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Multi-proxy record of orbital-scale changes in climate and sedimentation during the Weissert Event in the Valanginian Bersek Marl Formation (Gerecse Mts., Hungary)

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a b s t r a c t
The Valanginian positive carbon isotope excursion and associated environmental changes, known as the Weissert Event, is the first in the series of Cretaceous Earth system perturbations. Here, we develop a multiproxy cyclostratigraphy from a 31.2-m-thick Upper Valanginian to lowermost Hauterivian section of the Bersek Marl Formation in Gerecse Mountains, Hungary, comprising alternating marlstone layers of varying clay and carbonate content. The bulk carbonate d13C signal shows sustained, elevated values (up to 2.7‰) up to 19.2 m, followed by a decreasing trend upsection. Together with biostratigraphic data, this suggests that the lower part of the section was deposited during the plateau phase of the Late Valanginian Weissert Event. Spectral analyses of the multiproxy dataset, including magnetic susceptibility measurements and gamma-ray spectroscopy on the lower part of the section, led to the identification of precession, obliquity, and long and short eccentricity signals. A mean sedimentation rate of 14 m/Myr was calculated based on astronomical tuning. The cyclicity in the proxy signals reflects dilution cycles induced by the fluctuating rate of detrital runoff into the basin. This supports the idea that orbitally forced humid-arid cycles controlled the pelagic alternating sedimentation during the Early Cretaceous throughout the Tethyan area.

1. Introduction

The Cretaceous period is well known for oceanic anoxic events (OAEs) and carbon isotope excursions (CIEs), which have been linked to the volcanism of large igneous provinces (Erba, 2004; Jenkyns, 2010). The OAEs are episodes of increased organic carbon burial in sediments driven primarily by climate warming (Schlanger and Jenkyns, 1976). The CIEs often accompany the OAEs, but they may also occur independently, with no correlated organic rich deposits (Westermann et al., 2010; Föllmi, 2012). The Late Valanginian Weissert Event is the first positive CIE of the Cretaceous (Weissert et al., 1998; Erba et al., 2004;Weissert and Erba, 2004; Föllmi, 2012). As organic-rich deposits are not a characteristic of this carbon isotope excursion, it is best described as a stand-alone CIE rather than an OAE (Westermann et al., 2010; Kujau et al., 2012). The Weissert Event is notably associated with a widely distributed decline in carbonate production in neritic regions (Weissert et al., 1998; Föllmi et al., 2006), increases in atmospheric pCO2 (Morales, 2013), more humid climate conditions and intensified continental weathering (Duchamp-Alphonse et al., 2011; Kujau et al., 2013; Charbonnier et al., 2016), increases in nutrient availability in marine environments (Duchamp-Alphonse et al., 2007, 2014; Mattioli et al., 2014), and major turnover events in marine faunas (Reboulet and Atrops, 1997; Melinte and Mutterlose, 2001; Gréselle et al., 2011; Barbarin et al., 2012). Numerous studies have shown the global extent of the CIE which was first observed in deep-sea sediment cores from the Southeastern Gulf of Mexico (Cotillon and Rio, 1984), then subsequently observed in Italy (Lini et al., 1992; Channell et al., 1993; Bersezio et al., 2002; Erba et al., 2004; Sprovieri et al., 2006; Amodio et al., 2008), in the Vocontian Trough in Southern France (Hennig et al., 1999; van de Schootbrugge et al., 2000; Duchamp-Alphonse et al., 2007; Greselle et al., 2011; Charbonnier et al., 2013), in the Polish Basin (Morales et al., 2015), in the Southern Carpathians in Romania (Barbu and Melinte-Dobrinescu, 2008; Gradinaru et al., 2016), in Greenland (Moller et al., 2015), in the Neuquén Basin in Argentina (Aguirre-Urreta et al., 2008), in Northeastern Mexico (Adatte et al.,2001), in Western Siberia (Price and Mutterlose, 2004), and in various deep-sea sediment cores (Katz et al., 2005; Tremolada et al., 2006; Littler et al., 2011). Continental records for the Weissert Event are also known from the Crimea and Russia (Grocke et al., 2005;Nunn et al., 2010). In Hungary, the CIE has been documented in the Harskút section in the Bakony Mountains (Főzy et al., 2010),where the bulk rock d13C curve reported in Főzy et al. (2010) on Biancone-type carbonates shows a positive shift that is characterised by a sharp rise and a possibly suppressed plateau phase due to sedimentary condensation. The age of the Weissert Event and its relationship to the magmatism of a large igneous province has been subject to debate (Erba, 2004; Erba et al., 2004; Sprovieri et al.,2006; Jenkyns, 2010; Thiede and Vasconcelos, 2010; Martinez et al., 2013), in part due to significant uncertainties in the calibrated age of the Early Cretaceous stage boundaries (Hinnov and Ogg, 2007; Ogg et al., 2016). A recently obtained U-Pb age of amid-Hauterivian tuff layer in the Neuquén Basin, Argentina(Aguirre-Urreta et al., 2015), anchored the astrochronology of the Valanginian -Hauterivian stages (Martinez et al., 2013, 2015) and led to a revision of the age of onset of the Weissert Event, now dated at 135.22 ± 1.0 Ma. This age is undistinguishable from the most precise ages calculated for the flood-basalt activity of the Parana-Etendeka large igneous province (Thiede and Vasconcelos,2010; Janasi et al., 2011), suggesting a link between the two events (Martinez et al., 2015).This study focuses on the Bersek Marl Formation in Hungary that has an almost 150-year-old history of research. It was first described by Hantken (1868), who assigned an Early Cretaceous age to the marlstones of the Gerecse Mountains. Ninety years later, Fülop (1958) provided a thorough bio- and lithostratigraphic description of these deposits. Recently, a more detailed integrated biostratigraphy for the Bersek Quarry, established by Főzy (1995), Főzy and Fogarasi (2002), and Főzy and Janssen (2009), determined a Valanginian-Hauterivian age for the upper part of the formation. The first estimate of the average sedimentation rate of the Bersek Marl Formation is based on the assessed thickness of the formation and the estimated duration of deposition based on ammonoid stratigraphy (Fogarasi, 1995b). Given an assumed average sedimentation rate of 10 m/Myr, Fogarasi (1995b) posited that the deposition of marlstone-limestone couplets in the uppermost part of the Bersek Marl Formation and the lowermost part of the overlying Labatlan Sandstone Formation were controlled by precession cycles. Here, the sedimentary record of the Weissert Event is investigated at the Bersek Marl Formation to produce the first record of this Early Cretaceous CIE at this locality and within this basin. The first objective was to compile a d13C record for the upper part of the Bersek Marl Formation in order to identify whether the Weissert Event is entirely or partially recorded within this section. The second objective was to accurately estimate the sedimentary deposition rate by integrating cyclostratigraphic analysis on bulk rock d13C,magnetic susceptibility, and gamma-ray spectroscopy measurements. New calcareous nannoplankton and ammonoid biostratigraphic analyses were also conducted to improve the age constraint.

