17b Subzone also equates to the higher part of the Alpina Subzone of Calpionella standard Zone.

The NKT Zone approximately corresponds to the upper part of the B. jacobi Zone (the so-called P. grandis Subzone of most authors, or Subthurmannia floquinensis Zone of Hoedemaeker et al. 2016). The NK-1 Zone correlates at least to the lowest part of the T. occitanica ammonite Zone and to the high part of the Elliptica calpionellid Subzone.

It is proven that the FO of *Cruciellipsis cuvillieri* is a Late Tithonian event at several localities, and here it is clearly documented in the lower part of the Durangites spp. ammonite Zone (Fig. 4). The FOs of other nannofossil species such as *Polycostella senaria, P. parvistellatus, Nannoconus globulus globulus, N. erbae* and *Hexalithus strictus* are pinpointed in the upper part of the Durangites spp. Zone (Fig. 5). The FO of *Nannoconus wintereri* is registered as an almost concomitant event with the FO of the ammonite species *Berriasella jacobi*. Therefore, we consider the FO of *Nannoconus wintereri* as an important bio-event and propose it for further consideration as the most useful nannofossil bio-horizon in approximating the base of the B. jacobi Zone.

Discussion

There are just a few recent J–K boundary sections across the Mediterranean Tethys, where the calcareous nannofossil and ammonite record could be directly constrained at a relatively high resolution. These are the Río Argos section Z (Hoedemaeker et al. 2016) and Puerto Escaño (Pruner et al. 2010; Svobodová & Košťák 2016) in SE Spain and the Le Chouet section (Wimbledon et al. 2013; Frau et al. 2015, 2016a, b, c) in SE France. Recently, interesting results have been published from the eastern Crimea J–K boundary section Theodosia (=Feodosia in Guzhikov et al. 2012; Arkadiev et al. 2012; Bakhmutov et al. in press). We shall briefly discuss and compare our data with regard to the available data from these sections, filtering the most reliable bio-horizons (Fig. 12).

In the Mediterranean region, two- or three-fold zonal subdivisions are used for the Upper Tithonian, following reported bottom to top: Simplisphinctes Zone/Subzone, P. transitorius Zone/Subzone or the M. microcanthum Zone, and Durangites

