THE JURASSIC/CRETACEOUS TRANSITION IN THE BAKONY MOUNTAINS (TRANS-DANUBIAN RANGE, HUNGARY)

> *“All the fossils that we have ever found have always been found in the appropriate place in the time sequence. There are no fossils in the wrong place.”*
>
> Richard Dawkins (1941–), Answering to Reuters during a tour to promote his new book about evolution

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1. Introduction

The position of the Jurassic/Cretaceous (J/K) boundary is a longstanding problem as it is the last system boundary which is still not fixed. Since 1975 (Énay 2020), the base of the Berriasian stage is nominated as the boundary between the Jurassic and Cretaceous systems. In the past decades, the Berriasian Working Group led by W. Wimbledon added outstanding scientific achievements to place the J/K boundary to the base of the Berriasian. In 2016, the group voted the acme event of *Calpionella alpina*, as a marker of the base of

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Alpina Subzone to be the primary marker for the Tithonian/Berriasian (T/B) boundary (Wimbledon et al. 2020). However, even in the Tethys, calpionellids are not the only critical faunal elements of this interval: ammonites, calcareous dinocysts and nannofossils also have historical and significant role in the characterization of this period (Reháková & Michalík 1997, Frau et al. 2016a,b,c, Casellato & Erba 2021). In addition to the classical paleontological definition criteria on placing a stage or system boundary, independent methods as magneto-, chemo-, climate and cyclostratigraphy may provide important data to achieve supraregional correlation (see Grabowski et al. 2010, 2016, Schnabl et al. 2015, Manikin et al. 2019, Price et al. 2016, Deconick 1993, Schnyder et al. 2006, Galloway et al. 2020).

The J/K boundary interval of the Transdanubian Range (TR) manifests a distinct lithologic succession, depending on paleogeographic and paleobathymetric position of a particular section. The Late Jurassic was characterized by a large-scale basin-and-horst architecture, with pelagic sedimentation between the basins and non-deposition or condensation zones on horsts (Vörös & Galácz 1998). In addition, during the earliest Cretaceous the marginal zones of the Neotethys were uplifted (e.g. Gawlick et al. 2009, Missoni & Gawlick 2010a,b), what affected also the TR. As a consequence, the TR was subdivided into two basins – the proximal Gerecse Basin to the northeast and the distal Bakony Basin to the southwest – which were separated by a relatively elevated submarine plateau. The Gerecse Basin was subjected to fine-grained siliciclastic and argillite sedimentation, the submarine plateau was characterized by limited and condensed carbonate deposition, whilst in the Bakony Basin maiolica/biancone-type pelagic carbonates and siliceous oozes were deposited (Fülöp 1964, Tari 1994, Szederkényi et al. 2013, Grabowski et al. 2017, Lodowski et al. 2022).

Recently, new magnetostratigraphic and geochemical investigations were carried out on some Hungarian sections, namely Lókút (Grabowski et al. 2010, 2017, Lodowski et al. 2022) and Hárskút composite (HK-12 and HK-12/a) sections (Lodowski et al. 2022), and also from Szilas Ravine. Geochemical research is previously performed on HK-12 by Főzy et al. (2010) and on HK-II and Lókút LH-I by Price et al. (2016). A very recent ammonite collecting was done at HK-12/a which clarified the ammonite biostratigraphy of the section, as well as new stable carbon and oxygen isotope data is published here (Főzy et al. 2022a, this volume) from Szilas Ravine and Hárskút Édesvíz Key (HEK) sections.

In this chapter we summarize our new and already published integrated data in order to outline the J/K transition of the Bakony Mountains. Geochemical evidences are summarized and paleoenvironmental reconstruction is concluded, also new perspectives on the topic are briefly endorsed.

2. Material

Bakony Mountains is well known for its Jurassic and Cretaceous sequences among palaeontologists. Its Jurassic marine fauna is ypically Mediterranean *sensu* Cecca (1999), where ammonite assemblages comprise approximately 80% Phyllo- and Lytoceratidae. However, the J/K transition can be observed just in some particular sections, where upper Tithonian strata consist of ammonitico rosso-type marlstone (Hárskút HK-II, HK-12/a, Szilas Ravine, Fekete Hill and Rend-kő I and II) of Pálihálás Limestone Formation *or* whitish cream biancone/maiolica-type cherty limestone (Lókút) of Szentivánhegy Marlstone Formation. In all sections these gradually pass into a pelitic cream maiolica of the early Berriasian age. As the nature of the ammonitico rosso sedimentation and the local geotectonic regime predicts, sequences are mostly condensed, sometimes interrupted by hiati. For further descriptions of lithology, formations and localities see Szinger & Főzy (2022) and Főzy et al. (2022a), both this volume.

Systematic collecting of fossils from the area had been started in the 1960's, when the professional collecting team of the Hungarian Geological Institute presented thousands of fossils, and sections containing the supposed J/K transition of the Bakony Mountains were targeted. The successive collecting campaigns in the sections nearby the village of Hárskút as HK-12, HK-12/a, HK-II and Édesvíz Key (HEK) section were supervised by József Fülöp, that time director of the Hungarian Geological Institute. Results of this extended fieldwork were published mainly under his name (Fülöp 1964). Another important profile of the Szilas Ravine section was sampled in the 1980's under the supervision of Géza Császár. Field notes of Lókút LK-II, HEK and HK-II are at our disposal, so on the basis of strata thicknesses and lithology it was possible to correlate ammonitiferous beds to new sampling points. At Lókút, Hárskút HK-12 and HK-12/a sections, the nannofossil, calpionellid and the ammonite, stratigraphy of the uppermost Tithonian–Berriasian were revised by Lodowski et al. (2022) and Szives & Főzy (2022); the HK-II succession was completed by Horváth & Knauer (1986).

Ammonites of the J/K transition in the Bakony Mountains were not studied in details until now.

3. Ammonites

3.1. The J/K boundary interval from the ammonite point of view

The "state of the art" on the J/K boundary was summarized several times in the literature from Hoedemaeker (1981, 1982), Olóriz & Tavera (1989) to Énay (2020) and Wimbledon et al. (2011, 2020), so will be resumed just shortly here. Ammonite specialists of the SE France area considered Berriasian strata as the part of the Cretaceous (Coquand 1871, Mazenot 1939, Le Hégarat 1973) but already noticed it contains mixed ammonite faunas of the Jurassic and the Cretaceous. However, without well-defined stratotype section, the boundary between the two systems still remained obscure.

By meaning of ammonites, in a very simplified way, the J/K boundary interval can be outlined as a gradual turnover between Jurassic Ataxioceratidae and the Cretaceous Neocomitidae. From taxonomic point of view, the appearance of a new family, i.e. Neocomitidae, seemed more important than the extinction of Ataxioceratidae, which recognition encouraged Énay & Geyssant (1975) to propose a new J/K boundary to be placed to the base of the *Berriasella jacobi*/*Pseudosubplanites grandis* Zone (as the base of the Berriasian stage) where, as they realized, the first Neocomitidae suddenly seemed to appear. This motion was voted in Neuchatel in 1975, but as a long lasting consequence, the J/K boundary is the last system boundary that still has no selected GSSP until now. According to Hoedemaeker et al. (2016), 1.8 million years was added to the Berriasian stage by this motion in Neuchatel, so the duration of the Cretaceous epoch was extended.

However, a group of problems emerged around this motion mainly from three points: (1) ammonite specialists of this time interval (Mazenot 1939, Nikolov 1966, Le Hégarat 1973), besides in-situ collecting for themselves, were working, depicting type specimens on *museum materials* sometimes collected from uncertain levels; (2) early ammonite works lack of proper stratigraphy, no integrated micropaleontologic constrain was given, presence of slumps, condensation and hiati were not detected by that time; (3) low sea level around the J/K boundary (Gale et al. 2020) caused huge ammonite *provincialism*, besides different facies distribution resulted different coeval assemblages that were treated erroneously as not contemporaneous (Mazenot 1939). Sedimentologic inaccuracies and lack of proper sampling led to long lasting misinterpretation of the ammonite faunas, even the „lacunes de connaissances" already were noticed by Mazenot (1939). Le Hégarat (1973) corrected some of these problems (Énay 2020) and established a new age constrain for SE France sections, which is more or less in use nowadays as a Tethyan standard (Reboulet et al. 2018), recently revised by Szives & Főzy (2022). However, the huge provincialism has even more serious consequences as strongly limits the intraprovincial correlation possibilities.

Tavera (1985) added crucial informations to our knowledge on the J/K boundary interval ammonite faunas of the Mediterranean-Caucasian Subrealm (Westermann, 2000; Page, 2008; Lehmann et al. 2015) of the Tethys. After examining material from various localities of the Betic Cordilleras, he pointed out three steps of ammonite faunal „renovations" during the Late Jurassic–Early Cretaceous time interval. First renovation is at the transition of the lower and upper Tithonian (between the Volanense/Microcanthum Zones), the second is between the „Vulgaris"/"Jacobi" zones (namely around the present T/B boundary), and the third renewal is at the base of the Occitanica Zone (base of the middle Berriasian). According to Hoedemaeker et al. (2016), all renewals can be linked to major sea level changes, which can be demonstrated as certain levels that were manifested as mudflow deposits during rapid sea level falls in the Rio Argos section (Hoedemaeker et al. 2016). This seems a reasonable idea that some ammonite groups were, up to a certain level, more sensitive to sea level changes than others. It seems obvious these faunal turnovers may linked to paleoenvironmental changes and we "only" have to consider which one can be documented more precisely in a continuous section with reliable fossil record and calibrated to chemo-, cyclo-, climate- and magnetostratigraphic constrain in supraregional scale to serve as the base of the Cretaceous.

Contradictions and major problems on the biostratigraphic scheme easily can be recognized if we have a look on two different chapters, the Jurassic and Cretaceous of the same book – the Geological Time Scale (Ogg et al. 2016), where „Durangites" Zone is figured as different biochronozonal unit (fig. 2. in Ogg et al. 2016) in the Jurassic and in the Cretaceous chapters. However, this point was clarified in the latest volume (Hesselbo et al. 2020, Gale et al. 2020), but reflects the original problem: until the works of Bulot et al. (2014) and Frau and his collaborators (2016a,b,c), the ammonite biostratigraphy of this interval lent on chaotic taxonomy and collected from sections of disturbed deposition or obscure stratigraphy. Retain of "Jacobi" (Bulot et al. 2014) and "Durangites/Vulgaris" Zones and introduction of Andreaei Zone and Fischeri Subzone resulted significant recent changes to the zonal scheme (Gale et al. 2020) compared to previous ones. In Gale et al. (2020), an updated concept was adopted, as „Durangites" Zone was abandoned and changed to *Protacanthodiscus* *andreaei* Zone, but *Berriasella jacobi* Zone was still in use there. Standard ammonite zonation (Reboulet et al. 2018) needs improvement for this time interval, as several new taxonomic investigations were carried out (Bulot et al. 2014, Frau et al. 2016a,b,c).

Nevertheless, on the basis of ongoing studies on Hungarian ammonite assemblages, new improvements were also added on the zonation of the interval with the reintroduction of Volanense Zone (Cecca & Santantonio 1988), Chaperi Zone (Nikolov 1967), and introduction of Progenitor Zone (Szives & Főzy 2022) as replacements for the former "Jacobi" Zone.

3. 2. Late Tithonian–early Berriasian ammonite record and ammonite stratigraphy of the Bakony Mountains

Following the publication of Fülöp (1964), the ammonite and calpionellid stratigraphy of the uppermost Tithonian–Berriasian was revised for some sections, as of the Hárskút HK-12 and HK-II (Horváth & Knauer 1986). The ammonites of the J/K transition from the Bakony sections were not studied in detail until now, however a basic stratigraphic framework was constituted and some forms were depicted by Vígh (1984) and later by Főzy (1989, 2017) and Főzy et al. (2011). Discussions on the J/K transition from ammonite point of view, together with a critical revision of the Mediterranean ammonite zonal scheme is published recently by Szives & Főzy (2022).

Ammonites are preserved mostly as internal moulds, very often one side is dissolved due to the slow sedimentation and condensed nature of sequences in ammonitico rosso facies. Overall, 32 genera and 29 species determined, approximately a thousand specimens. Ammonites of the J/K interval from sections

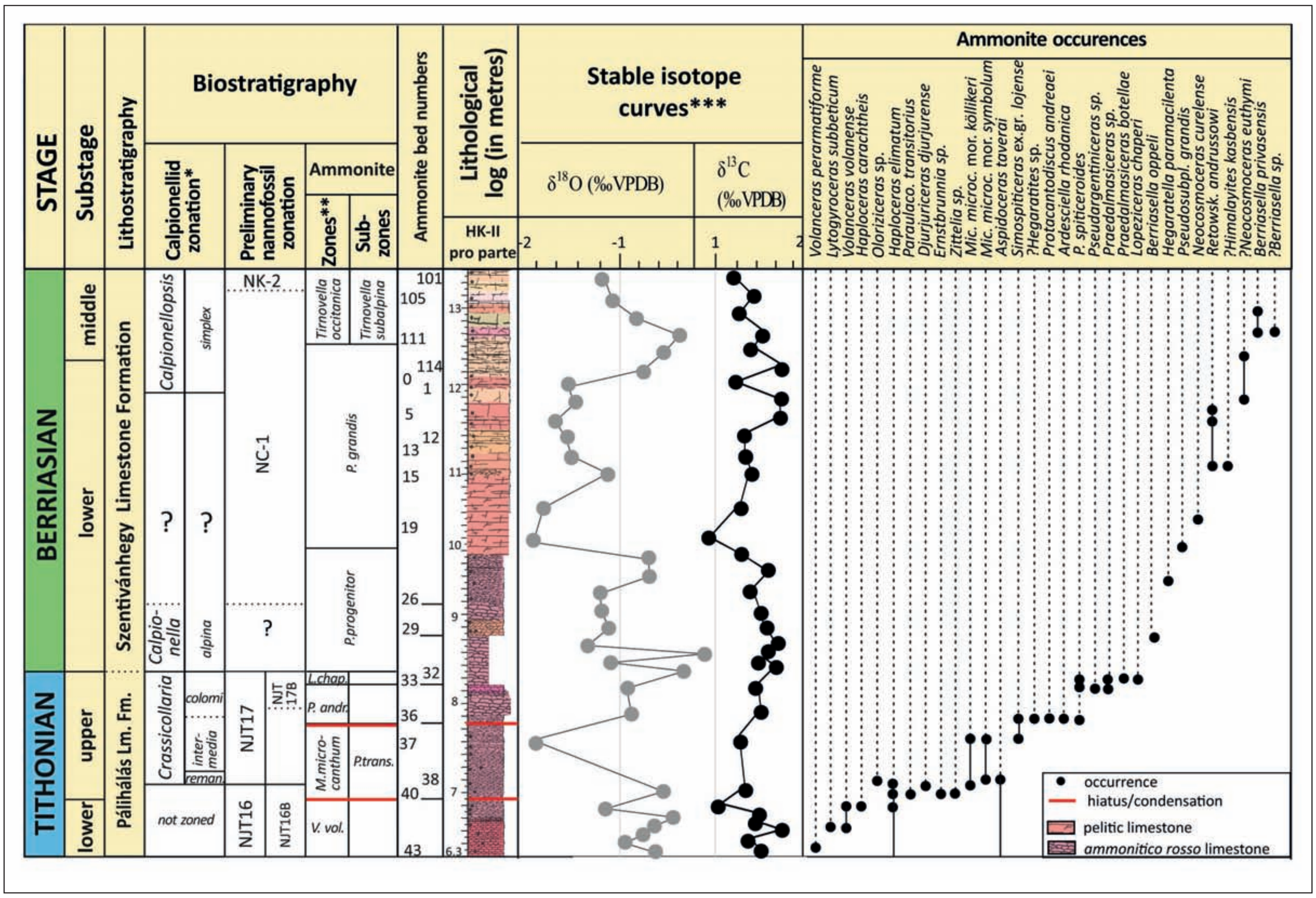


Figure 1 – Stratigraphy of the Hárskút, HK–II section, modified after Szives & Főzy (2022)