2. Geological setting

2.1. Tectonic and stratigraphic framework

The studied outcrop is situated in one of the abandoned yards of the Bersek Quarry, close to the village of Labatlan within the Gerecse Mountains (Fig. 1AeB). The GPS coordinates of the studied section are: 47.72145N and 18.52630E. The Gerecse Mountains form part of the Transdanubian Range, which in turn belongs the ALCAPA Terrane. During the Alpine orogeny, the Transdanubian Range was interlinked with the geological formations that now form part of the Southern Alps and the Northern Calcareous Alps(Fig. 1C). The Jurassic and Cretaceous strata of the Gerecse Mountains were deposited during the evolution of a Neotethys sub-basin, starting in the Late Triassic. The Late Jurassic pelagic carbonates sedimentation changed in the Berriasian, when the thrust front advanced towards the foreland, and clastic input became the dominant factor. This change marks the formation boundary between the Szentivanhegy Limestone Formation and the overlying Bersek Marl Formation. The clastic input further increased in the Barremian sediments, as inferred from a change in lithology from marlstone to sandstone, marking the base of the Labatlan Sandstone Formation (Főzy, 2013).The 31.2-m thick section studied lies entirely within the Bersek Marl Formation. The base of the studied section starts at the bottom of the quarry face in this yard and the underlying strata could subsequently not be sampled. This prevented the unambiguous correlation with other quarry yards that expose deeper strata. As a hiatus separates the top of the Bersek Marl Formation and the base of the overlying Labatlan Sandstone Formation, we decided to limit the top of the studied interval at the top of the Bersek Marl Formation(Fig. 1D). The section studied comprises marlstone layers with fluctuating carbonate content, limestone beds, and sporadic, thin sandstone intercalations. The colour of the marlstone transitions from grey to purple at 27.8 m, dividing the section into two informal units, which we will henceforth refer to as the “grey marlstone” and the “purple marlstone”. In the “grey marlstone ”unit of the Bersek Marl Formation, the bed thicknesses range from a few centimetres to a few decimetres, but the lithological contrast between beds is low, making challenging to recognise the bed boundaries in the field. The bedding of the “purple marlstone” is more apparent due to the higher lithological contrast. The bed thicknesses in this unit are around 0.2e0.3 m. Centimetre-thick green turbidite beds, synsedimentary faults and slumps only occur in the “grey marlstone”. Throughout the Bersek Quarry, the base of the overlying Labatlan Sandstone Formation is marked by a few metre-thick, green sandstone beds with an erosive base, that serve as a stratigraphical marker (hereafter referred to as the “greenarker bed”). A detailed stratigraphical column is provided as supplementary material. To date, three different stratigraphic sections have been logged and studied in detail at the Bersek Quarry (Fig. 1B). The cephalopod specimens and sediment samples, used for the studies by Főzy and Fogarasi (2002), Főzy and Janssen (2009), and Price et al. (2011), were collected from Section III of Fig. 1B by a team led by J. Fülop between 1963 and 65. The section studied by Főzy (1995), referred to as Section II in Fig. 1B, lies ~150meastwards from Section III, in a different quarry yard. Fogarasi (1995b) investigated sections practically identical to Section II and Section III. The section studied in this paper is labelled as Section I in Fig. 1B, and is located adjacent to Section II, in the same quarry yard but in a newly sampled segment of the quarry face. Ammonoid and calcareous nannoplankton biostratigraphy have been previously developed for the uppermost strata of the Bersek Marl Formation and the lowermost part of the succeeding Labatlan Sandstone Formation (Fozy,1995; Főzy and Fogarasi, 2002; Főzy and Janssen, 2009). The rich cephalopod fauna of the “purple marlstone” and the Labatlan Sandstone Formation allows the recognition of Mediterranean ammonoid zones, whilst macrofossils are scarcer in the underlying “grey marlstone”. The youngest strata of the Labatlan Sandstone Formation, immediately overlying the thick “greenmarker bed”, are earliest Barremian in age (Főzy, 1995; Főzy and Fogarasi, 2002; Főzy and Janssen, 2009). In Section III, the uppermost boundary of the oldest recognised ammonoid zone, theValanginian Varlheideites peregrinus Zone, is detected approximately12 m below the “green marker bed”. In the same section the youngest recognised ammonoid zones below the “green marker bed” are the Upper Hauterivian Pseudothurmannia ohmi and Balearites baelaris Zones. The calcareous nannoplankton assemblages of the same collection led to the recognition of the NK3/NC4 and possibly of the NC4/NC5 Zone boundaries below the base of the Labatlan Sandstone Formation (Főzy and Fogarasi, 2002; Főzy and Janssen, 2009). In Section II, studied by Főzy (1995), the characteristic Hauterivian ammonoid fauna is not present, suggesting a LateValanginian-Early Hauterivian age for the uppermost strata of this section, directly under the base of the “green marker bed”. Fig. 1. (A) Location of the Bersek Quarry section on a generalized map of structural units in Hungary (after Haas, 2012). (B) Satellite aerial view of the Bersek Quarry (Google Earthimage captured in 2014). The section studied in this paper is marked with “I”. Section “II” was studied by Fozy (1995) and Fogarasi (1995b). Section “III” was studied by Fozy andFogarasi (2002), Fozy and Janssen (2009), and Price et al. (2011). (C) Palaeogeographic reconstruction of the Western Tethys area during the Jurassic/Cretaceous transition (after Csontos and Vörös, 2004). SA e Southern Alps, LAA e Lower Austroalpine Nappes, MAA e Middle Austroalpine Nappes, TI e Tirolic Nappes (part of the Northern Calcareous Alps).(D) Photograph of the studied section. The boundary between the Labatlan Sandstone Formation and the Bersek Marl Formation is marked by the erosive “green marker bed”. The Bersek Marl Formation is divided into two informal units based on the colour of the marlstone: the “grey marlstone” and the overlying “purple marlstone”.The oldest strata of the Bersek Marl Formation belong tothe Felsovadacs Breccia Member. The oldest marlstone layers overlaying this unit are posited to be latest Berriasian/earliestValanginian in age, based on ammonite (Vigh, 1984) and nannoplankton(Fogarasi, 2001) biostratigraphy. These strata do not crop out at the Bersek Quarry, but are visible in other sections.

