FINAL REPORT

Improved calibration of selected parts of the Mesozoic time scale and its application in research on the history of biosphere

(OTKA Project K72633 – Principal Investigator: József Pálfy)

1. Introduction

The main aim of the project was to develop integrated stratigraphy in selected parts of the Mesozoic, use it towards refined calibration of the geologic time scale, enhance the possibilities for correlation, and interpret the results in the context of biotic evolution and environmental change. The backbone of such work is integrated ammonite biostratigraphy and U-Pb dating, but throughout the project we sought to employ a variety of stratigraphic methods (including biostratigraphy of other fossil groups, carbon isotope stratigraphy and other chemostratigraphies, cyclostratigraphy) in selected temporally and geographically diverse case studies. By doing so, the project delivered results partially diverging from what was first planned and envisioned, but fully in line with the original goal of employing the revised time scale and new stratigraphic knowledge towards a better understanding of salient biotic events of the Triassic, Jurassic and Cretaceous, and the history of biosphere in general.

2. New results in integrated ammonite biostratigraphy and U-Pb dating

2.1. Middle Triassic of the Balaton Highland

Middle Triassic strata in the Balaton Highland include fossiliferous formations with well-established and highly resolved ammonite biostratigraphy, and intercalated volcanogenic, tuffaceous beds that record distal volcanic activity. Such stratigraphic setting is an ideal target for time scale calibration studies, as demonstrated in previous studies (PÁLFY et al. 2003, VÖRÖS et al. 2003). Continued ammonite biostratigraphic work led to a refinement of the zonal subdivision of the Felsőörs section, an internationally recognized reference section (and former GSSP candidate) of the Anisian-Ladinian boundary. New excavation and sampling in the upper part of the Felsőörs section yielded important ammonoid finds, identified as belonging to the genera *Nevadites, Chieseiceras, Eoprotrachyceras* and *Falsanolcites*. Several specimens of *Chieseiceras chiesense* were found in a dm-thick clay layer with limestone nodules, regarded as the equivalent of the "*Chiesense* groove" of the Bagolino and other sections in the Giudicarie area (Northern Italy). The immediately overlying limestone bed yielded *Eoprotrachyceras* cf. *curionii* and *Falsanolcites* cf. *rieberi*. Together, these reliably prove the base of the Curionii Zone, corresponding to the base of the Ladinian Stage, the GSSP of which was recently established at Bagolino (VÖRÖS et al. 2008). The new data further improved the correlation between the ammonoid records of the Felsőörs section and the Global Stratotype Section at Bagolino. Therefore Felsőörs is considered as one of the most important reference sections for the Anisian-Ladinian boundary interval.

The refined zonal and subzonal biostratigraphic framework was integrated with new U-Pb dates, obtained using chemical abrasion pre-treatment of single crystals and the advanced mass spectrometry (CA-ID-TIMS method) in the NIGL-BGS lab in Keyworth (UK), in external collaboration with Q. G. CROWLEY. The new dates were obtained using this new methodology (as opposed to the previous TIMS measurements of multi-grain fractions of air-abraded zircons) on the same suite of samples as reported in PÁLFY et al. (2003). The revised ages are summarized in Table 1. These ages are slightly but systematically older than the earlier published ones, the 0.5–1.5 m.y. difference is accounted for by the superior performance of the new technique in eliminating Pb loss and minimizing the apparent younging of ages. These new dates, together with their biostratigraphic constraints, are in excellent agreement with similar newly published dates from the Southern Alps (WOTZLAW et al. 2017). A manuscript summarizing these results and the revised U-Pb ages is in preparation.

Table 1. Revised U-Pb ages from the Balaton Highland (Samples F100 – F109 from Felsőörs)