*Calpionellid zonation is taken from Horváth & Knauer (1986). **Ammonite zonation is after Szives & Főzy (2022). ***Stable isotope excursions of Price et al. (2016) are modified to the present lithologic log. Ammonite bed numbers are also corrected here compared to Vörös et al. (2019). Abbreviations: Lm. – limestone; Fm. – formation; *S. fall. – Semiformiceras fallauxi* Zone; V. vol. – *Volanoceras volanense* Zone; *M. microcanthum – Micracanthoceras microcanthum* Zone; P. trans. – *Paraulacosphinctes transitorius* Subzone; *P. andr. – Protacanthodiscus andreaei* Zone; *L. chap. – Lopeziceras chaperi* Zone; *P. progenitor – Praedalmasiceras progenitor* Zone; *P. grandis – Pseudosubplanites* grandis Zone. Colours in lithological log correspond to the colours of the fresh rock surfaces. The calpionellid zonation is not in accordance with the ammonite nannofossil stratigraphy which needs to be worked out.

are visualized in this volume, see Főzy et al. (2022b, this volume). Ammonites from Rendkő localities are under investigation and not figured hereby.

From the studied sections *pro parte*, presence of the following ammonite zones of the J/K interval are documented from the Bakony Mountains: Volanense Zone, Microcanthum Zone, Andreaei Zone, Chaperi Zone, Progenitor Zone, Grandis Zone. Due to its importance as a marker level, we also discuss briefly *Volanoceras volanense* Zone of the lower Tithonian (Szives & Főzy 2022).

3.2.1. Volanoceras volanense Zone

Énay & Geyssant (1975) listed *M. ponti* and *V. volanense* as components of a large assemblage which characterizes the Ponti Zone (op. cit., p. 49). A bit later, *Volanoceras volanense* Zone was established by Cecca & Santantonio (1988) on the basis of ammonite assemblages from ammonitico rosso sections of the Central Apennines. As none of the standard index ammonites (Hesselbo et al. 2020), *Djurjuriceras ponti* (Fallot & Termier, 1923) and *Burckhardtites peroni* (Roman, 1936) are reported from Mediterranean limestone facies, we prefer to use *Volanoceras volanense* Zone, as its index is easily recognizable and an abundant component of the Mediterranean (sensu Cecca, 1999) late Tithonian faunas, as well as of the Ponti assemblage. Further discussions see in Szives & Főzy (2022).

The Volanense Zone is well established in the following sections: HK-II (Figure 1) and HK-12/a.

3.2.2. Micracanthoceras microcanthum Zone

The Microcanthum Zone was introduced by Énay & Geyssant (1975), who proposed two zones for the upper Tithonian: the lower Microcanthum Zone and the upper Durangites Zone.

The Microcanthum Zone is a well–defined, easily recognizable biostratigraphic unit with a revised index species and a characteristic faunal assemblage, which may serve as a solid base for supraregional correlation (Boughdiri 2014). As the specific content of the genus and the taxonomic revision of the type species was given by Parent et al. (2011), Bulot et al. (2014) and Frau et al. (2016c), we support to keep its zonal rank. Further discussions see in Szives & Főzy (2022).

The Microcanthum Zone is established in the following sections: HK-II, HK-12/a (Figure 2), Szilas Ravine and Lókút.

Oloriziceras magnum Subzone

For the lower part of the Microcanthum Zone, Sarti (2020) recently introduced a new “Taxon-Range-Subzone” of *O. magnum* as a replacement subzone of Simplisphinctes Zone of Tavera (1985). In contrast to genus *Simplisphinctes* which is practically absent outside the Betic Cordilleras, presence of various *Micracanthoceras* morphotypes and *Haploceras elimatum* is significant in the Hungarian material. *Ernstbrunnia densecostata* and *Oloriziceras magnum* are exclusively present in the lower part of the Microcanthum Zone, so we support the use of *O. magnum* Subzone. Further discussions see in Szives & Főzy (2022).

The Magnum Subzone is established in the following sections: HK-II, HK-12/a (Figure 2), Szilas Ravine and Lókút.

Paraulacosphinctes transitorius Subzone

The Transitorius Zone was introduced by Sapunov (1977), and became widely accepted after Tavera (1985), who used it as an equivalent of the upper unit of the Microcanthum Zone of the late Tithonian, based on the total range of *Paraulacosphinctes transitorius*. Further discussions see in Szives & Főzy (2022). The Hungarian material confirms that *P. transitorius* is present both in the middle and upper parts of the Microcanthum Zone.

The Transitorius Subzone is established in the following sections: HK-II (Figure 1), HK-12/a (Figure 2), Szilas Ravine (Figure 3) and Lókút.

Moravisphinctes fischeri Subzone

Wimbledon et al. (2013, p. 451) suggested *Moravisphinctes fischeri* as an index fossil, and used the Fischeri Subzone as a replacement for the Transitorius Zone. We do not support its use as a replacement for the full Transitorius Zone (in the sense of Tavera, 1985), discussed by Szives & Főzy (2022). Instead, we use *M. fischeri* as a subzonal marker of the nominate subzone for the upper Microcanthum Zone between the FO of *M. fischeri* and the FO of *P. andreaei*. The subzonal faunal elemnts are present at Hárskút HK–12/a, Lókút and Szilas Ravine sections.

The Fischeri Subzone is established in the following sections: HK-12/a (Figure 2), Szilas Ravine (Figure 3) and Lókút.

3.2.3. Protacanthodiscus andreaei Zone

The revision of *Durangites* and its type species by Frau et al. (2015) shed new light on its taxonomy. The conlusion was that *Durangites* should be restricted to the Caribbean forms only. As a consequence, it was suggested to be abandoned as a widespread index taxon of the Mediterranean–Caucasian Subrealm. Instead, Andreaei Zone was suggested by Wimbledon et

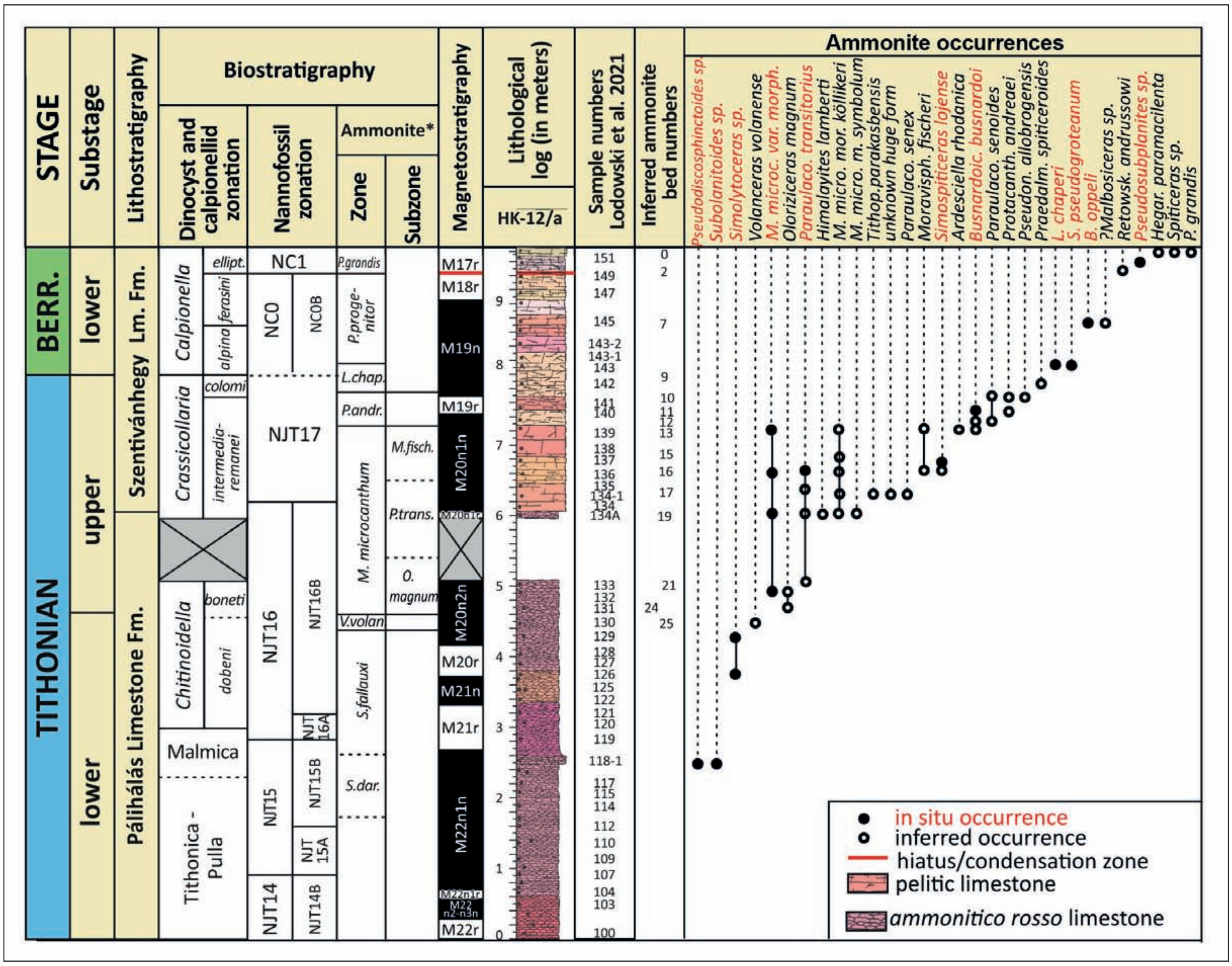


Figure 2 – Stratigraphy of the Hárskút, HK–12/a section. Dinocyst and calpionellid zonation, nannofossil biostratigraphy, magnetostratigraphy and lithologic log are taken from Lodowski et al. (2022)

*Ammonite zonation is after Szives & Főzy (2022). Abbreviations: *S. sem.* – *Semiformiceras semiforme* Zone, *O. magnum* – *Oloriziceras magnum* Subzone, *M. fisch.* – *Moravisphinctes fischeri* Subzone; furthers see on Figure 1. Colours in lithological log correspond to the colours of the fresh rock surfaces.

al. (2013) as a replacement for the "Durangites" Zone (Énay & Geyssant 1975, p. 45) or the equivalent "Vulgaris" Zone of Sarti (1988, p. 473). The faunal assemblage of Andreaei Zone is rather characteristic with the presence of *Busnardoiceras, Protacanthodiscus,* and *Proniceras*. Related to its FO, *Protacanthodiscus* appears together with *M. microcanthum* at HK–II section in bed 37.

The Andreaei Zone is established in the following sections of Hungary: HK-II (Figure 1), HK-12/a (Figure 2), Szilas Ravine (Figure 3) and Lókút (Figure 4).

3.2.4. Lopeziceras chaperi Zone

Nikolov (1967, p. 729) introduced the Chaperi Subzone as the youngest subzone of the late Tithonian Transitorius Zone. Fortunately, *Lopeziceras* appeared in situ at Hárskút 12/a section. Chaperi Zone marks the topmost Tithonian due to the current state of the T/B boundary (Tavera et al. 1994). Faunal content of the Zone in the Hungarian material is given by Szives & Főzy (2022).

The Chaperi Zone is established in the following sections: HK-II (Figure 1), HK-12/a (Figure 2), Szilas Ravine (Figure 3) and Lókút (Figure 4).

Elenaella cularense Subzone

Tavera et al. (1994) introduced *Elenaella cularense* as a horizon marker, a species with great abundance in the Puerto Escaño, Spain. Its total stratigraphic distribution is restricted to a narrow level that may serve to define the topmost Tithonian of certain areas of the Mediterranean *sensu* Cecca (1999). *E. cularense* is a useful index fossil that may characterize its nominal subzone of the Chaperi Zone. Further discussions see in Szives & Főzy (2022).

The Cularense Subzone is established in the Szilas Ravine (Figure 3) section.

3.2.5. Praedalmasiceras progenitor Zone

Introduction of *P. progenitor* Zone was given by Szives & Főzy (2022). In the Hungarian material *P. progenitor* occurs in the Szilas Ravine and Lókút LH–II/I sections, however other *Praedalmasiceras* species are present in all the examined sections. Its faunal content in the Hungarian sections is: *Praedalmasiceras* sp., *Praedalmasiceras progenitor*, *Praedalmasiceras* cf. *botellae, Spiticeras* sp. Besides, from literature compilations listed above, *Proniceras pronum, Berriasella* spp. (*chomeracensis, moreti, oppeli, oxycostata), Hegaratella paramacilenta, Pseudoneocomites beneckei* are parts of the assemblage. The Zone is also characteristic of some Vocontian sections (Frau et al. 2016b).

The Progenitor Zone is established in the following sections: HK-II (Figure 1), HK-12/a (Figure 2) and Szilas Ravine (Figure 3).

***Delphinella* informal unit**

Genus *Delphinella* may have a special importance in Berriasian biostratigraphy, however in Hungary it is rarely present. Hoedemaeker et al. (2016) mentioned that in ammonitico rosso/biancone sections *Delphinella* is absent or very rare, so is the case in Hungary. Only one specimen occurs in the HK-12 section (which is the upper composite to HK-12/a section, for details see Lodowski et al. 2022). Due to the scarity of our material, we cannot make any further biostratigraphic observations.

3.2.6. Pseudosubplanites grandis Zone

We support the use of the Grandis Zone in its original meaning established by Le Hégarat (1973), as an interval zone between the FO of *P. grandis* and the FO of *S. occitanica* or FO of *S. subalpina*. In the Hungarian material, *Hegaratella paramacilenta, Pseudosubplanites grandis, Pseudosubplanites* sp., *Spiticeras* sp., *Neocosmoceras curelense*, ?*Himalayites kasbensis* and *Retowskiceras andrussowi* characterize the interval between LO of *P. progenitor* and FO of *S. occitanica*.