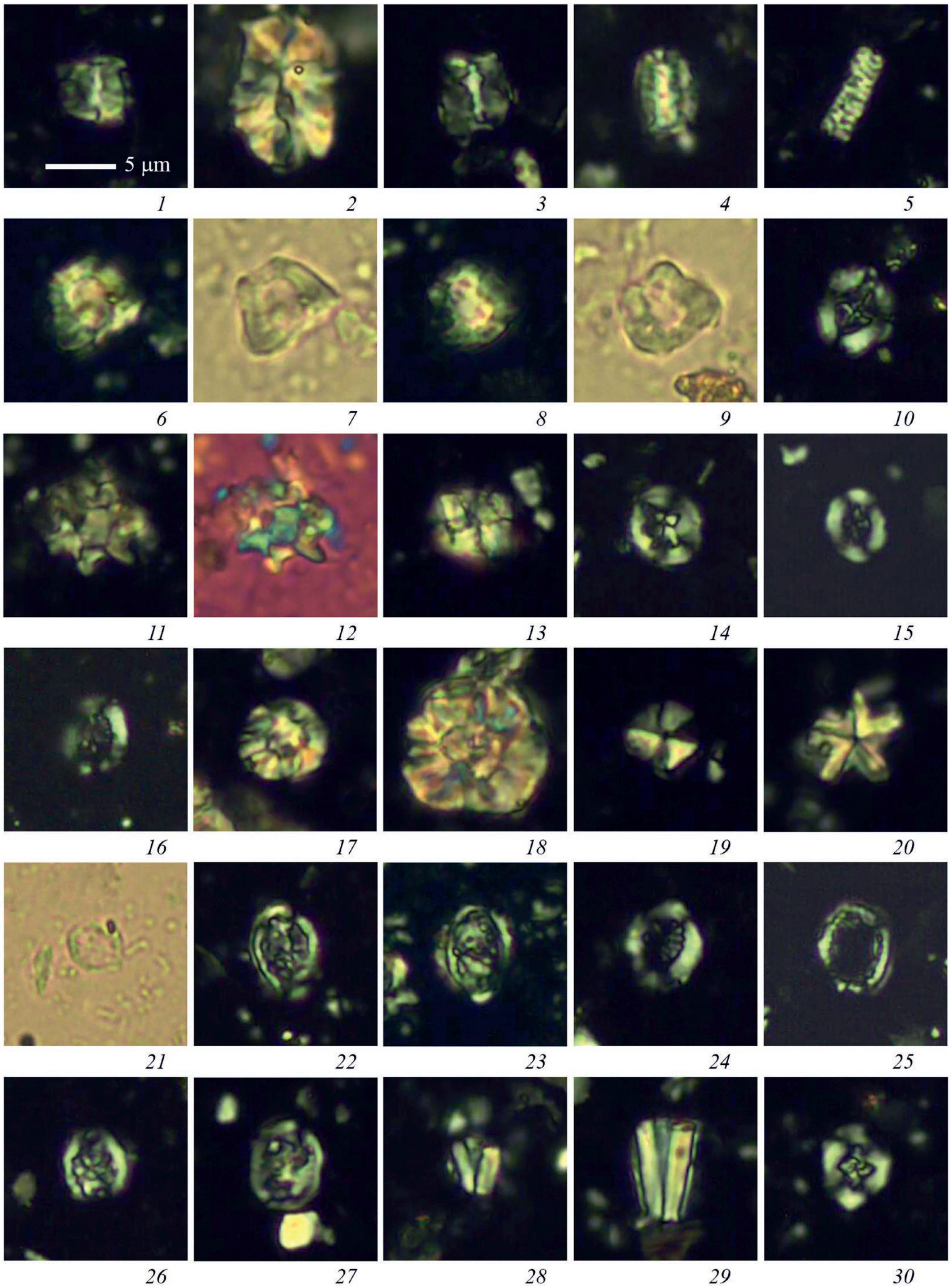

Fig. 8. Main calcareous nannofossil markers from the Upper Tithonian and Lower Berriasian of the Kopanitsa composite section. Magnification 2300×, scale bar 5 µm. *1 — Nannoconus infans,* sample Kpnc 1B-70, cross polarized light (XPL). *2 — Nannoconus compressus,* sample Kpnc 1B-70, XPL. *3 — Nannoconus erbae*, sample Kpnc 1B-79, XPL. *4 — Nannoconus erbae*, sample Kpnc 1B-70, XPL. *5 — Faviconus multicolumnatus,* sample Kpnc 1B-79, XPL. *6–7 — Nannoconus wintereri,* sample Kpnc 1C-6*, XPL and plane polarized light (PPL). *8–9 — Nannoconus wintereri,* sample Kpnc 1C-6*, XPL and PPL. *10 — Helenea conus,* sample Kpnc 1B-64, XPL. *11–12 — Acadialithus dennei*, sample Kpnc 1B-26, XPL and gypsum plate (GP). *13 — Acadialithus dennei*, side view, sample Kpnc 1B-28, XPL. *14 — Cruciellipsis cuvillieri,* sample Kpnc 1A-18, XPL. *15 — Helenea chiastia,* sample Kpnc 1B-46, XPL. *16 — Retecapsa surirella,* sample Kpnc 1B-28, XPL. *17 — Nannoconus globulus minor,* sample Kpnc 1B-44, XPL. *18 — Nannoconus globulus globulus,* sample Kpnc 2-3, XPL. *19 — Hexalithus strictus,* sample Kpnc 2-3, XPL. *20 — Polycostella parvistellatus,* sample Kpnc 1B-56, XPL. *21 — Stephanolithion laffittei,* sample Kpnc 2-3, plane polarized light (PPL). *22 — Umbria granulosa granulosa,* Kpnc 2-5, cross polarized light (XPL). *23 — Umbria granulosa granulosa,* sample Kpnc 1C-6A, XPL. *24 — Retecapsa surirella,* sample Kpnc 1B-72, XPL. *25 — Manivitella pemmatoidea,* sample Kpnc 1A-10, XPL. *26 — Rhagodiscus asper,* sample Kpnc 1B-50, XPL. *27 — Rhagodiscus asper,* sample Kpnc 1B-79, XPL. *28 — Conusphaera mexicana minor,* sample Kpnc 1B-46, XPL. *29 — Conusphaera mexicana mexicana,* sample Kpnc 1B-26, XPL. *30 — Helenea staurolithina,* sample Kpnc 1B-58, XPL.