Sample No.	Concordia ages reported in PÁLFY et al. (2003)	**Revised ages** (first row, CA-ID-TIMS concordia age, with 2σ errors including decay constant uncertainty, followed by the $^{206}Pb/^{238}U$ age and their characteristics)
F100	241.26 ± 0.55 Ma	242.79 ± 0.25 Ma (MSWD = 0.61, Probability of concordance = 0.44) 242.38 ± 0.28 [0.11%] (0 of 5 rejected, MSWD = 2.4, probability = 0.052)
F101	240.53 ± 0.49 Ma	242.41 ± 0.24 Ma (MSWD = 0.61, Probability of concordance = 0.44 242.38 ± 0.28 [0.11%] (0 of 5 rejected, MSWD = 2.4, probability = 0.052)
F105	240.53 ± 0.49 Ma	240.81 ± 0.69 Ma (MSWD = 2.0, Probability of concordance = 0.16) 240.71 ± 0.65 [0.27%] (0 of 4 rejected, MSWD = 0.22, probability = 0.89)
F109	240.42 ± 0.45 Ma	242.00 ± 0.22 Ma (MSWD = 2.2, Probability of concordance = 0.14) 242.04 ± 0.19 [0.080%] (0 of 12 rejected, MSWD = 1.02, probability = 0.42)
Litér	238.70 ± 0.98 Ma	239.67 ± 0.22 Ma (MSWD of concordance = 2.1, Probability = 0.15) 239.59 ± 0.08 [0.033%] (0 of 9 rejected, MSWD = 1.20, probability = 0.30)

2.2. Triassic-Jurassic boundary in the Haida Gwaii (Queen Charlotte Islands, Canada) and Alaska (US)

Previously obtained U-Pb zircon ages from near the Triassic-Jurassic system boundary, from the Queen Charlotte Islands (British Columbia, Canada) (PÁLFY et al. 2000*a*) and Puale Bay

(Alaska, US) (PÁLFY et al. 1999) contributed significantly to the calibration of the geological time scale (GRADSTEIN et al. 2004). In external collaboration with R. FRIEDMAN (University of British Columbia) and R. MUNDIL (Berkeley Geochronology Center), repeated age determination of archived zircons were carried out from the same samples, now using the single-grain CA-ID-TIMS method (FRIEDMAN et al. 2008, PÁLFY et al. 2008).

Eleven single zircon crystals were analyzed at UBC from the Kunga Island sample just below the T-J boundary. Three of them had minor inherited older Pb and one remained affected by Pb loss. A coherent cluster of seven analyses yields a weighted mean $^{206}Pb/^{238}U$ age of 201.7 ± 0.6 Ma that we regard as the crystallization age and it serves as a close approximation for the age of T-J boundary. It is ~1% older than the originally reported age of 199.6 ± 0.3 Ma (PÁLFY, 2000*a*), but consistent with recent dating of volcanic ash layers near the T-J boundary in Peru (SCHALTEGGER et al. 2008) and Nevada (SCHOENE et al. 2010).

Single-crystal ID-TIMS U-Pb analyses on a tuff of earliest Hettangian age from the Puale Bay section (sample 95JP1 in PÁLFY et al. 1999) where performed at BGC and yielded a coherent cluster with a weighted mean $^{206}Pb/^{238}U$ age of 200.7 ± 0.3 Ma. This date is also consistent with the recently revised age of the T-J boundary (OGG & HINNOV 2012). A manuscript is in preparation to report these revised ages from around the T-J boundary.

2.3. Lower Jurassic of British Columbia, Canada

Abundant volcanic ash layers and tuff intercalations in the volcanosedimentary sequences of the Canadian Cordillera yielded U-Pb ages that form the backbone of the calibrated Jurassic numeric time scale (PÁLFY et al. 2000*b*). Taking advantage of methodological advances in U-Pb dating, some previously dated units were redated and new samples were also analyzed in this project, by single zircon CA-ID-TIMS technique.

From Todagin Mtn. in northern British Columbia (Stikine terrane, Spatsizi River map area), sample 96JP14 was previously dated as 185.6 +6.1/-0.6 Ma, using air-abrasion pre-treatment and multi-grain fractions (PÁLFY et al. 2000*c*). The large asymmetric error was due to the complex isotopic systematics of zircon crystals, hence a re-analysis was warranted. The newly obtained age, 187.57 ± 0.26 [0.38] Ma as reported by our external collaborator R. FRIEDMAN (UBC), is significantly more precise and accurate. This is a weighted mean $^{206}Pb/^{238}U$ age on the basis of three concordant analyses, with MSWD = 0.57. Six other analyzed zircons yielded scattered $^{206}Pb/^{238}U$ ages in the range of 190–205 Ma, recording widespread presence of zircons with inherited cores and/or xenocrysts, responsible for the lack of precision in the previous analysis. Fossiliferous levels below and above the sampled tuff layer allow a biostratigraphic assignment into the Freboldi Zone, i.e. the upper part of the Lower Pliensbachian of the North American regional standard ammonite zonation (SMITH et al. 1988).