The Grandis Zone is established in the following sections: HK-II (Figure 1), HK-12/a (Figure 2) and Szilas Ravine (Figure 3).

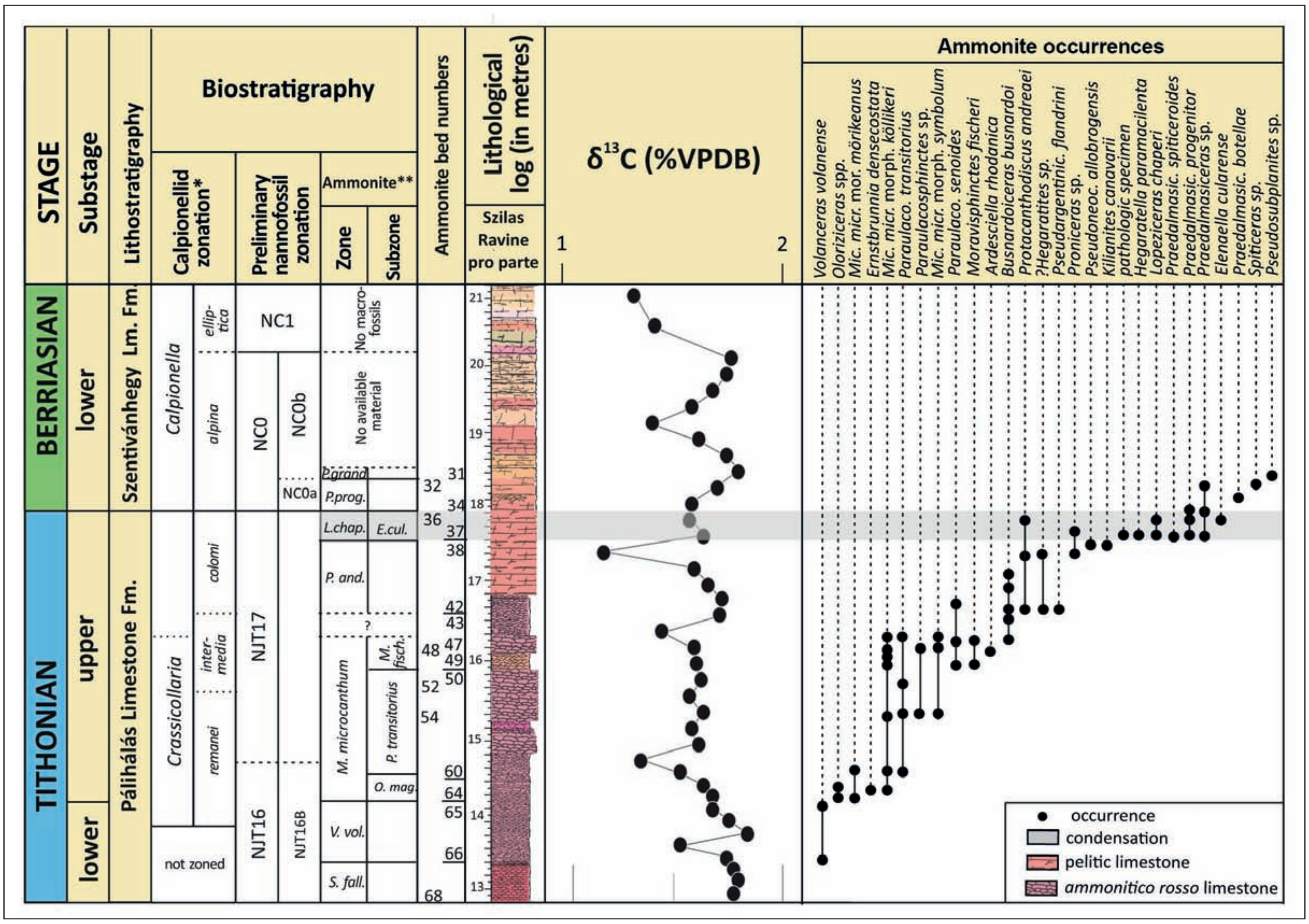


Figure 3 – Biostratigraphy of the Borzavár, Szilas Ravine section, modified from Szives & Főzy (2022)

*Calpionellid zonation is taken from Császár (1985). **Ammonite zonation is after Szives & Főzy (2022). Abbreviations: *E. cul.* – *Elenaella cularense* horizon; furthers see on Figures 1. and 2. Colours in lithological log correspond to the colours of the fresh rock surfaces.

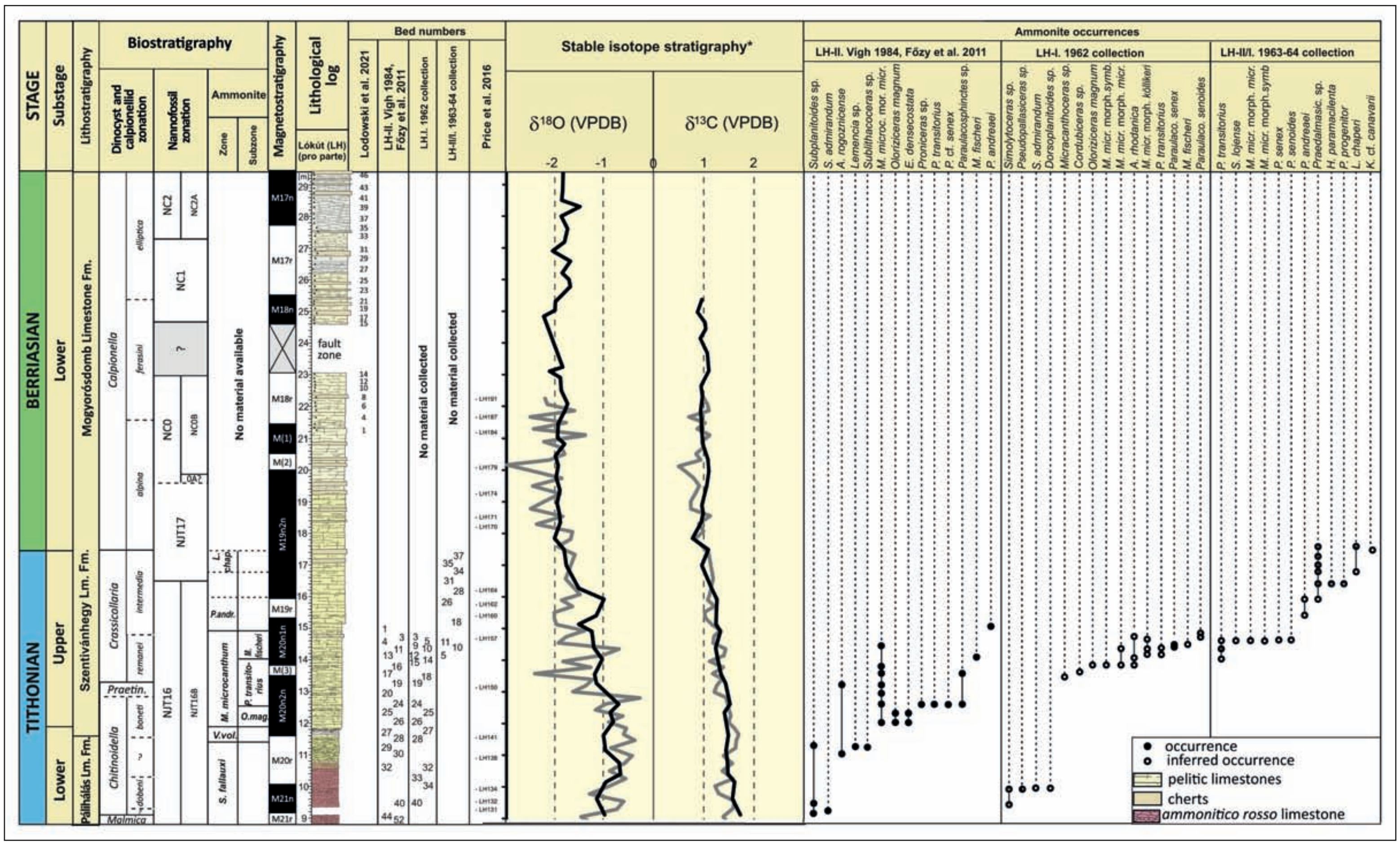


Figure 4 – Biostratigraphy of the Lókút section, modified from Szives & Főzy (2022)

Dinocyst, calpionellid, nannofossil zonation, magnetostratigraphy and the section log is taken from Lodowski et al. (2022). This log starts 2.5 metres above the log of Főzy et al. (2011) and Price et al. (2016), the latter two use the same scale, which has a zero point at the top of the radiolarite. *Stable isotope stratigraphy is corrected to the lithologic log (gray lines – Price et al. 2016; black lines – Lodowski et al. 2022, including data of Grabowski et al., 2010 and 2017). Ammonite zonation is after Szives & Főzy (2022). Abbreviations see on Figures 1–3. Colours in lithological log correspond to the colours of the fresh rock surfaces.

4. Brachiopods

Latest results on J/K transition of the brachiopod assemblages from the Bakony Mountains were published recently by Vörös et al. (2019) and also in Vörös (2022, this volume). The studied material was mostly collected from sections HK-II, HK-12, Szilas Ravine sections and some other localities (e.g. Eperkés Hill and Lókút Hill) of Tithonian and/or Berriasian age in the northern Bakony Mountains. The brachiopods are extremely abundant: among the 1277 identified specimens 940 were collected from the Tithonian and 337 from the Berriasian (including indeterminable specimens, identified only to genus level).

According to the results published by Vörös et al. (2019) the sections in the Bakony Mountains, straddling the J/K transition, yielded abundant and diverse brachiopod material (1277 specimens, 21 species), and this offered a possibility to determine the stratigraphic ranges of the brachiopod species. It was demonstrated that, according to the stratigraphical distribution recorded in the Bakony sections, the most abundant brachiopod species ranged continuously from the Tithonian to the Berriasian, i.e. no change or turnover appeared at the J/K boundary. These results endorsed those published from the Pieniny Klippen Belt of Poland and underscored that, at least in the intra-Tethyan realm, the brachiopod species invariably crossed the Tithonian/Berriasian boundary.

5. Nannofossils

5.1. History of nannofossil studies of the J/K interval from the area

Not many nannofossil studies were carried out on this time interval in Hungary. The nannoconids of the Bakony Mountains were first investigated by Báldi-Beke, whose results had been incorporated into the monograph of Fülöp (1964) written about the geology of the area. Meanwhile, pioneer work on the nannoconids of the HK-12 section was published by Báldi-Beke (1965), while a nannofossil stratigraphy of HK-12 section (beside other sections of the Gerecse Mountains) was presented by Fogarasi (2001). In the former Hungarian Geology Survey reports, some sections were investigated for nannofossil studies, but those were preliminary data with taxon lists and mostly lacking photographic illustrations or taxonomic descriptions. Recently, Kristallina Stoykowa (Grabowski et al. 2017) and Ottilia Szives (Lodowski et al. 2022) contributed to the nannofossil researches of Hungary.

5.2. The J/K boundary interval in the light of the nannofossil record: a compilation

State of the art studies on nannofossils was executed by Mutterlose et al. (2005) and Kanungo et al. (2017). Since the past decade, extensive investigations were in progress on taxonomy and biostratigraphy of the particular J/K transitional interval by Casellato (2010), Varol & Bowman (2019) and Casellato & Erba (2021). Here we briefly summarize nannofossils and the J/K interval on the basis of these above mentioned studies.

Diverse group of marine calcareous fossils averagely below 30μ in diameter are gathered together under a term "*calcareous nannofossil*". They are considered as one of the most important "innovations" of the Mesozoic oceans (Mutterlose et al. 2005). On the basis of their structural morphology, the group can be further divided into nannoliths, coccoliths and bigger (but below 62μ) calcispheres. Coccoliths could be holo- and heterococcoliths, the latter are divided to muroliths and placoliths (Mutterlose et al. 2005). Usually these diverse organisms can be related to foraminifers, sponges or calcareous dinoflagellates, but most frequently they are the calcified remains of haptophyte algae, inhabited both neritic and pelagic oceanic water masses. Existence of pleomorphism is proved by culturing living coccospheres (Cros et al. 2004), so it could be assumed some of the extant forms might also have diploid and haploid phase while producing different type of calcite "plates" (i.e. hetero- and holococcoliths).

Late Jurassic was a time of considerable reorganization of oceanic and climatic conditions due to major landmass breakups, extensive orogenic movements and volcanic activities in the circum-Tethyan area, which affected the evolution of the marine biota including calcareous nannofossils. As summarized by Casellato (2010), T/B time interval was a radiation period in nannofossil evolution caused by major paleoceanographic changes, characterized by low sea level. During the *Kuenen Event* (Roth 1989, Casellato 2010, Suchéras-Marx et al. 2019), the major carbonate production area has been shifted from shallow seas to open oceans as nannofossils contributed more and more to the primary carbonate production of the oceans. Beaufort et al. (2021) demonstrated that enhanced seasonality favours a larger range of coccolith sizes and reduced carbonate export, at least in the past 2.8M years.

Now it is proved that morphological evolution of coccolithophores was forced by Earth's orbital eccentricity (Beaufort et al. 2021), and environmental factors as seawater temperature, seawater clarity, $p\mathrm{CO}_2$ (acidity), sea level fluctuations, ratio of Ca^{+2} and Mg^{+2}. Nutrient supply can trigger controlling mechanisms of nannofossil distribution as well. Recent coccospheres are closely tight to climatic and environmental conditions, so supposedly it was similar in the past as well (Erba 1994, 2004), therefore they can be used as paleoproxies – if present. Usually present day nannoplankton favor stable, oligotrophic environments – we may suppose it was similar in the past. Nannofossils were widespread in all marine photic zone environments, but they are most abundant in warm (mostly oligotrophic), well stratified open oceanic settings (Bown et al. 2004) and also show bipolar paleobiogeographic distribution, based on Boreal and Tethyan epicontinental settings and ODP/DSDP sites of the Atlantic Ocean (Street & Bown 2000). During the J/K transition interval, low sea level seemed not been a major controlling factor for most nannofossils apart from some nannoliths including *Nannoconus,* that supposedly had a benthic life cycle stage (Bown et al. 2004) and probably occupied the lower photic zone (Erba, 1994).