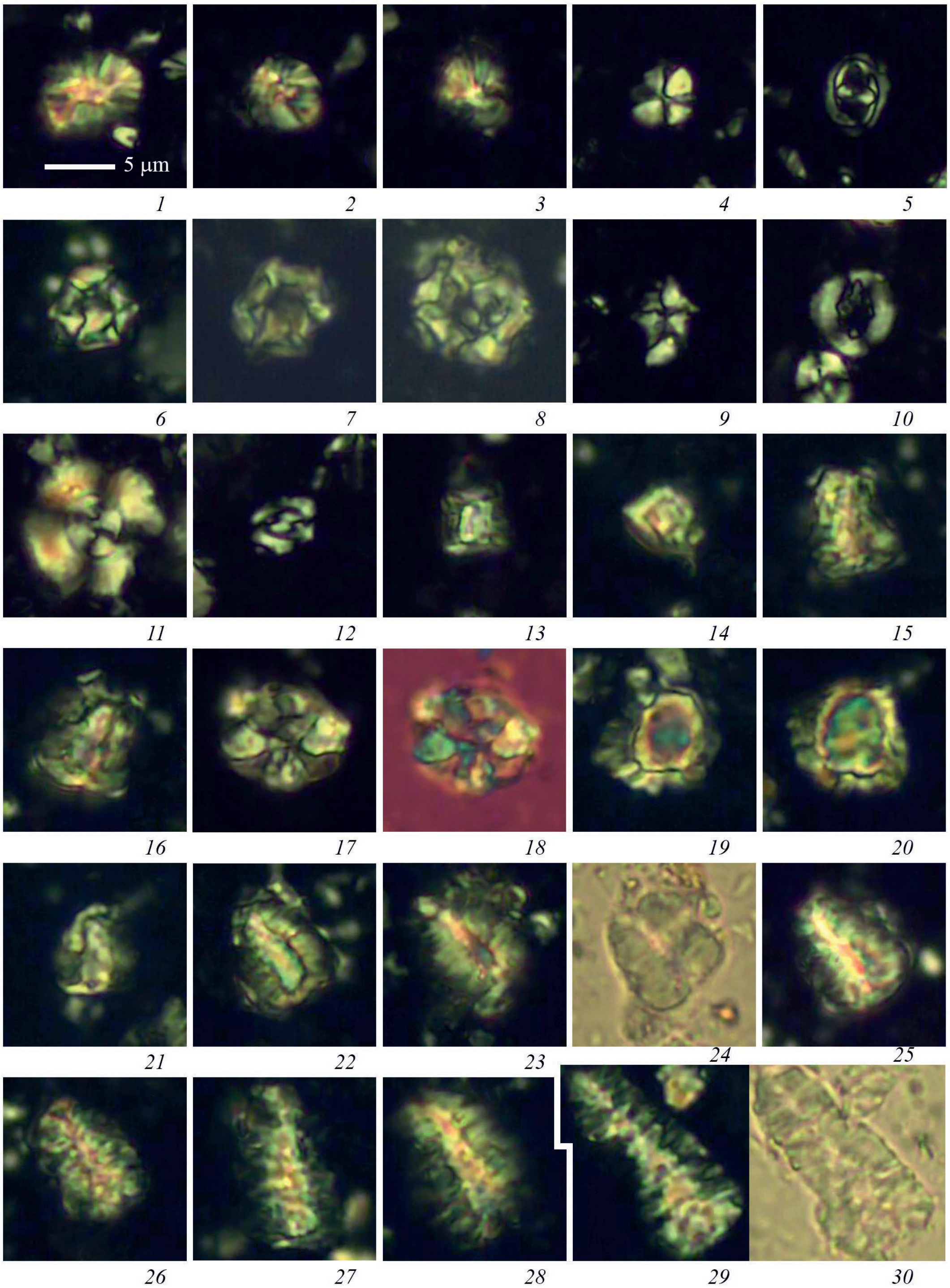

Fig. 9. Main calcareous nannofossil markers from the Upper Tithonian and Lower Berriasian of the Kopanitsa composite section. Magnification 2300×, scale bar 5 µm. *1 — Nannoconus compressus,* sample Kpnc 1B-28, XPL. *2 — Nannoconus puer,* sample Kpnc 1B-24, XPL. *3 — Nannoconus puer,* sample Kpnc 1A-22, XPL. *4 — Polycostella beckmannii,* sample Kpnc 1A-20, XPL. *5 — Zeugrhabdotus fluxus,* sample Kpnc 2-3, XPL. *6–8 — Acadialithus dennei,* sample Kpnc 1C-6*, XPL. *9 — Polycostella senaria,* sample Kpnc 1B-74, XPL. *10 — Cruciellipsis cuvillieri,* sample Kpnc 2-3, XPL. *11 — Watznaueria cynthae,* sample Kpnc 1B-70, cross polarized light (XPL). *12 — Watznaueria communis,* sample Kpnc 1B-48, XPL. *13 — Nannoconus quadratus*, sample Kpnc 1B-79, XPL. *14 — Nannoconus quadratus*, sample Kpnc 1C-6*, XPL. *15–16 — Nannoconus* sp. transitional forms between *N. wintereri* and *N. kamptneri minor*, sample Kpnc 1C-6*, XPL. *17–18 — Acadialithus* sp. (nov.?), sample Kpnc 2-5, XPL and GP. *19–20 — Nannoconus* sp. aff. *bucheri,* sample Kpnc 1C-6*, XPL. *21 — Nannoconus kamptneri minor,* sample Kpnc 1C-6*, XPL. *22 — Nannoconus kamptneri minor,* sample Kpnc 1C-6A, XPL. *23–24 — Nannoconus steinmannii minor,* sample Kpnc 1C-6A, XPL and PPL. *25–26 — Nannoconus steinmannii minor,* sample Kpnc 1C-6A, XPL. *27–28 — Nannoconus kamptneri kamptneri,* sample Kpnc 1C-49, XPL. *29–30 — Nannoconus steinmannii steinmannii,* sample Kpnc 1C-49, XPL and PPL.