2.2. Palaeogeographic setting

Interpretation of the sedimentary environment of the Bersek Marl Formation has been controversial. It has been successively regarded as a shallow marine deposit (Fülop, 1958), flysch (Csaszarand Haas,1984), a bathial slope deposit (Kazmer, 1987), or as part of a submarine fan sequence (Sztano, 1990). Fogarasi (1995a) noted that the total thickness and the sedimentation rate of the marlstone is smaller than would be expected for a submarine fan deposit and instead suggested a pelitic slope environment. According to the most recent study of Fodor et al. (2013), the Bersek Marl Formation was deposited on a forebulge, a slope facing the foreland basin, on the opposite side of the orogenic arc. It has been suggested that the difference in lithology between the “grey marlstone” and the “purple marlstone” is controlled by the basin evolution, where the deposition of “purple marlstone” could reflect an interval of subdued tectonic activity in an otherwise actively forming flexural basin (Fodor et al., 2013). The colour of the “grey marlstone” and the occurrence of small, charred plant fragments suggests suboxic bottom waters, while the reddish colour of the “purple marlstone”and the Zoophycos-type trace fossils could imply a transition to amore oxygenated environment (Fodor et al., 2013). Petrographicstudies of Csaszar and Argyelan (1994) and Argyelan (1995) identifiedthe source of distinctive heavy minerals in the turbidite bedsas the suture zone of the Neotethys. Coeval sandstone beds, in thecorresponding units in the Northern Calcareous Alps, the Schrambachand the Rossfeld Formations, have similar compositions (von Eynatten and Gaupp, 1999; Krische et al., 2013).

3. Material and methods

Fieldwork was carried out between April 2014 and August 2015, when the continuous 31.2-m thick Section I of Fig. 1B was measured and logged at the Bersek Quarry. A total of 241 bulk rock samples were collected with a uniform 0.1-m spacing in the lower16.8 m (169 samples) and with a 0.2-m spacing in the upper 14.4 m (72 samples). The samples were cut with a diamond saw blade with low revolution speed, washed with tap water to remove the weathered surfaces, and split into ~15 g subsamples that were later processed for analyses. To avoid metallic contamination that could bias the magnetic susceptibility measurements, the sample collection was done by hand, and the samples were stored in plastic bags. Bulk rock samples are deposited in the Department of Palaeontology and Geology of the Hungarian Natural History Museum, Budapest, under inventory numbers INV 2016.215.1e241.

3.1. Stable isotope analyses

The bulk rock carbonate carbon and oxygen stable isotope analyses were performed at the University of Plymouth, on a GV Instruments IsoPrime IRMS using a Gilson 222XL autosampler. For the measurements, ~0.5 mg powder was drilled from each of the 241 bulk rock samples. Isotope ratios are reported in d values relative to the Vienna Pee Dee belemnite (VPDB) standard. For the instrument calibration, the NBS-19, the IAEA-CO-8, and the IAEACO-9 standards were used. Upon replicate analyses, the standard deviation was calculated as 0.2‰ for d13C and 0.3‰ for d18O.

3.2. Magnetic susceptibility measurements

The magnetic susceptibility (MS) measurements were conducted at the Université de Pau et des Pays de l'Adour on an Agico Kappabridge MFK1-FA type instrument, with a 976 Hz 200 A/m field strength. A set of 169 samples, from the bottom 16.8 m of thesection, was analysed. Each sample was measured in triplicate toassess the reproducibility of the measurements. The results are given in m3/kg (mass susceptibility). The standard deviation of the measurements is 8 103 m3/kg.

3.3. Gamma-ray spectroscopy

The gamma-ray spectroscopy (GRS) measurements were conducted in the field using a hand-held Georadis RS-125 gamma-ray spectrometer. The instrument was fitted with a 103 cm3 Na(Ti) scintillation detector with a 0.06 m diameter detector head. The lower 16.8 m of the section were analysed, except for the lowermost three sampling spots that were covered with soil. The measurements were done on the same spots where the bulk rock samples were collected from, and each spot was analysed three times for a measurement time of 120 s. The total 40K, 238U, and 232Th content of the rocks are reported in uranium-equivalent ppm. The standard deviation was derived from 26 test measurements on one single spot, and it was calculated as 0.9 Ue ppm.

