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« Short » or « long » Rhaetian ? Astronomical calibration of Austrian key sections

Bruno Galbrun^{a,*}, Slah Boulila^a, Leopold Krystyn^b, Sylvain Richoz^{c,d},
Silvia Gardin^e, Annachiara Bartolini^e, Martin Maslo^b

^a Sorbonne Université, CNRS, Institut des Sciences de la Terre de Paris, IStEP, Paris, France

^b University of Vienna, Department of Paleontology, Vienna, Austria

^c Institute of Earth Sciences, NAWI Graz, University of Graz, Graz, Austria

^d Department of Geology, Lund University, Lund, Sweden

^e Sorbonne Université, MNHN, CNRS, Centre de Recherche en Paléontologie-Paris, CR2P, Paris, France

* Corresponding author : bruno.galbrun@sorbonne-universite.fr

Highlights

- First high resolution cyclostratigraphic study of a marine Rhaetian (Late Triassic) record
- Proposed minimal duration for the Rhaetian: 6.69 myr
- Suggested age for the Norian-Rhaetian boundary: 208.05 Ma

Abstract

The establishment of the Late Triassic time scale has given rise to considerable controversy, particularly regarding the Rhaetian duration and the inferred absolute age models. In this respect the astronomical polarity time scale (APTS) established from the continental successions of the Newark Basin (eastern North America) is considered as a reference record, although its completeness is questioned. Numerous magnetostratigraphic correlation schemes have been proposed between the APTS and biostratigraphically well-constrained Tethyan marine sections. This has led to two main contrasting options: a "short" Rhaetian duration (about 4-5 myr), and a "long" one (about 8-9 myr). Astronomical calibration of the Tethyan Rhaetian and estimate of its duration is necessary to help advance this debate. We have undertaken a cyclostratigraphic analysis of a Rhaetian composite record built from four overlapping Austrian reference sections. Magnetic susceptibility variations of the 131.5 m thick record are astronomically paced by the precession and 405-kyr orbital eccentricity cycles. 405-kyr orbital tuning allows to establish a floating time scale, and thus to suggest a minimum duration of 6.69 myr of the Rhaetian stage. Given the well-established radioisotopic age of the Rhaetian-Hettangian boundary of 201.36 Ma, an age no younger than 208.05 Ma for the Norian-Rhaetian boundary can be proposed. This result will contribute to the refinement of the Late Triassic time scale, but it does not solve the long-standing debate on bio-magnetostratigraphic correlations between the continental Newark APTS and the Tethyan marine sections, nor the question of the completeness of the Rhaetian Newark Basin.

Keywords

Rhaetian
Late Triassic time scale
Magnetic susceptibility
Cyclostratigraphy
405 kyr eccentricity tuning
Northern Calcareous Alps

1. Introduction

The end of Triassic witnessed major paleoenvironmental changes and biotic crises (e.g. Guex et al., 2012; Mc Roberts et al., 2012; Palfy and Kocsis, 2014; Tanner et al., 2004). To analyze the tempo and rate of the biotic and environmental turnovers occurring at the end of the Triassic (e.g. van de Schootbrugge et al., 2009, 2013; Clemence et al., 2010; Deenen et al., 2010; Preto et al., 2010; Ruhl and Kürschner, 2011; Gardin et al., 2012; Lindström et al., 2012; Mette et al., 2012; Richoz et al., 2012a; Suan et al., 2012; Blackburn et al., 2013; Lucas and Tanner, 2015; Tanner et al., 2016), an accurate estimate of the duration of the Late Triassic stages and in particular of the Rhaetian, the last Triassic stage, is of paramount importance.

A complete and precise time scale does not exist for the Late Triassic yet (see review in Hounslow and Muttoni, 2010; Lucas, 2010a,b; Mundil et al., 2010; Lucas et al., 2012; Ogg, 2012; Maron et al., 2015; Tanner and Lucas, 2015; Kent et al., 2017; Kent et al., 2018; Olsen et al., 2018). While the ages of the Early and Middle Triassic stage boundaries are well constrained, those of the Late Triassic are not well refined (e.g. Mundil et al., 2010; Ogg, 2012). So far, a reliable radioisotopic age of 230.9 Ma exists for the Late Triassic (Lower Tuvanian substage, Carnian stage; Furin et al., 2006). The Triassic-Jurassic (Rhaetian-Hettangian) boundary which is positioned within the aftermath of a great extinction due to the emplacement of the Central Atlantic Magmatic Province (CAMP), is radiometrically well dated at 201.31 ± 0.18 Ma in the Pucara Basin (Schaltegger et al., 2008; Schoene et al., 2010; Guex et al., 2012; Wotzlav et al., 2014) and astrochronologically assessed at 201.42 ± 0.02 Ma in the Newark-Hartford succession (Blackburn et al., 2013). For this boundary an age of 201.3 Ma is used in the most recent Geological Time Scale (Ogg, 2012; ICS, 2019). U-Pb dates of 205.70 ± 0.15 Ma and 205.30 ± 0.14 Ma from volcanic ash beds within the Rhaetian Aramachay Formation in the Pucara basin (Northern Peru) are more or less correlative with the last occurrence on the bivalve *Monotis*, corresponding more or less to the Norian-Rhaetian boundary (NRB) (Wotzlav et al., 2014). This suggests a Rhaetian duration of 4.14 myr. A recent U-Pb age of 205.20 ± 0.9 Ma in lower Rhaetian sediments of British Columbia (Golding et al., 2016) seems to confirm this age.

The duration of the Rhaetian stage has been the subject of a long debate for decades. Before the above reported radioisotopic ages, the Rhaetian chronology was mainly based on magnetostratigraphic correlations of different biostratigraphically constrained marine Tethyan sections using the floating astrochronology derived by the continental Newark Basin reference sequence where magnetostratigraphic data are also available (e.g. Channell et al., 2003; Gallet et al., 2000; Gallet et al., 2003, 2007; Muttoni et al., 2004, 2010; Olsen et al., 2011; Hüsing et al., 2011; Ogg, 2012; Maron et al., 2015; Kent et al., 2017). Unfortunately however there is not an unambiguous solution to these correlations (Ogg, 2012; Wotzlav et al., 2014; Maron et al., 2015) and the completeness of the Newark Basin sequence, especially the Rhaetian, is also debated (van Veen, 1995; Kozur and Weems, 2007, 2010; Kürschner et al., 2007; Olsen et al., 2011; Blackburn et al., 2013; Tanner and Lucas, 2015; Weems et al., 2016; Kent et al., 2017). Thus, the durations of the Rhaetian are estimated to be between ~ 9 myr (Hüsing et al., 2011; solution 1 of Ogg, 2012), 6 to 8 myr (Kent and Olsen, 1999; Muttoni et al., 2010; Olsen et al., 2011), 4 to 5 myr (Gallet et al., 2007 and solution 2 of Ogg, 2012) or even only 2 myr by exclusion of time-equivalents of the oldest Rhaetian ammonite zone, *Paracochloceras suessi* (Gallet et al., 2003; Walker and Geissman, 2009; Callegaro et al., 2012). The establishment of a Rhaetian duration with a reasonable uncertainty does not, however, solve the correlation problem between Tethyan marine sections and the Newark basin. For example, Maron et al. (2015) and Kent et al. (2017), assuming a complete Rhaetian in the Newark basin have recently proposed a magnetostratigraphic correlation with Pignola–Abriola section in Southern Italy, which is a candidate for the NRB GSSP. The boundary at Pignola–Abriola, defined with the first appearance of *M. posthersteini sensu* Rigo et al. (2005) would be indirectly dated at 205.7 Ma through its correlation to the Newark basin cyclostratigraphy, which roughly correspond to the dates of Wotzlav et al. (2014). However this implies that the FAD of *M. posthersteini sensu* Krystyn (1991), Krystyn et al. (2007a, b) at Steinbergkogel, the other candidate section for the NRB GSSP, is dated at 209.5 Ma (Maron et al., 2015, their Fig. 6) and that the time interval between the two definitions of the same species is surprisingly equivalent to the duration of the whole Rhaetian. Correlations are still problematic and the timing of the precursory bioevents before the end-Triassic mass-extinction is still not sufficiently precise (Ogg et al., 2016). There is a strong need to have a marine cyclostratigraphic scheme biostratigraphically well constrained and independent from the one of Newark basin.

Astronomical calibration of the Geological Time Scale through the identification within the sedimentary record of climate cycles forced by the Earth's orbital parameters (eccentricity, obliquity, precession), has emerged as the most efficient approach for refining the Mesozoic time scale during the past 15 years (Hinnov, 2000, 2014; Hinnov and Ogg, 2007). Given the chaotic behavior of the

solar system a direct astronomical calibration at whole eccentricity solution of sedimentary successions is not possible beyond 50 Ma (Laskar, 1990; Laskar et al., 2004) but the 405 kyr orbital eccentricity term is enough stable over 250 Ma to allow the construction of a reliable Mesozoic time scale (Kent et al., 2018). Therefore the recognition of 405 kyr eccentricity cycles in sedimentary records, leads to « floating time scales » that do not provide direct dating of the associated geological events, but allow an estimation of the time represented by a sedimentary succession. This methodology has been successfully applied to estimate the duration of several Mesozoic stages (e.g., Weedon et al., 1999; Grippo et al., 2004; Hinnov et al., 2009; Husson et al., 2009, 2011; Huang et al., 2010; Boulila et al., 2010, 2013, 2014; Charbonnier et al., 2013; Thibault et al., 2016).

In this work, we carried out astronomical calibration of Rhaetian marine reference successions in the Northern Calcareous Alps of Austria. The Austrian Late Triassic marine sedimentary successions are biostratigraphically the most complete and lithologically suitable for cyclostratigraphy. We analyzed four key sections encompassing the whole Rhaetian: (1) the Steinbergkogel section proposed as the Rhaetian GSSP (Krystyn et al., 2007a, b; Krystyn, 2010; Hüsing et al., 2011), (2) the Zlambach section which covers most of the lower and middle part of the Rhaetian (Matzner, 1986; Krystyn, 1991; Richoz and Krystyn, 2015), (3) the Eiberg section, covering the upper part of the Rhaetian, which was the subject of numerous stratigraphic and micropaleontologic studies (e.g., Kuss, 1983; Golebiowski, 1991; Clemence et al., 2010; Mette et al., 2012; Korte et al., 2017), and (4) the Kuhjoch section, Hettangian GSSP (Triassic-Jurassic boundary) (Kürschner et al., 2007; Ruhl et al., 2010b; Richoz et al., 2012b; Hillebrandt et al., 2013). Magnetic susceptibility (MS) was used as an indicator of climate change for cyclostratigraphic analysis. Our goals were to (1) demonstrate astronomical forcing of these Austrian Rhaetian sedimentary successions, (2) astronomically calibrate the duration of the Rhaetian using the 405 kyr orbital eccentricity cycle inferred from the MS variations, and (3) provide new time constraints for the Late Triassic.

All figured (Plates 1-2) and in the text mentioned fossils from the studied sections are housed in the collections of the Institute of Paleontology, Vienna University.

Fig 1 Rhaetian chrono- and bio-stratigraphy, modified from Kozur (2003), Krystyn (2008), Ogg (2012) and ICS (2019) and this study.

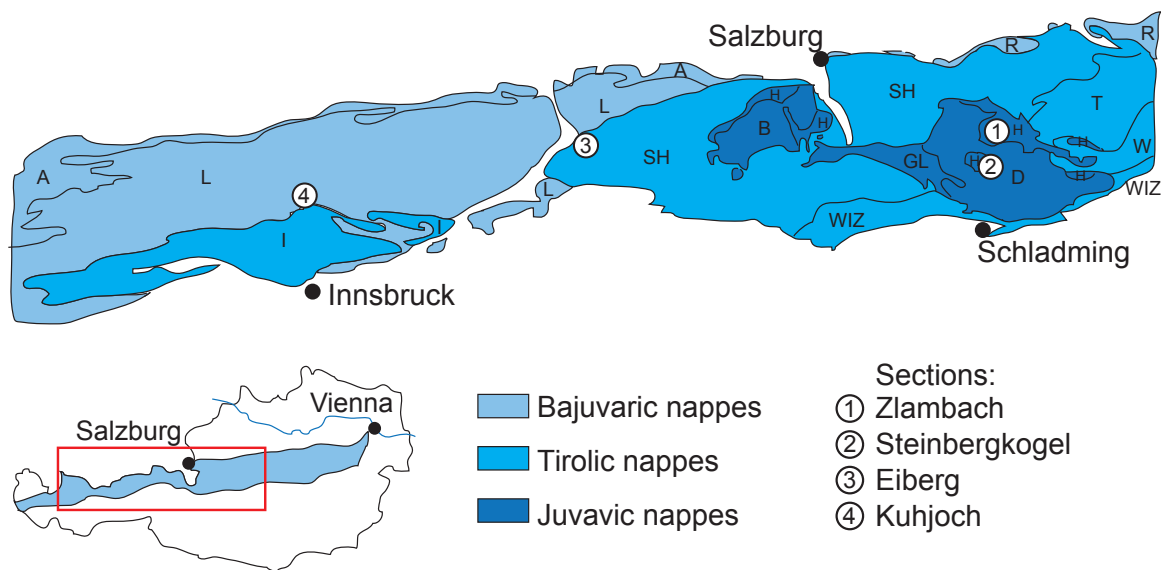
AGE (Ma)	Stage	Substage	Ammonoid Z/Subzone Standard		Pelagic bivalves	Conodont Zone/Subzone	
						Tethys/W- Pacific	North America
201.3 — 201.3 ±0.2	RHAETIAN		Choristoceras marshi	Choristoceras marshi	Otapiria	Misikella ultima	Norigondolella
C. ammonitiforme				Misikella posthernsteini			
Vandaites stuerzenbaumi			Vandaites stuerzenbaumi	Misikella rhaetica		Orchardella mosheri	
			Vandaites saximontanus				
			Paracochloceras suessi			Misikella posthernsteini	
						Misikella hernsteini	
						E. bidentata	
					Monotis rhaetica	M. posthernsteini	
205.4 — 209.5 — 208.5	NORIAN	SEVATIAN	Sagenites quinquepunctatus			Epigondolella bidentata	
					Misikella hernsteini		
				Monotis salinaria		Epigondolella bidentata	Epigondolella bidentata

2. Stratigraphic and geologic setting

2.1. Rhaetian chronostratigraphy

The definition of Late Triassic stages boundaries, especially the Rhaetian, has been debated for decades. A consensus on the definition of the NRB was reached choosing the appearance of the conodont species *Misikella posthernsteini*, a datum that is well constrained in several ammonoid-dated Tethyan sections (Krystyn, 2008, 2010). This boundary is marked by important turnover in ammonoids, conodonts, bivalves, radiolarian, palynomorphes (e.g. Krystyn et al., 2007a). Two sections are candidate for the Rhaetian GSSP, Steinbergkogel in Austria (Krystyn et al., 2007a,b; Gardin et al., 2012) and Pignola-Abriola in southern Italy (Rigo et al., 2015; Maron et al., 2015). It is important to stress that both GSSP candidates are defined on two different morphotypes of *M. posthernsteini* and thus the correlation of the boundary between the sections is not straightforward. These two diverging taxonomic interpretations are here designated as *M. posthernsteini* morphotype A (*sensu* Krystyn et al., 2007a, b; cf Supplementary material 1, Plate S1, 1-3) and *M. posthernsteini* morphotype B (*sensu* Rigo et al., 2015; cf Supplementary material 1, Plate S1, 4-9), the latter corresponding to *M. posthernsteini sensu strictu*. As they appear closely above each other (by one bed) in Steinbergkogel, no major time difference might be expected between their first occurrences (see below and additional information on the Steinbergkogel section in Supplementary Material 1). Alternatively, these close occurrences might be explained by an interval of condensation. The Rhaetian-Hettangian (Triassic-Jurassic) boundary corresponds to the first occurrence (FO) of the ammonite *Psiloceras spelae tirolicum* as defined in the Hettangian GSSP at Kuhjoch (Hillebrandt et al., 2013). If conodonts have become the main biostratigraphic tool for global correlation, the historical Triassic subdivisions are still based on ammonites. The ammonoid-rich successions of the Northern Calcareous Alps of Austria have been an essential element in establishing the global primary standard Triassic chronostratigraphy since the 19th century. The Rhaetian stage is subdivided into three ammonoid zones (Krystyn, 2008; Ogg, 2012) in ascending order: *Paracochloceras suessi*, *Vandaites stuerzenbaumi*, and *Choristoceras marshi* zones (Fig. 1). Other significant biochronological events close the NRB are the disappearance of the bivalve genus *Monotis* (Mc Roberts et al., 2008; Mc Roberts, 2010), the first appearance of key coccolithophorid species (Gardin et al., 2012; Demangel et al., this volume) and a major turnover in radiolarians (Carter, 1990). No substages were defined for the Rhaetian (Ogg, 2012).

Fig 2 The nappe complex of the Austrian Northern Calcareous Alps (modified from Mandl 2000 and Richoz and Krystyn 2015) and location of the studied sections (more detailed location maps can be found in Hillebrandt et al. 2013, Richoz et al. 2012b, Richoz and Krystyn 2015).



2.2. Geologic setting

The nappe complex of the Austrian Northern Calcareous Alps is one of the most prominent units of the Eastern Alps. This complex forms a 500 km long and 20 to 50 km wide thrust belt of sedimentary successions (Fig. 2). During the Permian and Triassic, these sediments were deposited on the passive continental margin of the "Hallstatt-Meliata-Ocean", a branch of the Tethys. One of the most characteristic morphological features of the Austrian Alps are large mountains plateaus built by the Late Triassic Dachstein carbonate platforms, up to 1200 m thick limestone series. These Dachstein limestone massifs show transitions to a south- and southwest adjacent slope, bordering the open marine deeper Hallstatt shelf (Mandl, 2000).

Around Lake Hallstatt, at about 130 km southeast of Salzburg, Norian and lower Rhaetian in part condensed red or grey pelagic limestones of the Hallstatt Formation (Middle and Upper Triassic) crop out widely. This Hallstatt succession ends with an increased terrigenous input during the lower Rhaetian. The marly Zlambach Formation from the basin between the Dachstein platform and the Hallstatt facies realm interfingers in the lower to middle Rhaetian with the Hallstatt limestone and replaces it completely in the late Rhaetian. In the Lake Hallstatt area we analyzed two sections: the Steinbergkogel section proposed as the reference section for the NRB (Krystyn et al., 2007a, b) and the Kleiner Zlambach section which is the type locality of the Zlambach Formation (Matzner, 1986).