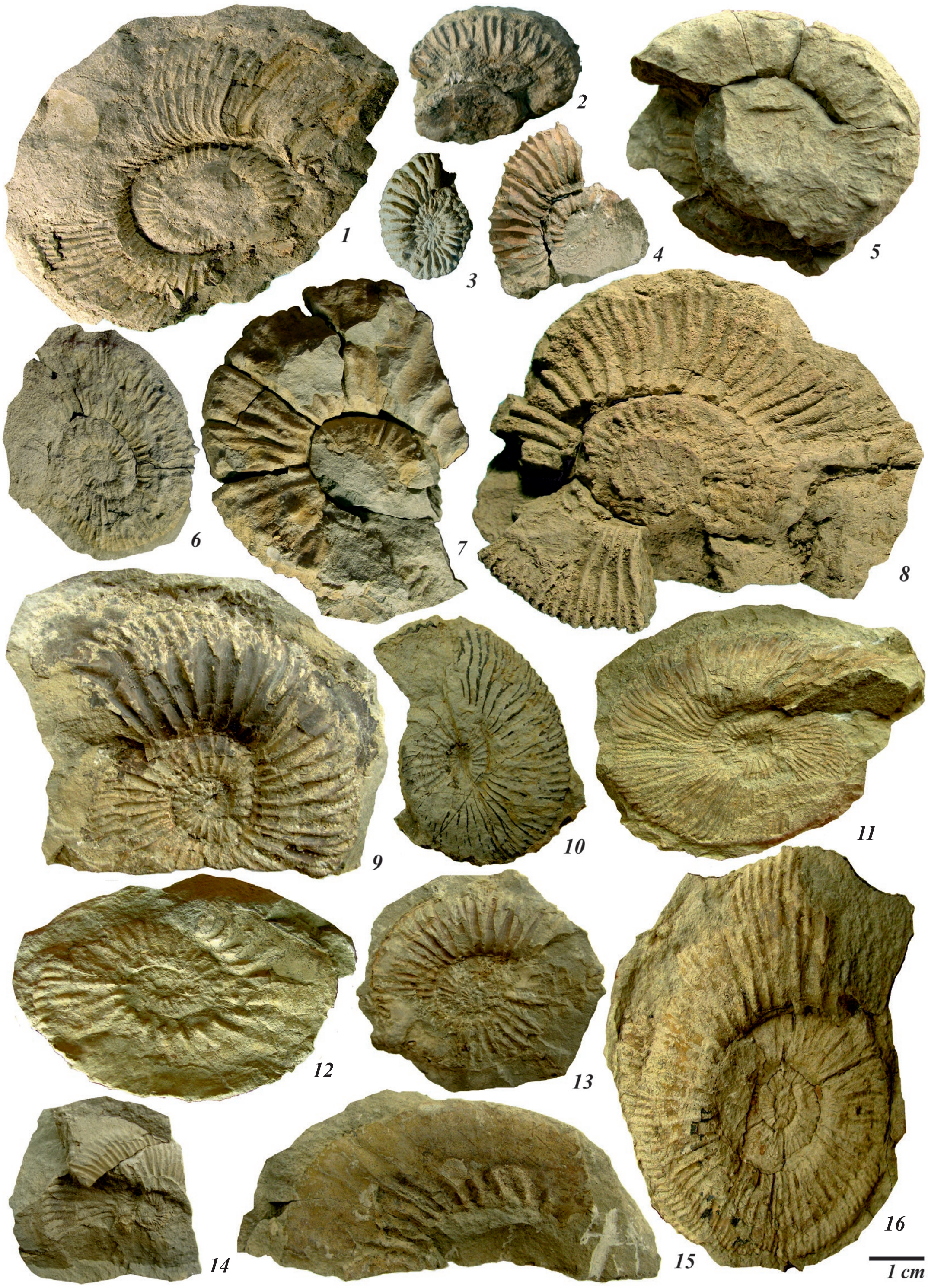

Fig. 10. Main ammonite markers from the Upper Tithonian and Lower Berriasian of the Kopanitsa composite section. Explanation: *1 — Paraulacosphinctes transitorius*, Micracanthoceras microcanthum Zone, Paraulacosphinctes transitorius Subzone, Radibosh subsection, MP-SU K_1 10483. *2 — Durangites singularis*, Durangites spp. Zone, Kopanitsa 1A subsection, MP-SU K_1 10484. *3 — Durangites astillerensis*, Ibid., MP-SU K_1 10485. *4 — Corongoceras radians*, Micracanthoceras microcanthum Zone, Paraulacosphinctes transitorius Subzone, Radibosh subsection, MP-SU K_1 10486. *5 — Micracanthoceras* aff. *microcanthum*, Ibid., MP-SU K_1 10487. *6 — Micracanthoceras* cf. *microcanthum*, Ibid., MP-SU K_1 10488. *7 — Protacanthodiscus* aff. *andreaei*, Durangites spp. Zone, Kopanitsa 1A subsection, MP-SU K_1 10489. *8 — Neoperisphinctes falloti*, Ibid., MP-SU K_1 10490. *9 — Pseudosubplanites* aff. *hegarati*, B. jacobi Zone, Kopanitsa 1C subsection, MP-SU K_1 10491. *10 — Berriasella jacobi*, Ibid. MP-SU K_1 10492. *11 — Pseudosubplanites ponticus*, Ibid., MP-SU K_1 10493. *12 — Dalmasiceras gigas*, B. jacobi Zone, Kopanitsa 2 subsection, MP-SU K_1 10494. *13 — Berriasella oxicostata* (Jacob), Ibid., MP-SU K_1 10495. *14 — Delphinella* cf. *crimensis*, B. jacobi Zone, Kopanitsa 1C subsection, MP-SU K_1 10496. *15 — Dalmasiceras (E.)* cf. *cularense*, B. jacobi Zone, Kopanitsa 2 subsection, MP-SU K_1 10497. *16 — Fauriella shipkovensis*, Ibid., MP-SU K_1 10498.

spp./Durangites vulgaris Zone (Tavera 1985; Geyssant 1997; Sarti 1988; Zeiss 2003). Recently, Wimbledon et al. (2013), Bulot et al. (2014) and Frau et al. (2015, 2016a, b, c), regarding Upper Tithonian ammonite fauna from SE France, considered the genus *Durangites* to be exclusively distributed in the Mexican region. All records of the genus mentioned in the Mediterranean region are assigned by these authors to juvenile and microconch forms of genus *Protacanthodiscus*, or to the new genus *Boughdiriella* (Frau et al. 2015). This team proposed the replacement of the Durangites spp. Zone by the Protacanthodiscus andreaei Zone within the upper part of the Upper Tithonian (Frau et al. 2015). However, as Hoedemaeker et al. (2016) correctly noted, "the Andreaei Zone of Bulot (in Wimbledon et al. 2013) is a junior synonym of the Durangites vulgaris Zone". Regardless of the fact that the genus *Durangites* shares common features with *Protacanthodiscus* (Enay et al. 1998), the occurrences of its species have been well-documented throughout the Mediterranean region (Tavera 1985; Enay et al. 1998; Ivanov et al. 2010, etc.). In our opinion, the species belonging to genus *Durangites* are sufficiently distinguishable and their geographic distributions could not be restricted only to the Mexican region.

Frau et al. (2016a, b, c) discussed the content and vertical range of some well-known Lower Berriasian genera such as *Berriasella, Dalmasiceras* and *Delphinella* and made a revision of the index-species *B. jacobi*, assigning it to the genus *Strambergella*. They identified four time-successive ammonite assemblages in sections of SE France, with the *Elenaella cularense* [=*Dalmasiceras (E.) cularense*] assemblage as the oldest, whereas an assemblage, dominated by *Strambergella jacobi* (=*B. jacobi*) and *Strambergella carpathica* is the youngest one. Our observations from the expanded Kopanitsa 1C and 2 sections do not corroborate such a stratigraphic differentiation. Moreover, it should be noted that *D. (E.) cularense* occurs within the upper levels of both our subsections, co-occurring with *Fauriella shipkovensis*. Hoedemaeker et al. (2016) compared the faunal composition of the B. (Hegaratella) jacobi Zone of sections from SE Spain and SE France. They suggested that in the successions of the same age, the abundance, impoverishment, rarity or absence of some of the typical lower Berriasian genera such as *Dalmasiceras, Delphinella* and *Pseudosubplanites* could be due to different palaeoecological settings.