3.4. Time series analyses for cyclostratigraphy

Cyclostratigraphic analyses were made on bulk carbonate d13C, magnetic susceptibility, and gamma-ray spectroscopy signals. Prior to spectral analysis, the raw data series were linearly interpolated every 0.1 m and long-term trends were removed. The detrending procedures applied here aim at reducing the power of the lowest frequencies towards zero whilst maintaining the powers of higher frequencies. The trends were removed from the d13C, the MS, and the GRS data series by subtracting a 3rd-order polynomial regression, a 5th-order polynomial regression, and a linear regression, respectively. The spectrum of the whole series was calculated using the multitaper method applied with three 2p-tapers (2p-MTM;Thomson, 1982, 1990). Confidence levels were calculated using robust red-noise modelling, modified according to Tukey's endpoint rule (Tukey, 1977; Mann and Lees, 1996; Meyers, 2014). In addition to the power spectra, two evolutive spectrograms were generated per dataset using Time-Frequency Fast Fourier Transform(TeF FFT).

Firstly, for longer periodicities, an 8-m sliding window and a 0.1-m window step were applied to the completed trended series. Secondly, for shorter periodicities, a 4-m slidingwindow and a 0.1-m window step were applied after a second lowpassfilter was subtracted from the detrended series to exclude low frequency, high-power cyclicities. The power spectra and the evolutive spectra are then interpreted together. Variations in the sedimentation rate can result in one Milankovitch-cycle being expressed over several frequencies on the 2p-MTM spectra of the sedimentary series (e.g., Weedon, 2003; Martinez et al., 2016). Changes in the sedimentation rate can be recognised in the evolutive spectra by the deviation of the spectral bands, assigned to the cyclicity in question (Martinez et al., 2015). To isolate certain frequencies from the rest of the series, Taner band-pass filters were applied (Taner, 2003; Meyers, 2014).

3.5. Calcareous nannoplankton

Study of the calcareous nannoplankton assemblages was not intended to be comprehensive and was therefore restricted to 12samples. Successive highly calcareous and highly clay-rich marlstones from both the "grey marlstone" (samples BQ53eBQ56) and the "purple marlstone" (samples BB48eBB51) were targeted, which corresponded with alternating cycles of peak and minimum carbonate content. Another four samples were studied in order to help define the suspected Valanginian-Hauterivian stage boundary (samples BB 1e4). Standard smear slide preparation followed the conventional technique described by Bown (1998). The slides were studied at 1000 magnification under cross-polarized light using an Olympus BX51 microscope with an oil immersion objective. For each sample, 40 fields of view were scanned and the number of complete, non-fragmented coccoliths counted to quantify total nannoplankton abundance (Table 1).

3.6. Ammonoids

During the fieldwork in 2014 and 2015, no systematic fossil collection was performed, but several ammonoid specimens were collected both ex situ and in situ from Section I. The biostratigraphic subdivision of Section II is based on a small-scale but systematic ammonoid collection, which yielded about two dozen ammonoids below the "green marker bed" (Főzy, 1995). The cephalopod fauna of Sections I and II is comparable with the fauna of the lower part of Section III, more specifically with Section C of Főzy and Janssen(2009). This section comprises beds labelled from 200 to 258, and yielded 1660 fossil cephalopod specimens, collected bed-by-bed, which served as a solid foundation for biostratigraphy. Undoubtedly, this fauna originates from below the "green marker bed" (Fig. 2 in Főzy and Janssen, 2009); however, due to the lack of detailed documentation of the collection, its precise position remains uncertain.

3.7. X-ray fluorescence measurements

X-ray fluorescence (XRF) measurements were made on a suite of8 samples to estimate the carbonate content of beds with different lithologies. A total of 20 elements was analysed with a Thermo Scientific Niton XL3t 900 GOLDDþ portable XRF analyser, equippedwith a 50 kV X-ray tube and a silver target anode, at the Research Centre for Natural Sciences, Hungarian Academy of Sciences, Budapest. For quantitative analysis, the standard less fundamental parameters method was used with Compton-normalization. For data evaluation, Excel and Statistical 12 software was used. TheCaCO3 content was calculated from the XRF data by multiplying theCaXRF content, given in weight percent, by 2.5. The standard error of the CaXRF measurements is lower than 0.2 wt%.

4. Results

4.1. Stable isotope analyses

At the Bersek Quarry section, the bulk carbonate d13CVPDB values range from 0.2‰ to 3.6‰, with an average of 2.6‰ (Fig. 2). The isotope curve can be divided into two parts on the basis of long term trends. From 0 m to 19.2 m above the base of the section, the curve is stable with no long-term trend, with values oscillating between 1.6‰ and 3.6‰ and an average value of 2.7‰. The second part of the curve, starting from 19.4 m above the base, displays a decreasing trend, with values dropping to a range between 2.8‰and 0.2‰.
The bulk carbonate d18OVPDB values vary between 5.6‰and 1.3‰, with an average of 2.7‰ (Fig. 2). The curve shows a slight trend towards increasing values. These negative values are depleted compared to unaltered marine calcite (van deSchootbrugge et al., 2000). The slight covariance of d13C and d18O values suggests some degree of diagenetic overprint. As the oxygen isotopes are generally more prone to alteration than the carbon isotope values (Sprovieri et al., 2006), we interpret only the latter in the following discussion.

4.2. Magnetic susceptibility measurements

The magnetic susceptibility values fall between 6.266 108 m3/kg and 125.01 106 m3/kg, with an average of 44.781 108 m3/kg (Fig. 2). Three samples (BQ4, BQ17, and BQ37) show values over 160 108 m3/kg and are considered as outliers as they contain sand grains originating from nearby turbidite beds, disturbing the information from the pelagic chronic sedimentation. Three minima can be found at 3 m, 10 m, and 14.5 m. No distinctive long-term drift can be observed in the magnetic susceptibility values.