Another re-analyzed sample which is crucial for time scale calibration is from the Lower Toarcian of Yakoun River (Wrangellia terrane, Queen Charlotte Islands, British Columbia). The originally reported age of 181.4 ± 1.2 Ma (PÁLFY et al. 1997) was revised and improved in precision by our external collaborator D. CONDON (NIGL-BGS). A weighted mean $^{206}Pb/^{238}U$ age of 181.657 ± 0.044 [0.085] Ma was obtained on the basis of four concordant zircons using the single-crystal CA-ID-TIMS technique. The dated volcanic ash layer occurs in the most fossiliferous, ammonite-bearing Toarcian section in North America, where tight biostratigraphic constraints allow its assignment to the middle Toarcian Crassicosta Zone (JAKOBS et al. 1994, PÁLFY et al. 1997).

2.4. Lower Cretaceous of Chilean Patagonia

New data from underexplored regions, such as South America, help global correlation, our understanding of geologic, biotic and environmental events, and the geologic time scale calibration. Together with C. SALAZAR from Chile, J. PÁLFY and I. FŐZY conducted two weeks of field work in the Aisén Basin, a Cretaceous back arc basin in Chilean Patagonia, forming part of the larger Austral Basin. A newly discovered, thick stratigraphic section at Rio Simpson contains an extended record of Lower Cretaceous formations, suitable for integrated stratigraphic research. Our study focused on fossiliferous strata and zircon-bearing volcanic tuff layers in the Katterfeld Formation, using ammonite biostratigraphy and U-Pb radioisotopic dating, complemented with carbon isotope and Sr isotope stratigraphy, with the first results presented in an MSc thesis supervised by the PI (KESJÁR 2014). The ammonite fauna is dominated by the endemic genus *Favrella*, represented by three species, of which *F. americana* appears first in the Lower Hauterivian, followed by *F. wilkensi* in the Upper Hauterivian. Due to the high paleolatitude, the ammonite fauna is of low diversity and correlation with the Tethyan faunas is difficult. For U-Pb dating at one of the leading facilities, an internal grant of the NIGL-BGS laboratory in Keyworth, UK, was secured, in collaboration with D. CONDON. Two biostratigraphically constrained tuff layers from the Rio Simpson section yielded zircon U-Pb ages of 129.35 ± 0.05 Ma and 127.52 ± 0.03 Ma (KESJÁR et al. 2017). AGUIRRE-URRETA et al. (2015, 2017) presented similar ages from a correlative section in the Neuquén Basin, from the base of the Upper Hauterivian and near the Hauterivian/Barremian boundary. Together with other numerical ages reported by VENNARI et al. (2014) and GHIGLIONE et al. (2015), the Early Cretaceous timescale can now be improved by new constraints and tie-points from South America. A manuscript summarizing our results is nearing completion and will be submitted soon.

3. New contributions to and application of other stratigraphic methods

3.1. Biostratigraphy

Here we list the results of ammonite biostratigraphic studies that were not directly integrated with U-Pb radioisotopic dating, as well as biostratigraphic work on other fossil groups, in most cases as part of an integrated stratigraphic approach.

A quantitative palynological and palynostratigraphical analysis of the black shale-bearing succession at Réka Valley in the Mecsek Mountains was carried out in the MSc thesis work of

V. BARANYI (2012), supervised by the PI of this project, with the results later published in detail (BARANYI et al. 2016). In this study, five sequential palynomorph assemblages were distinguished. These reveal major shifts in organic-walled phytoplankton communities, driven by paleoenvironmental changes. Assemblage 1 is characterized by a moderately diverse phytoplankton community and high levels of terrestrial palynomorphs. Assemblage 2 records a significant peak of the euryhaline dinoflagellate cyst *Nannoceratopsis*. Assemblage 3 is distinguished by dominance of highly opportunistic prasinophytes and the temporary disappearance of all dinoflagellate cyst taxa. Assemblages 4 and 5 represent distinctive phases of a prolonged recovery phase with low diversity phytoplankton assemblages and intermittently high levels of terrestrially-derived palynomorphs. These results allow reliable correlation with other Toarcian sections in both Tethyan and Northwest European localities, and are also significant in the context of analyzing the Toarcian Oceanic Anoxic event.