Regarding Puerto Escaño, it has to be highlighted that the Upper Tithonian–Lower Berriasian succession there is very condensed and every bed is topped by a small hiatus (see comments of Hoedemaeker et al. 2016). The thicknesses of the ammonite zones are very thin and all nannofossil bio-horizons are closely spaced (Fig. 12). Since some primary markers (i.e. *N. steinmannii minor, N. kamptneri minor, N. steinmannii steinmannii* and *N. kamptneri kamptneri*) first occurred together at the base of bed 35 (Svobodová & Košťák 2016), we believe that the entire NKT Zone is missing in this section. The presence of this particular hiatus has already been suggested by Svobodová & Košťák (2016). Therefore, the hiatus is evident, but it can be detected only by nannofossils.

Our data from Kopanitsa section are generally comparable to those reported from the Le Chouet section (Wimbledon et al. 2013). The FOs of *N. globulus minor, N. wintereri, N. kamptneri minor* and *N. steinmannii minor* are consistent in both sections, within the equivalent ammonite zones (Fig. 12). However, some inconsistencies are also evident: the FOs of *N. globulus globulus, C. cuvillieri, H. strictus* and *Umbria granulosa granulosa* are registered at younger levels in Le Chouet (within NJT 17b Subzone and B. Jacobi Zone). In Kopanitsa they occurred in a different stratigraphic order and, notably, at older levels (NJT 17a Subzone and Durangites spp. Zone) (Fig. 12).

The Kopanitsa composite section shows the greatest lithological similarity to the Crimean sections near Feodosia–Dvuyakornaya buhta and St. Ilia Cape (Guzhikov et al. 2012). Furthermore, the ammonite record in both locations is quite similar — despite the lack of *Durangites*, the M. microcantum Zone (with P. transitorius beds) and B. jacobi Zone (with B. jacobi and P. grandis Subzones) have been proved by Guzhikov et al. (2012). Recent study of the same coastal succession in the eastern Crimea provides a new, detailed insight on the magnetostratigraphy, ammonites, calpionellids and calcareous nannofossils occurrences (Bakhmutov et al. in press).

The best agreement of nannofossil data is between Kopanitsa and Río Argos (Casellato & Gardin *in* Hoedemaeker et al. 2016). Unfortunately, the ammonite data are limited to the B. jacobi Zone. Nevertheless, the following primary and secondary bio-horizons have been found in the same stratigraphic order in both sections: FOs of *Umbria granulosa minor, Retecapsa surirella, Hexalithus strictus, N. wintereri, N. kamptneri minor, N. steinmannii minor, N. kamptneri kamptneri, N. steinmannii steinmannii* (Fig. 12). These bio-horizons can be confirmed as reliable for correlations. However, there are also some discrepancies regarding the FOs of *C. cuvillieri* and *N. globulus globulus*: both species are registered at older levels at Kopanitsa than in Río Argos section. Obviously the latter could not be used as reliable bio-horizons. Although the main disagreement is in the relative positioning of the NJT 17a nannofossil Subzone: in the Durangites spp. Zone at Kopanitsa, but in the Berriasella jacobi Subzone at Río Argos (Fig. 12).

Conclusions

Calcareous nannofossil, calpionellid and ammonite distributions have been directly constrained across the continuous Jurassic–Cretaceous boundary interval of the expanded Kopanitsa composite section, SW Bulgaria. Several important biostratigraphic results have been obtained, which can be summarized as follows:

- The topmost part of NJT 16b and the base of NJT 17a nannofossil Subzones correlate with the Microcanthum/Transitorius ammonite Subzone. The major part of the NJT 17a Subzone equates to the Durangites spp. ammonite Zone, whereas the NJT 17b Subzone correlates with the