4.3. Gamma-ray spectroscopy

The gamma-ray spectroscopy values fall between 27.5 Ue ppm and 46.8 Ue ppm (Fig. 2). As the organic matter content does not change significantly in the studied section and the turbidite beds are too rare and thin to considerably change the measured values, the gamma-ray values produced here are considered to reflect the changes in the detrital vs. carbonate contribution in the sediment. The minima of the gamma-ray spectroscopy curve are located at the same stratigraphic levels as those in the magnetic susceptibility curve. The gamma-ray spectroscopy curve shows a long-term trend toward slightly decreasing values.

4.4. Time series analyses for cyclostratigraphy

The power spectrum of the magnetic susceptibility signal shows spectral peaks over the 99% confidence level (CL) with periods of 5.12 m and 0.23 m, and over the 95% CL with periods of 1.60 m and0.28m(Fig. 3A). Other peaks exceed the 90% CL with periods of 0.56 and 0.40 m, but do not reach the 95% CL. As they are observed in the other proxies and in the evolutive spectral analyses, these peaks will be discussed in the following sections of the manuscript. In the spectrogram focussing on the low frequencies (Fig. 4H), the peak centred on 5.12m is detected throughout the series with the highest spectral power around 12 m above the base of the section. This band first increases from 3.8 m to 7.9 m, from the base of the section to 6 m above the base, and then decreases to ~5 m, towards

Table 1

Calcium carbonate content and total nannoplankton abundance of selected samplescollected from the “grey marlstone” and the “purple marlstone” units. Sample Level (m) Unit CaCO3 (wt%) NannoplanktonAbundance

Fig. 2. Bulk carbonate d13C, d18O, gamma-ray spectroscopy (GRS), and magnetic susceptibility (MS) signals measured at the Bersek Quarry. The thick lines below each signal denote the long-term trend. The inset shows the correlation between the d13C and d18O values, divided into two sets based on the trend in the d13C signal: plateau phase (0e18.2 m, circles) and slow decrease (18.3e31.2 m, squares). The asterisk marks the end of the plateau phase of the Weissert Event.

15 m above the base. In the spectrogram focussing on the high frequencies (Fig. 4I), the peak centred on 1.60 m first shows a bifurcation to two periods at 1.6 m and 0.9 m, from the base of thesection to 5 m above the base. After an interval from 5 m to 7 m above the base of the section, the band appears again from 7 m to 13 m above the base, with a period evolving from 1.3 m to 1.9 m. In the upper part of the section, the expression of this band is observed with a period of 0.9 m. The peaks of periods 0.23 m and 0.28 m appear from 4 m to 13 m above the base of the section. Another band of periods is observed with periods ranging from0.4 m to 0.6 m at 5 m, 13 m and 16 m above the base of the series. The power spectrum of the gamma-ray spectroscopy signal shows peaks over the 99% CL with periods of 5.12 m and 0.81 m(Fig. 3B). A peak with a period of 0.57 m reaches the 95% CL. Another peak is observed with a period of 1.60 m over the 90% CL.Although this peak does not reach the 95% CL, we will discuss the expression of this peak on the spectrograms. No significant peak with periods shorter than 0.3 m can be recognised because,

Fig. 3. 2p-MTM power spectra of the magnetic susceptibility (A), gamma-ray spectroscopy (B), and the bulk carbonate d13C (C) signals. The peaks are interpreted as the 405 kyr “long” eccentricity, the 100-kyr “short” eccentricity, the obliquity, and the precession cycles. The indicated values denote the periods of the main significant peaks in metres. The width of the filters used to separate the long eccentricity is as follows: 0e0.3516 for the magnetic susceptibility, 0e0.3906 for the gamma-ray spectroscopy, and 0e0.2930 cycles/m for the d13C signal. The width of the filters used to separate the short eccentricity is as follows: 0.5078e1.3672 cycles/m for the magnetic susceptibility and for the gamma-ray spectroscopy signals, and 0.3529e1.5294 cycles/m for the d13C signal. 2p-MTM power spectra of the tuned magnetic susceptibility (D), gamma-ray spectroscopy (E) and the bulk carbonate d13C (F) signals.

Fig. 4. Detrended signals of the d13C (A), gamma ray spectroscopy (D), and magnetic susceptibility (G) measurements, and the corresponding filtered long eccentricity filter output signals. The first spectrograms of each signal (B, E, H)focuses on the low frequencies, while the second spectrograms (C, F, I) represent the whole spectrum. The second spectrogram is filtered, thus the frequencies of the respective first spectrograms are not represented. The inset shows the short eccentricity signals filtered form the magnetic susceptibility (J), gamma-ray spectroscopy (K), and the d13C signals (L). The 12 dotted lines indicate the age model used for the tuning. The width of the Taner-filters is shown on Fig. 3.