An integrated stratigraphic study, on the basis of ammonites, belemnites, calpionellids and stable isotope ratios was carried out in the Lower Cretaceous carbonate succession of the Hárskút, Közöskút Ravine profile (HK-12) in the Bakony Mts. (FŐZY et al. 2010). Abundant and diverse cephalopod assemblages occur in middle and late Berriasian *Rosso Ammonitico* facies, in a nearly complete sequence spanning the *Tirnovella occitanica* and *Fauriella boissieri* Zones. The overlying Lower Valanginian strata are condensed, but also yield rich assemblages of the *Thurmanniceras pertransiens* and *Busnardoites campylotoxus* Zones. The cephalopod fauna of the Late Valanginian *Saynoceras verrucosum* Zone is much less diverse. The overlying 19 m interval of Biancone-type marl yielded no megafossils. The uppermost part of the profile late Hauterivian cephalopods were found. These results allow reliable correlation with other Lower Cretaceous sections in Tethyan localities, and are also significant in the context of the Weissert Event.

3.2. Chronostratigraphy

The selection and voting process of the GSSP of Triassic-Jurassic system boundary took place near the beginning of this OTKA project and the GSSP in the Kuhjoch section was ratified in 2011 (MORTON 2012, HILLEBRANDT et al. 2013). However, our field work (together with a structural geologist, M. PALOTAI) in the stratotype section and in the area demonstrated structural complexities that compromise the suitability of the GSSP, which is located within the overturned, tight, and almost upright Karwendel syncline that was formed at semibrittle deformation conditions, confirmed by axial planar foliation. Tight to isoclinal folds at various scales were related to a tectonic transport to the north. Brittle faulting occurred before and after folding as confirmed by tilt tests (the rotation of structural data by the average bedding). Foliation is ubiquitous in the incompetent units, including the Kendlbach Formation at the GSSP. A reverse fault (inferred to be formed as a normal fault before folding) crosscuts the GSSP sections, results in the partial tectonic omission of the Schattwald Beds, and thus makes it impossible to measure a complete and continuous stratigraphic section across the whole Kendlbach Formation. Based on these observations, the Kuhjoch section does not fulfil the specific requirement for a GSSP regarding the absence of tectonic disturbances near boundary level (PALOTAI et al. 2017).

3.3. Chemostratigraphy

A carbon isotope anomaly near the Triassic-Jurassic boundary has served as a useful correlation tool. In this project, we attempted to search for additional geochemical signals and obtained a temporally highly resolved, multi-proxy dataset from the Kendlbachgraben section in the Northern Calcareous Alps in Austria (PÁLFY & ZAJZON 2012). The section belongs to the same paleogeographic unit (Eiberg Basin) and share similar stratigraphy with the recently selected base Jurassic Global Stratotype Section and Point at Kuhjoch. Micromineralogic study of the topmost bed of the Rhaetian Kössen Formation revealed pseudomorphs of altered, euhedral pyroxene and amphibole crystals. Their well-faceted morphology is consistent with their origin from distal mafic volcanic ash fallout. Spherical grains were also observed in the same bed, likely representing clay-altered volcanic glass. Clay minerals of this bed include low- to medium-charged smectite and Mg-vermiculite, both typical alteration products of mafic rocks. The same bed yielded a rare earth element pattern that differs from all other levels in an enrichment of heavy REEs, hinting at some minor contribution from mafic magmatic material. These features from a layer that was deposited very near to the T-J boundary are interpreted as direct evidence of CAMP volcanism, coeval or immediately preceding the end-Triassic extinction and the initial negative carbon isotope anomaly. The kaolinite-dominated clay mineral spectrum of the overlying boundary mudstone records intensive weathering under hot and humid greenhouse conditions. Redox-sensitive minor and trace elements do not support the development of widespread anoxia in the studied section. Although pyrite is common in several layers, framboid size indicates formation within a reductive zone, below the sediment/water interface, rather than in an anoxic water column. Our data provide a direct link between uppermost Triassic marine strata and CAMP-derived material.