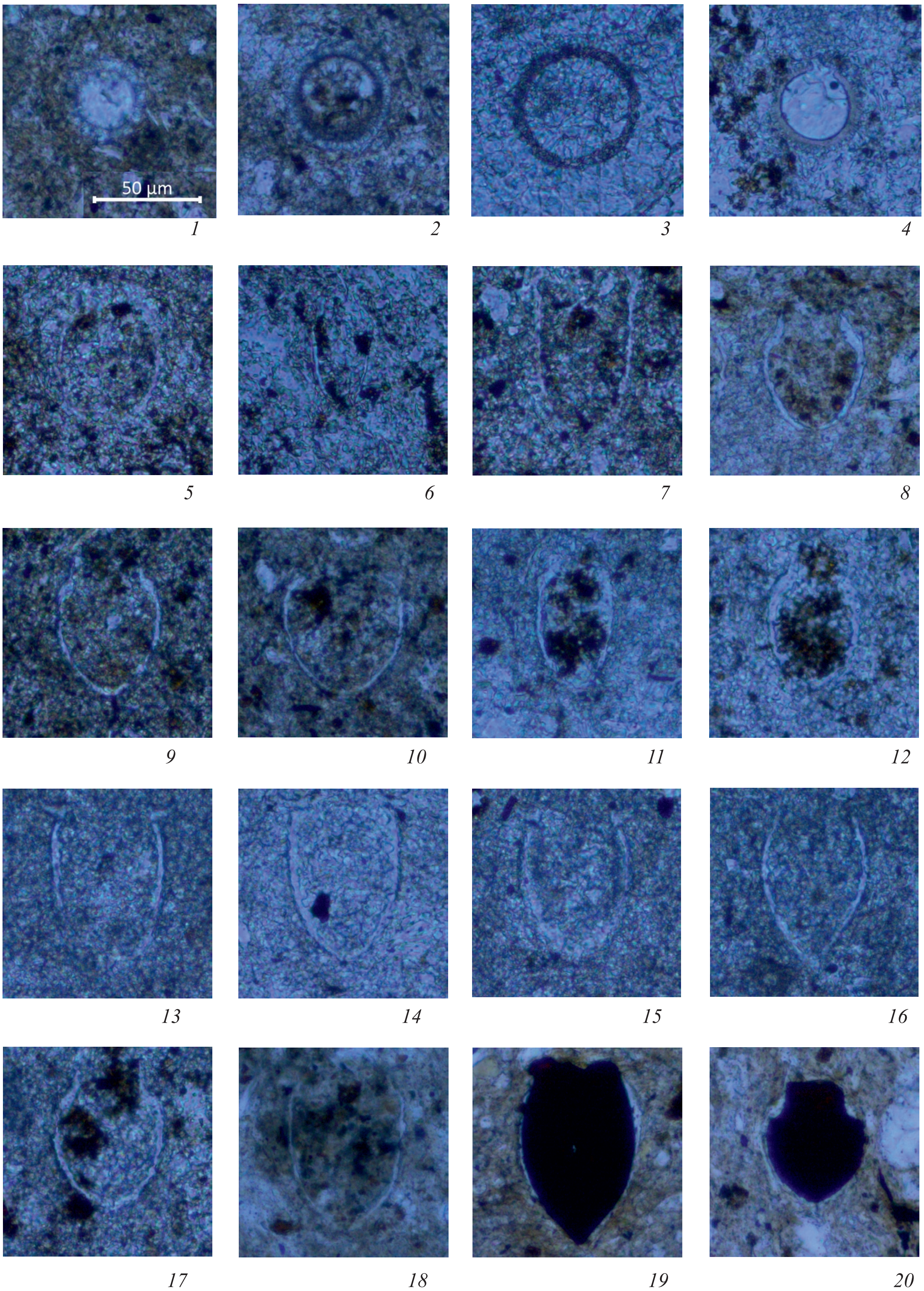

Fig. 11. Cysts of calcareous dinoflagellates and calpionellids, recorded in the Kopanitsa composite section, scale bar 50 µm. Explanation: *1 — Colomisphaera lapidosa*, sample Rdb-3. *2 — Cadosina semiradiata semiradiata*, sample Kpnc 1A-5. *3 — Cadosina semiradiata fusca*, sample Kpnc 1A-7. *4 — Cadosina semiradiata fusca*, sample Kpnc 1C-6. *5 — Calpionella elliptalpina*, sample Kpnc 1A-7a. *6 — Crassicollaria massutiniana*, sample Kpnc 1A-7a. *7 — Crassicollaria intermedia*, sample Kpnc 1A-7b. *8–9 — Calpionella alpina*, sample Kpnc 1C-3a. *10 — Lorentziella hungarica*, sample Kpnc 1C-3a. *11 — Crassicollaria parvula*, sample Kpnc 1C-6b. *12 — Calpionella* cf. *elliptica*, sample Kpnc 1C-6b. *13 — Remaniella borzai*, sample Kpnc 1C-5a. *14 — Remaniella colomi*, sample Kpnc 1C-5a. *15 — Remaniella ferasini*, sample Kpnc 1C-5a. *16 — Tintinnopsella carpathica*, sample Kpnc 1C-5a. *17 — Calpionella alpina*, sample Kpnc 1C-6a. *18 — Tintinnopsella carpathica*, lorica filled by pyrite, sample Kpnc 1C-48. *19 — Tintinnopsella carpathica*, lorica filled by pyrite, sample Kpnc 1C-48. *20 — Calpionella alpina*, lorica filled by pyrite, sample Kpnc 1C-48.