irrespective of the 0.1 m sample step, the measurements cannot be regarded pointwise. Due to its size, the detector collects 95% of the signal from a 0.3 m radius which smoothens the short-term signal and increases the effective Nyquist-frequency of the GRS signal. In the spectrogram focussing on the low frequencies (Fig. 4E), the cyclicity band centred on 5.12 m is observed throughout the series with high spectral power. Its period increases from 4.8 m to 7.0 from the base of the section to 7 m above the base, and then decreases to 3.0 m towards 16 m above the base. In the spectrogram focussing on the high frequencies (Fig. 4F), the cyclicity band centred on 1.60 is apparent throughout the section, with periods ranging from 2.0 m to 0.9 m. The band centred on 0.57 m appears from 2.5 m to 6.5 m above the base of the section. The power spectrum of the d13C signal shows cyclicities over the99% CL with periods of 0.59 m, 0.32 m, and 0.21 m, and peaks over the 95% CL with periods of 5.23 m, 1.96 m, 0.74 m and 0.29 m(Fig. 3C). In the spectrogram focused on low frequencies (Fig. 4B),the cyclicity band centred on 5.23 m is observed with high amplitudes from the base of the section to 9 m above the base, and from18 m above the base to the top of the section. From 10 m to 18 above the base of the section, this band has much lower amplitudes. Its period varies between 5.7 m ad 5.1 m. On the spectrogram focused on the high frequencies (Fig 4C), the band centred on1.96mis observed from the base of the section to 3mwith a period of 1.8 m. It appears transiently around 14 m and 19 m above the base of the section, with periods of 1.7 m and 2.2 m, respectively. It then appears as a continuous band from 23 m to the top of the series. The band with periods ranging from 0.74 m to 0.58 m first appears around 6 m above the base of the section with a period of0.8 m. It is then observed from 8 m to 12 m above the base of the section with two periods of 0.8 m and 0.6 m. It reaches the highest amplitudes from 15 m to 27 m above the base of the section. In this interval, this band has periods decreasing from 0.8 m to 0.6 m. It is then expressed from 28 m above the base to the top of the section with a period of 0.9 m. The band of periods ranging from 0.32 m to0.29 m appears between 8 m and 12 m above the base of the section. The peak centred on 0.43 m is observed with low amplitudes around 3 m and 18 m above the base of the section. Comparing the power spectra with the spectrograms of the three signals distinguishes three periodicity bands. The most prominent periodicity in all three signals appears in the spectrograms focussing on the high frequencies with a mean period of~5 m. The peaks at 1.60mand 1.96mform the next band of periods,
with a mean period of ~1.7 m. The peaks ranging from 0.95 m to0.43 mare only apparent in the GRS and the d13C signals and have a mean period of ~0.6 m. The peaks ranging from 0.32mto 0.21mare
only apparent in the magnetic susceptibility and the d13C signals and has a mean period of ~0.3 m.

4.5. Calcareous nannoplankton

Nannoplankton in the studied samples have low abundance and medium to poor preservation. Reworking appears negligible despite the presence of fragmentary specimens. Diagenetic overprint, not uncommon for Cretaceous assemblages of a similar old age, is manifest in partial dissolution of specimens. The predominant taxa belong to the cosmopolitan genera Watznaueria and Nannoconus which are also abundant in other Tethyan localities (e.g., Duchamp-Alphonse et al., 2007). For nannofossil-based biostratigraphic assignment and recognition of marker taxa, the zonal scheme of Bown (1998) was used. The presence of marker taxa and recognized first and last appearance datum (FAD and LAD) events allow recognition of nannoplankton zones NK3-NC4 throughout the studied section, whereas diagnostic species of the younger NC4-NC5 Zones are absent. Key marker species whose presence proves the NK3 and NC4 Zones are Calcicalathina oblongata (occurring in all samples) and Cruciellipsis cuvillieri. Subzone-level subdivision within the zones NK3 and NC4 is not possible as it would require recognition of marker taxa Eiffellithus windii, Rucinolithus wisei and Eiffellithus striatus, none ofwhich have been identified within Section I. Another notable absence is that of Tubodiscus verenae, the marker species used elsewhere to determine the boundary between nnnoplankton zones NK3 andNC4. Thus, the combined use of NK3-NC4 Zones is recommended, suggesting thatthe most likely chronostratigraphic assignment of Section I is the upper Valanginian, possibly ranging into the lower Hauterivian.

4.6. Ammonoids

As Section I, the focus of this study, and Section II (Főzy, 1995)are situated close to each other in the same quarry yard, it is not surprising that they represent very similar stratigraphic ranges for the “grey marlstone” and “purple marlstone” strata below the “green marker bed”. These ranges include the Upper Valanginian, and possibly extend into the lowermost Hauterivian. Some of the most diagnostic ammonoids of these sections are illustrated in Fig. 5. However, Section III (Főzy and Janssen, 2009) is more complete below the “green marker bed” and represents, at least partially, most of the higher Hauterivian ammonoid zones, including the Crioceratites loryi, Subsaynella sayni, Plesiospitidiscusligatus, Balearites balearis, and Pseudothurmannia ohmi Zones.

Fig. 5. Representative ammonoids collected from Section I (this study) and Section II(Fozy, 2005). Figured specimens are deposited in the Department of Palaeontology andGeology of the Hungarian Natural History Museum, Budapest, with inventory numbersprefixed by “INV”. (A) Neocomites neocomiensis; INV. 2016.192; Section I, 14.9 m. (B)Lytoceras sp.; INV. 2016.193; Section I, ex situ. (C) Olcostephanus sp.; INV. 2016.194; Section I, 1.7 m. (D, E) Jeanthieuloyites sp.; INV. 2016.195); Section I, ex situ. (F) Phyllopachyceras winkleri; INV. 2016.196; Section I, 5.0 m. (G) Oosterella sp.; INV. 2016.197;Section I, ex situ. (H, I) Neocomites sp.; INV. 2016.198); Section II, Bed 26. (J) Neolissocerasgrasianum; INV. 2016.199; Section II, Bed 26. (K) Olcostephanus densicostatus;(INV. 2016.200), Section II, Bed 27. (L) Teschenites callidiscus; INV. 2016.201; Section II,ex situ. (M) Teschenites subflucticulus; INV. 2016.202; Section II, Bed 26. (N) Jeanthieuloyites cf. quinquestriatus; INV. 2016.203; Section II, Bed 16. (O) Jeanthieuloyites cf.quinquestriatus; INV. 2016.204; Section II, Bed 28.

4.7. X-ray fluorescence measurements

Elemental geochemistry measurements were conducted primarily to determine the carbonate content of the marlstone and its relationship to the lithology and the nannoplankton abundance(Table 1). The carbonate content of the beds in the “grey marlstone “is quite consistent, fluctuating around 65%. On the contrary, in the “purple marlstone” the contrast between the strata is more pronounced, changing from around 40% in the clay-rich beds to as high as 90% in the calcareous beds. In both units, the carbonate content and the total nannoplankton abundance show a strong positive correlation (R2 ¼ 0.99).