The Eiberg Basin is a late Rhaetian intraplatform depression north-west of the Dachstein platform, which can be traced over 200 km in western Austria. In the Eiberg Basin deeper facies succeed over shallow water sequences during the Rhaetian. Ongoing subsidence in late Rhaetian allows the prevalence of marine conditions through the Rhaetian-Hettangian (Triassic-Jurassic) boundary. In the Eiberg basin two sections have been investigated: Eiberg and Kuhjoch. The Eiberg section covers the middle and upper part of the Rhaetian and was the subject of many stratigraphic studies (e.g., Golebiowski, 1991; Clemence et al., 2010; Mette et al., 2012; Korte et al., 2017). The Kuhjoch section was chosen as it represents the Hettangian GSSP (Triassic-Jurassic boundary) (Hillebrandt et al., 2013). The Austrian Northern Calcareous Alps allow thus to analyze the well preserved upper Triassic sedimentary records of various paleoenvironmental settings from lagoon to reefs, intraplatform basin, slope, pelagic plateau within a good biostratigraphic framework (Mandl, 2000; Krystyn, 2008; Richoz et al., 2012b; Richoz and Krystyn, 2015).

2.3. The studied sections

2.3.1. The Steinbergkogel section

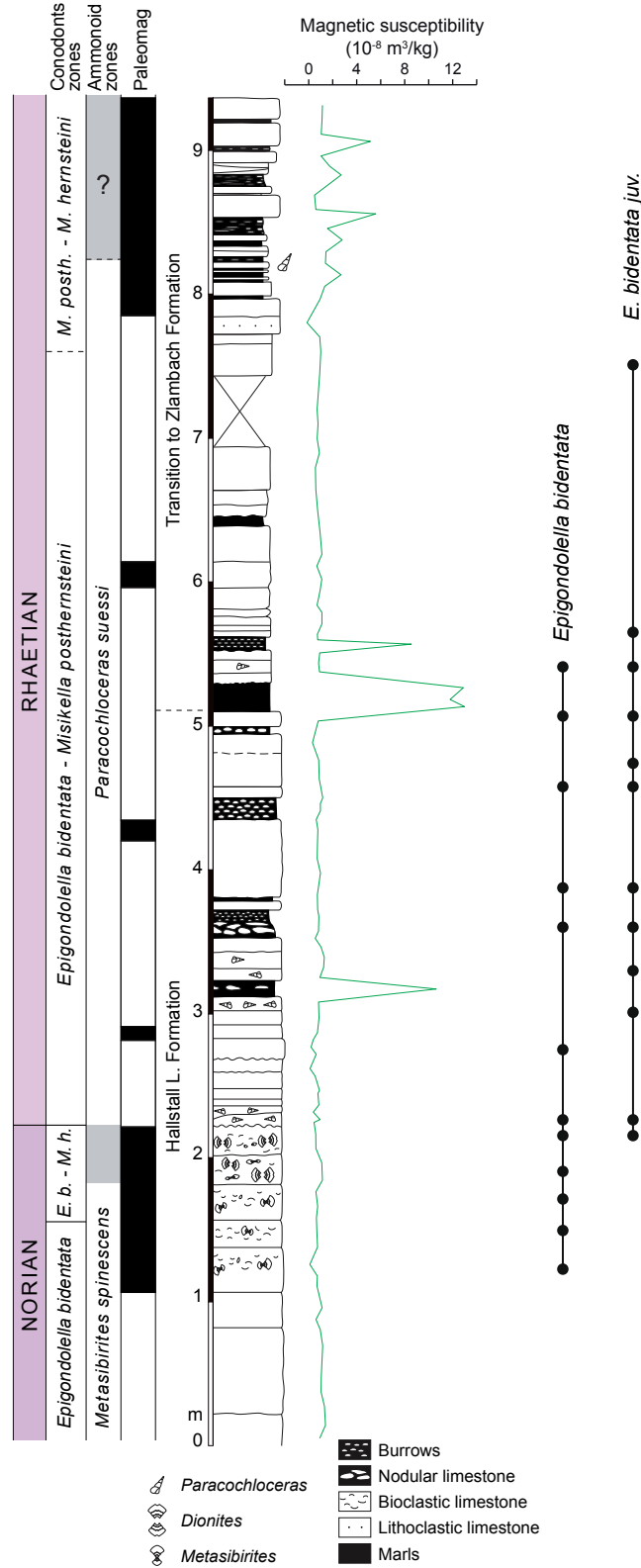
The Steinbergkogel section (Fig. 3) is located to the southwest of Bad-Isch in an abandoned quarry one kilometer west of Lake Hallstatt (coordinates 47°33'50"N, 13°37'34"E). This 10 m thick section is proposed as the Rhaetian GSSP (i.e., Norian-Rhaetian boundary) (Krystyn et al., 2007a,b; Krystyn, 2010). The lower part of the section consists of thick-bedded fine-grained pelagic limestones bed (bioclastic wackestones of Hallstatt facies) predominantly red or grey of latest Norian to earliest Rhaetian age. Thin clay interbeds appear in the upper part of the section, and the top shows a gradual transition to grey marls of the Zlambach Formation. The NRB is marked with the FAD of the conodont *Misikella posthernsteini* morph. A, and by the transition from the Upper Norian *Metasibirites spinescens* to the Rhaetian *Paracochloceras suessi* ammonoid zones. Based on the common records of *Paracochloceras suessi*, the lower Rhaetian has – compared to the Kleiner Zlambach section – a relatively reduced thickness of approximately 6 m. Monotids of the *Monotis salinaria* group are common in the red Hallstatt limestone underlying the section. Several important nannofossils events were also recognized (Gardin et al., 2012; Demangel et al., this volume).

2.3.2. The Zlambach section

Three kilometers north of Lake Hallstatt, the Grosser Zlambach and Kleiner Zlambach are tributaries of the Traun River and name-giving for the Rhaetian Zlambach Formation. Along the Kleiner Zlambach we analyzed a section (base: 46°38'47.0"N, 13°40'10.7"E; top: 46°38'45.8"N, 13°40'01.9"E) which is a composite of four sub-sections precisely correlated bed-by-bed using marker beds together with the ammonoid faunas (Fig. 4). It consists of an autochthonous background sedimentation of alternating marls and marly micritic limestones which dominates here clearly the allochthonous carbonate sedimentation of rare distal fine-grained turbidites (Matzner, 1986; Krystyn, 1987, 1991; Richoz et al., 2012b; Richoz and Krystyn, 2015); thickness of the marls increases up-section. The Kleiner Zlambach succession covers most of the *Paracochloceras suessi* zone, the whole *Vandaites*

stuerzenbaumi z. and parts of the *Choristoceras marshi* z. As the latter is only incompletely exposed we stopped our sampling at its base.

Fig 3 Biostratigraphy, lithostratigraphy, magnetostratigraphy, MS variations and of the Steinbergkogel section (modified from Krystyn et al. 2007a,b, Krystyn 2010).



The 55 m thick section starts with a covered interval of 3-4 m above a gliding breccia composed of Upper Norian Pötschen Limestone components dated by conodonts. For the unexposed base we have found within the Kleiner Zlambach two correlating localities demonstrating the basal Rhaetian age of this interval: one 300 m down-stream to the SW known as "Taferlkogel" (47°38'39,3"N, 13°39'49,8"E) with *Paracochloceras canaliculatum* and another 1,1 km N up-stream (47°39'23,0"N, 13°40'59,0"E) containing the conodonts *Epigondolella bidentate* juv. (= *Parvigondolella andrusovi* auct.), *Misikella hernsteini* and *M. posthernsteini* morph. A.

As the Zlambach Fm. bears worldwide the richest and most complete record of Triassic heteromorph ammonoids, it is of specific importance for the biochronological subdivision of the Rhaetian stage. One of the major outcome of this study is the extraordinary long range of "*Choristoceras*" *haueri* from the early to the middle Rhaetian excluding the form from use as zonal guide. Also Maslo's (2008) reported two-fold subdivision of the *Vandaite*s *stuerzenbaumi* z. can be confirmed by our study. Conodont data underline the importance of *Misikella rhaetica* for a safe discrimination of Alpine middle Rhaetian strata though its first occurrence date within the *Vandaite*s *stuerzenbaumi* z. has still to be resolved.

2.3.3. The Eiberg section

The Eiberg section (Fig. 5) is located in an active cement quarry (47°33"N, 12°10'07"E) about 3 km south of Kufstein (North Tyrol). This section was palaeogeographically situated in the central part of the Eiberg Basin (Golebiowski, 1991); its connection with the open Tethys allows biostratigraphic correlations to sections of the Hallstatt area using ammonoids and conodonts. This section covers the Hochalm Member which corresponds timely to the *Paracochloceras suessi* and *Vandaite*s *stuerzenbaumi* zones, and the Eiberg Member which represents the top of the *Vandaite*s *stuerzenbaumi* zone and a complete *Choristoceras marshi* z. The upper part of the Hochalm Member is visible on the southern part of the quarry and consists mainly of shallow water bioclastic limestones as proximal then distal tempestites, and marls (Golebiowski, 1991). The top of this member marks a deepening and a transition phase from an open marine lagoon to the intraplatform basin deposition milieu of the Eiberg Member. On the northern part of the quarry we only analyze the Eiberg Member more suitable for cyclostratigraphic analysis as constituted of more monotonous alternations of limestones and marls. The studied section is 55 m thick, it belongs the last 3 meters of the *Vandaite*s *stuerzenbaumi* z. and most of the *Choristoceras marshi* z. up to a 20 cm thick topmost bed, regionally labelled as « T-bed » (Kürschner et al., 2007), which differs by dark color, increased clay content and platy fabric. This bed represents the end-Triassic mass-extinction. A negative $\delta^{13}\text{C}_{\text{bulk org}}$ excursion occurs at its upper part and extends at the base of the Tiefengraben Member (Kürschner et al., 2007; Hillebrandt et al., 2013). This excursion correlates with the initial Carbon Isotope Excursion (CIE) well known in numerous other Triassic-Jurassic reference sections (Palfy et al., 2001; Hesselbo et al., 2002; Guex et al., 2004; Todaro et al., 2018). The CIE correlates also with an initial increase in Ir (Tanner et al., 2016).

The first few meters of marls of the following Tiefengraben Member below the Rhaetian-Hettangian boundary cannot be sampled due to a prominent fault.

2.3.4. The Kuhjoch section

Kuhjoch (47°29'02"N, 11°31'50"E) is an expanded Rhaetian-Hettangian boundary marine section (Fig. 6), and represents the Hettangian GSSP (i.e., Triassic-Jurassic boundary) (Hillebrandt et al., 2013). Our sampling starts 3 m below the top of the Eiberg Member represented by well-bedded grey bioturbated limestone. The 20 cm thick topmost bed of this Member is the regional darker higher clay content « T-bed », which was also recognized at the top of the previous Eiberg section. An abrupt lithological change occurs from the basinal carbonates of the Eiberg Member to the marls and clayey sediments of the Tiefengraben Member. This lithological change corresponds to the main extinction level, where characteristic Triassic fauna disappears. The first three meters of the Tiefengraben Member are characterized by grey to brownish marls known as Schattwald Beds. Above, yellowish weathering marls passing into grey argillaceous marls up to 3.2 m above the Schattwald beds where the ammonite *Psiloceras spelae tirolicum* marks the Triassic-Jurassic boundary. Thirteen meters of marls above the « T-bed » were finally sampled at Kuhjoch, the next 7 meters were sampled at a neighbouring locality (Ochsentaljoch) about 750 m to the west of Kuhjoch, where this interval is better exposed. We cover thus the whole Tiefengraben Member of the Kendelbach Formation. Minor faults are present at Kuhjoch as described by Hillebrandt et al. (2013). Palotai et al. (2017) believe that the thickness of the Schattwald beds is underestimated due to tectonic complications and could be as

much as 4-5 m thick (about 2 m in our Fig. 6). Our careful and detailed lithostratigraphy and regional comparisons disagree with this estimation and in our opinion the Schattwald beds thickness at Kuhjoch is close to the one proposed by Hillebrandt et al., (2013). In any case, the stratigraphic interval concerned is very short, probably no longer than a few thousand years, and therefore does not really affect our estimated total duration for the Rhaetian (see section 4.5).

More detailed biostratigraphic, lithostratigraphic and palaeogeographical descriptions of these four sections can be found in Kürschner et al. (2007), Ruhl et al. (2009, 2011), Richoz et al. (2012b), Zajzon et al. (2012), Hillebrandt et al. (2013), Richoz and Krystyn (2015), Tanner et al. (2016).

Fig 4 Lithostratigraphy, MS variations and biostratigraphy of the Zlambach section.

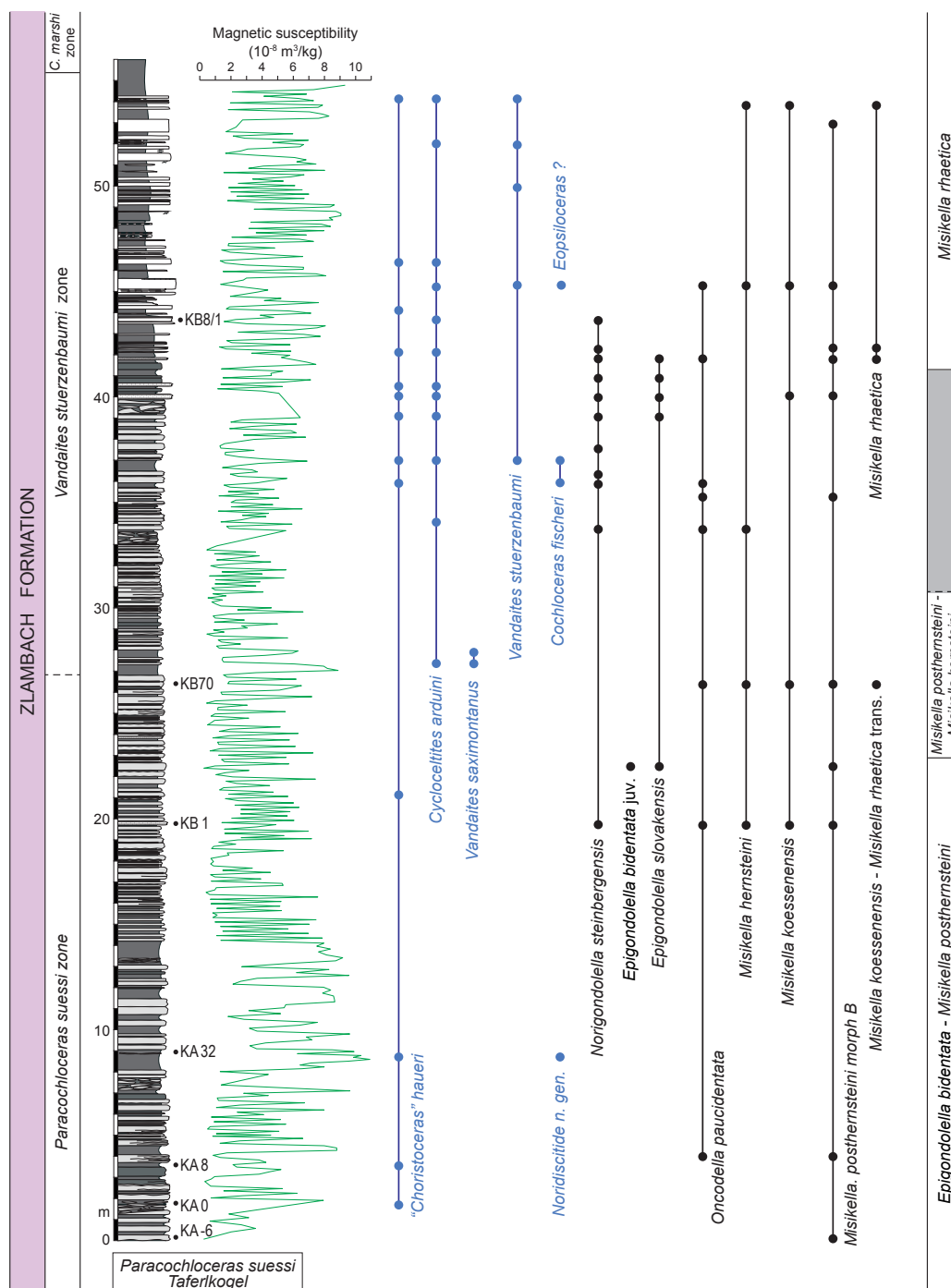


Fig 5 Lithostratigraphy, MS variations and biostratigraphy of the Eiberg section. Box with lower *M. ultima* record refers to occurrence of the species in the Koessen Weißloferbach B section in Mostler et al. (1978) and its correlation to Eiberg by Golebiowski (1991).