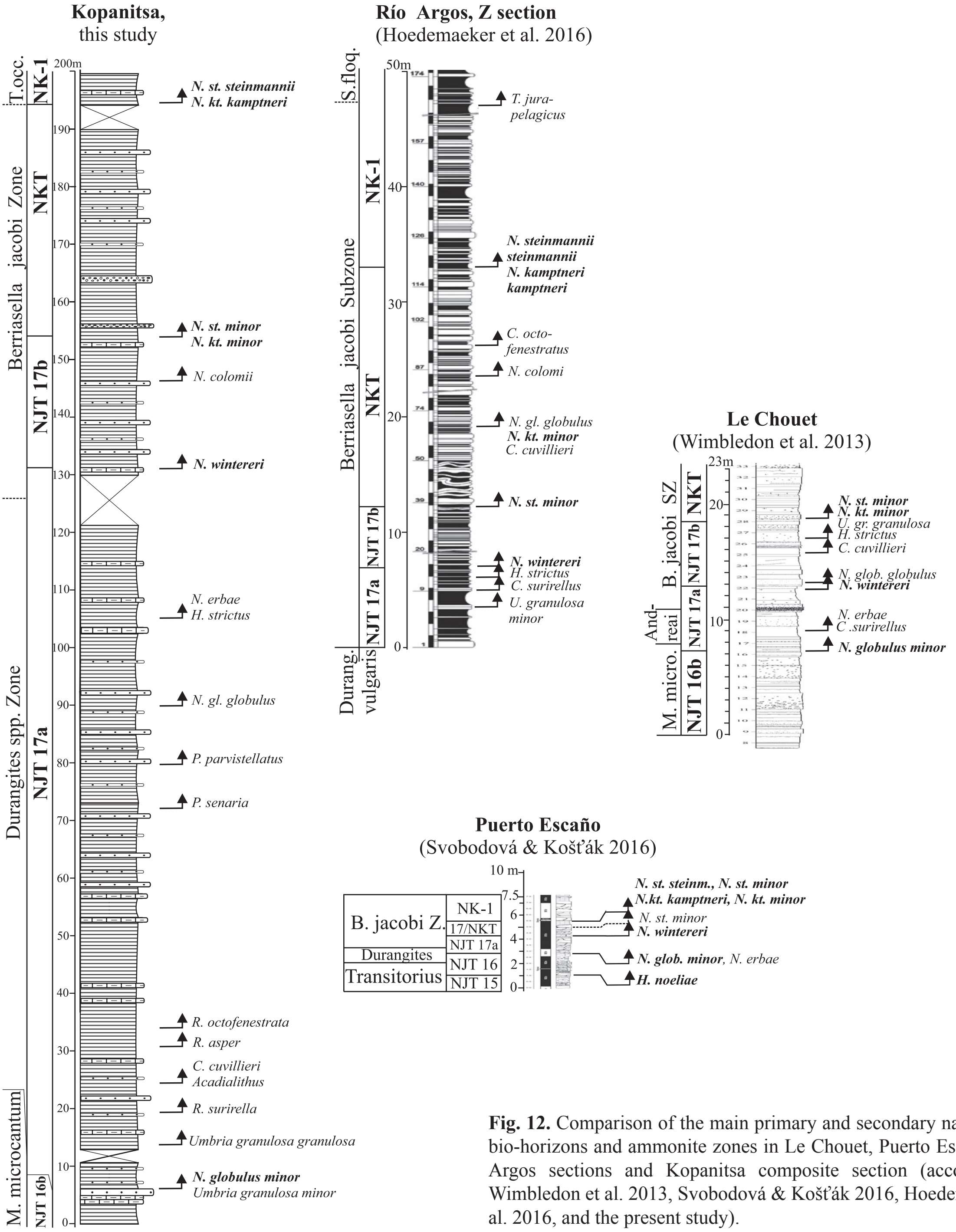

Fig. 12. Comparison of the main primary and secondary nannofossil bio-horizons and ammonite zones in Le Chouet, Puerto Escaño, Río Argos sections and Kopanitsa composite section (according to Wimbledon et al. 2013, Svobodová & Košťák 2016, Hoedemaeker et al. 2016, and the present study).

lower part of the B. jacobi ammonite Zone. The NKT nannofossil Zone corresponds to the upper part of the B. jacobi Zone and the NK-1 Zone correlates to the lowest part of the T. occitanica ammonite Zone at least.

- The calcareous nannofossil group underwent fast evolutionary diversification during Late Tithonian to Early Berriasian times, producing a series of successive bio-events. The FOs of *N. globulus minor, N. wintereri, N. kamptneri minor, N. steinmannii minor, N. kamptneri kamptneri* and *N. steinmannii steinmannii* are confirmed as reliable bio-horizons for correlations, at least in the Mediterranean Tethys area.
- Actually, the nannofossils provide the highest stratigraphic resolution within the J–K boundary interval and therefore are the only biostratigraphic tool, which could reliably detect hiatuses/gaps in the sedimentary record, especially when condensed. The same is not valid for the other microfossil groups, or for the ammonites.
- The FO of *C. cuvillieri* is a Late Tithonian event, clearly documented in the lower part of the Durangites ammonite

Zone. Therefore it should be removed from the bio-horizons proposed to constrain the Jurassic–Cretaceous boundary interval in the Tethyan Realm (Wimbledon et al. 2013).
- Genus *Acadialithus*, with a short range in the Upper Tithonian NJT 17a–NJT 17b Subzones interval, should be further sought and used for biostratigraphic purposes in the J–K boundary interval.
- The FO of *N. wintereri* fairly well approximates the FO of *Berriasella jacobi*, since this bio-horizon could have a high relevance to be explored in approximating the base of the Berriasian Stage.
- In terms of the ammonites, the FOs of *N. steinmannii minor* and *N. kamptneri minor* are Berriasian events, occurring within the middle part of B. jacobi Zone, approximating the FO of *Pseudosubplanites grandis*.
- The calpionellids occurrence reveals the presence of the Late Tithonian (Intermedia Subzone) and Early Berriasian (higher part of the Alpina Subzone, Ferasini Subzone and Elliptica Subzone), although it was impossible to place accurately the onset of the successive calpionellid subzones. The calpionellid study enables us to identify more precisely the relative position of the J–K boundary according to the formal decision of the Berriasian working group — the base of the Alpina Subzone.
- The microfacies analysis suggests a steep slope of a steepened ramp as the most likely depositional environmental of the sediments studied.