As part of our work in the Aysén Basin in Chilean Patagonia, an organic carbon isotope curve was developed from this part of the Lower Cretaceous in South America for the first time. The $\delta^{13}C_{org}$ values from base to the top show an increase from -27‰ to -24‰ and then oscillate around -24.5‰. The pronounced positive shift in the lower part of the section permits correlation with the Late Hauterivian segment in the global curve, known mostly from carbonate carbon analyses of Tethyan sections (FÖLLMI et al. 2006). However, the shift may also be explained by more localised effect of bottom-water upwelling in the Aisén/Austral Basin during the Hauterivian sea-level rise (KESJÁR et al. 2017).

3.3. Cyclostratigraphy

The T-J boundary section at Csővár, a locality of previous multifaceted studies (PÁLFY et al. 2007), was subjected to an analysis of sedimentary cyclicity (HAAS et al. 2010). The 55-m-thick Rhaetian part of the section comprises five fourth-order cycles, which may reflect Milankovitch forcing, possibly preserving the long eccentricity signal. This suggests that deposition of the upper Rhaetian part of the Csővár section took at least ~2 m.y. Significantly in the context of end-Triassic biotic and environmental crisis, the following events took place within a single, presumably 400 ky cycle in the latest Rhaetian: 1) disappearance of ephemerally abundant platform-derived biota, 2) decline of both planktonic and benthic biota (reduction in biogenic sedimentary components, and conodont and foraminiferan diversity), 3) significant perturbation of the biosphere as documented by marine and terrestrial palynomorph assemblages, 4) geochemical anomalies in C and O isotopes; and 5) concurrent reduction of TOC.

4. Contribution to the calibration of geological time scale

4.1. The Triassic time scale

The calibration of the Triassic time scale, especially that of the Late Triassic, was poorly constrained and fraught with large errors in the successive editions of the Geological Time Scale (GTS) (GRADSTEIN et al. 2004, OGG et al. 2008) prior to the commencement of this project. With a team of international collaborators, a new compilation was published that addressed this problem and offered improvements (MUNDIL et al. 2010). This review of geochronological data underlying the geological time-scale for the Triassic yielded a significantly different time scale calibration than that published in GTS 2004. This is partly due to the availability of new radioisotopic data, but mostly because strict selection criteria were applied and complications arising from biases (both systematic and random) were accounted for. The ages for the base and the top of the Triassic were constrained by U-Pb ages to 252.3 and 201.5 Ma, respectively. Robust age constraints also exist for the Induan–Olenekian boundary (251.2 Ma) and the Early-Middle Triassic (Olenekian-Anisian) boundary (247.2 Ma), resulting in a surprisingly short duration of the Early Triassic, which has implications for the timing of biotic recovery and major changes in ocean chemistry during this time. Furthermore, the Anisian–Ladinian boundary is constrained to 242.0 Ma by recently obtained U-Pb and $^{40}Ar/^{39}Ar$ ages. Radioisotopic ages for the Late Triassic are scarce, and the only reliable and biostratigraphically-controlled age is from an upper Carnian tuff dated to 230.9 Ma, yielding a duration of more than 35 Ma for the Late Triassic. All of these ages are from U-Pb analyses applied to zircons with uncertainties at the permil level or better. This compilation helped resolving some of the issues associated with inaccurate and misinterpreted data in previous publications. However, further advances will require revision of some of the data presented there.

4.2. The Jurassic time scale

The current state of Jurassic time scale calibration was reviewed at the beginning of the project (PÁLFY 2008). The then available versions of the Geological Time Scale (GRADSTEIN et al. 2004, OGG et al. 2008) relied heavily on previous work of the PI of this project (PÁLFY et al. 2000*b*). The latter work relies heavily on U-Pb and $^{40}Ar/^{39}Ar$ dates, whereas the GTS2004 emphasizes complementary scaling methods using strontium isotope stratigraphy, cyclostratigraphy and magnetostratigraphy. U-Pb and $^{40}Ar/^{39}Ar$ dates remain the backbone of the time-scale, and fourteen recently published ages were added to the database of calibration points. Floating cyclostratigraphies already cover a significant portion of the Jurassic, allowing measurements of durations that need to be anchored and linked to chronostratigraphy. Where tie-points are sparse, reliance on scaling methods remains necessary. Possibilities of refinements have been identified, both in extending the underlying age database through addition of new U-Pb dates from the North and South American Cordillera, and revisiting the dating of important samples utilizing more advanced dating techniques (chemical abrasion, and use of single crystals and isotope dilution). A database of biostratigraphically constrained U-Pb ages from the North and South American Cordillera has been developed and maintained, to facilitate further refinement in time scale calibration.