As a consequence of their rapid evolution during this J/K interval, nannofossils can be used as reliable biochronological tools (Casellato & Erba 2021) as well, besides their paleoenvironmental usefulness. In the Late Jurassic, among several other taxa, appearance of heavily calcified nannoliths as *Faviconus*, *Conusphaera* and especially *Nannoconus* contributed hugely to the global carbonate accumulation. These nannofossil biogenic fluxes have been identified for the first time by Bornemann et al. (2003), who named an event as "Nannofossil Calcification Event (NCE)" dated by the late Tithonian. It is manifested on field as sedimentation changing from siliceous to mostly calcareous. After an extensive study on the interval, Casellato (2010) has been observed a younger NCE event named "Nannofossil Calcification Event II (NCE II)" and constituted an age constrain with magnetic polarity and calpionellid zones. Prior the NCE event, acme of *Faviconus* corresponds to CM22n, *Conusphaera mexicana* to CM21n, and *Polycostella* to upper CM21n (Casellato 2010). Besides these taxa, the accumulation of *Watznaueria* species also contributed to NCEs. *Watznaueria* appeared in the Aalenian (Young et al. 2017), and unites heavily calcified, mostly huge placolith species. NCE II corresponds to the acme of *Nannoconus* (lower CM20r and lower CM19n). These intervals were recently revised (Casellato & Erba 2021) and on the basis of literature compilations, the reliability of first (FO) and last occurrences (LO) of selected taxa were evaluated. The nannofossil zonation is also slightly modified due to the taxonomic studies of Varol & Bowman (2019). FOs of several new taxa had been recognized (Bown, 1992, Bown & Cooper 1998) at the J/K boundary, importance of *Nannoconus* increased, and this genus became the dominant element in the neritic settings of the Tethyan Realm, supposedly inhabited the deeper photic zone.

5.3. Summary of the Tithonian–Berriasian nannofossil record and stratigraphy of the Bakony Mountains

In recent years, stratigraphic and paleoenvironmental investigations were focused on the J/K transition interval in the Bakony Mountains by Főzy et al. (2011), Grabowski et al. (2010, 2017), Price et al. (2016), Vörös et al. (2019, 2020) and Lodowski et al. (2022). From the localities mentioned in this book, HK-II *pro parte*, Szilas Ravine *pro parte* and Hárskút Édesvíz Key (HEK) sections nannofossil age constrain was established for the first time for the J/K boundary interval.

Calibration of nannofossil events to magnetozones, calpionellid and ammonite stratigraphy was an issue since Bralower et al. (1989) until to Casellato & Erba (2021). On the basis of the Hungarian sections, we may add some details to the refinement of the calibration (Lodowski et al. 2022). Nannofossil biostratigraphy used here is based on Casellato (2010) and Casellato & Erba (2021), accepting the taxonomic remarks of Varol & Bowman (2019). The latter affect the usefulness of some secondary marker taxa used by Casellato (2010) and adopted by the GTS (Hesselbo et al. 2020, Gale et al. 2020) as well. Nannofossil taxonomy is based on the Nannotax website (Young et al. 2017). Taxonomic remarks on calcareous nannofossils of this time interval were summarized after Lodowski et al. (2022).

From the studied sections, presence of the following nannozones of the T/B interval are documented from the Bakony Mountains: NJT14, NJT15, NJT16, NJT17, NC0, NC1 and NC2. Recorded nannofossil taxa for Hárskút and Lókút sections are published in details by Lodowski et al. (2022), while quantitative statistical analysis of the nannofossil assemblage with new geochemical results will be published in a forthcoming paper.

NJT14 Zone (Kimmeridgian–lowermost lower Tithonian). Presence of this nannozone (Figure 2) is documented only from HK-12/a section by Lodowski et al. (2022) by the FO of the NJT14A index taxon (Casellato & Erba, 2021), *C. maledicto*. This nannozone is supposedly present in some other sections (lower part of HK-II and Szilas Ravine, Rend-kő I and II) although not investigated yet.

NJT15 Zone (upper lower Tithonian). Presence of this nannozone is documented only from HK-12/a section by Lodowski et al. (2022) only, where the base of this Zone is marked with the FO of the primary zonal marker, *C. mexicana minor* (sample HK107, Lodowski et al. 2022). FO of the subzonal marker, *P. beckmanni* in sample 112 marks the base of the NJT15B Subzone. This event is predated by FO of *C. mexicana mexicana* in sample HK109, what is in concordance with zonation provided by Casellato and Erba (2021). This nannozone is supposedly present in other sections (lower part of HK-II and Szilas Ravine, Rend-kő I and II) although not investigated yet.

NJT16 Zone (lower–upper Tithonian transition). Presence of this nannozone (Figures 2, 4) is first documented from HK-12/a by Lodowski et al. (2022), from the Lókút sections by Grabowski et al. (2017), HK-II and from the Szilas Ravine sections (Figures 1, 3; also see in Szives & Főzy 2022). From HK-12/a section the primary zonal marker – *Helenea chiastia* – was found only in fragments, so the base of the NJT16 Zone was established on the basis of the FO of its secondary marker *Hexalithus noeliae* in bed HK119. According to Casellato & Erba (2021), the base of the NJT16B Subzone is defined with the FO's of *Nannoconus infans* and *N. puer*, here first occurring in samples HK121 and HK125. This nannozone is supposedly present in other sections (HK-II, Szilas Ravine, Rend-kő I and II) although not fully investigated yet.

NJT17 Zone (upper Tithonian). Presence of this nannozone (Figures 2, 4) is first documented from HK-12/a by Lodowski et al. (2022) and Lókút sections by Grabowski et al. (2017), Hárskút Édesvíz (HEK) section (Vörös et al. 2020), HK-II section (Figure 1, also see in Szives & Főzy 2022) and Szilas Ravine sections (Figure 3). The base of this zone is marked by the FO of *Nannoconus globulus minor* (at HK-12/a in HK134-1 sample). However, there is a slight discrepancy between the interpolation of base of NJ17 at Lókút and at HK-12/a sections compared to the latest compilation given by Casellato & Erba (2021). If compared to magneto-, calpionellid and ammonite stratigraphy, base NJT17 at Lókút should have been found at significantly lower position in the *intermedia* calpionellid subzone, in M20n2n. In contrast, at HK-12/a, base of NJT17 seems even lower, within magnetosubzone M20n1n. However, both FOs fall within the reliability interval of the species *fide* Casellato & Erba (2021), but this phenomenon needs to be checked.

NC0 Zone (Tithonian–Berriasian transition). Presence of this nannozone is first documented from HK-12/a by Lodowski et al. (2022) and Lókút by Grabowski et al. (2017), Hárskút Édesvíz (HEK) section (Vörös et al. 2020) and Szilas Ravine sections (Figure 3). The base of NC0A Subzone at bed 140 is marked by the FO of a small nannoconus, which, instead of *N. wintereri*, resembles more to *Nannoconus alvus*, a much younger species, therefore it was determined with *affinis*. As pointed out first by Casellato & Erba (2021), FO of the *N. wintereri* is the most reliable key event around the J/K boundary in terms of calcareous nannofossil events; it pre-dates the FO of *N. steinmannii minor*. This phenomena is also observed within the HK-12/a section, where *N.* aff. *alvus* appears 80 cm below the FO *N. steinmannii minor*. The former NKT Zone at Lókút comprises the lower part of the lower Berriasian, between samples LO1 to LO14 (Alpina and Ferasini Subzones). Previously Stoykova (in Grabowski et al., 2017) put the base of the NKT calcareous nannofossils Zone at their bed 62, where the FO of *N. steinmannii minor* was observed. The last occurrence of *Conusphaera mexicana mexicana* is observed within the sample LO3 (bed 73 of Grabowski et al., op. cit.). NC0B Subzone was also documented from the topmost part of the HK-12/a section. It is defined by the FO of the *N. steinmannii minor* (HK144); the bioevent was voted by the Berriasian Working Group (Wimbledon 2017) as a secondary marker of the Tithonian–Berriasian boundary. *N. steinmannii minor* systematically appears around the base of the *Calpionella alpina* calpionellid Subzone (Pszczółkowski 2009, Pszczółkowski et al. 2005, Grabowski et al. 2019). In the HK 12/a section, this nannofossil event is being described from 20 centimeters above the base of the Alpina Subzone.

NC1 Zone (lower Berriasian). Presence of this nannozone is first documented from HK-12 and Lókút sections by Lodowski et al. (2022), HEK section (Vörös et al. 2020) and HK-II (Figure 1). The lower boundary of the NC1 Zone is marked by the FO of *N. steinmannii steinmannii* (Bralower et al. 1989); the species occurs within the topmost part of the HK-12/a section (from sample HK150 upwards). However, no lateral view of *N. steinmannii steinmannii* was observed within the lowermost part of the HK-12 section (samples HK1–HK14), hence the presence of the nannozone can only be assigned indirectly by the appearance of the next, NC2 Zone primary marker, *R. angustiforata* in the sample HK13. This zone can be also fixed indirectly from Lókút as well. Between beds LO1–LO14, no nannoconids resembling the longitudinal view of *N. steinmannii steinmannii* were observed, therefore the lower limit of the nannozone is uncertain. Specimens wider than 10μ in cross-section – probably those of *N.steinmannii steinmannii* – appear in the sample LO15. Consequently, we have chosen to define the base of the NK-1 nannozone at bed LO15, within the upper part of the Ferasini calpionellid Subzone (compare with Grabowski et al. 2017, 2019).

NC2 Zone (upper lower Berriasian). Presence of this nannozone is first documented from HK-12 and Lókút sections by Lodowski et al. (2022), HEK section (Vörös et al. 2020) and preliminary from HK-II (Figure 1).

NC2A Subzone (uppermost lower–upper Berriasian). In HK-12 section is marked by the FO of the zonal index, *R. angustiforata* in bed HK13. Nannofossil assemblage is very poor until bed HK30, barren samples (HK21–HK23) also occur. Most of the assemblage comprises of nannoconids and watznaueriales; delicate forms are very rarely present, huge species as *Cruciellipsis cuvillieri* (in sample HK36) are dissolved. Although the zonal marker *R. angustiforata* was found just as disintegrated fragments, FO of both *Rucinolithus wisei* (bed LO39) and *H. circumradiatus* (bed LO41) support the presence of the subzone. At Lókút, the lower limit of the zone is marked by FO of its zonal marker, *R. angustiforata* in the bed LO33. NC2A Subzone covers the uppermost part of the section studied, namely beds LO33 -LO47.

NC2B Subzone (lowermost Valanginian). At HK-12, the subzonal marker, *P. fenestrata* is present, the appearance of *Rucinolithus wisei* in bed 40, *M. speetonensis and L.* aff. *bollii* in bed 42 support the presence of this subzone. Sampling of Lodowski et al (2022) at HK-12 has stopped below the condensed bed named "bed 10" in Főzy et al. (2010). Upwards, presence of the Valanginian Weissert Event is confirmed from HK-12 by Főzy et al. (2010) and recently from HEK (Vörös et al. 2020) by the brachiopod turnover and the nannofossil abundance variations. Our latest result, a $\delta^{13}C$ stable isotope data (Főzy et al. 2022a, this volume) obtained from HEK section, confirmed the position of the Weissert Event previously suggested by nannofossil and brachiopod distributional observations. The presence of NC3 Zone also be pointed out, but this is out of the scope of this paper.

6. Characteristic microfauna on the J/K transition – focus on calpionellid assemblages

The most important microfaunal elements of the Upper Jurassic lithostratigraphic units are the saccocomids, radiolarians, globochaetes, bivalve filaments (*Bositra),* calcareous dinoflagellate cysts, planktonic foraminifers and the calpionellids. The composition and temporal changes of these assemblages are the determinative and distinguishing features of the Upper Jurassic–Lower Cretaceous formations of the Bakony Mountains. Extinction of saccocomids at the end of the Jurassic, the raise of the planktonic forams during the Late Jurassic and the permanent presence of calpionellids at the J/K transition clearly characterize this era.

Research on the J/K sequences of the Bakony Mountains provided important data to the calpionellid stratigraphy and evolution given by Nagy (1986), Knauer (1963) and Tardi-Filácz (1986). The meeting of the Working Group for the Jurassic–Cretaceous boundary in 1984 at Sümeg (Hungary) was an important contribution to the calpionellid stratigraphy and the establishment of the calpionellid zonation. It should be mentioned that most recent calpionellid investigations in Hungarian sections were carried on by Andrzej Pszczółowski (Grabowski et al. 2010, Lodowski et al. 2022).

At international scale, the most relevant research in calpionellid studies and the standardization of calpionellid zones are based on the works of Remane (1971), Remane et al. (1986), Remane (1986), Pop (1994, 1997), Reháková & Michalik (1997), Blau & Grün (1997). During the 1980s and 1990s, the description and differentiation between forms was in the focus of studies, besides the calpionellid zonation and its stratigraphic role was also established. Later, the significance of calpionellids in the determination of the Tithonian/Berriasian boundary was the main subject of research (Michalik & Reháková 1997, Lakova et al. 1999, Andreini et al. 2007, Lakova & Petrova 2013, Michalik et al. 2021). Synthetizing the data on Tethyan calpionellids was primarily due to Berriasian Working Group I led by W. Wimbledon.

***Chitinoidella* Zone** in the lower Tithonian was represented by the early genus of calpionellids which appeared in a fauna depleting in saccocomids and calcareous dinocysts (Plate 1/1). The Chitinoidella Zone did not appear in the first traditionally accepted zonation by Remane et al. (1986) which applied the A (Crassicollaria) – B-C (Calpionella) – D (Calpionellopsis) – E (Calpionellites) Zone classification.

During the late Tithonian, the diversification of calpionellids resulted in the formulation of the ***Praetintinnopsella*** and later the more characteristic ***Crassicollaria* Zone** (Plate 1/2–4). At the Tithonian/Berriasian boundary, the clear and exact separation of the *Crassicollaria* and *Calpionella* Zones is needed. The *Crassicollaria* Zone is well established in the following sections: Szilas Ravine, Hárskút HK-II, HK12/a, HK-12 and Lókút.

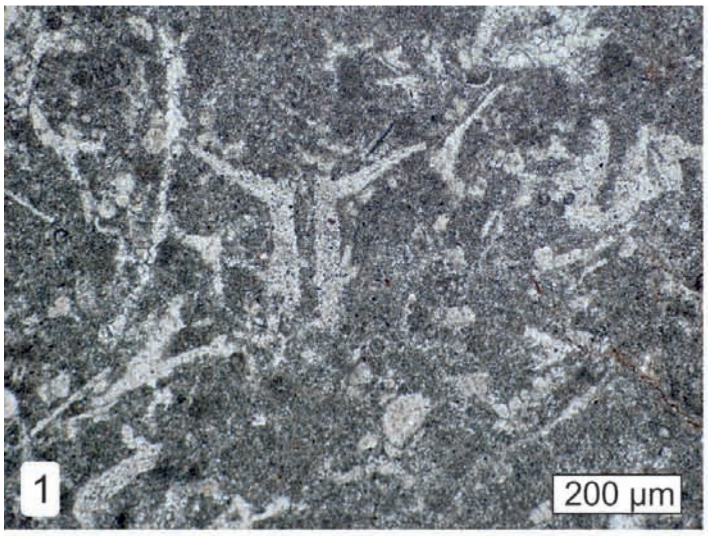
The base of the ***Calpionella* Zone** is marked by the '*Calpionella alpina* event' (Allemann et al. 1971; 2nd Planktonic Conference, Roma, 1970), however the zone is divided into three subzones, Alpina, Ferasini and Elliptica, from older to younger, respectively.