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Supplementum

Appendix A

Taxonomic index of calcareous nannofossil species in alphabetical order

Acadialithus dennei Howe, 2017
Assipetra infracretacea (Thierstein, 1973) Roth, 1973
Conusphaera mexicana mexicana Trejo, 1969
Conusphaera mexicana minor (Trejo, 1969) Bown & Cooper, 1989
Cruciellipsis cuvillieri (Manivit, 1956) Thierstein, 1971
Cretarhabdus conicus Bramlette & Martini, 1964
Cyclagelosphaera argoensis Bown, 1992
Cyclagelosphaera deflandrei (Manivit, 1966) Roth, 1973
Cyclagelosphaera margerelii Noël, 1965
Cyclagelosphaera brezae Applegate & Bergen, 1988
Diazomatolithis galicianus Kaenel & Bergen, 1996
Faviconus multicolumnatus Bralower *in* Bralower et al., 1989
Helenea chiastia Worsley, 1971
Helenea conus (Worsley, 1971) Rutledge & Bown *in* Bown et al., 1998
Helenea staurolithina Worsley, 1971
Hexalithus noeliae (Noël, 1956) Loeblich & Tappan, 1966
Hexalithus strictus Bergen, 1994
Lithraphidites carniolensis Deflandre, 1963
Manivitella pemmatoidea (Deflandre *in* Manivit, 1965) Thierstein, 1971
Miravetesina favula Grün *in* Grün and Allemann, 1975
Nannoconus alvus Perch-Nielsen, 1988
Nannoconus aff. *bucheri* Brönnimann, 1955
Nannoconus colomii (de Lapparent 1931) Kamptner, 1938
Nannoconus compressus Bralower & Thierstein *in* Bralower et al., 1989
Nannoconus concavus Perch-Nielsen, 1988
Nannoconus erbae Casellato, 2010
Nannoconus globulus globulus Brönnimann, 1955
Nannoconus globulus minor (Brönnimann, 1955) Bralower *in* Bralower et al., 1989
Nannoconus infans Bralower *in* Bralower et al., 1989
Nannoconus kamptneri kamptneri Brönnimann, 1955
Nannoconus kamptneri minor (Brönnimann, 1955) Bralower *in* Bralower et al., 1989
Nannoconus puer Casellato, 2010
Nannoconus quadratus (Noël 1959) Deres & Achéritéguy 1980
Nannoconus steinmannii minor (Kamptner, 1931) Deres & Achéritéguy, 1980
Nannoconus steinmannii steinmannii Kamptner, 1931
Nannoconus wintereri Bralower & Thierstein *in* Bralower et al., 1989
Polycostella beckmannii Thierstein, 1971
Polycostella senaria Thierstein, 1971
Polycostella parvistellatus (Varol, 1991)
Retecapsa crenulata (Bramlette & Martini, 1964) Grün *in* Grün and Allemann, 1975
Retecapsa octofenestrata (Bralower *in* Bralower et al., 1989) Bown in Bown & Cooper, 1998
Retecapsa surirella (Deflandre & Fert, 1954) Grün *in* Grün and Allemann, 1975
Rhagodiscus asper (Stradner, 1963) Reinhardt, 1967
Rhagodiscus gallagheri Rutledge & Bown, 1996
Stephanolithion laffittei Noël, 1957
Umbria granulosa granulosa Bralower & Thierstein *in* Bralower et al., 1989
Umbria granulosa minor Bralower & Thierstein *in* Bralower et al., 1989
Watznaueria barnesiae (Black *in* Black & Barnes, 1959) Perch-Nielsen, 1968
Watznaueria britannica (Stradner, 1963) Reinhardt, 1964
Watznaueria communis Reinhardt, 1964
Watznaueria cynthae Worsley, 1971
Watznaueria manivitiae (Bukry, 1973) Moshkovitz & Ehrlich, 1987
Zeugrhabdotus cooperi Bown, 1992
Zeugrhabdotus embergeri (Noël, 1958) Perch-Nielsen, 1984
Zeugrhabdotus erectus (Deflandre *in* Deflandre & Fert, 1954) Reinhardt, 1965
Zeugrhabdotus fluxus Casellato, 2010

Appendix B

Taxonomic index of ammonite species in alphabetical order

Berriasella jacobi Mazenot, 1939
Berriasella cf. *jauberti* Mazenot, 1939
Berriasella oxicostata (Jacob) in Mazenot, 1939
Berriasella cf. *subcalisto* (Toucas, 1890)
Berriasella aff. *tithonica* Tavera, 1985
Berriasella cf. *tithonica* Tavera, 1985
Corongoceras hyspanicum Tavera, 1985
Corongoceras cf. *mendozanum* (Behrendsen, 1922)
Corongoceras cf. *minor* Tavera, 1985
Corongoceras radians Tavera, 1985
Dalmasiceras (Elenaella) cf. *cularense* (Mazenot, 1939)
Dalmasiceras gigas Djanélidzé, 1922
Delphinella cf. *crimensis* (Burckhardt, 1912)
Delphinella cf. *delphinensis* (Kilian, 1889)
Delphinella janus (Retowski, 1893)
Djurjuriceras sp. indet.
Durangites acanthicus Burckhardt, 1912
Durangites astillerensis Imlay, 1939
Durangites aff. *fusicostatus* Burckhardt, 1912
Durangites cf. *gigantis* Tavera, 1985
Durangites singularis Tavera, 1985
Durangites cf. *vulgaris* Burckhardt, 1912
Fauriella shipkovensis (Nikolov & Mandov, 1967)
Himalayites sp. indet.
Micracanthoceras aff. *microcanthum* (Oppel, 1865)
Micracanthoceras cf. microcanthum (Oppel, 1865)
Neoperisphinctes falloti (Kilian, 1889)
Paraulacosphinctes cf. *senoides* Tavera, 1985
Paraulacosphinctes transitorius (Oppel, 1865)
Protacanthodiscus andreaei (Kilian, 1889)
Pseudosubplanites cf. *combesi* Le Hégarat, 1973
Pseudosubplanites grandis (Mazenot, 1939)
Pseudosubplanites aff. *hegarati* Hoedemaeker, 2016
Pseudosubplanites lorioli (Zittel, 1868)
Pseudosubplanites ponticus (Retowski, 1893)
Pseudosubplanites subrichteri (Retowski, 1893)
Spiticeras sp.
Subalpinites aff. *aristidis* (Kilian, 1895)
Tithopeltoceras sp. indet.

Appendix C

Taxonomic index of calcareous dinocyst and calpionellid species in alphabetical order

Cadosina semiradiata semiradiata (Wanner, 1940)
Cadosina semiradiata fusca (Wanner, 1940)
Colomisphaera carpathica (Borza, 1964)
Colomisphaera fortis Řehánek, 1982
Colomisphaera lapidosa (Vogler, 1941)
Stomiosphaera sp.

Calpionella alpina Lorenz, 1902
Calpionella elliptalpina Nagy, 1986
Calpionella elliptica Cadish, 1932
Crassicollaria intermedia (Durand-Delga, 1957)
Crassicollaria massutiniana (Colom, 1948)
Crassicollaria parvula Remane, 1962
Lorenziella hungarica Knauer and Nagy, 1964
Remaniella ferasini (Catalano, 1965)
Remaniella catalanoi Pop, 1996
Remaniella colomi Pop, 1996
Remaniella borzai Pop, 1994
Tintinnopsella carpathica (Murgeanu and Filipescu, 1933)
Tintinnopsella doliphormis (Colom, 1939)