5. Discussion

5.1. Biostratigraphy

The ammonoid fauna at the Bersek Quarry has a clear Mediterranean affinity that can be compared with the well-documented cephalopod assemblages of sections in the Vocontian Trough and the Provence Platform in France (Reboulet, 1995), the Betic Cordillera in Spain (Company et al., 2003), and the Northern Calcareous Alps in Austria (Lukeneder, 2005). In Sections I, II and III,long-ranging phylloceratids and lytoceratids are the most commonforms, but these do not allow a precise biostratigraphic subdivision. However, in Sections I and II, the occurrence of Oosterella and largelcostephanids (e.g., Olcostephanus densicostatus) is diagnostic and indicates a Late Valanginian to earliest Hauterivian age. The neocomitids in these sections (e.g., Neocomites neocomiensis, Teschenitessubflucticulus and Teschenites callidiscus) are also assigned to the Valanginian. T. callidiscus, found only in an ex situ block, is the index form of the uppermost Valanginian T. callidiscus Zone of Reboulet(1995), the equivalent of the T. callidiscus Subzone of the Criosarasinellafurcillata Zon in Reboulet et al. (2014). Section III,described in detail in Fozy and Janssen (2009), is more biostratigraphically complete. Most of the Hauterivian ammonoid zones were, at least partially, documented from the sequence of marlstone below the “green marker bed” (Fozy and Janssen, 2009).In the lower part of Section III, the common appearance of the large- and small-sized olcostephanids (Olcostephanus densicostatus and Olcostephanus nicklesi) is diagnostic. The middle and upper part of this section is characterized by the abundance of crioceratids(including Crioceratites nolani and Crioceratites duvali). The genera Abrytusites and Plesiospitidiscus appear in the upper part of Section III. Also important is the occurrence of some rare, but stratigraphically important taxa, such as Olcostephanus jeannoti, Subsaynellasayni, and Subsaynella mimica, Euptychoceras meyrati and Pseudothurmannia ohmi. The bloom of the representatives of the family Holcodiscidae,characterised by a smooth band on the ventrolateral region (e.g. Jeanthieuloyites spp.), is a unique feature of the Bersek fauna and was observed in all three sections. Such an abundance of the Spitidiscus-related species is unknown from the classical Upper Valanginian sections in France (Reboulet, 1995), but were reported by Avram (1995) from the Carpathians. The comparison of the ammonoid faunas of the three Bersek Quarry sections reveals that Section I and II are Late Valanginian or Late Valanginian to earliest Hauterivian in age, whereas Section III also includes younger strata up to the Upper Hauterivian strata. This difference can be explained by the submarine erosion during deposition of the “green marker bed”, that removed the unconsolidated Middle to Upper Hauterivian layers of sediment from Sections I and II.A crucial issue is the lack of Acanthodiscus radiatus, the zonal index of the lowermost Hauterivian Acanthodiscus radiatus Zone, which appears mainly in the successions of platform deposits in southeast France (e.g., Reboulet, 1995). This species is missing from the deeper water fauna recovered at the Bersek Quarry. Nevertheless, the Valanginian/Hauterivian boundary can be drawn in Section III. The coeval first appearance of the genus Saynella (represented by a big, smooth specimen) and Olcostephanus hispanicus, together with the bloom of the genus Crioceratites, suggests that the boundary can be placed between Bed 236 and Bed 237 (Főzy and Janssen, 2009). These ammonoids were absent in Section I and II, where fewer total fossils were collected. Therefore, the Valanginian/Hauterivian boundary cannot be confidently drawn in these sections, but the possibility of its presence cannot be excluded. Our nannoplankton biostratigraphic results are in good agreement with those drawn from the ammonoids and concur with the conclusions of previous studies by Fogarasi (1995b, 2001) and Fozyand Fogarasi (2002), which were based on significantly larger sampling (130 smear slides) and documented the presence of 63nannofossil taxa from Section III. These earlier semi-quantitative analyses also observed the dominance of common Tethyan forms such as C. oblongata, Nannoconus sp. and W. barnesiae. Although many Tethyan marker species were reported and permit biostratigraphic assignment from the NK3 Zone upwards, two key taxa for defining zone and subzone boundaries, T. verenae andLithraphidites bollii, have not been reliably recorded (Főzy and Fogarasi, 2002). However, in Section III, Fogarasi (2001) documented the successive LADs of two marker species that range though Section I in our samples, C. cuvillieri and C. oblongata, thus establishing that deposition of the Bersek Marl Formation continued into nannoplankton zone NC5, and the “green marker bed” is best assigned to the NC5b-c Subzones. Thus, the nannoplankton biostratigraphic evidence also suggest that the base of the “green marker bed” is erosive and the topmost “purple marlstone ”layers are highly diachronous between sections I and III, being not younger than earliest Hauterivian in the former, and as young as Late Hauterivian in the latter.

5.2. Recognition of the Weissert Event

The shape of the bulk carbonate d13C curves during the Weissert Event is similar across most of the previously reported sections (Price et al., 2016). At the Early-Late Valanginian transition, the d13C values rise steeply to values that are approximately 1e2‰higher than before the onset. After this increase, a plateau phase of elevated d13C values is observed, that is followed by a slow and gradual decline. During the Valanginian and Hauterivian, the plateau of the Weissert Event is the only interval where the d13Cvalues stabilise at high values (Price et al., 2016).The d13C curve of the Bersek Quarry shows elevated values around 2.7‰until an inflexion point at 19.2mabove the base of the section. From there on, the values are gently decreasing. The good preservation of the orbital cyclicities supports the primary origin of the high values and the overall trends (see also discussion in Pellenard et al., 2014). Therefore, based on the inferred latest Valanginian/ earliest Hauterivian age of the Bersek Quarry section, it is reasonable to interpret the inflexion in the bulk carbonate d13Ccurve as marking the termination of the plateau phase of the Weissert Event.