As an internationally accepted determination, the '*Calpionella alpina* event' (*Calpionella Zone*, *Alpina* Subzone) is characterized by the extinction of *Crassicollaria* and the rapid increase of spherical *Calpionella alpina* Lorenz, 1902 (it is not equivalent with the first occurrence of *C. alpina* Lorenz, 1902). It is important to note that the first occurrence of *C. alpina* Lorenz, 1902 happened during the late Tithonian in the Crassicollaria Zone (Intermedia Subzone). It is a limiting factor during the investigation that calpionellids were not diverse and abundant enough in the Tithonian to gain ideal axial sections of the loricae appropriate for statistically representative analysis. Samples from younger formations contain large amount of loricae which can provide more ideal sections for the exact determination. The determination of the '*C. alpina* event' is supported by two methods. On the one hand, the statistical analysis applies the occurrences and relative abundances of *Crassicollaria* and *Calpionella* species (Lakova 1994). On the other hand, the morphometric analysis of *Calpionella* species

Plate 1 – Characteristic thin section photomicrographs from the J/K boundary in the Bakony Mountains.

(PPL plane-polarized light, XPL crossed-polarized light)

1. Saccocoma sp. in biomicrite packstone textured lower Tithonian limestone (Saccocoma facies) Szilas Ravine (bed77), PPL.
2. Calpionella elliptalpina Nagy, 1986 in biomicrite packstone textured upper Tithonian limestone (Crassicollaria intermedia Subzone). Szilas Ravine (bed 41), PPL.
3. Crassicollaria brevis Remane, 1962 in biomicrite packstone textured upper Tithonian limestone (Crassicollaria intermedia Subzone). Szilas Ravine (bed 35), PPL.
4. Crassicollaria intermedia Durand Delga, 1957 in biomicrite packstone textured upper Tithonian limestone (Crassicollaria Intermedia Subzone). Szilas Ravine (bed 35), PPL.
5. Abundant smaller-sized (spherical) Calpionella alpina Lorenz, 1902 in micritic limestone (Calpionella alpina Subzone). Szilas Ravine (bed 29), PPL.
6. Calpionella alpina Lorenz, 1902 in micritic limestone (Calpionella alpina Subzone). Szilas Ravine (bed 28), PPL.
7. Abundant calpionellids (Crassicollaria and Calpionella) in micritic limestone (Crassicollaria intermedia Subzone). Hárskút HK (bed No. 33), PPL.
8. Calpionella alpina Lorenz, 1902 in micritic limestone (Calpionella alpina Subzone). Hárskút HK (bed 31), PPL.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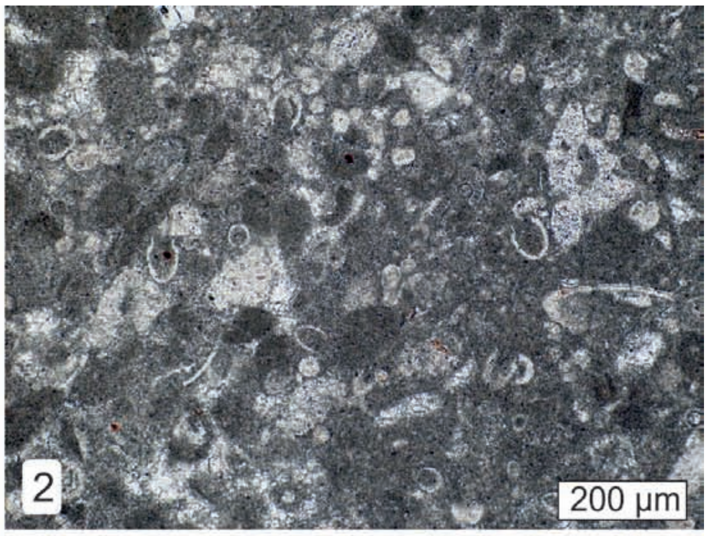
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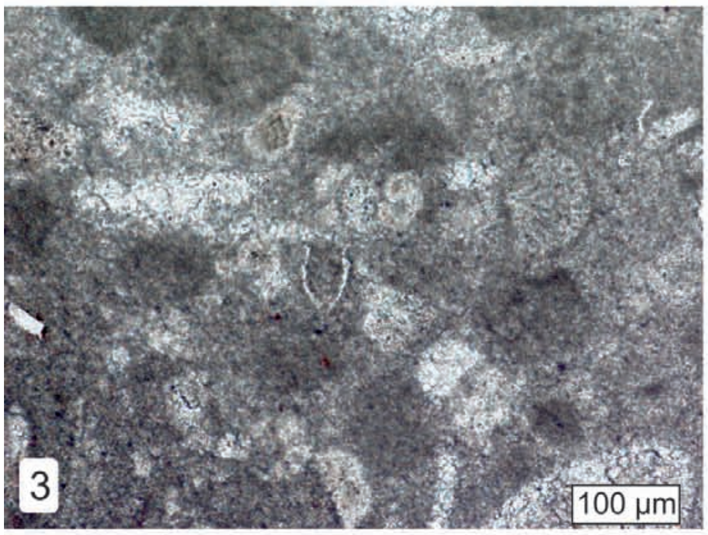
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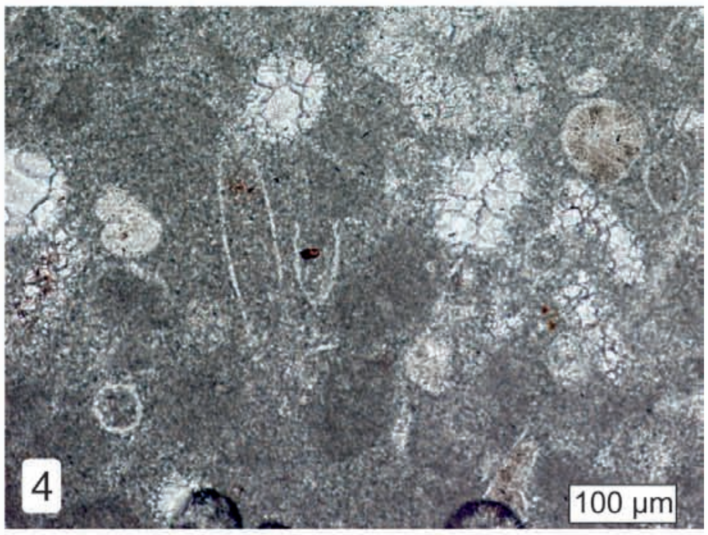
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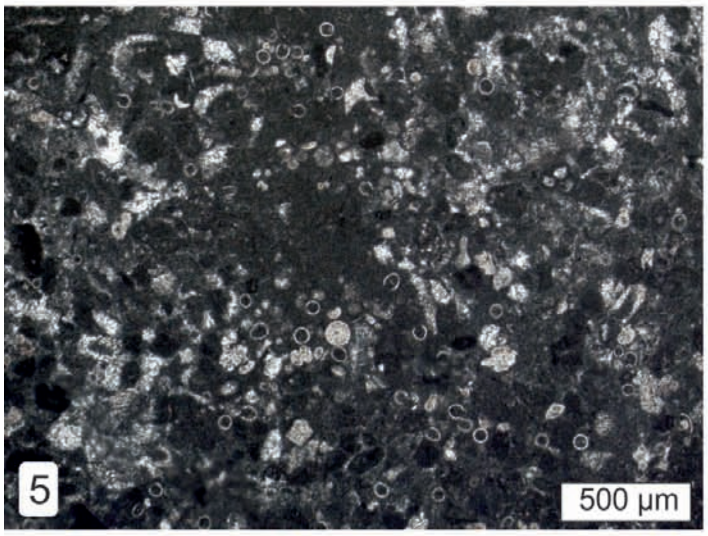
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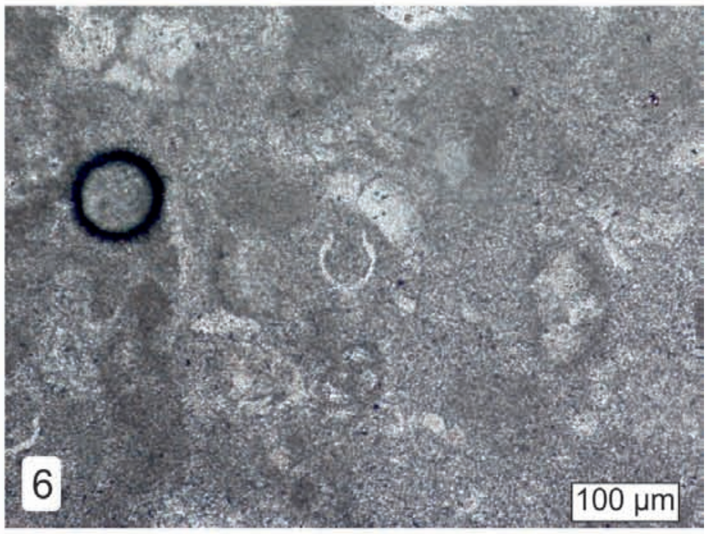
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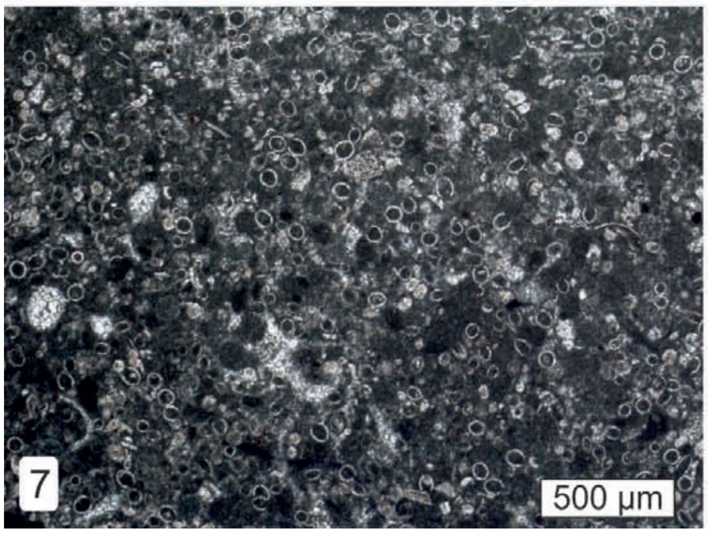
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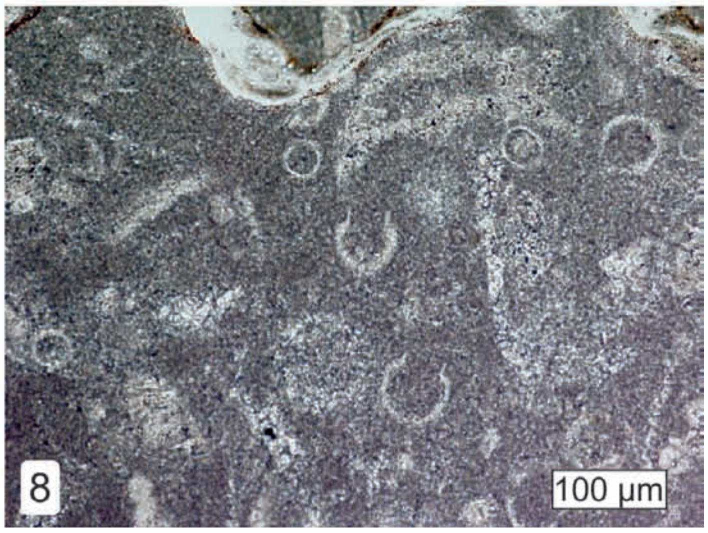
8
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is based on the research by Kowal-Kasprzyk and Reháková (2019).

In the Bakony Mountains the J/K transition is manifested in the Szentivánhegy Limestone and the Mogyorósdomb Limestone Formations in the following outcrops: Szilas Ravine, Hárskút Édesvíz Key Section (HEK), HK-II, Zirc Márvány Quarry, HK-12/a, HK-12 and Lókút sections (Lodowski et al. 2022).

The **Szilas Ravine** represents a continuous transition from the Tithonian *Saccocoma facies* to the *Calpionella facies* in the Szentivánhegy Limestone Formation. The upper Tithonian *Crassicollaria* Zone is indicated by *Crassicollaria massutiniana* (Colom, 1948), *Crassicollaria intermedia* Durand Delga, 1957, *Calpionella grandalpina* Nagy, 1986, *Calpionella elliptalpina* Nagy, 1986 and *Crassicollaria brevis* Remane, 1962 in beds 48–35 (*Intermedia* Subzone) (Plate 1/2–4). Characteristic forms of *Calpionella alpina* Lorenz, 1902 appear in beds 35–31 (*Colomi* Subzone), while spherical forms of *C. alpina* Lorenz, 1902 become abundant in beds 31/29 indicating the *Calpionella* Zone, *Alpina* Subzone, i.e. the Tithonian/Berriasian boundary (Plate 1/5,6). Another characteristic outcrop of the Szentivánhegy Limestone Formation is the **Hárskút HK-II**, where a continuous transition from the lower Tithonian *Globochaete*, *Saccocoma facies* to the *Calpionella facies* can be observed. Calpionellids appear in bed No. 37 and become more diverse (*Crassicollaria brevis* Remane, 1962, *Calpionella elliptalpina* Nagy, 1986, *Crassicollaria intermedia* Durand Delga, 1957) indicating the *Crassicollaria* Zone, *Intermedia* Subzone in beds 37–35 (Plate 1/7). Further classification into subzones is difficult due to subordinate appearance of *C. alpina* Lorenz, 1902 in bed 35 (?*Colomi* Subzone). It becomes abundant in beds 32/30 (*Calpionella* Zone, *Alpina* Subzone) indicating the Tithonian/Berriasian boundary (Plate 1/8). A discontinuous succession was discovered at **Hárskút Édesvíz Key Section (HEK)** which is not ideal (with less characteristic microfauna) concerning the investigation of the J/K boundary. The section starts with the *Saccocoma facies* (lower Tithonian) Pálihálás/Szentivánhegy Formation (bed 68). Bed 62 contains Berriasian age calpionellids, thus the Tithonian/Berriasian boundary must be estimated among beds 62 and 67. The absence of the microfauna in these beds can be the result of a sedimentary hiatus or specific environmental (or diagenetic?) circumstances. Beds below the Borzavár Limestone at **Zirc Márványbánya** succession are of Tithonian age. Due to the condensed nature of the ammonitico rosso-type formation (sedimentation in submarine horsts, topographic highs) stratigraphically relevant planktic forms are subordinate compared to the benthic ones. In this case, calpionellids cannot identify exactly the Tithonian/Berriasian boundary due to the condensed nature and the possible hiatus between the Szentivánhegy/Borzavár Limestone Formations. Based on recent research of Bakony Mountains sections (Lodowski et al. 2022), **Hárskút HK12/a and HK-12** contains the Tithonian/Berriasian boundary at bed 143 (*Alpina* Subzone, *Calpionella* Zone). Lodowski et al. (2022) and Grabowski et al. (2010, 2017) mentioned the **Lókút** succession and identified the Tithonian/Berriasian boundary.