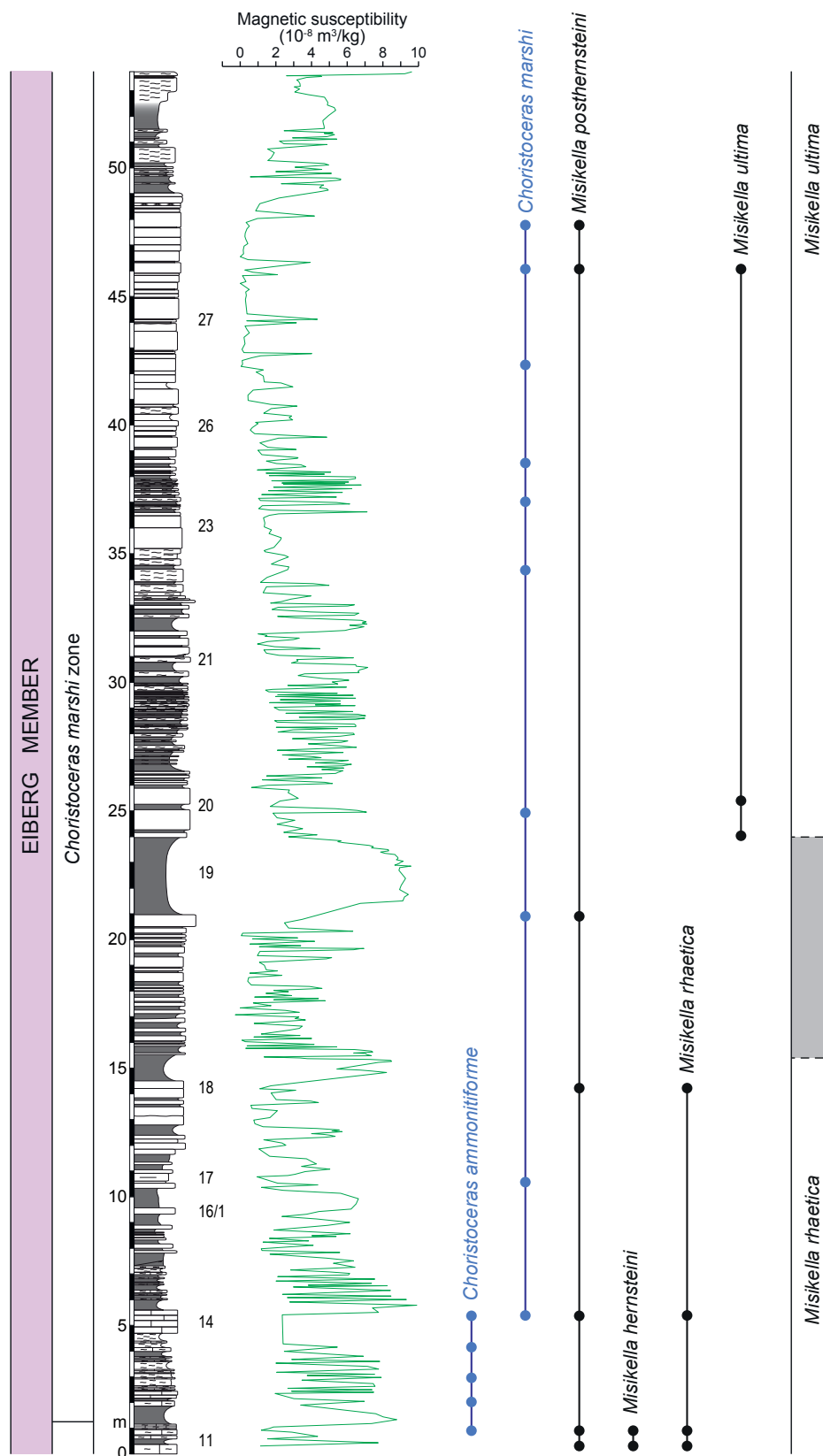
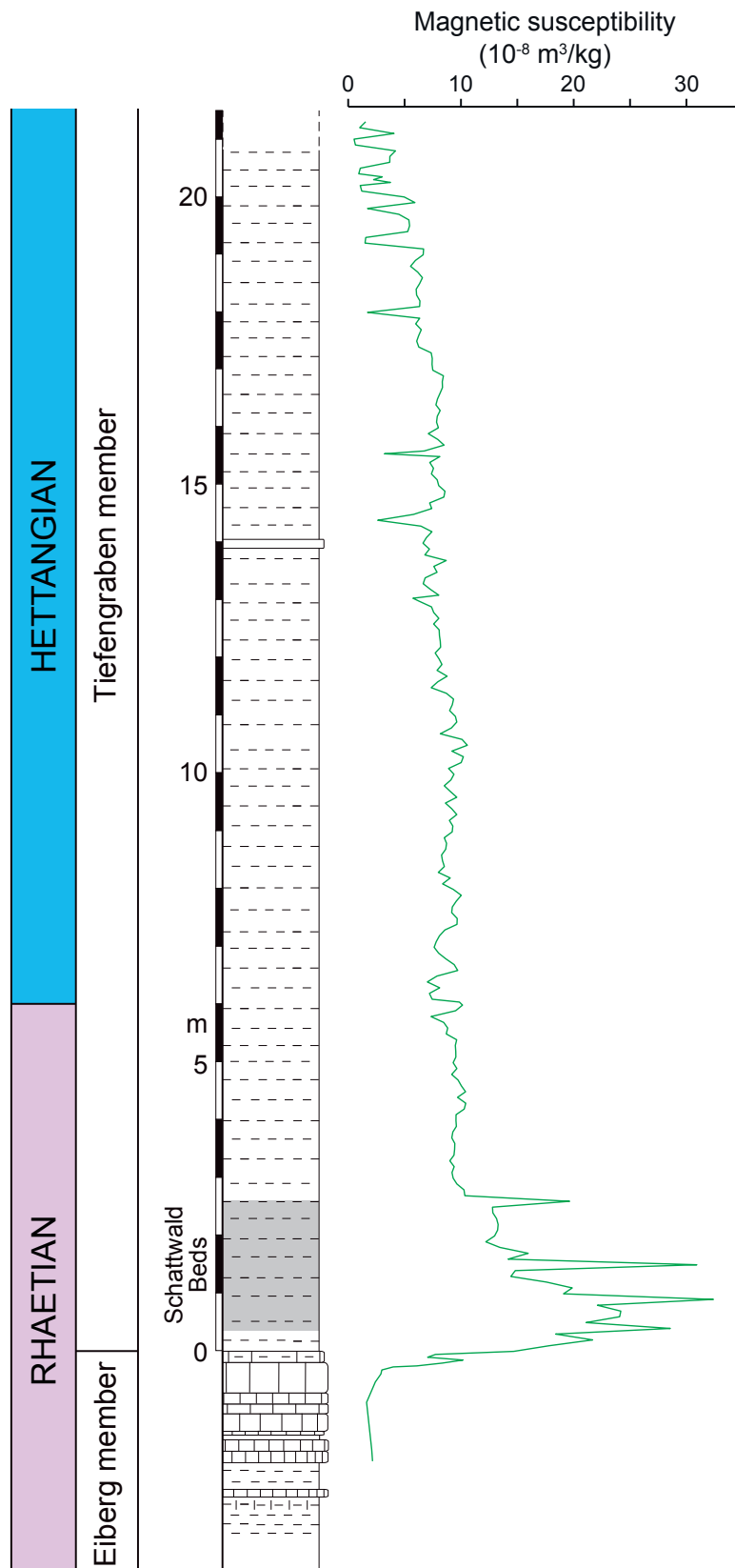


Fig 6 Stratigraphy and MS variations of the Kuhjoch and Ochsentaljoch sections (lithology and biostratigraphy modified from Hillebrandt et al. 2013).



3. Methods

3.1. Magnetic Susceptibility

Magnetic Susceptibility (MS) is a paleoclimatic proxy commonly used for cyclostratigraphy to identify astronomical-paced cycles (e.g. Mayer and Appel, 1999; Weedon et al., 1999; Boulila et al., 2008, 2010, 2014; Huret et al., 2011; Husson et al., 2012, 2014). MS measures the ability of a substance to acquire magnetization when a small external magnetic field is applied (e.g. Evans and Heller, 2003). High frequency MS variations in marine sedimentary sequences most often reflect variations of terrestrial input (mainly weak positive MS from paramagnetic clay minerals) diluted by diamagnetic calcium carbonate (very weak negative MS) (Ellwood et al., 2000). MS variations therefore reflect variations in lithology, which may have been driven by climate changes that in turn were orbitally controlled via changes in insolation on the Earth's surface induced by cyclical variations in the Earth's tilt and the Earth-Sun distance. MS was measured on samples from each studied section every 10 cm using a Kappabridge Agico MFK-1B (2×10^{-8} SI sensitive), the values are reported after weight normalization (Supplementary material 2).

3.2. Time-series analysis

Following removal of long-term trends in MS series we performed spectral analysis using the multitaper method (MTM, Thomson, 1982) associated with the robust red noise modelling (Mann and Lees, 1996) as implemented in the SSA-MTM Toolkit (Ghil et al., 2002). The link between the cycles highlighted by spectral analysis and orbital frequencies estimated for the Late Triassic (Laskar et al., 2004) was tested by the method of frequency ratios (Mayer and Appel, 1999). This method is very effective in the case of marly-limestones alternations to infer astronomical control of the sedimentation (Boulila et al., 2008; Charbonnier et al., 2013), this is achieved when the detected cycle frequency ratios are close to orbital parameter ratios. The main challenge is to clearly identify the 405 kyr eccentricity parameter which is the only astronomical parameter that can be accurately calculated over the last 250 myr given the chaotic behavior of the orbital motions in the inner solar system (Laskar et al., 2004).

The next step is to carry out an orbital tuning in order to convert the MS record from depth domain to time domain using the 405 kyr eccentricity term. To tune the record, we used the "LinAge" function provided in AnalySeries (Paillard et al., 1996). New spectral analyses were performed on the tuned MS record, which were compared to spectral analysis of Earth's orbital parameters for the time interval corresponding to Rhaetian time (approximately 200-210 Ma).

To extract cycles from the MS tuned record we used low- and band-pass filtering. Finally estimating the duration of the record, and therefore Rhaetian, is established by direct 405 kyr eccentricity cycle counting.

4. Results

4.1. Magnetic Susceptibility (MS) variations

The Hallstatt massive fine-grained pelagic limestones of the Steinbergkogel section are characterized by very low MS values (0.09 to $1.4 \cdot 10^{-8} \text{m}^3/\text{kg}$) (Fig. 3). This range of MS values is characteristic of mainly diamagnetic behaviour of CaCO_3 . Only three interbedded clay levels are characterized by higher MS values up to $1.3 \cdot 10^{-7} \text{m}^3/\text{kg}$. The last two meters of the section which marks the gradual transition to grey marls of the Zlambach Formation display a slight increase of MS value up to 5 to $6 \cdot 10^{-8} \text{m}^3/\text{kg}$. MS variations of the Steinbergkogel section thus do not follow a cyclic pattern.

The Zlambach section is characterized by high frequency MS variations corresponding to marl and marly limestone couplets of the Zlambach Formation (Fig. 4). The lowest MS values, about $0.3 \cdot 10^{-8} \text{m}^3/\text{kg}$, are from the limestones beds, and the highest, up to $10 \cdot 10^{-8} \text{m}^3/\text{kg}$, are from marly levels with higher paramagnetic contribution from clay minerals. Superimposed to this strong high frequency cyclic pattern a few meters-thick low-frequency modulation cyclicity appears over the whole section. Similarly a significant upward increase trend in MS values reflects a progressive enrichment in clays.

MS variations from the Eiberg section are quite similar to the Zlambach section: high frequency cyclic pattern corresponding to marl-limestone couplets modulated by low-frequency cycling (Fig. 5). As thicker the marly intervals are, higher the MS values. The massive limestone beds in the

upper part of the section display the lowest MS values of about 0.4 to 0.5 $10^{-8} \text{m}^3/\text{kg}$. The topmost bed of the section, the dark clayed « T-bed », display a sharp increase of the MS up to $10 \cdot 10^{-8} \text{m}^3/\text{kg}$.

At Kuhjoch the « T-bed » is also characterized by a sudden increase of MS values (Fig. 6). This increase continues in the grey to brownish-redish marls of the Schattwald Beds up $30 \cdot 10^{-8} \text{m}^3/\text{kg}$. Above these Schattwald Beds MS slowly decreases and reach similar values to those of the Rhaetian 10 m above the Triassic-Jurassic boundary suggesting recovery of similar paleoenvironmental conditions.

4.2. The Rhaetian composite section of MS variations

Since a cyclostratigraphic study is more robust if a long interval is analyzed, especially to highlight a succession of several 405 kyr cycles, we constructed a composite section of MS variations for the whole Rhaetian (Fig. 7). This was easy because the four studied sections overlap.

Considering conodonts, ammonites, and calcareous nannofossils, the base of the Zlambach section can be approximately correlated to the middle of the Steinbergkogel section, no more than 2 m above the Norian-Rhaetian boundary, a correlation also supported by geochemical data (Kovacs et al., this volume). Thus the Steinbergkogel section does not contribute for more than 2 m to our composite Rhaetian record.

The boundary between the *Vandaites stuerzenbaumi* and *Choristoceras marshi* zones is identified on both Zlambach and Eiberg sections and makes it possible to correlate them easily. The correlation between Eiberg and Kuhjoch sections is also easy owing to the regional black marly « T-bed » present at the very top of the Eiberg section and the base of the Kuhjoch section. In these two sections the « T-bed » is marked by a sudden increase in the MS intensity (Figs. 5-6).

From these correlations results a whole Rhaetian composite section of 131.5 m thick with 1301 MS measurements. MS variations exhibit evident cyclic patterns over a wide range of frequencies (Fig. 7b). In particular, a cyclicity of about 7-8 m of period is often clearly visible in MS variations: it appears as amplitude modulation of approximately 22-24 high-frequency cycles (Fig. 7c, d). This pattern, common in the Mesozoic sedimentary records, was previously interpreted as amplitude modulation of high frequency precession cycles by low-frequency 405 kyr eccentricity cycles (Boulila et al., 2008; Charbonnier et al., 2013).

4.3. Spectral analysis

Preliminary spectral analyses conducted separately on the two main sections, Zlambach and Eiberg, gave similar results in terms of cycle thicknesses and their ranking (Supplementary material 1, Fig. S1). This allowed us to build a composite Rhaetian record.

Most of the record is represented by alternating limestones and marly limestones, but the topmost part above the « T-bed » (roughly the Kuhjoch-Ochsentaljoch section) is only formed by marls. This abrupt lithologic change likely reflects most probably decrease in sedimentation rate which can be linked to a major crisis of carbonate producers. We therefore chose to undertake spectral analysis on each of these two intervals, the lower, 110 m thick, corresponds to Steinbergkogel, Zlambach and Eiberg composite record, and the upper, 21 m thick, to the Kuhjoch-Ochsentaljoch section.

First, MS data were linearly interpolated to 2 cm regular spacing. Second, on the lower 110 m thick interval, an irregular long-term trend (Fig. 7b) was subtracted by a 15% weighted average of the data before spectral analysis. Power spectra (Fig. 8a) show the presence of numerous significant frequencies resulting in part from a variable sedimentation rate. Numerous peaks from 0.28 to more than 7.5 m exceed the 95% CL, with some exceeding the 99% CL. Visual inspection of MS variations shows that wavelengths of 0.3 to 0.5 m correspond to the various thicknesses of the elementary marl-limestone couplets throughout the record. Interestingly a peak of greater amplitude is centered on wavelength of 7.60 m (Fig. 8a). Such 7.60 m peak represents a regular cyclicity throughout the section (Supplementary material 1, Fig. S2), and could correspond to the orbital eccentricity parameter of 405 kyr as previously suggested (subsection 4.2 and Fig. 7c-d). However, to interpret all the observed frequencies in terms of possible orbital periods, we compared their ratios to orbital period ratios relative to the Late Triassic time (Laskar et al. 2004). Spectral period ratios are very close to orbital period ratios. This is specially true for ratios between the prominent 7.60 m period and observed spectral periods which are remarkably close to ratios between the 405 kyr eccentricity period and Milankovitch band orbital periods: short eccentricity, obliquity and precession. We interpret wavelengths from 0.30-0.40 m as matching the precession periods, those around 0.60-0.70 m as obliquity periods and wavelength 1.34 m corresponds probably to short eccentricity e_1 . Accordingly,

the strong peak of 7.60 m mean thickness corresponds most likely to the 405 kyr long eccentricity component.

Fig 7 Biostratigraphy and MS variations of the Rhaetian composite record built from four Austrian reference sections (Steinbergkogel, Zlambach, Eiberg, Kuhjoch). **(a)** Rhaetian ammonite standard zones. **(b)** Raw MS variations. A 15% weighted average of the series is indicated, showing a long-term variation (thick grey line). **(c)** MS variations of a 10-m interval from Eiberg section. **(d)** MS variations of a 20-m interval from Zlambach section. The lowest MS values are recorded in the limestones beds, and the highest values from marly levels with higher paramagnetic contribution from clay minerals. A 20% weighted average of the MS series is performed to highlight a low frequency (about 8 m thick) cycle (thick dashed grey line). MS show a strong modulation of 22-24 high frequency cycles (marl-limestone couplets) by low frequency cycles of about 7-8 m thick (black arcs). The high frequency MS cycles are interpreted as precession cycles, and the low frequency ones as the 405 kyr eccentricity cycles.