5. Biotic change in the Triassic and Jurassic based on analyses of the Paleobiology Database (PBDB) and other synoptic studies

Data entry and analysis of the Triassic and Jurassic marine invertebrate diversity histories using the Paleobiology Database was in the focus of an MSc and later PhD thesis work of Ádám Kocsis, supervised by the PI of this project. Overall, this resulted in accumulation of considerable knowledge and experience regarding the use of PBDB in Hungary (Kocsis et al. 2015). The first specific project was completed in analyzing the radiolarian fossil record through the Triassic and Jurassic (Kocsis et al. 2014), prompted by interest in the ~60-Myr interval in the Late Triassic to Early Jurassic, when a major mass extinction took place at the end of Triassic, and several biotic and environmental events of lesser magnitude have been recognized. Climate warming, ocean acidification, and a biocalcification crisis figure prominently in scenarios for the end-Triassic event and have been also suggested for the early Toarcian. Radiolarians, as the most abundant silica-secreting marine microfossils of the time, provide a control group against marine calcareous taxa in testing selectivity and responses to changing environmental parameters. We analyzed the origination and extinction rates of radiolarians, using data from the PBDB and employing sampling standardization, the recently developed gap-filler equations and an improved stratigraphic resolution at the substage level. The major end-Triassic event is well-supported by a late Rhaetian peak in extinction rates. Because calcifying and siliceous organisms appear similarly affected, we consider global warming a more likely proximate trigger of the extinctions than ocean acidification. The previously reported smaller events of radiolarian turnover fail to register above background levels in our analyses. The apparent early Norian extinction peak is not significant compared to the long-term trajectory, and is probably a sampling artifact. The Toarcian Oceanic Anoxic Event, previously also thought to have caused a significant radiolarian turnover, did not significantly affect the group. Radiolarian diversity history appears unique and complexly forced, as its trajectory parallels major calcareous fossil groups at some events and deviates at others.

Encouraged by the success of this work, further PBDB-based studies have been carried out or are in progress since the completion of the OTKA project (VÖRÖS et al. 2016). The diversity history of brachiopods and its relationship to morphologic traits explained by adaptive and competitive pressures was also analyzed using a more traditional approach (VÖRÖS 2010). This study showed that after the end-Permian mass extinction, the phylum Brachiopoda attained a secondary peak of diversity in the Mesozoic, as the extant orders Rhynchonellida and Terebratulida diversified. Their apparent escalatory trends are interpreted as a response to increasing predation pressure during the Mesozoic marine revolution. The temporal changes in ornamentation of Mesozoic rhynchonellid and terebratulid brachiopods were escalation-related adaptation, analogous to mid-Paleozoic processes. Temporal changes in ornamentation and taxonomic diversity of Mesozoic Rhynchonellida and Terebratulida was documented in detail at the genus level. The early Mesozoic trends are best explained by a continuous effort to adapt to the threat of gradually increasing durophagous and boring predation. The Late Jurassic decline and Cretaceous minima in diversity and ornamentation of rhynchonellids suggest that the clade became a victim in the Mesozoic marine revolution. By contrast, terebratulids kept pace with the amplifying predation: the degree of their ornamentation increased and their diversity only moderately decreased after the Jurassic. From that time until the present, the two clades followed diverging evolutionary pathways. Rhynchonellids gave up the arms race, the coarsely ornamented forms gradually disappeared from the fossil record, and the clade abandoned the level-bottom communities to survive in environments with less predation pressure. Terebratulids increased their ornamentation and other antipredatory tools, and remained a fairly successful clade in the marine habitats.