In addition to their stratigraphic importance, calpionellids are indicators of the environmental changes. They are sensitive to the water temperature, sea-level change, water chemistry and the nutrient supply. These factors determined their frequency and the shape and size of the loricae, as well. Sedimentology, microfacies and other faunal assemblages are also important and independent indicators of the depositional environment.

7. Magnetostratigraphy of the J/K transition in the TR

The first magnetostratigraphic investigations of the Upper Jurassic–Lower Cretaceous of the TR were performed by Márton (1982, 1985, 1986). However, these studies were lacking full biostratigraphic and lithologic documentation, what hampered correlation between the magnetostratigraphy and biozonation; besides, an outdated magnetostratigraphic position of the J/K boundary (=lower part of the magnetozone M16n; compare e.g. Márton 1982 with Ogg & Lowrie, 1986) was adopted by the author. Detailed investigations, integrating bio- and magnetostratigraphic methods, were later performed by Grabowski et al. (2010) and Lodowski et al. (2022) in the vicinity of Lókút (LO-I, LO-II sections) and Hárskút (HK-12, HK-12/a sections) villages. Their magnetostratigraphic interpretations were based on correlation with Geomagnetic Polarity Time Scale (GPTS; Ogg, 2020), micro- and nannofossil stratigraphy, and subsequent comparison with western Tethyan stratigraphic scheme (Lodowski et al. 2022). The Tithonian–lower Valanginian of the Hárskút succession accounts for the total number of 23 magnetic polarities, recording the M22r–M13r interval (Lodowski et al., op. cit.). However, the record is not continuous; observational gaps appear in the middle of the HK-12/a section (estimated for ca. 80 cm in thickness), as well as between the HK-12/a and HK-12 sections (ca. 0.5 m) (Figure 5). Moreover, adopted methodology allowed for documentation of two hiatal/condensation zones within the succession: the one within the lower Berriasian of the HK-12/a section (between M18r and M17r) and the other in the upper Berriasian of the HK-12 section (within M16n; see red lines in lithological logs on Figure 5). The occurrence of hiati and/or condensation zones within the Hárskút succession might be expected taking into account its horst paleobathymetric setting. A continuous record of the J/K transition is in turn ensured by Lókút succession, deposited within more internal parts of the Bakony Basin. There, a sequence of 14 magnetic reversals accounts for the interval between the lower Tithonian magnetozone M21r and the lower Berriasian magnetozone M17n (Grabowski et al. 2010, Lodowski et al. 2022). The entire interval is recorded by the original LO-I section (equal to LH-II in Szives & Főzy (2022) and Főzy et al. 2022a,b this volume), which was studied over the years by Vígh (1984), Főzy et al. (2011), Grabowski et al. (2010, 2017) and Lodowski et al. (2022), however stratigraphy of the interval which is cut by a fault zone (at the boundary between M18r and M18n magnetozones) is additionally ensured by the LO-II section (Figure 5).

Below we discuss only the most characteristic and stratigraphically important correlation intervals for the J/K transition. These are: 1) long normal polarity interval within the lower Tithonian (M22n1n magnetosubzone); 2) the lower/upper Tithonian boundary; 3) the Tithonian/Berriasian boundary; 4) the base of the Elliptica calpionellid Zone; 5) the lower/upper Berriasian boundary; 6) the Berriasian/Valanginian boundary. Characteristics of

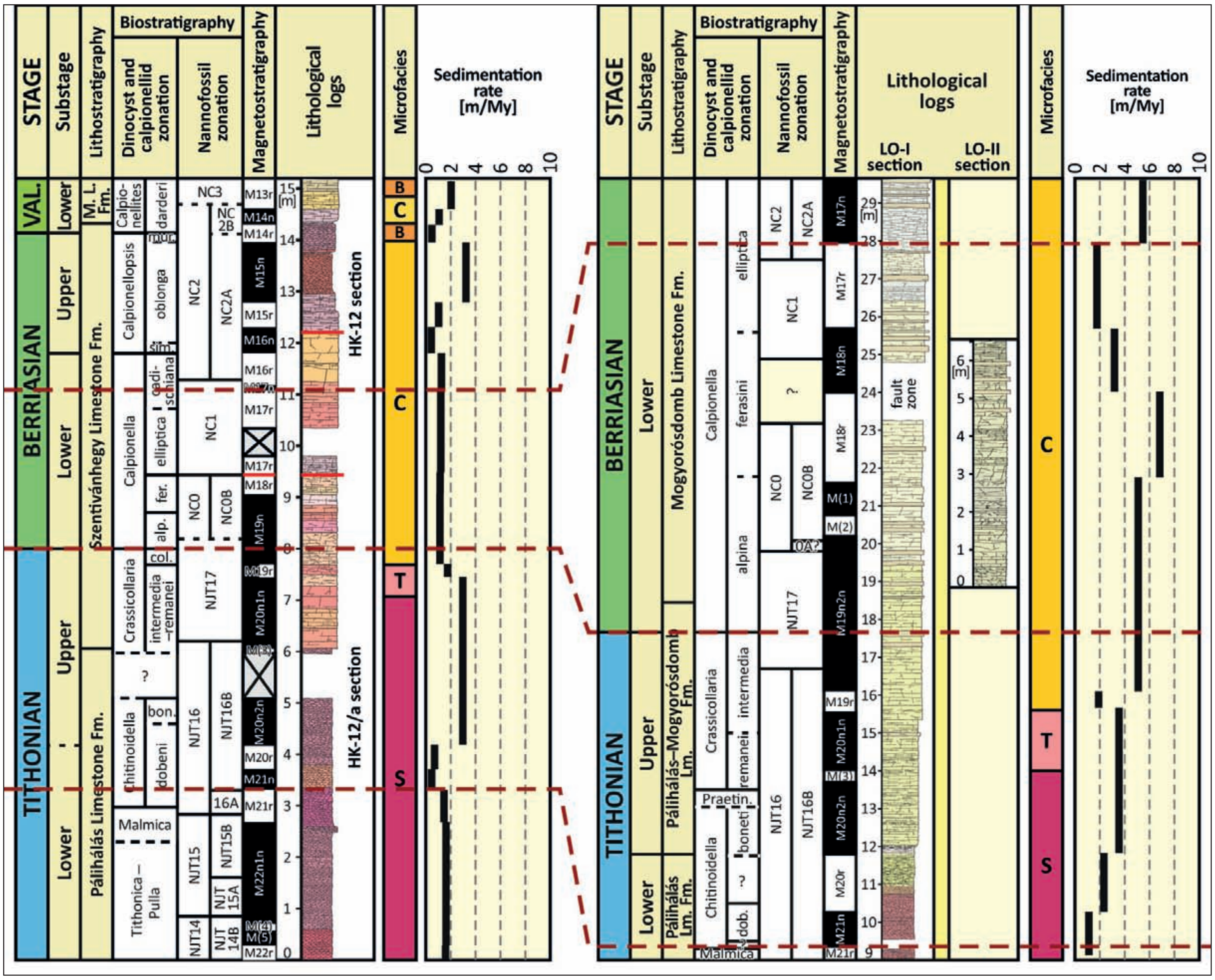

Figure 5 – Lithological logs, stratigraphy (dinocyst, calpionellid, nannofossil, magnetostratigraphy), microfacies succession and sedimentation rates of the Hárskút (left) and Lókút (right) successions

Abbreviations: VAL. –Valanginian, M. L. Fm. – Mogyorósdomb Limestone Fm.; dob. – *dobeni*; bon. – *boneti*; col – *colomi*; alp. – *alpina*; fer. – *ferasini*; sim. – *simplex*; mur. – *murgeanui*. Explanations for magnetostratigraphy: in Lókút: M(1) – M19n1n; M(2) – M19n1r; M(3) – M20n1r; in Hárskút: M(4) – M22n1r; M(5) – M22n2n. Explanations (microfacies): S – *Saccocoma*-dominated microfacies; T – transitional microfacies; C – calpionellid-dominated microfacies; B – bioclastic packstones. Dashed red lines indicate correlation levels.

these events as documented from Hárskút and Lókút sections (Grabowski et al. 2010, 2017, Lodowski et al. 2022) are summarized below.

M22 interval was documented only in the Hárskút succession, where magnetozone M22r (as well as M22n1r and M22n2n magnetosubzones) falls in the Tithonica–Pulla and NJT14 zones. Albeit either the base of the M22n1n magnetosubzone falls in the *Tithonica–Pulla* Zone, the interval is characterized by theNJT14/NJT15 zonal boundary (Figure 5).

The lower/upper Tithonian boundary is usually approximated to the base of the M20n2n magnetosubzone (e.g. Hesselbo et al. 2020, Lodowski et al. 2022). In Hárskút it falls in the upper part of the *Chitinoidella dobeni* calpionellid Subzone, in the NJT16B calcareous nannofossil Subzone. In turn in Lókút it correlates with the base of the *Chitinoidella boneti* Subzone (Figure 5).

The Tithonian–Berriasian boundary has been fixed at the base of the Alpina calpionellid Subzone, which is known to fall in the lower part of magnetozone M19n (within magnetosubzone M19n2n; e.g. Grabowski, 2011, Wimbledon et al. 2020). Lókút succession provides a full record of magnetozone M19n, what accounts for magnetosubzones M19n2n, M19n1r ("Brodno" reversal) and M19n1n. Long normal polarity interval M19n2n records both the *Crassicollaria* to *Calpionella* turnover (Intermedia/Alpina Subzones boundary), as well as the topmost part of the NJT16B calcareous nannofossil Zone, entire NJT17 Zone and the lowermost part of the NC0 Zone (Figure 5, Grabowski et al. 2010, 2017). Slightly different and less complete record of the Tithonian/Berriasian boundary characterizes the Hárskút succession. There, the long normal polarity above magnetozone M19r covers the Colomi, Alpina and the lower part of the Ferasini calpionellid Subzones. Due to that Lodowski et al. (2022) interpreted this interval as (more general) M19n, suggesting that magnetosubzone M19n1r was not observed e.g. due to insufficient sampling resolution or a short hiatus within the rock record. Nevertheless, similarly like in Lókút, M19n covers the boundary between the NJT17 and NC0 calcareous nannofossil Zones (Figure 5).

The base of the Elliptica calpionellid Subzone roughly correlates with the base of M17r magnetozone and NC1 calcareous nannofossil Zone (fig. 4 in Lodowski et al. 2022, see also Wimbledon et al. 2020); corresponding is observed also in the TR sections. In Lókút the base of relatively long M17r magnetozone correlates with the base of the Elliptica calpionellid Subzone, yet it falls already in the NC1 calcareous nannofossil Zone. The interpretation is a bit more complicated in case of the Hárskút succession. There, a reversed polarity interval documented from the topmost part of the HK-12/a section was split into two magnetozones (M18r and M17r), suggesting a hiatus covering the upper part of M18r, entire M18n and the lower part of the M17r magnetozones (Figure 5, Lodowski et al. 2022). This assumption was based on the fact, that neither Elliptica nor NC1 biozones are known to appear as low as within the M18r magnetozone (e.g. Grabowski et al. 2010, Wimbledon et al. 2020, Casellato & Erba 2021, Lodowski et al. 2022), whilst magnetostratigraphic correlation with underlying Ferasini and NC0 biozones is undoubtful (Figure 5, Lodowski et al. 2022). In addition, due to the fact that it entirely falls in the NC1 nannofossil Zone as well as records the Elliptica/Cadischiana subzonal boundary, a reversed polarity interval at the base of the HK-12 section was also interpreted as magnetozone M17r (Figure 5, Lodowski et al. 2022).

The lower/upper Berriasian boundary (=the base of the *Calpionellopsis* calpionellid Zone; e.g. Grabowski et al. 2016, Wimbledon et al. 2020) may be observed only in the Hárskút HK-12 section, where the base of the Simplex Subzone correlates with the base of M16n magnetozone (Figure 5, Lodowski et al., 2022). Noteworthy is a surprisingly low thickness of the magnetozone (compare e.g. with Ogg 2020); this is interpreted as resulting from a hiatus/condensation zone within the interval; this may be noticed also in the field (fig. 13 in Lodowski et al. 2022).

The Calpionellopsis/Calpionellites zonal boundary is customarily adopted as a secondary marker for the Berriasian/Valanginian boundary (see Kenjo et al. 2020). In the HK-12 section this event falls in the M14r magnetozone; besides it roughly correlates with the base of the NC2B nannofossil Subzone (Lodowski et al. 2022).

8. Geochemical data

8. 1. Stable carbon and oxygen isotopes

Carbon isotope data concerning the Tithonian–Berriasian of the TR were published by Főzy et al. (2010), Price et al. (2016), Grabowski et al. (2017) and Lodowski et al. (2022).

The most characteristic trend seen is of decreasing $\delta^{13}C$ values through the Tithonian of both Lókút and Hárskút sections (Figure 6). For the entire Berriasian relatively light carbon isotopes are maintained. An abrupt increase in δ^{13}C is observed only within the upper Valanginian of the Hárskút HK-12 section, where the Weissert carbon isotope event was documented by Főzy et al. (2010; not shown on figures herein). These observations are consistent with data from other western Tethyan sections (compare e.g. with fig. 6 in Price et al. 2016 and see also Lodowski et al. 2022). The most recent contribution on stable isotope data is given to the Szilas Ravine, see Főzy et al. (2022a, this volume).

Stable oxygen isotope data (Figure 6) come from the same dataset as the results of δ^{13}C measurements published in Lodowski et al. (2022) and are presented here for the first time. These were performed in the Stable Isotope Laboratory of the GeoZentrum Nordbayern, Erlangen, Germany, using a Gasbench II connected to a ThermoFisherDelta V Plus isotope ratio mass spectrometer. Reproductibility and accuracy was monitored by replicate analysis of laboratory standards calibrated by assigning δ^{18}O values of -2.20‰ to NBS19 and -23.2‰ to NBS18 references; reproducibility was ±0.05 (1 std.dev.). Both in the Hárskút and Lókút succession δ^{18}O manifests a decreasing Tithonian–lower Berriasian trend (Figure 6), what is in agreement with data presented by Price et al. (2016). Noteworthy, the Tithonian oxygen isotope signature is lighter in Lókút, for ca. 1 ‰ VPDB, whilst Hárskút provides more variable δ^{18}O record. Characteristic are elevated δ^{18}Ovalues within the Alpina Subzone of both successions (see Figure 6 and compare with Price et al., op. cit.). The upper Berriasian–lower Valanginian of the Hárskút succession depicts generally increasing trend, from ca. -2 to -0.5 ‰ VPDB (see also Főzy et al. 2010), however single measurements are strongly variable (Figure 6).