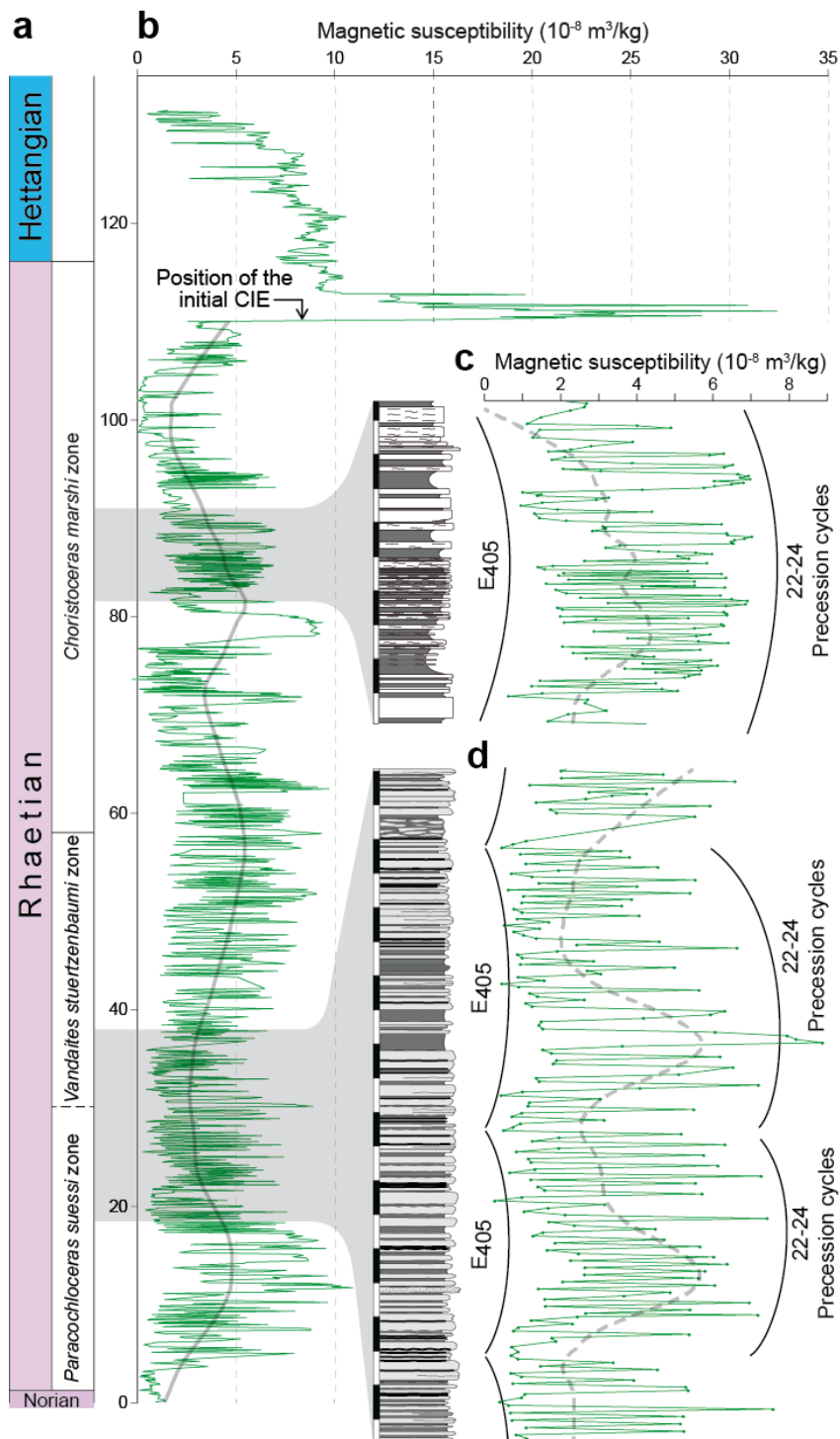
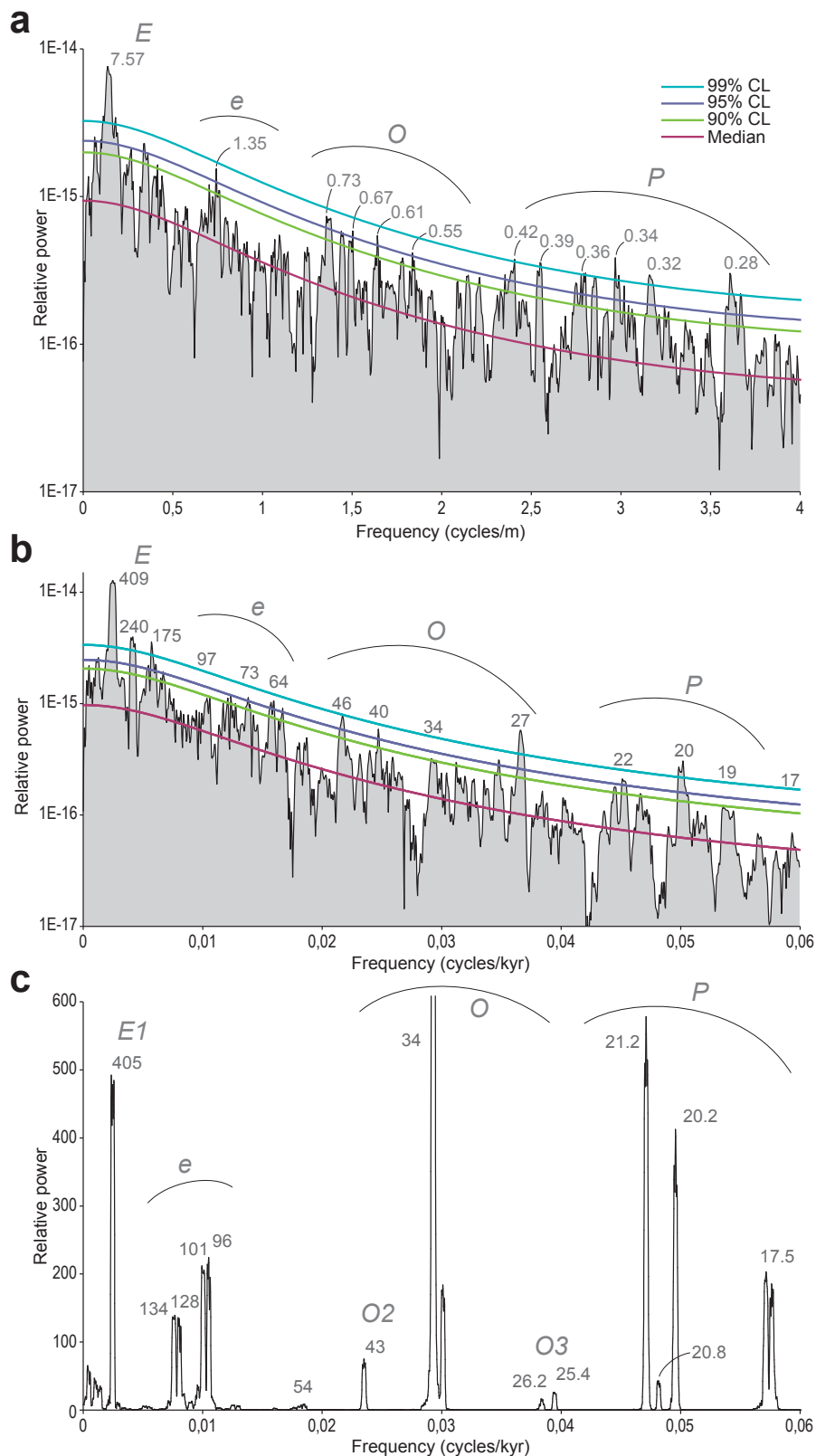


Fig 8 Time-series analysis of MS variations of the lower part of the composite record (Steinbergkogel, Zlambach and Eiberg sections) and comparison with the astronomical model La2004 (Laskar et al. 2004). **(a)** 2π -MTM power spectrum of detrended MS series (removal of 15% weighted average of the data shown in Fig. 7b). Numerous peaks exceeding 99% and 95% CL are labelled (in metres). **(b)** Spectrum of detrended 405 kyr tuned MS series (shown in Fig. 9c). Several peaks exceeding 99% and 95% CL are labelled (in kyr). **(c)** Spectrum of La2004 (Laskar et al. 2004) astronomical parameters in ETP format (e.g., Imbrie et al. 1984) for the interval 200-210 Ma.



4.4. Astronomical calibration

To check the above cyclostratigraphic interpretation we tuned the mean 7.60 m thick MS cycles to the 405 kyr eccentricity period. The assignment to 405 kyr cycles was carried out through guidance of band-pass filtering and considering the MS minima in limestones (Fig. 9). Then we compare the spectrum of the tuned MS record with the spectrum of the theoretical astronomical periods estimated for the 200-210 Ma interval.

First long-term trend was subtracted by a 15% weighted average of the tuned data. The tuned power spectra (Fig. 8b) show significant frequencies consistent with La2004 astronomical model (Laskar et al., 2004). The 0.34-0.42 m periods are calibrated to 20-22 kyr and correspond to the precession component P1 (20.2-21.2 kyr). The ensemble of wavelengths of 0.55-0.73 m is calibrated to period band ranging from 27 to 47 kyr. This period band corresponds to the predicted astronomical obliquity periods: components O3 (25.4 and 26.2 kyr), O1 (33 and 34 kyr) and O2 (43 kyr). No prominent peak could represent the theoretical periods of short eccentricity. Some other well expressed peaks, 174 and 250 kyr, does not seem represent classical astronomical periods. Similar periods were also recognized in different Mesozoic records: 170 and 210 kyr in a Valanginian succession of southeastern France (Charbonnier et al., 2013), 171 kyr in a Oxfordian succession of southeastern France (Boulila et al., 2010), 200 kyr in a Toarcian succession of the Paris Basin, France (Boulila et al., 2014). A 173 kyr cyclicity was also reported in a middle Eocene North Atlantic record and was interpreted as amplitude modulation of obliquity (Boulila et al., 2018). Finally the most prominent peak is calibrated to 409 kyr and is evidently related to the long eccentricity period of 405 kyr.

In summary, the tuned calibrated periods show clear correspondances with Late Triassic astronomical periodicities at the precession and obliquity cycle bands. The 405 kyr eccentricity is recorded in the spectra with a strong peak, but not the short eccentricity which appears with low peaks. This behaviour was also observed for other Mesozoic successions, as the Kimmeridgian and Valanginian limestone-marl alternations of southeastern France (Boulila et al., 2008; Charbonnier et al., 2013). In sum the results of the cyclostratigraphic analysis show a clear evidence of an orbital forcing of the Austrian Rhaetian limestone-marl alternations succession: the precession was the main driver of the deposition, with a modulation by prominent 405 kyr orbital eccentricity period which will allow to time calibrate the Rhaetian sedimentary record.

The band-pass filtering of the raw MS variations allows to highlight sixteen 405 kyr eccentricity cycles in the lower analyzed interval (base of Steinbergkogel, Zlambach and Eiberg sections). These 16 cycles are labelled Rha 1 to Rha 16, from top to the base of the record. These sixteen 405 kyr eccentricity cycles, assuming no significant hiatuses or condensation in the record, provide, an approximate duration of 6.42 myr (Fig. 9).

4.5. Spectral analysis of the Kuhjoch-Ochsentaljoch section

The Kuhjoch-Ochsentaljoch section starts above the « T-bed » (which corresponds to the end-Triassic initial Carbon Isotope Excursion - CIE) and covers only part of the Hettangian (Fig. 10a). The Hettangian is one of the shortest stages in Mesozoic, its duration is estimated at around 2 myr (ICS, 2019). The cyclostratigraphic study of the St Audrie's Bay (Somerset, UK) section (topmost Rhaetian to lower Sinemurian) has established a reliable astronomical calibration of the Hettangian (Ruhl et al., 2010a; Hüsing et al., 2014).

The above studies suggest a duration of 1.8 myr for Hettangian. This duration is also supported by a 199.43 ± 0.10 Ma $^{238}\text{U}/^{206}\text{Pb}$ age for the base of Sinemurian in the Pucara Basin of Peru (Schaltegger et al., 2008; Guex et al., 2012). Biostratigraphic correlations between St Audrie's Bay and the Kuhjoch section were proposed by Hillebrandt et al. (2013, their figure 27). These correlations suggest that the duration of the 21 m thick interval after the CIE in the Kuhjoch-Ochsentaljoch section and its equivalent in St Audrie's is quite short, no more than a few hundred thousand years. Since the identification of several 405 kyr is almost impossible at Kuhjoch-Ochsentaljoch due to the reduced thickness of the section, we seek to highlight short eccentricity and precession cycles.

We generated two spectra (Fig. 10b,c). One is focused on the very short interval (4.5 m thick) corresponding to the Schattwald Beds. This interval is characterized by a sharp increase of MS values, high frequency fluctuations and a rapid decrease of MS. The power spectrum shows a single frequency corresponding to a period of about 0.28 m (Fig. 10b). The second analyzed interval starts above the Schattwald Beds until the top of the record. Obviously this interval is characterized by cyclicities of several frequencies. The power spectrum reveals the presence of significant periods: 0.30, ~0.44, ~0.61, ~1.28, ~2.87 m (Fig. 10c). Their ratios suggest that ~0.44 m probably corresponds

to precession, ~ 0.61 m to obliquity and ~ 2.87 m to short eccentricity. These values are quite comparable to those observed on the underlying Eiberg section prior to the end-Triassic crisis. On the other hand, the Schattwald Beds reflect a drop in carbonate production resulting from a biocalcification crisis, and the single cyclicity of 0.28 m most probably corresponds to precession cycles that are 0.40 m thick below and above the Schattwald Beds. On the basis of these interpretations and with the help of raw data band-pass filtering (Fig. 9d), we could estimate the durations of the different intervals considered. The Schattwald Beds represent 9-10 precession cycles, i.e. a duration of about 190 kyr. The interval between the top of the Schattwald Beds and the Rhaetian-Hettangian boundary represents less than one short eccentricity cycle, about 80 kyr. Thus the mass extinction interval, constrained between the mass extinction level (marked by the regional « T-bed »/Initial CIE) and the beginning of recovery (marked by the first occurrence of the ammonite *Psiloceras spelae tirolicum* at the Rhaetian-Hettangian boundary), should have a whole duration of about 270 kyr

Fig 9 405 kyr eccentricity tuning of MS data of the lower part of the composite record built from Eiberg, Zlambach and lower part of the Steibergkogel sections. **(a)** Ammonite zonation of the 110 m thick Rhaetian record. **(b)** Raw MS variations. A Gaussian band-pass (0.132 ± 0.07 cycles/m) filter output is applied to highlight the ~ 7.6 -m thick cycles interpreted as the 405 kyr eccentricity cycles (Rha 1 to Rha 16). **(c)** 405 kyr floating time scale of the Rhaetian stage. **(d)** Astronomical estimate of durations of the ammonites zones of the Rhaetian.

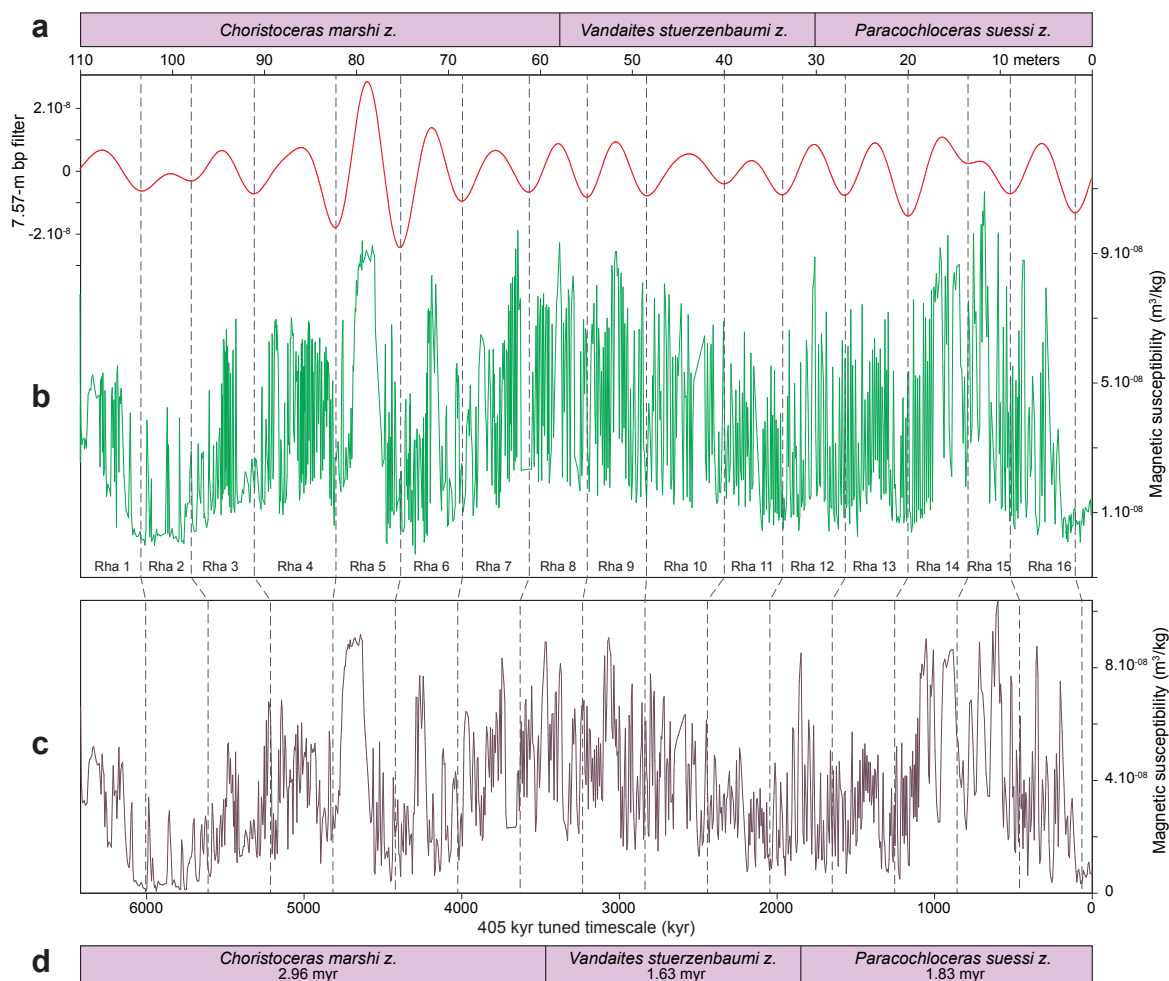
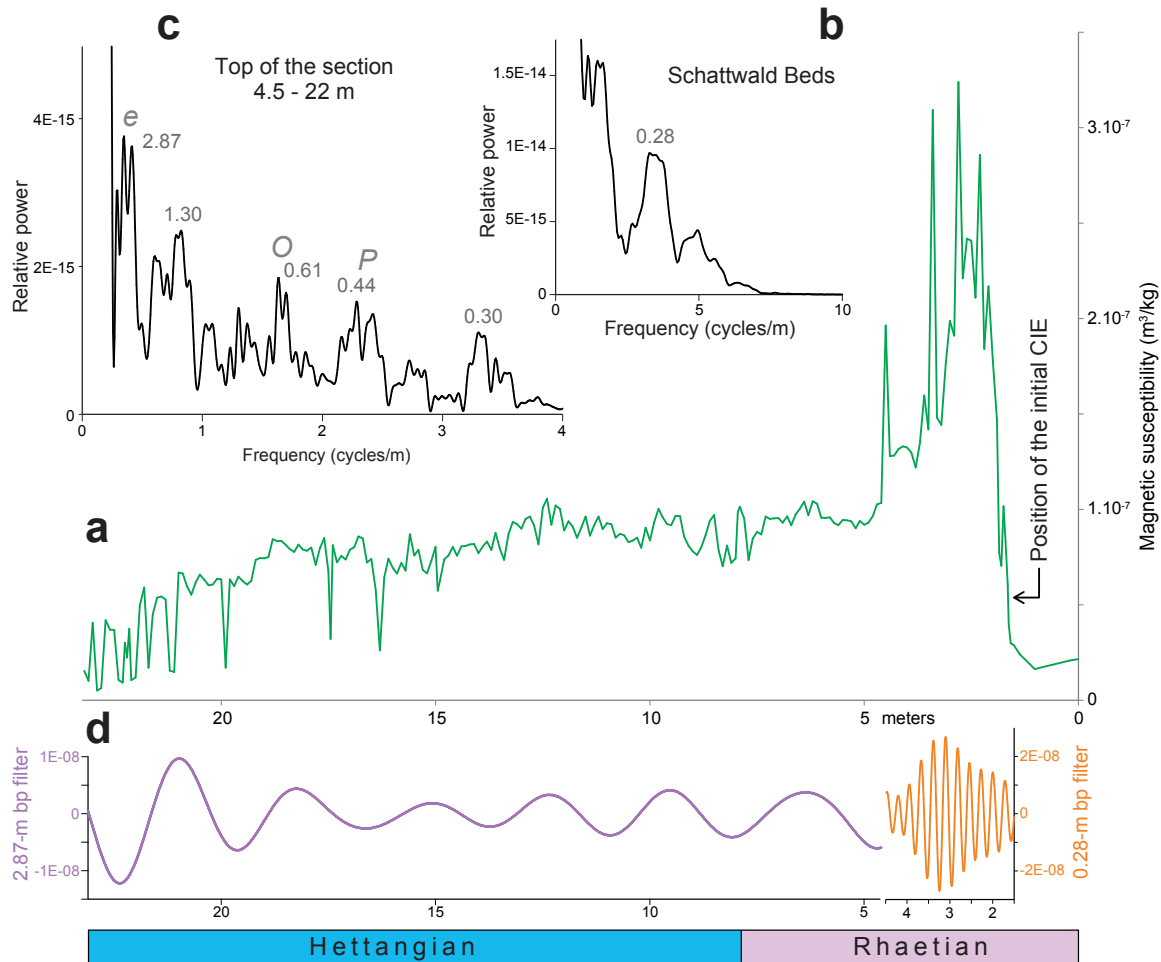


Fig 10 Spectral analysis of the Kuhjoch-Ochsentaljoch section. **(a)** Raw MS variations. **(b)** Power spectrum of a short interval (1 to 4.5 m) of the Schattwald Beds. A truncated peak on the spectrum corresponds to a trend of the whole interval, and a 0.28 m peak corresponds to the high frequency cycles visible on MS variations. **(c)** Power spectrum obtained over the interval from 4.5 m to the top of the studied section. A low frequency truncated peak of more than 5 m corresponds possibly to low-frequency MS variations, but the studied interval is too short to be affirmative. The ratios of the significant periods suggest that ~ 0.44 m likely corresponds to precession, ~ 0.61 m to obliquity and ~ 2.87 m to short eccentricity. The 0.30 m period can be interpreted as a sub-Milankovitch period. **(d)** A Gaussian band-pass (0.348 cycles/m) filter output is applied on the upper studied interval to highlight the $\sim 2,87$ -m thick cycles interpreted as short eccentricity cycles. A Gaussian band-pass (3.57 cycles/m) filter output is applied on the Schattwald Beds to highlight the $\sim 0,28$ -m thick cycles interpreted as probable precession cycles (see text).