6. Insights into selected Mesozoic events of rapid environmental and biotic change

6.1. Triassic-Jurassic boundary events

One of the main goals for improving the calibration of time scale at the T-J boundary is to assess the temporal relationship of volcanism of the Central Atlantic Magmatic Province (CAMP) with marine and terrestrial mass extinction. Establishing synchrony is necessary for (but does not in itself proves) their causal relationship. Partly on the basis of this OTKA project, we reviewed the recent developments in this topic (PÁLFY & KOCSIS 2014). Studies of various fossil groups and synoptic analyses of global diversity document the extinction and subsequent recovery. The concomitant environmental changes are manifested in a series of carbon isotope excursions (CIE), suggesting perturbations in the global carbon cycle. The source of isotopically light carbon remains debated (methane from hydrate dissociation vs. thermogenic methane), but either process is capable of amplifying an initial warming, resulting in runaway greenhouse conditions. Excess CO_2 entering the ocean causes acidification, an effective killing mechanism for heavily calcified marine biota that appears implicated in the reef crisis. The spatial and temporal extent of CAMP volcanism is established through a growing data set of radiometric ages and volcanism is now demonstrated to be synchronous with the environmental and biotic crisis. Since the CAMP is one of the largest Phanerozoic large igneous provinces, volcanic CO_2-driven warming is plausible as a key factor in the chain of Triassic-Jurassic boundary events. Greenhouse warming may have been punctuated by short-term cooling episodes due to H_2S emission and production of sulfate aerosols, a process more difficult to trace in the stratigraphic record. Taken together, recently generated data significantly increase the support for CAMP volcanism as a viable trigger for the environmental and biotic changes around the Triassic-Jurassic boundary. A direct link of the extinction level in marine strata with plausibly CAMP-derived material was found in the Kendlbachgraben section (Northern Calcareous Alps, Austria), in the form of distinctive rare earth element abundance patterns, clay minerals, and aerially transported mafic minerals (PÁLFY & ZAJZON 2012, ZAJZON et al. 2012),

6.2. The Toarcian Oceanic Anoxic Event

Major paleoenvironmental and paleoceanographical changes occurred during the Early Jurassic Toarcian Oceanic Anoxic Event (T-OAE), due to a perturbation of the global carbon cycle and a crisis in marine ecosystems. The OTKA project supported the MSc thesis work of V. BARANYI (2012), which investigated the sequence of environmental change and regional differences during the T-OAE through a study of organic-walled phytoplankton and other palynomorphs that are well-suited, but has been underutilised in the research of this event. This study concluded that the successive disappearance of phytoplankton taxa and the gradual takeover by opportunistic euryhaline species at the onset of the T-OAE were related to several phenomena (BARANYI et al. 2016). These include reduced salinity in the surface waters, establishment of a stable pycnocline and deterioration of nutrient recycling, followed by oxygen deficiency throughout much of the water column. Comparison with coeval European successions proves that the paleoenvironmental changes during the T-OAE were not entirely synchronous, and local factors also influenced the phytoplankton communities. In the Mecsek Basin, regional freshening of the surface waters and increased terrestrial input due to the proximity of the hinterland had a greater influence on phytoplankton communities compared to the open oceanic setting of the Tethys to the south.

The results of the OTKA project effectively prompted continuing research by the team members and their collaborators in the Réka Valley section. After the termination of the OTKA project, further work refined the calcareous nannoplankton biostratigraphy, established the presence of the well-known major negative carbon isotope anomaly, and placed constraints on its duration using cyclostratigraphy and astrochronology (MÜLLER et al. 2017).

6.3. The Early Cretaceous Weissert Event

An integrated stratigraphic study of the Hárskút section in the Bakony Mts. was primarily aimed at detecting the signature of the Early Cretaceous Weissert Event (FŐZY et al. 2010). Stable isotope analysis shows a well-defined positive $\delta^{13}C$ excursion in the Valanginian strata, identified for the first time in Hungary. Although correlated with a possible anoxic event (known as the Weissert Event), as in many other sections, no black shale or organic-rich level is recorded at Hárskút. However, it clearly coincides with a horizon of stratigraphic condensation, signaled by both an unusual concentration of ammonites on a single bedding plane, and a concurrent jump in the carbon isotope ratio. A major change is also observed in the calpionellid assemblages. Taken together, these signals hint at changes in ocean chemistry adversely affecting the calcareous microplankton, hence the carbonate production and deposition.

The discovery of stratigraphic signatures of the Weissert Event in a section in Hungary prompted further research by our team and our international collaborators, after closing of the OTKA project. These efforts led to the recognition of the Weissert Event in the thick siliciclastic sequence of the Bersek Hill in Gerecse Mts, where the duration of the event was also constrained by astrochronology (BAJNAI et al. 2017).

7. References

Official publications from OTKA Project no. 72633 are marked by grey highlight.

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