8. 2. Geochemistry of elements

Variations of concentrations of certain elements may be interpreted either in terms of clastic input, redox conditions or paleoproductivity. Aluminum (Al) is commonly adopted as a proxy of lithogenic influx (e.g. Lodowski et al. 2022), authigenic U may be used for

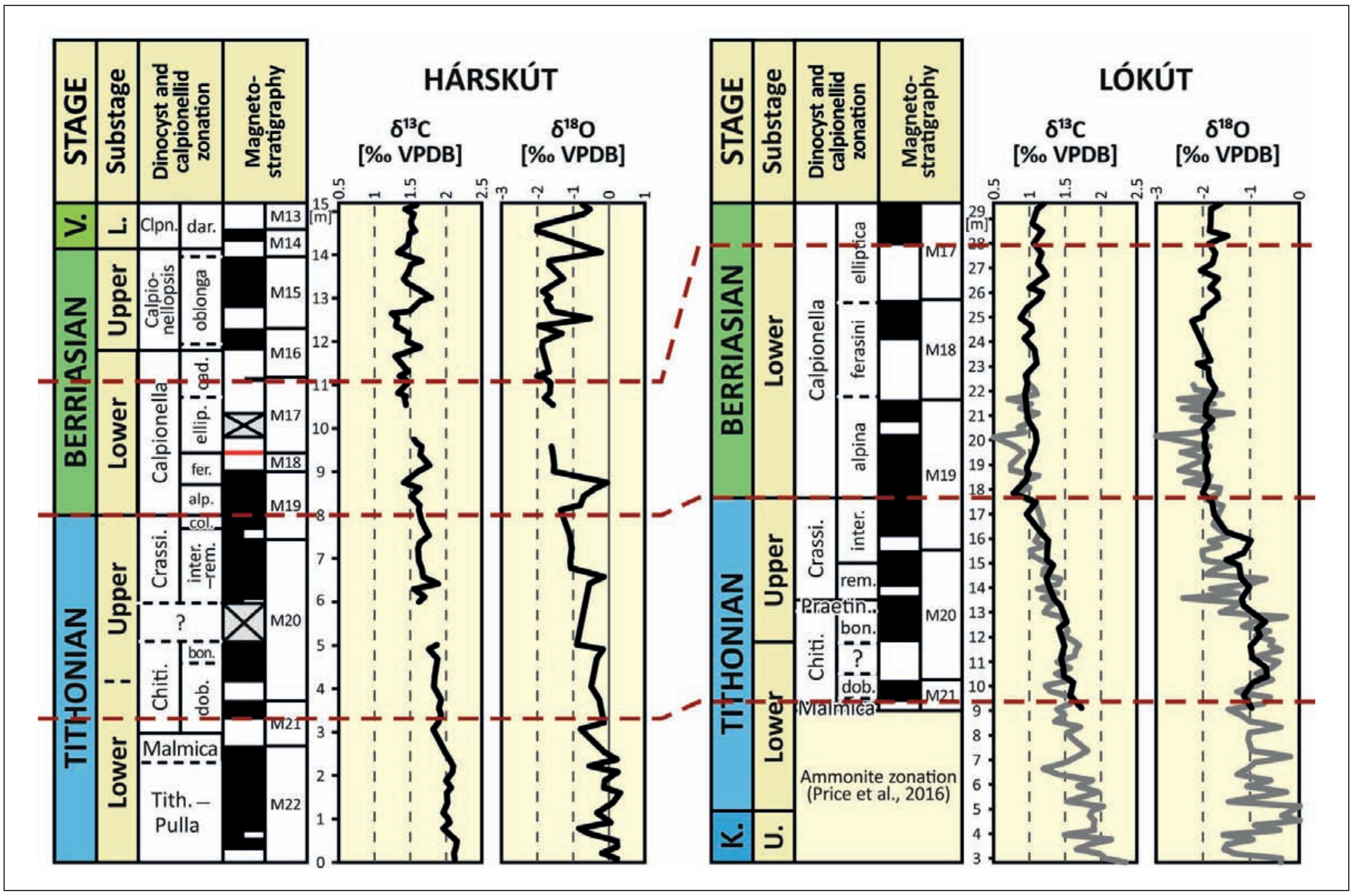

Figure 6 – Stable carbon and oxygen isotopes in the Hárskút and Lókút successions

Dashed red lines indicate correlation levels. Data combined from Price et al. (2016; Lókút, gray lines), Grabowski et al. (2017; Lókút, black lines), Lodowski et al. (2022; Hárskút and Lókút, black lines). Abbreviations: K. – Kimmeridgian; V. – Valanginian; L. – lower; U. – upper; Tith. – *Tithonica*; Chiti. – *Chitinoidella*; Praetin. – *Praetintinnopsella*; Crassi. – *Crassicollaria*; Clpn. – *Calpionellites*; dob. – *dobeni*; bon. – *boneti*; rem. – *remanei*; inter. – *intermedia*; col. – *colomi*; alp. – *alpina*; fer. – *ferasini*; ellip. – *elliptica*; cad. – *cadischiana*; dar – *darderi*.

estimations of paleoredox conditions of bottom-waters (Jones & Manning 1994), whilst paleoproductivity of surface waters may be evaluated via phosphorus and barium concentrations (e.g. Tribovillard et al. 2006). Detailed geochemical investigations of the Tithonian–Berriasian deposits were hitherto conducted only by Grabowski et al. (2017) and only in the Lókút LO-I section. Concerning Hárskút, only Al concentrations were published so far by Lodowski et al. (2022). Consequently, in order to compare paleoenvironmental signals recorded in both the Hárskút and Lókút successions here we present yet unpublished data for P, Ba and U concentrations. Laboratory analyses were conducted at the Bureau Veritas Mineral Laboratories, Canada Ltd. using multi-acid MA250 method (Bureau Veritas Minerals Schedule of Services & Fees 2019); mean detection levels (MDL) are as follows: $MDL_P = 0.001$ %; $MDL_{Ba} = 1$ ppm; $MDL_U = 0.1$ ppm.

Both Hárskút and Lókút sections depict a decreasing Al contribution through the entire Tithonian–lower Berriasian. Above, in the upper Berriasian and the lower Valanginian deposits increased Al concentrations are noted, however this phenomenon may be followed only in stratigraphically more extended Hárskút succession (Figure 7).

In order to allow further paleoredox interpretations, an Authigenic U formula of Jones & Manning (1994) was adopted:

$$\text{Authigenic U} = U_{\text{SAMPLE}} - \frac{Th_{\text{SAMPLE}}}{3}$$

This allowed to exclude a terrigenous component of uranium. In consequence, consistently low, near-zero values are observed through the lower Tithonian of both Hárskút and Lókút successions, whereas the upper Tithonian -lower Berriasian interval accounts for relatively less oxic conconditions at the seafloor (Figure 7).

Herein we adopt P and Ba concentrations as basic paleoproductivity proxies. However, similarly like in the case of U, to avoid effect of lithogenic admixture, raw concentrations of these elements were re-calculated using "excess" formula (e.g. Grabowski et al. 2021): **Al**, where D is a "detrital" constant, which

$$X_{\text{EXCESS}} = X_{\text{SAMPLE}} - [Al_{\text{SAMPLE}} \times D],$$

may be approximated to the lowest $\frac{X}{Al}$ ratio in the dataset, whilst X is considered element. As a result, both Hárskút and Lókút successions are characterized by a P-minimum near the lower/upper Tithonian boundary, as well as elevated concentrations starting near the Tithonian/Berriasian boundary and continuing above, through the lower Berriasian (Figure 8). Similar may be applied to the Ba_{EXCESS} curve, which depicts low (in Hárskút) or slightly increasing (in Lókút) Tithonian trends and elevated values in the lower Berriasian.

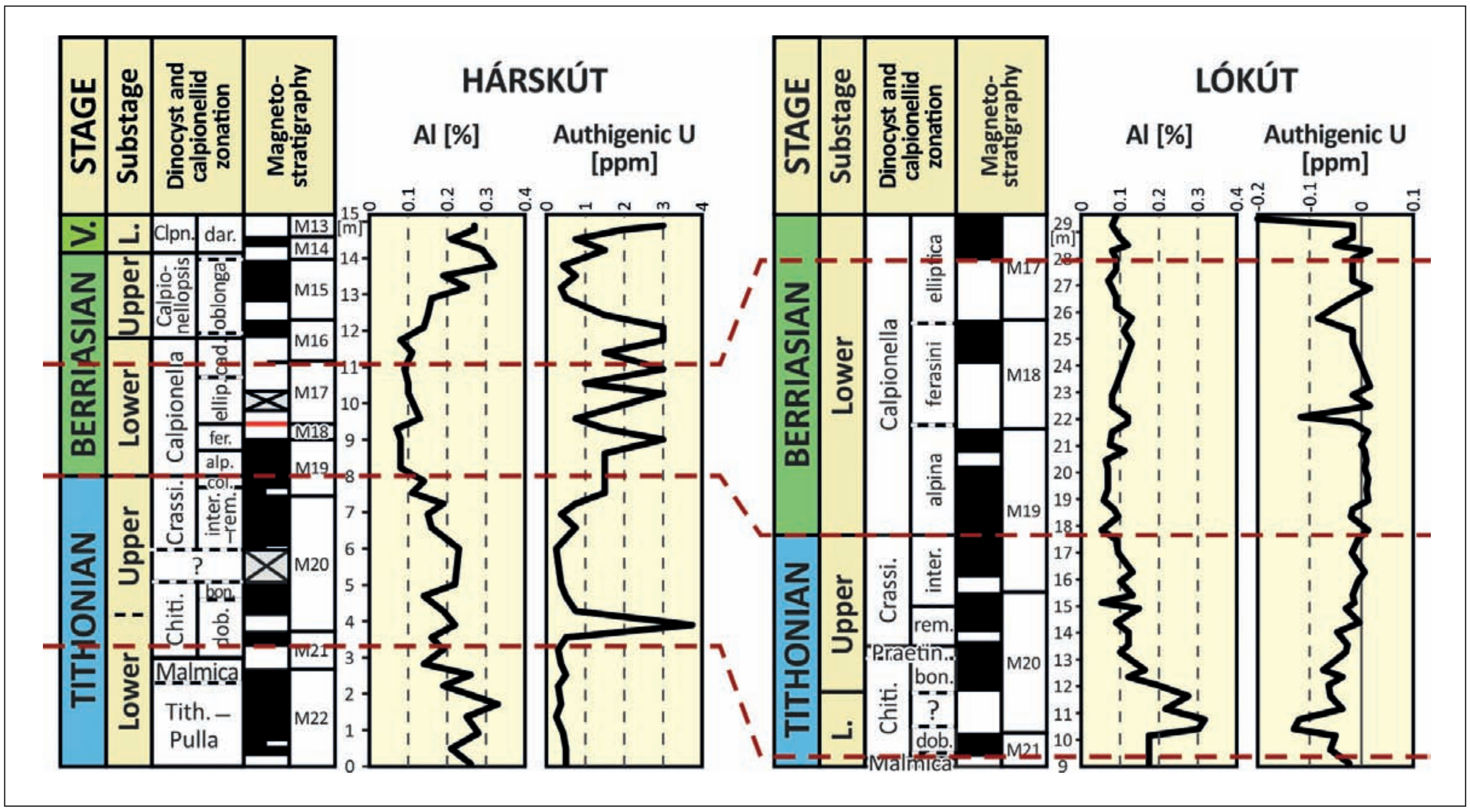

Figure 7 – Aluminum and authigenic uranium concentrations in the Hárskút and Lókút successions. Dashed red lines indicate correlation levels

Dashed red lines indicate correlation levels. Abbreviations as on Figure 6.

9. Sedimentology

The most detailed and up-to-date sedimentologic data for the J/K transition in the TR comes from the Lókút and Hárskút successions (Grabowski et al. 2010, 2017, Lodowski et al. 2022). The former provides an insight into pelagic sedimentation of marginal parts of the Bakony Basin, whilst in the latter forebulge (submarine plateau) facies are recorded. Both successions cover the interval of transition from the ammonitico rosso-type nodular limestones into the maiolica-type pelagic limestones (see lithologic logs on Figure 5). However, this phenomenon is diachronous: in Lókút nodular limestones disappear near the lower/upper Tithonian boundary (the upper part of magnetozone M20r), whilst in Hárskút ammonitico rosso-type facies range up to the base of the upper Tithonian Crassicollaria calpionellid Zone (the base of M20n1n magnetosubzone, slightly below the base of the NJT17 calcareous nannofossil Zone). Interestingly, nodular limestones reappear in the upper part of the Hárskút succession, within the upper Berriasian–lowermost Valanginian of the HK-12 section, what represents one of the youngest occurrences of the ammonitico rosso-type facies reported to date (compare with Cecca et al. 1992, Lukeneder 2011).

A separate issue is the uppermost Jurassic–lowermost Cretaceous microfacies succession of the TR. Its most characteristic feature is a *Saccocoma*-to *Calpionella*-dominated sedimentation turnover. Noteworthy, both in the Hárskút and Lókút sections this phenomenon is observed within the corresponding interval, namely near the top of the upper Tithonian M20n magnetozone (Figure 5, Lodowski et al. 2022). As discussed by Grabowski et al. (2019) and Lodowski et al. (op cit.), disappearance of *Saccocoma*-dominated microfacies may be traced through the uppermost Jurassic rocks of numerous Western Tethyan sections; moreover, the *Saccocoma*-*Calpionella* turnover apparently correlates with a period of nannofossil calcification events (NCE's; see e.g. Bornemann et al. 2003, Casellato 2010), falling in M20n1n–M19r magnetozones, apparently between NCE I and II (Lodowski et al. 2022). Consequently, environmental perturbances likely contributing to NCEs– amongst them climate, level of atmospheric pCO_2 and oceanic Mg/Ca ratio (see Bornemann et al. 2003, Tremolada et al. 2006, Casellato 2010) – may also have been important for demise of Saccocomidae.