5. Discussion – Implications for the Late Triassic time Scale

5.1. Astronomical duration of the Rhaetian inferred from the Austrian sections – Comparison with U-Pb dates

Our cyclostratigraphic study of the Austrian Rhaetian sections shows, (1) that the interval between the NRB (i.e. appearance of the conodont *Misikella posthernsteini* morph. A, sensu Krystyn et al., 2007a, b) and the uppermost Rhaetian initial CIE (corresponding to the well known regional « T-bed ») has a minimum duration of 6.42 myr, and (2) that the interval from the « T-bed » to the Rhaetian-Hettangian boundary (constrained by the FO of the ammonite *Psiloceras spelae*) has an approximate duration of 270 kyr. This leads us to propose a minimum total duration of 6.69 myr for the whole Rhaetian. Though in the Zlambach section the boundary between the *Paracochloceras suessi* and *Vandaites stuerzenbaumi* zones lacks for a 5 m interval precise zonal guide fossils, we use for our analyses as viable boundary level the FO of *Vandaites saximontanum*. The durations of the three

Rhaetian ammonite zones can be calculated approximately as follows: the *Paracochloceras suessi* zone would have a duration of 1.83 myr, *Vandaites stuerzenbaumi* z. of 1.63 myr, and *Choristoceras marshi* z. of 2.96 myr (Fig. 9).

Reliable radio-isotopic dates constrained by marine-based biostratigraphy within the Norian-Hettangian interval are scarce, except for the Rhaetian-Hettangian boundary whose age is well constrained by the analysis of volcanic ash beds from the Pucara basin (Levanto section, Aramachay Formation, Pucara Group, northern Peru) and the New York Canyon (Nevada, USA) (Schoene et al., 2010). In both sections, the boundary is recognized by the FO of the ammonite *Psiloceras spelae*. Thus a $^{206}\text{Pb}/^{238}\text{U}$ age of the Triassic-Jurassic boundary can be calculated to be 201.31 ± 0.18 Ma. Recently new numerical ages have been obtained in the Levanto section which displays an apparent complete upper Norian to lower Sinemurian marine sedimentary sequence (Wotzlaw et al., 2014). During this study, the authors recalculated the older age reported by Schoene et al., (2010) using a new tracer calibration and updated the Rhaetian-Hettangian boundary age of 201.36 ± 0.17 Ma, older by $\sim 0.025\%$. This anchoring point has been used for our Rhaetian « floating astrochronology » to suggest a 208.05 Ma age of the NRB as defined by the FAD of conodont *Misikella posthernsteini* morph A.

The Levanto section presents several other volcanic ash layers on which radiometric ages were also calculated. An age of 205.50 ± 0.35 Ma was obtained for the supposed NRB on this section (Wotzlaw et al., 2014) resulting in an estimated duration of the « Peruvian » Rhaetian of 4.14 myr, a duration that highly differs from our « Austrian » astronomical estimate of 6.69 myr. It is difficult to explain this more than 2 myr difference between the two domains and we do not have a definitive answer. What we can argue is that certainly the NRB is not defined in the same way in the two palaeo-biogeographical realms. In the Levanto section the Late Norian is recognized by the LO of the bivalve *Monotis subcircularis*, a species widely distributed in the circum-Pacific (Panthalassa Ocean) and interpreted as the stratigraphic counterpart of the Tethyan *Monotis salinaria* (Mc Roberts, 2010). In the Tethyan Province, specifically on the Steinbergkogel section, the NRB is marked by the FO of conodont *Misikella posthernsteini* while the LO of the bivalve *Monotis salinaria* is an older bio-horizon that lies slightly below (Krystyn et al., 2007a). The disappearance of large monotid bivalves is recognized as a worldwide bio-horizon taking place at the top of the Norian (Mc Roberts et al., 2008; Mc Roberts, 2010). Following our new data, *Monotis subcircularis* in Peru and *Monotis salinaria* in Austria would disappear diachronously by more than two myr. Although their occurrence in two widely separated oceans, this 2 myr lag does not seem very reasonable.

The completeness of the Levanto section could also be questioned. The lowest ash layer on this section dated as 205.70 ± 0.15 Ma, is located several meters above the LO of *Monotis subcircularis* (Wotzlaw et al., 2014, their figure 2) and a sedimentary hiatus cannot be totally ruled out considering the outcrop conditions. The U-Pb age of 205.20 ± 0.9 Ma obtained from lower Rhaetian sediments of British Columbia (Golding et al., 2016) should also be taken with caution. As a matter of facts, the zircons come from a reworked layer just above a sedimentary gap and a hardground. The layer is biostratigraphically well constraint to the lower Rhaetian, but there is no estimate of the missing portion. The absolute ages reported above should be considered as a minimum age for the Norian-Rhaetian boundary although there are no solid arguments to exclude the possibility of an older age.

Estimates of the duration of the end-Triassic mass extinction interval were proposed by different authors. Thanks to U/Pb datations of the Pucara basin (North Peru) and the New York Canyon (Nevada, USA) sections, Schoene et al. (2010) suggested that the mass extinction interval, constrained between the last occurrence of the latest Triassic ammonoid *Choristoceras crickmayi* and the first occurrence of the Jurassic ammonite *Psiloceras spelae*, would have a duration of $70 +220/-70$ kyr. Based on the cyclostratigraphic analysis of the St Audrie's Bay (Somerset, UK) Ruhl et al. (2010a) suggested that the end-Rhaetian mass extinction interval and coinciding negative CIE may be represented by 1–2 precession cycles (~ 20 to 40 kyr) while the following interval to the first Jurassic ammonite occurrence is defined by 6 precession cycles (~ 120 kyr). This estimation is shorter than our (~ 270 kyr). However, given the high level of uncertainty of the different methods used and the correlation problems existing between records from separated biogeographic realms, the end-Triassic extinction durations remain comparable.

5.2. Comparison with the Newark APTS

Till now the Newark Basin (New Jersey-Pennsylvania, USA) continental sedimentary sequence is widely considered as a reliable astronomical tuned polarity time scale (APTS) for the Late Triassic through Early Jurassic. The establishment of the Newark-APTS started 30 years ago (Olsen, 1986) and has recently been synthesized (Kent et al., 2017). The reliability of this continental Triassic

APTS and correlations to Tethyan marine records have been intensively discussed (e.g., Tanner and Lucas, 2015). After a brief summary of the whole succession, the focus below will be centred on the Rhaetian part.

The Newark Supergroup encompasses a thick succession of fluvial and lacustrine sedimentary rocks with some intercalated volcanites extending from the Carnian (Late Triassic) to the Sinemurian (Early Jurassic). In the 1990s, several stratigraphically overlapping drill holes allowed the establishment of a continuous rock record more than 6000 m thick. The basal Carnian Stockton Formation is 1000 m thick and consists of fluvial sandstones, conglomerates and mudstones. Above follows the Late Carnian Lockatong Formation, 800 m thick, formed of variously coloured mudstones of lacustrine origin. It is overlain by the 2700 m thick Passaic Formation (Norian-Rhaetian?) mainly consisting of mudstones and sandstones. The upper Passaic Formation (Rhaetian?) is predominantly represented by red sandstone of alluvial origin, and is capped by "the Newark extrusive zone" which consists of basalt units with rare sedimentary intercalations. Cyclic deposits in the Newark Basin were explored by McLaughlin's pioneering work in the 1930s and 1940s (McLaughlin, 1945). Later in the 1960s Van Houten was the first to suggest a periodicity, probably due to orbital precession, in the lacustrine cycles of the Lockatong Formation (Van Houten, 1964). The first quantitative cyclostratigraphic analyses were carried out in the 1980s and 1990s (Olsen, 1986; Olsen & Kent, 1996, 1999). A relative deposition depth ranking was assigned to each lithology of the identified cycles, and the obtained data set was subjected to spectral analysis. Frequencies of Milankovitch band, precession to long eccentricity, were recognized over the whole sedimentary formations of the Newark Basin, not just within the only truly cyclical Lockatong Formation (Olsen & Kent, 1996, 1999; Olsen et al., 1996; Kent et al., 2017). Sixty-six 405 kyr eccentricity cycles were counted for the Newark Basin succession, resulting in a duration of more than 26 myr. Immediately above the Passaic Formation an U/Pb radiometric age of 201.52 Ma was obtained from a volcanic level of the "Newark extrusive zone" (Schoene et al., 2010, Blackburn et al., 2013). This important calibration point allowed to convert the established floating astronomical time scale into an absolute numerical time scale. In addition, the 201.5 Ma tie-point is very close to the datation of the Rhaetian-Hettangian boundary biostratigraphically well constrained on the Peruvian record, i.e. 201.36 Ma (Wotzlaw et al., 2014), and is used as an important argument to affirm the upper Passaic Formation a Rhaetian age.

Based on magnetostratigraphic studies on overlapping drill cores and outcrop sections Kent et al. (2017) established a complete magnetic polarity sequence for the Newark Basin. Using cyclostratigraphy this was then converted to a Newark-APTS with an absolute age ranging from approximately 199 to 233 Ma (e.g., Kent et al., 2017, their figure 1; Maron et al., 2015). Attempts to cross-correlate the Newark astrochronology with biochronologically well-dated marine Tethyan sections failed since they did not provide a cyclic signature. Magnetostratigraphy seemed therefore the only solution to achieve a direct chronostratigraphic correlation between Newark and the Tethyan sections, and to establish a reliable Late Triassic integrated chronology. In one of the first syntheses Kent and Olsen (1999) suggested that the Rhaetian of the Newark Basin had a duration of approximately 6 myr (by counting fifteen 405 kyr eccentricity cycles) and that the Norian-Rhaetian boundary should be dated around 207-208 Ma, a value quite close to our current estimation of 208.05 Ma. In recent years, various (bio)magnetostratigraphic correlations schemes between the Newark APTS and Tethyan marine sections were suggested by subsequent authors. Further attempts to synchronise these schemes with radiometric ages have led to a complicated and confusing pattern when comparing the various interpretations, i.e. Wotzlaw et al. (2014, their figure 3), Kent et al. (2017, their figure 15) and Li et al (2017, their figure 1). One main result was the unusual two-fold duration proposals for the Rhaetian i.e. a "short" Rhaetian of about 4-5 myr, as well as a "long" Rhaetian of about 8-9 myr as already seen in Ogg, 2012. Of these two, the "short" Rhaetian option does imply that most of the Rhaetian is missing in the Newark Basin, an hypothesis apparently corroborated by stratigraphic breaks in the Passaic Formation derived from biostratigraphic data (see below).

Due to its non-marine nature, the biostratigraphy of the Newark Supergroup is exclusively based on palynomorphs, conchostracans and tetrapod vertebrates, groups with often long stratigraphic ranges (Lucas and Tanner, 2007; Lucas et al., 2012; Tanner and Lucas, 2015). Only conchostracans should allow a high-resolution Rhaetian zonation according to Kozur and Weems (2007). Established in the Germanic basin, this zonation has been applied to the conchostracan faunas of the Newark Basin. When comparing both, Kozur and Weem (2007) concluded that some bio-zones are missing and that the uppermost Norian and most of the Rhaetian are not represented by sediments in the Newark Basin (Kozur and Weem, 2010, and review in Tanner and Lucas, 2015, their figure 8). As palynological data seem to point in the same direction, Tanner and Lucas (2015) assumed of a potential gap of at least 3 myr in the cyclostratigraphic record of the Newark Basin.

The possible incompleteness of the Newark Basin has been strongly opposed by Kent et al. (2017 – calling it "the persistent refrain of the missing Rhaetian") by challenging the reliability of conchostracans as biostratigraphic indicators. They also rejected the magnetostratigraphic correlation between the Newark Basin and the Norian-Hettangian marine Oyuklu section from Turkey, where Gallet et al. (2007) proposed a reasonable correlation that also induced the hypothesis of an absence of a large part of the Rhaetian in the Newark Basin. Kent et al. (2017) and Maron et al. (2019) suggested another magnetostratigraphic correlation with the Germanic-type St. Audrie's Bay section in United Kingdom (Hounslow et al., 2004), to demonstrate that no Rhaetian time is missing in the Newark Basin. However their solution implies a 3.5 myr interval between the definition of *M. posthersteini sensu* Krystyn et al. (2007a, b) and the definition *sensu* Maron et al. (2015), Rigo et al. (2015). This duration, equivalent to half of the Rhaetian has no palaeontological sense. Clearly, for the moment, no satisfying proposed solution exists for bio-magnetostratigraphic correlations.

Besides the debate on the completeness of the Rhaetian in the Newark Basin, the cyclostratigraphic interpretations themselves may be questioned. Specifically the depth rank assignment to the cycle-typifying lithologies used as basis for the cyclostratigraphic analysis is somewhat subjective, in particular for the upper Passaic Formation where repetitive fluvial sandstones provide no significant cyclic pattern (Tanner and Lucas, 2015), resulting in a signal of smaller amplitude in this interval (Kent et al., 2017, their figure 1) and leading to a weaker precession cycles record and in turn to less clear eccentricity cycles. These problems have to be addressed when the astrochronology of the Newark Basin is considered as a basis for estimating the duration of the Rhaetian, and might explain why some authors consider the Newark cyclostratigraphy as unsuitable to unambiguously locate and date the base of the Rhaetian (Tanner and Lucas, 2015).

We believe that for the time being no unambiguous correlations can be achieved between the supposed Rhaetian Newark Basin astronomical time scale and our cyclostratigraphic results on the Alpine Rhaetian. Our minimum 6.69 myr estimate of the Rhaetian duration can be considered as "intermediate" between a "short" and a "long" Rhaetian but it validates neither of these two options. It further does not validate any bio-magnetostratigraphic correlation scheme between the Newark-APTS and the Tethyan marine sections corresponding to these two options. Similarly, our result does not validate or invalidate the missing Rhaetian hypothesis for the Newark Basin.

5.3. Comparison with the Sichuan basin

Recently a combined cyclostratigraphy and magnetostratigraphy study of the Upper Triassic Xujiahe Formation (Sichuan Basin, South China) offered interesting results (Li et al., 2017). This formation consists mainly of cyclic sandstones, mudstones and shales, deposited under lacustrine or fluvial conditions. Its biostratigraphy is derived from non-marine fossil groups: bivalves, ostracods, plants, sporomorphs. All these groups allow a broad Norian-Rhaetian age assignment to the Xujiahe Formation, but the NRB cannot be defined. Numerous U-Pb dates of detrital zircons from several sections through the Sichuan Basin indicate a maximal age for the majority of this formation as being not older than 207-209 Ma (Li et al., 2017).

Cyclostratigraphic analyses of Xujiahe sections were worked out by using gamma-ray and magnetic susceptibility variations. These analyses have allowed Li et al. (2017, their figure 10) to recognize all Milankovitch band periods, from precession to 400 kyr eccentricity cycles and to estimate the duration of the Xujiahe Formation in the Qilixia section to 5.9 myr as well as the durations of the identified magnetic polarity zones. The parallel established magnetostratigraphy should allow, according to the authors, a "unique correlation" with the Newark APTS and a projected placement of the NRB in Xujiahe, resulting in a "short" Rhaetian. The authors also conclude that their cyclostratigraphy and magnetostratigraphy of the Xujiahe Formation verify the upper 6 myr of the Newark APTS and that their study does not support the hypothesis of the major Rhaetian gap in Newark. Their conclusions seem in our opinion a little premature since they are based on a magnetostratigraphy with certain limitations. The magnetostratigraphic results obtained from three sections (out of four over-lapping sub-sections studied) recall the difficulties when trying to obtain reliable magnetostratigraphic data from continental sedimentary successions. Only 10% of the analyzed samples allow to define exactly a normal or reversed polarity with additional 15 to 20% of approximative polarity results. This leads to a magnetic polarities sequence that suffers from gaps and several magnetic polarity zones defined by a restricted number of samples. Establishing a reliable magnetostratigraphic correlation with the Newark-APTS (and marine Tethyan sections) is, in our view, rather difficult if not impossible since the "black and white fingerprint" can be significantly distorted due to frequent variations in sedimentation rate and possible hiati. Magnetostratigraphic correlations can only really be established without too much uncertainty if there is a reference geomagnetic polarity

time scale for the respective time period available. Such a reference by sequences of oceanic magnetic anomalies exists for post-Mid-Jurassic times but is unfortunately not possible for the Triassic.

As our proposed Austrian Rhaetian astronomical time scale lacks – except for Steinbergkogel – magnetostratigraphic results, we cannot further contribute to this debate and do not attempt in a correlation with either the Newark APTS or the cyclostratigraphy of the Chinese Xujiahe Formation.

6. Conclusions

In order to progress in establishing a reliable Late Triassic GTS, an astronomical time scale on Tethyan marine successions, independent from that of the Newark Basin APTS, is of paramount importance. The results of our study point in this direction: for the first time a high resolution cyclostratigraphic study of a composite marine Rhaetian record provides an astronomical calibration of this Late Triassic stage and a carefully constructed estimate of its duration. The main results of our study can be summarised as follows:

- The studied 131 m thick Rhaetian record was built from four overlapping reference sections (Steinbergkogel, Zlambach, Eiberg and Kuhjoch) in the Northern Calcareous Alps of Austria. The Norian-Rhaetian boundary (NRB) is identified by the FAD of conodont *Misikella posthernsteini* morph. A in the Steinbergkogel section (Rhaetian GSSP candidate), and the Rhaetian-Hettangian boundary is marked by the FO of the ammonite *Psiloceras spelae tirolicum* on the Kuhjoch section (Hettangian GSSP).
- Cyclostratigraphic analysis of magnetic susceptibility variations of the Rhaetian record revealed astronomical forcing at Milankovitch band. The 405 kyr eccentricity component is recognized and was used to astronomically calibrate the record.
- Basing on the 405 kyr orbital tuning, a minimum duration of the Rhaetian stage is estimated as 6.69 myr. Durations of the *Paracochloceras suessi*, *Vandaiteles stuerzenbaumi* and *Choristoceras marshi* ammonite zones are 1.83, 1.63 and 2.96 myr, respectively. The duration of the interval from the end-Triassic mass-extinction (initial CIE) to the Rhaetian-Hettangian (Triassic-Jurassic) boundary is estimated at 270 kyr.
- Given the well established age of the Rhaetian-Hettangian boundary of 201.36 Ma, an age no younger than 208.05 Ma can be suggested for the NRB. This result is not in agreement with U/Pb age of 205.50 Ma proposed from the Levanto section (Peru). However the NRB is not biostratigraphically defined in the same way between the two biogeographic realms: the FAD of conodont *Misikella posthernsteini* morph. A in Austria, and the LO of the bivalve *Monotis subcircularis* in Peru.
- This minimum Rhaetian duration estimated at 6.69 myr is “intermediate” between the “short” Rhaetian (4-5 myr) and the “long” Rhaetian (8-9 myr) options.

The present study constitutes an important step in contributing to the Late Triassic time scale, but it does not yet resolve the controversies of the long-standing debate on bio-magneto-stratigraphic correlations between the continental Newark APTS and the Tethyan marine sections, nor the question of the completeness of the Rhaetian Newark Basin.

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References

- Blackburn, T.J., Olsen, P.E. et al. 2013. Zircon U-Pb geochronology links the end-Triassic extinction with the Central Atlantic Magmatic Province. *Science* 340, 941–945.
- Boulila, S., Galbrun, B., Gardin, S., 2013. Cyclostratigraphy and recent developments in the astronomical calibration of the Geological Time Scale. *Ciências da Terra*, Lisboa 18, 29-34.
- Boulila, S., Galbrun, B., Hinnov, L.A., Collin, P.Y., 2008. High-resolution cyclostratigraphic analysis from magnetic susceptibility in a Lower Kimmeridgian (Upper Jurassic) marl-limestone succession (La Méouge, Vocontian Basin, France). *Sediment. Geol.* 203, 54-63.

- Boulila, S., Galbrun, B., Hinnov, L.A., Collin, P.Y., Ogg, J.G., Fortwengler, D., Marchand, D., 2010. Milankovitch and sub-Milankovitch forcing of the Oxfordian (Late Jurassic) Terres Noires Formation (SE France) and global implications. *Basin Research* 22, 717–732.
- Boulila, S., Galbrun, B., Huret, E., Hinnov, L.A., Rouget, I., Gardin, S., Bartolini, A., 2014. Astronomical calibration of the Toarcian Stage: implications for sequence stratigraphy and the duration of the early Toarcian OAE. *Earth Planet. Sci. Lett.* 386, 98–114.
- Boulila, S., Vahlenkamp, M., De Vleeschouwer, D., Laskar, J., Yamamoto, Y., Pälike, H., Kirtland Turner, S., Sexton, P.F., Westerhold, T., Röhl, U., 2018. Towards a robust and consistent middle Eocene astronomical timescale. *Earth Planet. Sci. Lett.* 486, 94–107.
- Callegaro, S., Rigo, M., Chiaradia, M., Marzoli, A., 2012. Latest Triassic marine Sr isotopic variations, possible causes and implications. *Terra Nova* 24, 130–135.
- Carter, E.S., 1990. New biostratigraphic elements for dating Upper Norian strata from the Sandilands Formation, Queen Charlotte Islands, British Columbia, Canada. *Marine Micropal.* 15, 313–328.
- Channell, J.E.T., Kozur, H.W., Sievers, T., Mock, R., Aubrecht, R., Sykora, M., 2003. Carnian–Norian bio-magnetostratigraphy at Silicka Brezova (Slovakia): Correlation to other Tethyan sections and to the Newark Basin. *Palaeogeo. Palaeoclim. Palaeoecol.* 191, 65–109.
- Charbonnier, G., Boulila, S., Gardin, S., Duchamp-Alphonse, S., Adatte, T., Spangenberg, J., Follmi, K., Colin, C., Galbrun, B., 2013. Astronomical calibration of the Valanginian “Weissert” event from the Orpierre marl-limestone succession (Vocontian Basin, southeastern France). *Cretaceous Res* 45, 25–42.
- Clémence, M.E., Gardin, S., Bartolini, A., Paris, G., Beaumont, V., Guex, J., 2010. Benthic-planktonic evidence from the Austrian Alps for a decline in sea-surface carbonate production at the end of the Triassic. *Swiss J. Geol.* 103, 293–315.
- Deenen, M.H.L., Ruhl, M., Bonis, N.R., Krijgsman, W., Kuerschner, W.M., Reitsma, M., van Bergen, M.J., 2010. A new chronology for the end-Triassic mass extinction. *Earth Planet. Sci. Lett.* 291, 113–125.
- Demangel, I., Kovacs, Zs., Richoz, S., Gardin, S., Krystyn, L., Baldermann, A., Piller, W.E. (this issue). Development of early calcareous nannoplankton in the Late Triassic, Northern Calcareous Alps (Austria). *Global Planetary Change*.
- Ellwood, B.B., Crick, R.E., El Hassani, A., Benoist, S.L., Young, R.H., 2000. Magnetosusceptibility event and cyclostratigraphy method applied to marine rock: detrital input versus carbonate productivity. *Geology* 28, 1135–1138.
- Evans, M.E., Heller, F., 2003. *Environmental Magnetism Principles and Applications of Environmental Magnetism*. International Geophysics Series 86. Academic Press, London.
- Furin, S., Preto, N., Rigo, M., Roghi, G., Gianolla, P., Crowley, J.L., Bowering, S.A., 2006. High-precision U–Pb zircon age from the Triassic of Italy: implications for the Triassic time scale and the Carnian origin of calcareous nannoplankton and dinosaurs. *Geology* 34, 1009–1012.
- Gallet, Y., Besse, J., Krystyn, L., Marcoux, J., Guex, J., Theveniaut, H., 2000. Magnetostratigraphy of the Kavaalani section (southwestern Turkey): Consequence for the origin of the Antalya Calcareous Nappes (Turkey) and for the Norian (Late Triassic) magnetic polarity timescale. *Geophys Res. Lett.* 27, 2033–2036.
- Gallet, Y., Krystyn, L., Besse, J., Marcoux, J., 2003. Improving the Upper Triassic numerical time scale from cross-correlation between Tethyan marine sections and the continental Newark Basin sequence. *Earth Planet. Sci. Lett.* 212, 255–261.
- Gallet, Y., Krystyn, L., Marcoux, J., Besse, J., 2007. New constraints on the End-Triassic (Upper Norian-Rhaetian) magnetostratigraphy. *Earth Planet. Sci. Lett.* 255, 458–470.
- Gardin, S., Krystyn, L., Richoz, S., Bartolini, S., Galbrun, B., 2012. Where and when the earliest coccolithophores? *Lethaia* 45, 507–523.
- Ghil, M., Allen, R.M., Dettinger, M.D., Ide, K., Kondrashov, D., Mann, M.E., Robertson, A., Saunders, A., Tian, Y., Varadi, F., Yiou, P., 2002. Advanced spectral methods for climatic time series. *Rev. Geophys.* 40, 1.1–1.41.
- Golding, M.L., Mortensen, J.K., Zonneveld, J.P., Orchard, M.J., 2016. U-Pb isotopic ages of euhedral zircons in the Rhaetian of British Columbia: Implications for Cordilleran tectonics during the Late Triassic. *Geosphere* 12, 1606–1616.
- Golebiowski, R., 1991. Becken und Riffe der alpinen Obertrias - Lithostratigraphie und Biofazies der Kössener Formation, in: Nagel, D., Rabeder, G. (Eds.), *Exkursionen im Jungpaläozoikum und Mesozoikum Österreichs*. Österreichische Paläontologische Gesellschaft, Wien 79–119.
- Grippo, A., Fischer, A.G., Hinnov, L.A., Herbert, T.D., Premoli Silva, I., 2004. Cyclostratigraphy and chronology of the Albian stage (Piobbico core, Italy), in: D’Argenio, B., Fischer, A.G., Premoli Silva, I., Weissert, H., Ferreri, V. (Eds.) *Cyclostratigraphy: Approaches and Case Histories*.

- Society for Sedimentary Geology. Special Publication 81, 57–81.
- Guex, J., Bartolini, A., Atudorei, V., Taylor, D., 2004. High-resolution ammonite and carbon isotope stratigraphy across the Triassic-Jurassic boundary at New York Canyon (Nevada). *Earth Planet. Sci. Lett.* 225, 29-41.
- Guex, J., Schoene, B., Bartolini, A., Spangenberg, J.E., Schaltegger, U., O'Dogherty, L., Taylor, D., Bucher, H., Atudorei, V., 2012. Geochronological constraints on post-extinction recovery of the ammonoids and carbon cycle perturbations during the Early Jurassic. *Palaeogeog. Palaeoclim. Palaeoecol.* 346-347, 1–11.
- Hesselbo, S.P., Robinson, S.A., Surlyk, F., Piasecki, S., 2002. Terrestrial and marine extinction at the Triassic-Jurassic boundary synchronized with major carbon-cycle perturbation: a link to initiation of massive volcanism? *Geology* 30, 251-254.
- Hillebrandt, A.V., Krystyn, L., Kürschner W.M., Bonis, N.R., Ruhl, M., Richoz, S., Schobben, M.A.N., Urlichs, M., Bown, P.R., Kment, K., McRoberts, C.A., Simms, M., Tomasovych, A., 2013. The Global Stratotype Sections and Point (GSSP) for the base of the Jurassic System at Kuhjoch (Karwendel Mountains, Northern Calcareous Alps, Tyrol, Austria). *Episodes* 36, 162-198.
- Hinnov, L.A., 2000. New perspectives on orbitally forced stratigraphy. *Ann. Rev. Earth Planet. Sci.* 28, 419-475.
- Hinnov, L.A., 2014. Cyclostratigraphy and its revolutionizing applications in the earth and planetary sciences. *Geol. Soc. Am. Bull.* 125, 1703–1734.
- Hinnov, L.A., Ogg, J.G., 2007. Cyclostratigraphy and the Astronomical Time Scale. *Stratigraphy* 4, 239-251.
- Hinnov, L.A., Ogg, J.G., Huang, C., Galbrun, B., Huret, E., Boulila, S., Husson, D., Locklair, R., 2009. Current status of the Mesozoic Astronomical Time Scale. GSA Annual Meeting, 18-21 October 2009, Portland, USA.
- Hounslow, M.W., Muttoni, G., 2010. The geomagnetic polarity timescale for the Triassic: linkage to stage boundary definitions, in: Lucas, S.G. (Ed.), *The Triassic Timescale*. *Geol. Soc. London Sp. Pub.* 334, 61-102.
- Hounslow, M.W., Posen, P.E., Warrington, G., 2004. Magnetostratigraphy and biostratigraphy of the Upper Triassic and lowermost Jurassic succession, St. Audrie's Bay, UK. *Palaeogeog. Palaeoclim. Palaeoecol.* 213, 331–358.
- Huang, C., Hinnov, L.A., Fischer, A.G., Grippo, A., Herbert, T., 2010. Astronomical tuning of the Aptian Stage from Italian reference sections. *Geology* 38, 899–902.
- Huret, E., Thiesson, J., Tabbagh, A., Galbrun, B., Collin, P.Y., 2011. Improvement of cyclostratigraphic studies by processing of high resolution magnetic susceptibility logging : example of the PEP 1002 borehole (Bure, Meuse, France). *C. R. Géosciences* 343, 379-386.
- Hüsing, S.K., Beniast, A., van der Boon, A., Albels, H.A., Deenen, M.H.L., Ruhl, M., Krijgsman, W., 2014. Astronomically-calibrated magnetostratigraphy of the Lower Jurassic marine successions at St. Audrie's Bay and East Quantoxhead (Hettangian–Sinemurian; Somerset, UK). *Palaeogeog. Palaeoclim. Palaeoecol.* 403, 43–56.
- Hüsing, S.K., Deenen, M.H.L., Koopmans, J.G., Krijgsman, W., 2011. Magnetostratigraphic dating of the proposed Rhaetian GSSP at Steinbergkogel (Upper Triassic, Austria): implications for the Late Triassic time scale. *Earth Planet. Sci. Lett.* 302, 203–216.
- Husson, D., Galbrun, B., Laskar, J., Hinnov, L.A., Thibault, N., Gardin, S., Locklair, R.E., 2011. Astronomical calibration of the Maastrichtian (Late Cretaceous). *Earth Planet. Sci. Lett.* 305, 328-340.
- Husson, D., Galbrun, B., Thibault, N., Gardin, S., Huret, E., Coccioni, R., 2012. Astronomical duration of polarity Chron C31r (Lower Maastrichtian): cyclostratigraphy of the ODP Site 762 (Indian Ocean) and the Contessa Highway section (Gubbio, Italy). *Geol. Mag.* 149, 345-351.
- Husson, D., Hinnov, L.A., Locklair, R., Galbrun, B., Ogg, J.G., Huang, C., Huret, E., 2009. Development of an Astronomical Time Scale for the Cretaceous Period. AAPG Annual Convention, 7-10 June, Denver, Colorado, USA
- Husson, D., Thibault, N., Galbrun, B., Gardin, S., Minoletti, F., Sageman, B., Huret, E., 2014. Lower Maastrichtian cyclostratigraphy of the Bidart section (Basque country, SW France): a remarkable record of precessional forcing. *Palaeogeog. Palaeoclim. Palaeoecol.* 395, 176-197.
- ICS 2019. <http://www.stratigraphy.org/ICSChart/ChronostratChart2019-05.pdf>
- Imbrie, J., Hays, J.D., Martinson, D.G., McIntyre, A., Mix, A.C., Morely, J.J., Pisias, N.G., Prell, W.L., Shackleton, N.G., 1984. The orbital theory of Pleistocene climate: support from a revised chronology of the marine $\delta^{18}\text{O}$ record, in: Berger, A.L., Imbrie, J., Hays, J.D., Kukla, G., Saltzman, B. (Eds.), *Milankovitch and Climate, Part 1*, Reidel Publishing Co, Dordrecht 269-305.

- Kent, D.V., Olsen, P.E., 1999. Astronomically tuned geomagnetic polarity time scale for the Late Triassic. *J. Geophys. Res.* 104, 12831–12841.
- Kent, D.V., Olsen, P.E., Muttoni, G., 2017. Astrochronostratigraphic polarity time scale (APTS) for the late Triassic and Early Jurassic from continental sediments and correlation with standard marine stages. *Earth-Sci. Rev.* 166, 153–180.
- Kent, D.V., Olsen, P.E., Rasmussen, C., Lepre, C.J., Mundil, R., Irmis, R.B., Gehrels, G.E., Giesler, D., Geissman, J.W., Parker, W.G., 2018. Empirical evidence for stability of the 405 kyr Jupiter-Venus eccentricity cycle over hundreds of millions of years. *Proc. Nat. Acad. Sci.* 115, 6153–6158.
- Korte, C., Thibault, N., Ullmann, C.V., Clémence, M.E., Mette, W., Olsen, T.K., Rizzi, M., Ruhl, M., 2017. Brachiopod biogeochemistry and isotope stratigraphy from the Rhaetian Eiberg section in Austria: potentials and limitations. *Neues Jahrb. Geol. Palaontol.* 284/2, 117–138.
- Kovacs, Zs., Demangel, I., Richoz, S., Hippler, D., Baldermann, A., Krystyn, L. (this issue). New constraint on the evolution of $^{87}\text{Sr}/^{86}\text{Sr}$ of seawater during the Upper Triassic. *Global Planetary Change*.
- Kozur, H.W., 2003. Integrated ammonoid, conodont and radiolarian zonation of the Triassic and some remarks to Stage/Substage subdivision and numeric age of the Triassic stages. *Albertiana* 28, 57–74.
- Kozur, H.W., Weems, R.E., 2007. Upper Triassic conchostracan biostratigraphy of the continental rift basins of eastern north America: Its importance for correlating Newark supergroup events with the Germanic basin and the international geologic timescale. *New Mexico Mus. Natural History Science Bulletin* 41, 137–188.
- Kozur, H.W., Weems, R.E., 2010. The biostratigraphic importance of conchostracans in the continental Triassic of the northern hemisphere, in: Lucas, S.G. (Ed.), *The Triassic Timescale*. London Geol. Soc., Sp. Pub. 334, 315–417.
- Krystyn, L., 1987. Zur Rhät-Stratigraphie in den Zlambach-Schichten (vorläufiger Bericht). *Sitzungsber. Österr. Akad. Wiss. Math-Natur. Kl.* 196/3, 21–36.
- Krystyn, L., 1991. Die Fossilagerstätten der alpinen Trias, in: Nagel, D., Rabeder, G. (Eds.), *Exkursionen im Jungpalaäozoikum und Mesozoikum Österreichs*. Österreichische Paläontologische Gesellschaft, Wien, 24–78.
- Krystyn, L., 2008. An ammonoid-calibrated Tethyan conodont time scale of the Late Upper Triassic. *Ber. Geol. B-A.* 76, 9–11.
- Krystyn, L., 2010. Decision report on the defining event for the base of the Rhaetian stage. *Albertiana* 38, 11–12.
- Krystyn, L., Bouquerel, H., Kürschner, W.M., Richoz, S., Gallet, Y., 2007a. Proposal for a candidate GSSP for the base of Rhaetian stage, in: Lucas, S.G., Spielmann, J.A. (Eds.), *The Global Triassic*. New Mex. Mus. Nat. Hist. Sci. Bull. 41, 189–199.
- Krystyn, L., Richoz, S., Gallet, Y., Bouquerel, H., Kürschner, W.M., Spötl, C., 2007b. Updated bio- and magnetostratigraphy from Steinbergkogel (Austria), candidate GSSP for the base of the Rhaetian stage. *Albertiana* 36, 164–173.
- Kürschner, W.M., Bonis, N.R., Krystyn, L., 2007. Carbon-Isotope stratigraphy of the Triassic – Jurassic transition in the Tiefengraben section, Northern Calcareous Alps. *Palaeoeco. Palaeoclim. Palaeoecol.* 244, 257–280.
- Kuss, J., 1983. Depositional environments of proximal intraplatform basins: Sedimentation, paleoecology and geochemistry of the Kössen Beds (Upper Triassic, Northern Alps). *Facies* 9, 61–172.
- Laskar, J., 1990. The chaotic motion of the Solar System: A numerical estimate of the size of the chaotic zone. *Icarus* 88, 266–291.
- Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A.C.M., Levrard, B., 2004. A long-term numerical solution for the insolation quantities of the Earth. *Astron. Astrophys.* 428, 261–285.
- Li, M., Zhang, Y., Huang, C., Ogg, J., Hinnov, L., Wang, Y., Zou, Z., Li, L., 2017. Astronomical tuning and magnetostratigraphy of the Upper Triassic Xujiahe Formation of South China and Newark Supergroup of North America: Implications for the Late Triassic time scale. *Earth Planet. Sci. Lett.* 475, 207–223.
- Lindström, S., van de Schootbrugge, B., Dybkjar, K., Pedersen, G.K., Fiebig, J., Nielsen, L.H., Richoz, S., 2012. No causal link between terrestrial ecosystem change and methane release during the end-Triassic mass extinction. *Geology* 40/6, 531–534. doi: 10.1130/G32928.1.
- Lucas, S.G., 2010a. The Triassic timescale: an introduction, in: Lucas, S.G. (Ed.), *The Triassic Timescale*. Geol. Soc. London Sp. Pub. 334, 1–16.