9.1. Sedimentation rates

Magnetostratigraphic calibration allowed for calculation of sedimentation rates; these were calculated on the basis of observed thickness of a given interval and its estimated duration,

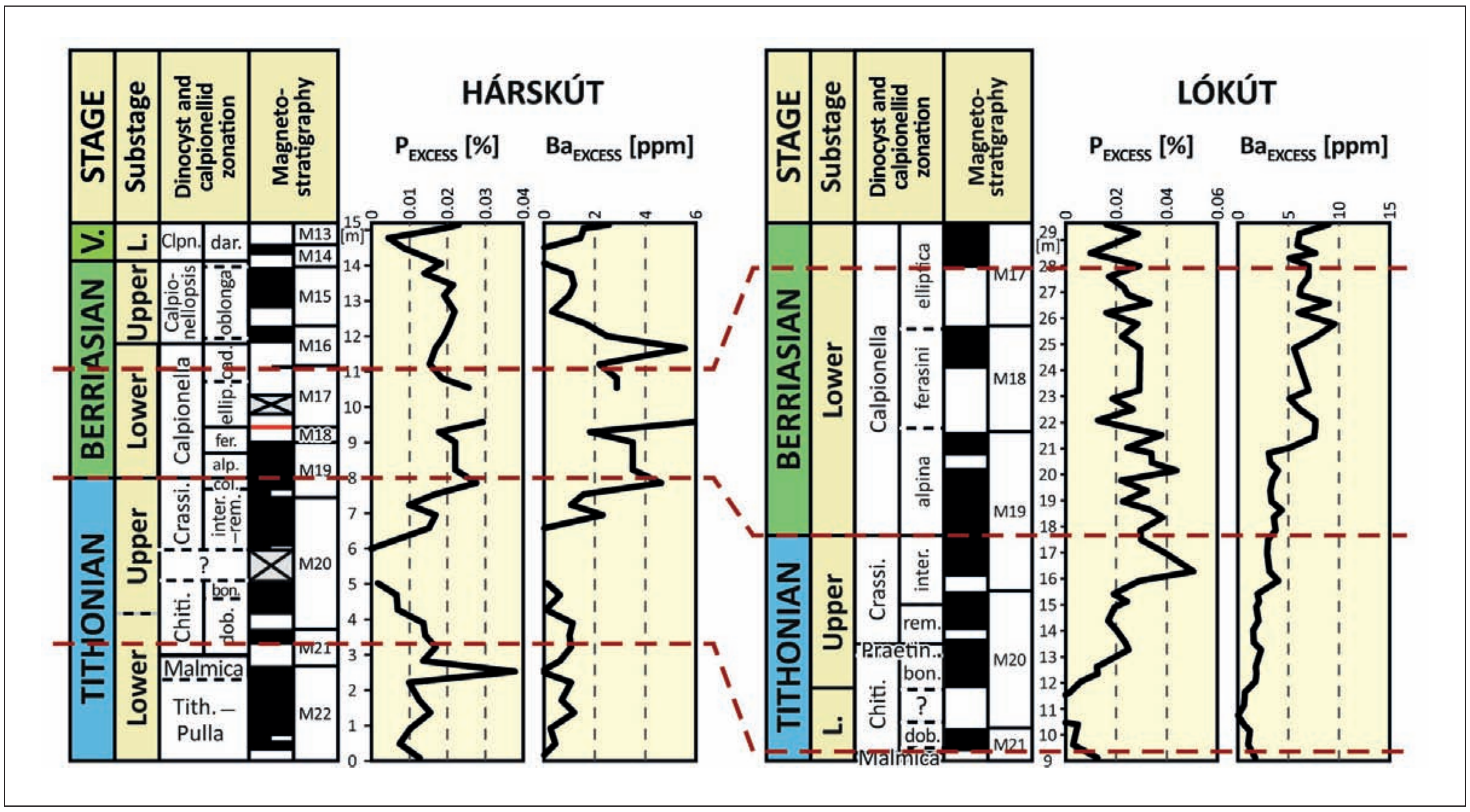

Figure 8 – Excess (authigenic) P and Ba concentrations in Hárskút and Lókút successions

Dashed red lines indicate correlation levels. Abbreviations as on Figure 6.

adopting the GPTS (Ogg, 2020). These are low in both Hárskút and Lókút succession (below 7 m/Myr), however, their trends differ between the two localities. The entire Tithonian–lower Valanginian of the Hárskút succession is characterized by very low (< 2 m/Myr) deposition rates, with local increases only within magnetozones M20n and M15n. In turn, an increasing trend is observed within the lower Tithonian–lower Berriasian (M21r–M18r) of the in Lókút succession (Figure 5). These differences are thought to result from distinct paleobathymetric setting, thus different styles of deposition in the two localities. Hárskút succession, located on a submarine elevation, was likely subjected to bottom currents and sediment leaching, what could result in more condensed record as observed hiatuses as well.

10. Conclusions

10.1. Integrated stratigraphy of the late Tithonian–early Berriasian interval

At some sections, ammonites are calibrated against magnetostratigraphy (Grabowski et al. 2010, 2017, Lodowski et al. 2022 for HK-12, HK-12/a, Lókút), calpionellid stratigraphy (Grabowski et al. 2010, 2017, Lodowski et al. 2022 for HK-12, HK-12/a, Lókút, Horváth & Knauer (1986) for HK-II) and nannofossil stratigraphy (Grabowski et al. 2010, 2017, Lodowski et al. 2022 for HK-12, HK-12/a, HK-II, Lókút, and Vörös et al. 2019, 2020 for Hárskút Édesvíz Key and Szilas Ravine), respectively. Ammonite zonation of the J/K boundary interval was recently revised by Szives & Főzy (2022), besides a brief critical revision of some stratigraphically important genera. This calibration of fossil groups compared to magnetostratigraphy allowed to create a multiple age constrain to the ammonite assemblages. According to these integrated data, a continuous biochronostratigraphic framework had been suggested for the J/K transition interval from the base of the late Tithonian Volanense to the base of early Berriasian Grandis Zones (Figure 9).

Ponti (Énay & Geyssant 1975) or Volanense (Cecca and Santantonio 1988) Zones cover more or less the same time interval (discussion see in Szives & Főzy 2022). Base of Microcanthum Zone (Énay & Geyssant 1975) is marked by the FO of the index species, *M. microcanthum.* Frau et al. (2016c) suggested that first occurrence datum (FAD) of *M. microcanthum* falls within the Boneti Subzone of the Chitinoidella standard Zone, in M20n2n magnetozone. Our results from Lókút, HK-12/a and HK-II sections assure this. Data from Szilas Ravine (Horváth & Knauer 1986) contradict this observation, however it needs re-investigation. New data from HK-12/a indicate that already – at least the upper part – the Volanense Zone falls into the Boneti Subzone of the Chitinoidella Zone (Szives & Főzy 2022). As a consequence, the base of the Microcanthum Zone has to place into the Boneti Subzone, in M20n2n as well. This is in a slight contrast with Frau et al. (2016c), who suggested that the base of the Microcanthum Zone falls lower, around the top of M20r. The subsequent Andreaei Zone falls in the upper M20n1n–lowermost M19n2n magnetozones interval. Data from Szilas Ravine and HK-II sections need further investigations.

10.2. Paleoenvironments of the Bakony Mountains

The area can be chracterized by simultaneous occurrence of pelagic/open marine and benthic organisms on the basis of the Bakony Mts sections. This indicates a segmented marine sea bottom characterized with deep water/deep basin and shallow water/elevated ridges. This idea is also supported by the sedimentological (e.g. redeposition) and lithological features, and reconstructs a large-scale basin-and-horst architecture proposed and assured by previous research (Galácz &Vörös 1972, Vörös & Galácz 1998, Lodowski et al. 2022, Fodor & Főzy 2022, this volume).

Grabowski et al. (2017) discussed decreasing terrigenous input observed in the Tithonian–lower Berriasian deposits of the Lókút succession as resulting from decline of continental weathering, related to climate aridization. This interpretation was supported later by the study of Lodowski et al. (2022); new data coming from the Hárskút and Lókút sections showed an excellent compatibility between the Al trends observed in both successions (Figure 7). Besides, Lodowski et al. (op cit.) interpreted the late Berriasian increase in lithogenic influx as resulting from the uplift and erosion of the Neotethyan Collision Belt, the same mechanism which led to appearance of siliciclastic sedimentation in the area of Gerecse Hills (e.g. Tari 1994, Fodor et al. 2013) and other Tethyan sections (e.g. Grabowski et al. 2021).

As may be inferred from authigenic U curves (Figure 7), in both Hárskút and Lókút successions the lower Tithonian interval is characterized by near-zero values, therefore generally oxic seafloor conditions. Conversely, relatively elevated (and above zero) authigenic U within the late Tithonian–early Berriasian deposits allow to infer about bottom-waters being subjected to limited oxygen deficiency during this time. Paleoproductivity proxies, in turn, this (P_{EXCESS} and Ba_{EXCESS} on Figure 8) depict an early Tithonian and an early Berriasian period of increased accumulation of these elements; noteworthy, this process was noticeably more sufficient during the early Berriasian, what coincides with elevated authigenic U values. Ultimately, Price et al. (2016) discussed the latest Jurassic decline in δ^{13}C as related to increasing oligotrophic conditions, thus lowered organic carbon burial. However, this model does not match to the interpretation of Grabowski et al. (2017), according to which the uppermost Tithonian–lower Berriasian peaks in trace metals resulted from the occurrence of upwelling. This assumption relied of the fact that increasing concentrations of productive elements correlate with decreas-

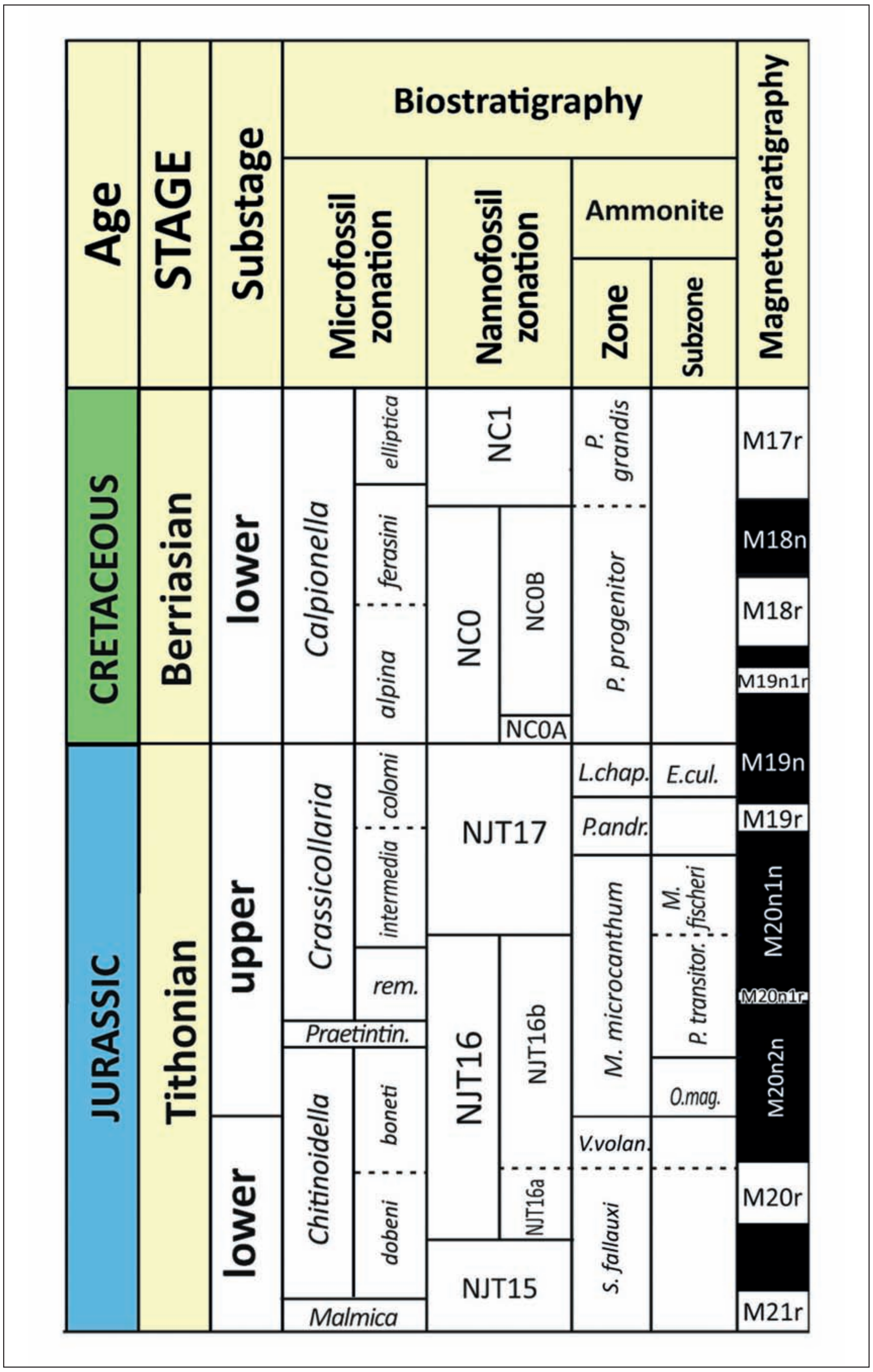

Figure 9 – Integrated stratigraphical scheme of the Tithonian/Berriasian interval (after Szives & Főzy, 2022)

ing amount of lithogens (which is true also in the case of the Hárskút succession; compare Al on Figure 7 with Figure 8), therefore clastic input could not have been driving an elevated supply of nutrients. Even so, the interpretation of Grabowski et al. (2017) accounts for a huge discrepancy, that is correlation between the onset of an arid climate mode, abundance of (oligotrophic) nannoconids and the occurrence of upwelling, which should have resulted in increasing fertility of sea-surface. As an alternative explanation we consider an effect of progressing climate aridization and related weakening of monsoonal upwelling processes (for details on monsoonal upwelling see e.g. De Wever, 2014). In this case the onset of an arid climate mode during the late Tithonian is thought to have resulted in less intense atmospheric (monsoonal) circulation, hence upwelling mechanism itself. This should have inevitably led to less mixed water column and (limited) stratification, as evidenced by redox proxies (Figure 7). Moreover, such conditions might have slowdown the nutrient shuttle, allowing larger amount of micronutrients being buried, instead of being subjected to biorecycling in the upper ocean (see e.g. Falkowski, 2012). Consequently, elevated concentrations of trace metals within the lower Berriasian (Figure 8) should be considered as resulting from (climate-driven) perturbations in seawater circulation, rather than reflecting actual changes in the sea-surface productivity.

11. Further perspectives

As it is demonstrated above, ammonitico rosso – maiolica/biancone sections of the Bakony Mountains are condensed, however the degree of condensation is variable. Related to the J/K transition interval, the most prosperous section is Rend-kő I as a most spectacular target for integrated studies, however ammonites were collected from a nearby, Rend-kő II section. Preliminary nannofossil investigations have to be completed on Hárskút Édesvíz Key Section (HEK) where they are good indicators of the Weissert Event. The newly obtained stable C and O isotope excursion from HEK section is published in this volume (Főzy et al. 2022a). Besides, at Szilas Ravine and HK-II sections, nannofossil investigations need to be completed, whilst calpionellid data has to be fully updated.

As the position of J/K boundary is still pending, these sections may contribute and add data to expansion of our knowledge and finally depicting the last missing system boundary in the global geochronological table.

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