- Lucas, S.G., 2010b. The Triassic chronostratigraphic scale: history and status, in: Lucas, S.G. (Ed.), *The Triassic Timescale*. Geol. Soc. London Sp. Pub. 334, 17-39.
- Lucas, S.G., Tanner, L.H., 2007. Tetrapod biostratigraphy and biochronology of the Triassic–Jurassic transition on the southern Colorado Plateau, USA. *Palaeogeog. Palaeoclim. Palaeoecol.* 244, 242–256.
- Lucas, S.G., Tanner, L.H., 2015. End-Triassic nonmarine biotic events. *J. Palaeogeography* 4, 331-348.
- Lucas, S.G., Tanner, L.H., Kozur, H.W., Weems, R.E., Heckert, A.B., 2012. The Late Triassic timescale: Age and correlation of the Carnian-Norian boundary. *Earth-Sci. Rev.* 114, 1–18.
- Mandl, G.W., 2000. The Alpine sector of the Tethyan shelf - Examples of Triassic to Jurassic sedimentation and deformation from the Northern Calcareous Alps. *Mitt. Österreich. Geol. Gesell.* 92, 61–78.
- Mann, M.E., Lees, J.M., 1996. Robust estimation of background noise and signal detection in climatic time series. *Clim. Change* 33, 409–445.
- Maron, M., Muttoni, G., Rigo, M., Gianolla, P., Kent, D.V., 2019. New magnetobiostratigraphic results from the Ladinian of the Dolomites and implications for the Triassic geomagnetic polarity timescale. *Palaeogeog. Palaeoclim. Palaeoecol.* 517, 52–73.
- Maron, M., Rigo, M., Bertinelli, A., Katz, M.E., Godfrey, L., Zaffani, M., Muttoni, G., 2015. Magnetostratigraphy, biostratigraphy, and chemostratigraphy of the Pignola-Abriola section: new constraints for the Norian-Rhaetian boundary. *Geol. Soc. Am. Bull.* 127, 962–974.
- Maslo, M., 2008. Taxonomy and stratigraphy of the Upper Triassic heteromorphic ammonoids: preliminary results from Austria. *Ber. Geol. B-A.* 76, 15–16.
- Matzner, C.H., 1986. Die Zlambach-Schichten (Rhät) in den Nördlichen Kalkalpen. Eine Plattform-Hang-Beckenentwicklung mit allochthoner Karbonatsedimentation. *Facies* 14, 1–104.
- Mayer, H., Appel, E., 1999. Milankovitch cyclicity and rock-magnetic signatures of paleoclimatic changes in the early Cretaceous Biancone Formation of the Southern Alps, Italy. *Cret. Res.* 20, 189-214.
- Mc Laughlin, D.B., 1945. Type sections of the Stockton and Lockatong Formations. *Proceedings of the Pennsylvania Academy of Science* 19, 102–103.
- Mc Roberts, C.A., 2010. Biochronology of Triassic bivalves. In: Lucas SG (ed) *The Triassic Timescale*. Geol. Soc. London Sp. Pub. 334, 201-219.
- Mc Roberts, C.A., Krystyn, L., Hautmann, M., 2012. Macrofaunal response to the end-Triassic mass extinction in the west-Tethyan Kossen Basin, Austria. *Palaio* 27, 607–616.
- Mc Roberts, C.A., Krystyn, L., Shea, A., 2008. Rhaetian (Late Triassic) *monotis* (bivalvia: pectinoida) from the Eastern Northern Calcareous Alps (Austria) and the end-Norian crisis in pelagic faunas. *Palaeontology*, 51, 721–735.
- Mette, W., Elsler, A., Korte, C., 2012. Palaeoenvironmental changes in the Late Triassic (Rhaetian) of the Northern Calcareous Alps: Clues from stable isotopes and microfossils. *Palaeogeog. Palaeoclim. Palaeoecol.* 350-352, 62-72.
- Mostler, H., Scheuring, B., Urlichs, F., 1978. Zur Mega- und Mikrofauna und Mikroflora der Kössener Schichten vom Weißloferbach in Tirol unter besonderer Berücksichtigung der in der Suessi- und Marshi-Zone auftretenden Conodonten. *Schriftenreihe Erdwiss. Komm. Österr. Akad. Wiss.* 4, 141-174.
- Mundil, R., Palfy, J., Renne, P.R., Brack, P., 2010. The Triassic time scale: new constraints and a review of geochronological data. in: Lucas, S.G. (Ed.), *The Triassic Timescale*. Geol. Soc. London Sp. Pub. 334, 41-59.
- Muttoni, G., Kent, D.V., Jadoul, F., Olsen, P.E., Rigo, M., Galli, M.T., Nicora, A., 2010. Rhaetian magneto-biostratigraphy from the Southern Alps (Italy): constraints on Triassic chronology. *Palaeogeog. Palaeoclim. Palaeoecol.* 285, 1–16.
- Muttoni, G., Kent, D.V., Olsen, P.E., Di Stefano, P., Lowrie, W., Bernasconi, S.M., Hernandez, F.M., 2004. Tethyan magnetostratigraphy from Pizzo Mondello (Sicily) and correlation to the Late Triassic Newark astrochronological polarity time scale. *Geol. Soc. Am. Bull.* 116, 1043-1058.
- Ogg, J.G., 2012. Triassic, in: Gradstein, F.M., Ogg, J.G., Schmitz, M., Ogg, G., (Eds.), *The Geologic Timescale 2012*. Elsevier, Amsterdam, 681-722.
- Ogg, J.G., Ogg, G., Gradstein, F.M., 2016. *A concise Geological Time Scale*. Elsevier, Amsterdam, 240 p.
- Olsen, P.E., 1986. A 40-million-year lake record of early Mesozoic orbital climatic forcing. *Science* 234, 842–848.
- Olsen, P.E., Kent, D.V., 1996. Milankovitch climate forcing in the tropics of Pangea during the Late Triassic. *Palaeogeog. Palaeoclim. Palaeoecol.* 122, 1-26.

- Olsen, P.E., Kent, D.V., 1999. Long-period Milankovitch cycles from the Late Triassic and Early Jurassic of eastern North America and their implications for the calibration of the Early Mesozoic time-scale and the long-term behavior of the planets. *Phil. Trans. Roy. Soc. Lond. A* 357, 1761–1786.
- Olsen, P.E., Kent, D.V., Cornet, B., Witte, W.K., Schlische, R.W., 1996. High-resolution stratigraphy of the Newark rift basin (early Mesozoic, eastern North America). *Geol. Soc. Am. Bull.* 108, 40–77.
- Olsen, P.E., Kent, D.V., Whiteside, J.H. 2011. Implications of the Newark Supergroup-based astrochronology and geomagnetic polarity time scale (Newark-APTS) for the tempo and mode of the early diversification of the Dinosauria. *Earth Env. Sci. Trans; Roy. Soc; Edinburgh* 101, 201-229.
- Olsen, P.E., et al. 2018. Colorado Plateau Coring Project, Phase I (CPCP-I): a continuously cored, globally exportable chronology of Triassic continental environmental change from western North America. *Sci. Dril.* 24, 15–40.
- Paillard, D., Labeyrie, L., Yiou, P., 1996, Macintosh program performs timeseries analysis. *Eos* 77, 379.
- Pálffy, J., Demény, A., Haas, J., Hetényi, M., Orchard, M.J., Vetö, I., 2001. Carbon isotope anomaly and other geochemical changes at the Triassic-Jurassic boundary from a marine section in Hungary. *Geology* 29, 1047-1050.
- Pálffy, J., Kocsis, T.Á., 2014. Volcanism of the Central Atlantic Magmatic Province as the trigger of environmental and biotic changes around the Triassic–Jurassic boundary. In : Keller G, Kerr AC (eds) *Volcanism, impacts and mass extinctions: causes and effects*. *Geol. Soc. Am. Spec. Pap.* 505, 245–261.
- Palotai, M., Pálffy, J., Sasvári, A., 2017. Structural complexity at and around the Triassic–Jurassic GSSP at Kuhjoch, Northern Calcareous Alps, Austria. *Int. J. Earth Sci.* DOI 10.1007/s00531-017-1450-4
- Preto, N., Kustatscher, E., Wignall, P.B., 2010. Triassic climates - State of the art and perspectives. *Palaeogeog. Palaeoclim. Palaeoecol.* 290, 1-10.
- Richoz, S., Krystyn, L., 2015. The Upper Triassic events recorded in platform and basin of the Austrian Alps, the Triassic/Jurassic GSSP and Norian/Rhaetian GSSP candidate, in: Richoz, S. (Ed.), *Field trip in the Eastern and Southern Alps (Austria, Italy), STRATI 2015, Graz, Austria*. *Berichte Geol Bund* 111, 75-136.
- Richoz, S., van de Schootbrugge, B., Pross, J., Püttmann, W., Quan, T.M., Lindström, S., Heunisch, C., Fiebig, J., Maquil, R., Schouten, S., Hauzenberger, C.A., Wignall, P.B. 2012a. Hydrogen sulphide poisoning of shallow seas following the end-Triassic extinction. *Nature Geosciences* 5, 662-667. doi: 10.1038/NGEO1539.
- Richoz, S., Krystyn, L., Von Hillebrandt, A., Martindale, R., 2012b. End-Triassic crisis events recorded in platform and basin of the Austrian Alps. The Triassic/Jurassic and Norian/Rhaetian GSSPs. *Field Trip Guide 29th IAS Meeting of Sedimentology Schladming/Austria*. *J. Alp. Geol.* 55-S, 321-374.
- Rigo, M., Bertinelli, A., Concheri, G., Gattolin, G., Godfrey, L., Katz, M., Maron, M., Muttoni, G., Sprovieri, M., Stellin, F., Zaffani, M., 2015. The Pignola-Abriola section (southern Apennines, Italy): a new GSSP candidate for the base of the Rhaetian Stage. *Lethaia*, DOI: 10.1111/let.12145
- Rigo, M., De Zanche, V., Mietto, P., Preto, N., Roghi, G., 2005. Biostratigraphy of the Calcarei con Selce formation. *Boll. Soc. Geol. Ital.* 124, 293–300.
- Ruhl, M., Bonis, N.R., Reichart, G.J., Sinninghe-Damste, J.S., Kürschner, W.M., 2011. Atmospheric carbon injection linked to end-Triassic mass extinction. *Science* 333, 430–434.
- Ruhl, M., Deenen, M.H.L., Abels, H.A., Bonis, N.R., Krijgsman, W., Kürschner, W.M., 2010a. Astronomical constraints on the duration of the early Jurassic Hettangian stage and recovery rates following the end-Triassic mass extinction (St Audrie's Bay/East Quantoxhead, UK). *Earth Planet. Sci. Lett.* 295, 262–276.
- Ruhl, M., Kürschner, W.M. 2011. Multiple phases of carbon cycle disturbance from large igneous province formation at the Triassic-Jurassic transition. *Geology* 39, 431–434.
- Ruhl, M., Kürschner, W.M., Krystyn, L., 2009. Triassic-Jurassic organic carbon isotope stratigraphy of key sections in the western Tethys realm (Austria). *Earth Planet. Sci. Lett.* 281, 169–187.
- Ruhl, M., Veld. H., Kürschner, W.M. 2010b. Sedimentary organic matter characterization of the Triassic-Jurassic boundary GSSP at Kuhjoch (Austria). *Earth Planet. Sc. Lett.* 292, 17-26.
- Schaltegger, U., Guex, J., Bartolini, A., Schoene, B., Ovtcharova, M., 2008. Precise U-Pb age constraints for end-Triassic mass extinction, its correlation to volcanism and Hettangian post-extinction recovery. *Earth Planet. Sci. Lett.* 267, 266-275.

- Schoene, B., Guex, J., Bartolini, A., Schaltegger, U., Blackburn, T.J. 2010. A correlation between the Triassic–Jurassic boundary mass extinction and flood basalt eruption at the 100 ka-level using ID-TIMS U/Pb zircon geochronology. *Geology* 38, 387–390.
- Suan, G., Föllmi, K.B., Adatte, T., Bomou, B., Spangenberg, J.E., Van De Schootbrugge, B., 2012. Major environmental change and bonebed genesis prior to the Triassic-Jurassic mass extinction. *J. Geol. Soc. London* 169, 191-200.
- Tanner, L.H., Kyte, F.T., Richoz, S., Krystyn, L., 2016. Distribution of iridium and associated geochemistry across the Triassic-Jurassic boundary in sections at Kuhjoch and Kendlbach, Northern Calcareous Alps, Austria. *Palaeogeo. Palaeoclim. Palaeoecol.* 449, 13-26.
- Tanner, L.H., Lucas, S.G., 2015. The Triassic-Jurassic strata of the Newark Basin, USA: A complete and accurate astronomically-tuned timescale? *Stratigraphy* 12, 47-65.
- Tanner, L.H., Lucas, S.G., Chapman, M.G., 2004. Assessing the timing and causes of Late Triassic extinction. *Earth Sci. Rev.* 65, 103–139.
- Thibault, N., Galbrun, B., Gardin, S., Minoletti, F., Le Callonnec, L., 2016. The end-Cretaceous in the southwestern Tethys (Elles, Tunisia) : orbital calibration of paleoenvironmental events before the mass extinction. *Int. J. Earth Sciences* 105, 771-795.
- Thomson, D.J., 1982. Spectrum estimation and harmonic analysis. *Proceedings of the IEEE* 70, 1055–1096.
- Todaro, S., Rigo, M., Randazzo, V., Di Stefano, P., 2018. The end-Triassic mass extinction: A new correlation between extinction events and $\delta^{13}\text{C}$ fluctuations from a Triassic-Jurassic peritidal succession in western Sicily. *Sed. Geol.* doi:10.1016/j.sedgeo.2018.03.008
- Van de Schootbrugge, B., Bachan, A., Suan, G., Richoz, S., Payne, J.L., 2013. Microbes, mud and methane: cause and consequence of recurrent Early Jurassic anoxia following the end-Triassic mass-extinction. *Palaeontology* 56/4, 685–709.
- Van de Schootbrugge, B., Quan, T.M., Lindström, S., Püttmann, W., Heunisch, C., Pross, J., Fiebig, J., Petschick, R., Röhring, H-G., Richoz, S., Rosenthal Y., Falkowski, P.G., 2009. Floral changes across the Triassic/Jurassic boundary linked to flood basalt volcanism. *Nature Geoscience* 2/8, 589-594.
- Van Houten, F.B., 1964. Cyclic lacustrine sedimentation, Upper Triassic Lockatong Formation, central New Jersey and adjacent Pennsylvania. *Kansas Geol. Surv. Bull.* 169, 497–532.
- Van Veen, P.M., 1995. Time calibration of Triassic/Jurassic microfloral turnover, eastern North America: comment. *Tectonophysics* 245, 93–95.
- Walker, J.D., Geissman, J.W., 2009. 2009 GSA Geologic Time Scale. *GSA Today* 60–61.
- Weedon, G.P., Jenkyns, H.C., Coe, A.L., Hesselbo, S.P., 1999. Astronomical calibration of the Jurassic time-scale from cyclostratigraphy in British mudrock formations. *Phil. Trans. Roy. Soc. London* 357, 1787-1813.
- Weems, R.E., Tanner L.H., Lucas, S.G., 2016. Synthesis and revision of the lithostratigraphic groups and formations in the Upper Permian?–Lower Jurassic Newark Supergroup of eastern North America. *Stratigraphy* 13, 111-153.
- Wotzlaw, J.F., Guex, J., Bartolini, A., Gallet, Y., Krystyn, L., Mc Roberts, C.A., Taylor, D., Schoene, B., Schaltegger, U., 2014. Towards absolute time calibration of the Upper Triassic: The duration of the Rhaetian. *Geology* 42, 571-574.
- Zajzon, N., Kristály, F., Pálffy, J., Németh, T., 2012. Detailed clay mineralogy of the Triassic–Jurassic boundary section at Kendlbachgraben (Northern Calcareous Alps, Austria). *Clay Mineralogy* 47, 177–189.

Plate 1

1-3: *Misikella posthernsteini* Kozur & Mock morph. B, Kleiner Zlambach – 1, 0 m asb, 2, 4 m asb and 3, 19,8 m asb.

4: *Misikella hernsteini* (Mostler), Kleiner Zlambach – 4 m asb

5: *Misikella koessenensis* – *M. rhaetica* trans. Form, Kleiner Zlambach – 26,4 m asb

6: *Misikella rhaetica* (Kozur & Mock), Eiberg –1 m asb

7-9: *Misikella rhaetica* (Kozur & Mock) – 7, Kleiner Zlambach – 43,8 m asb, 8, Eiberg – 14,5 m asb, 9, Kleiner Zlambach – 43,8 m asb

12: *Norigondolella steinbergensis* (Mosher), Kleiner Zlambach – 19,8 m asb

13: *Oncodella paucidentata* (Mostler), Kleiner Zlambach – 39 m asb

14: *Epigondolella slovakensis* Kozur & Mostler, Kleiner Zlambach – 39 m asb

15: *Misikella ultima* (Kozur & Mock), Eiberg – 46,5 m asb

asb = above section base

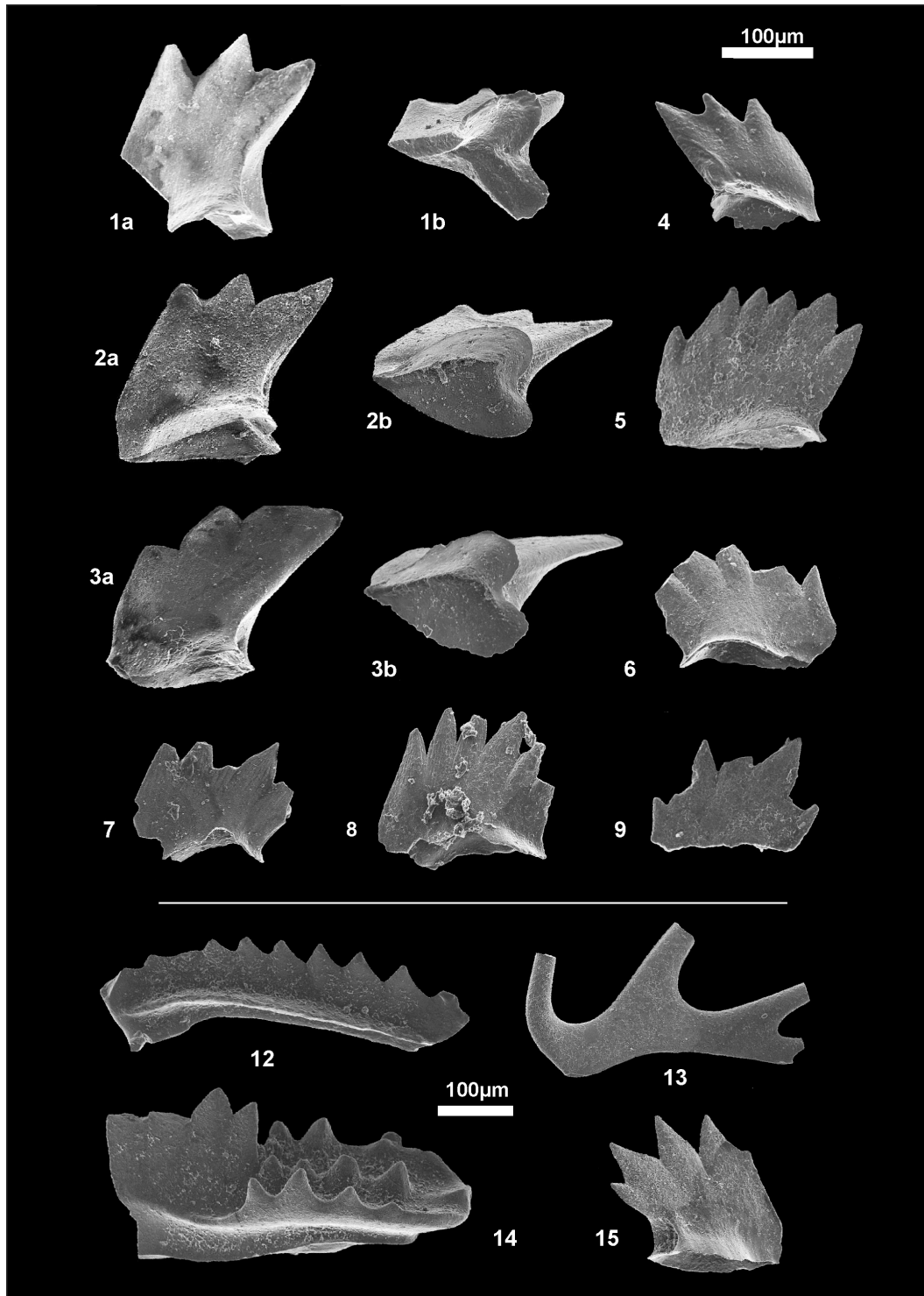


Plate 2

1: *Paracochloceras canaliculatum* Mojsisovics, Kleiner Zlambach – Taferlkogel

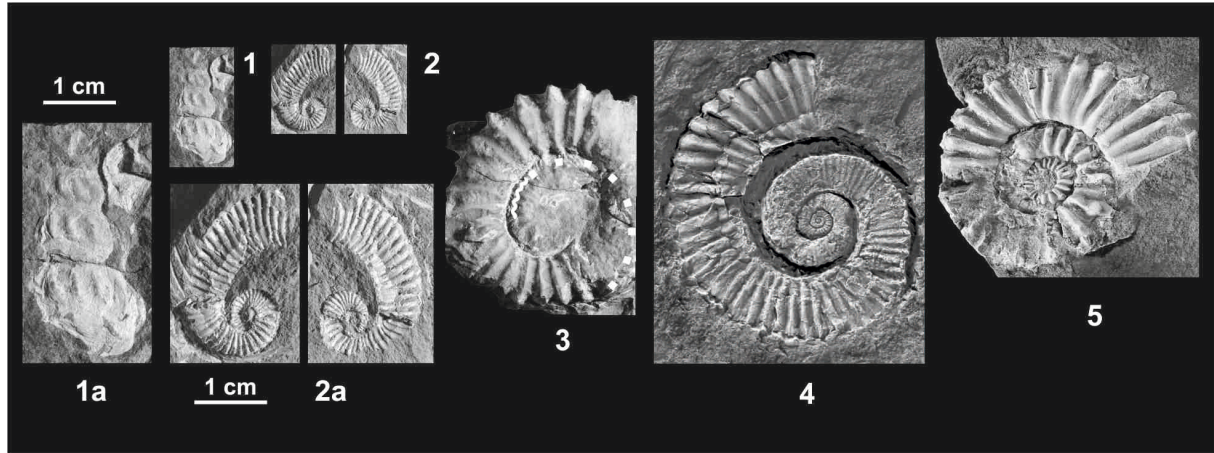
2: *Vandaites saxinontanus* (Mojsisovics), Kleiner Zlambach – 27 m asb

3: „*Choristoceras*“ *haueri* Mojsisovics, Kleiner Zlambach – 8,5 m asb

4: *Choristoceras ammonitiforme* (Guembel), Eiberg – 4 m asb

5: *Choristoceras marshi* (Hauer), Eiberg – 37 m asb

Natural size, except 1a and 2a (2x); asb = above section base



Supplementary material 1

Additional cyclostratigraphic analyses of the sections and additional stratigraphic informations on the Steinbergkogel section.

Figure S1. (a) 2π -MTM power spectrum of detrended MS variations of the Eiberg section (removal of 15% weighted average of the data shown in Fig. 5 of the main text). (b) 2π -MTM power spectrum of detrended MS variations of the Zlambach section (removal of 15% weighted average of the data shown in Fig 4 of the main text).

The prominent peak of 7-8 m corresponds most likely to the 405 kyr long eccentricity component (see main text).

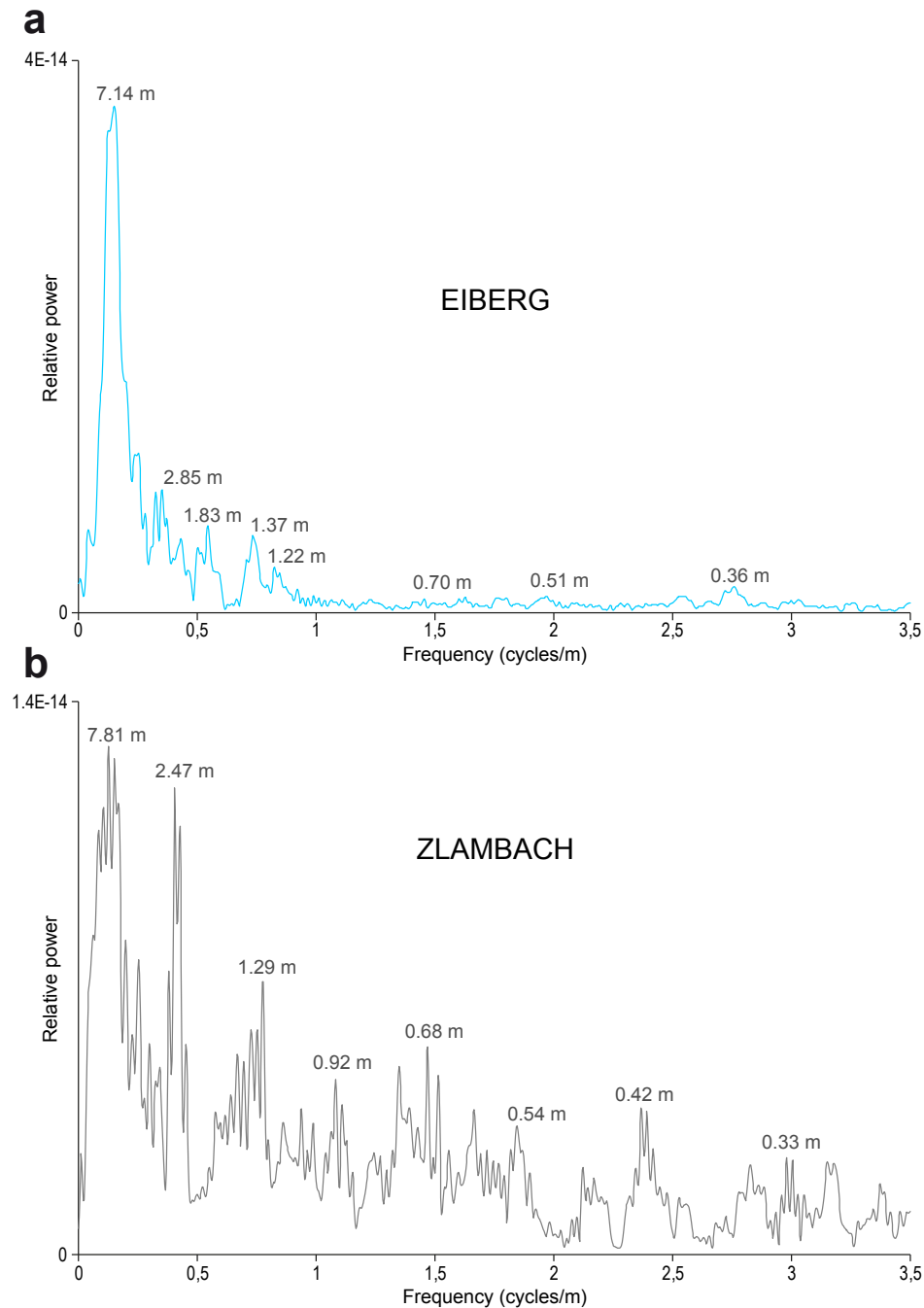
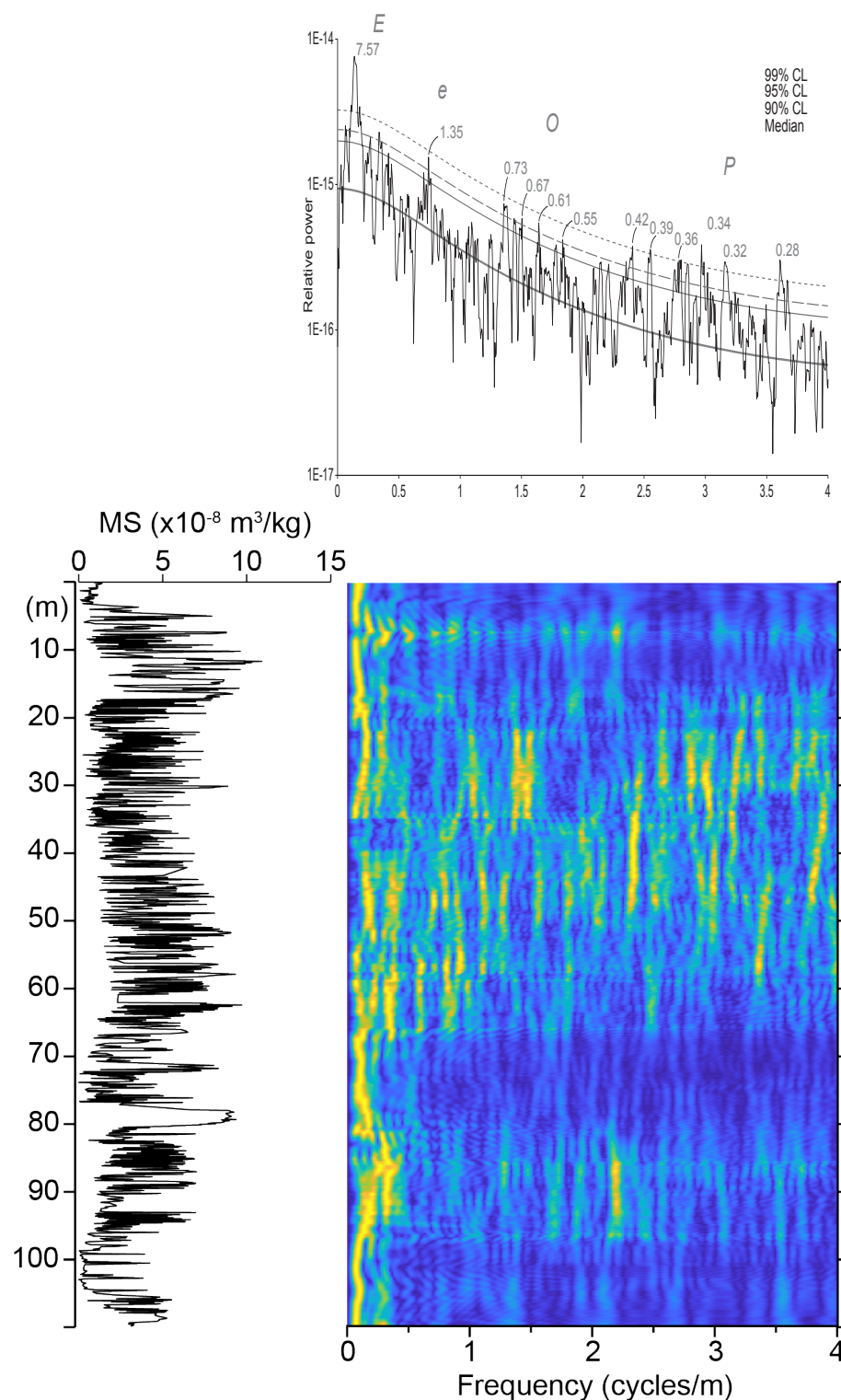


Figure S2. Amplitude spectrogram of the raw MS data (window = 15 m, step = 0.2 m) using the *Acycle* software (Li et al., 2019). The power spectrum (top of the figure) is from Fig.8A of main text). Note the strong 7.6 m spectral line depicting the 405 kyr eccentricity cyclicity.



Reference:

Li, M., Hinnov, L., Kump, L., 2019. *Acycle*: Time-series analysis software for paleoclimate projects and education. *Computers & Geosciences* 127, 12–22.

Plate S1. *Misikella posthernsteini* from Steinbergkogel section, scale bar 180 μm :

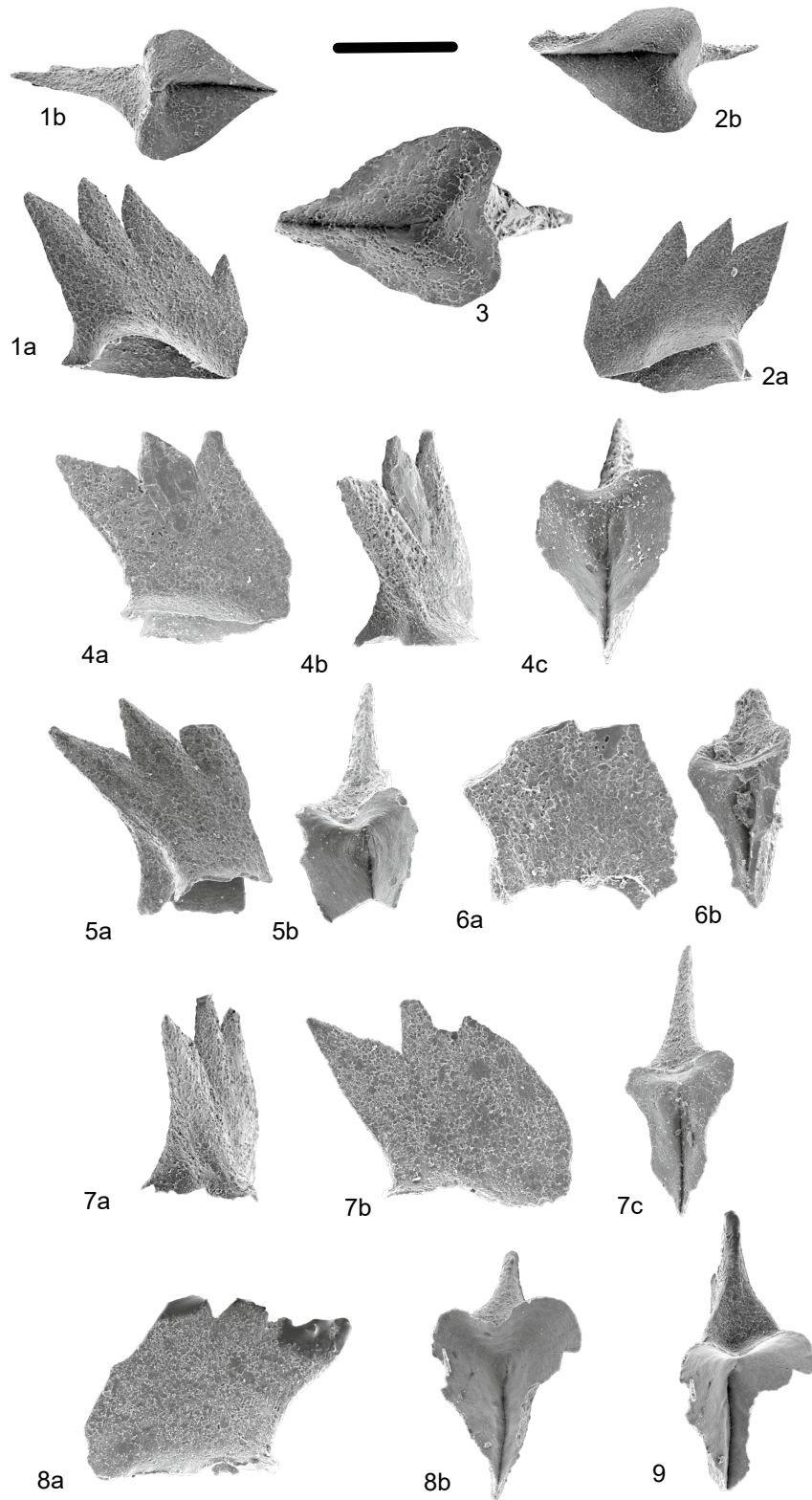
1-2 : Morphotype A, bed 111A (base of bed 111)

3 : Morphotype A, bed 112

4-6 : Morphotype B, bed 112A

7-9 : Morphotype B, bed 12C

For position of bed numbers refer to Gardin *et al.*, 2012, their Fig. 5.



Additional informations on the Steinbergkogel section.

At Steinbergkogel, the *Misikella posthernsteini* morph A date is coeval to the most distinct ammonoid changes around the Norian–Rhaetian boundary, both in the leiostracean and trachyostracean groups (Krystyn, 2008); and it is closely above a major change, respectively disappearance, in pelagic bivalves (monotids) allowing almost worldwide correlations in marine basinal strata. The *posthernsteini* morph A date is further close to a conspicuous spread of the nannoplankton and the onset of new Rhaetian forms (Gardin et al., 2012; Demangel et al., this vol.). Physical events include a prominent magnetic polarity change from a long normal magnetozone to a distinct reversed magnetozone occurring just below the *posthernsteini* morph A datum (Krystyn et al., 2007; Hüsing et al., 2011). This reversed interval includes several thin normals constituting a characteristic pattern that, besides Steinbergkogel, has been retrieved in other Tethyan sections, i.e. Italy (Pignola – Rigo et al., 2015) and Turkey (Oyuklu – Gallet et al., 2007), and is used for high-resolution palaeomagnetic correlations (Maron et al., 2015).