5.3. Astronomically forced cyclic changes in the record

The ratio of the observed three key periodicities to each other (5.1:1.7:0.6:0.2e0.3) is broadly similar to the ratio of the mean long eccentricity, short eccentricity, obliquity, and precession periods (405:100:36.6:21), according to the La2004 model (Laskar et al.,2004). Therefore, the recognised ~5 m, ~1.7 m, ~0.6 m, and~0.2e0.3 m periods are interpreted as the 405-kyr (“long”) eccentricity, the 100-kyr (“short”) eccentricity, the obliquity, and the precession cycles, respectively. To test this interpretation, the magnetic susceptibility, the gamma-ray spectroscopy signals, and the lower part of the d13C signal were calibrated using the proposed short eccentricity signal filtered from the magnetic susceptibility signal, in which 12 complete short eccentricity cycles can be counted (Fig. 4JeL). The magnetic susceptibility is used here as a reference because the high-resolution of this signal allows the detection of short periods, unlike the GRS signal, so that the evolution of the short eccentricity can be monitored throughout the series on spectrograms (Fig. 4I).In addition, the eccentricity cycles appear continuous on spectrograms of the magnetic susceptibility signal, unlike the d13C signal(Fig. 4C). However, at levels 1.6 m, 5.7 m and 10.5 m the evolutive spectrum of the MS series shows bifurcation in the short eccentricity band (Fig. 4I), so that its evolution is unclear. The power spectrum of the tuned magnetic susceptibility signal shows prominent peaks at 360 kyr, 105 kyr, and 41 kyr (Fig. 3D).These are nearly identical to the expected periods of the long eccentricity, short eccentricity, and the obliquity cycles. The other peak at 29 kyr can be a consequence of short-term variations of the sedimentation rate or a consequence of aliasing in intervals showing lower sedimentation rates. The power spectrum of the tuned gamma-ray spectroscopy signal shows prominent peaks at360 kyr, 109 kyr, and 41 kyr, that corresponds to the long eccentricity, short eccentricity, and obliquity periods, respectively(Fig. 3E). The power spectrum of the tuned d13C signal shows prominent peaks at 500 kyr, 106 kyr, and 42 kyr, reasonably representing the long eccentricity, the short eccentricity, and the obliquity periods, respectively (Fig. 3F).The amplitude modulation of the 100-kyr band filtered in the magnetic susceptibility signal was further investigated. To define the amplitude modulation of the proposed short eccentricity signal, Hilbert transform was applied to the tuned band-passed signal(Fig. 6; Meyers, 2014). The enveloping amplitude modulation signal shows maxima roughly coinciding with the maxima of the proposed long eccentricity signal filtered from the magnetic susceptibility(Fig. 6A). The main peak on the corresponding 2p-MTMpower spectrum has mean period of 418 kyr, close to the period of the 405-kyr eccentricity cycle (Fig. 6B). The main modulator of the short eccentricity signal in geological time series is the long eccentricity. The close relationship between the amplitude modulation signal of the presumed short eccentricity signal and the presumed long eccentricity signal reinforces our cyclostratigraphical interpretation.

5.4. Sedimentation rate

The average sedimentation rate at the lower part of the Bersek Quarry section is 14 m/Myr. It varies between 9 and 19 m/Myr, with maxima around 1 m, 6 m, and 13 m above the base of the section. The band-pass filter output signals corresponding to the long eccentricity signal are identified in the same phase in the gamma-ray spectroscopy and the magnetic susceptibility datasets, with maxima around 1m, 6 m, and 14mabove the base of the section (Fig. 8). These maxima almost coincide with the maxima of the sedimentation rate. The first two long eccentricity cycles in the d13C signal appear to be in antiphase compared to the magnetic susceptibility and gamma-ray spectroscopy signals, but then become in-phase with them around 15 m above the base. In this part of the section, the amplitude of the long eccentricity filter output signal is low, therefore it is likely that the shift in the phase is only apparent and does not result from palaeoenvironmental changes. The plateau phase of the Weissert Event in the Bersek Quarry section spans until 19.2 m above the base. It was shown, that the deposition of lowermost 16.8 m of the section took approximately1.25 Myr. It is regarded here as a minimum estimate for the plateau phase of the Weissert Event, since the entire plateau phase is likely not preserved here and not all the preserved interval is included in this interval. Our minimum duration estimate nonetheless agrees with the durations calculated in contemporaneous sections (e.g. Martinez et al., 2015).The average 10 m/Myr sedimentation rate estimated by Fogarasi(1995b) falls within the range of our results. He suggested that the0.2-m thick marlstone-limestone couplets could indicate precession cycles. According to our calculations, a marlstone-limestone couplet driven by precession forcing should be approximately0.1e0.3 m thick. This is also the variation that is observable in the field in the “purple marlstone” unit. The average sedimentation rate during the Late Valanginian -Early Hauterivian in the Gerecse Mountains is significantly lower than in the Vocontian Trough. The average sedimentation rate during this time at the Orpierre and the La Charce/Vergol/Morenas sections is around 48 m/Myr(Charbonnier et al., 2013; Martinez et al., 2013), and at the Angles/Fig. 6. (A) Amplitude modulation of the short eccentricity band filtered in the tuned magnetic susceptibility signal. (B) 2p-MTM power spectrum of the amplitude modulation signal. The main peak has mean period of 418 kyr, close to the period of the 405-kyr eccentricity cycle. Reynier section is around 40 m/Myr (Martinez et al., 2013). In the Umbria-Marche Basin, a sedimentation rate of 17 m/Myr was calculated for the Late Valanginian-Early Hauterivian, which is comparable to our results (Sprovieri et al., 2006).

5.5. Impact of the sample distance on the cyclostratigraphic interpretations

The precession cycles have shown to have periods close to the detection limit of our measured series (Fig. 3). Low-density sampling in the studied time series can cause distortion of the spectrum in the precession band, making the record of the orbital cycles unclear (Weedon, 2003). Furthermore, a highly fluctuating sedimentation rate can smooth the power spectrum at high frequencies and decrease the power and significance levels of the spectral peaks in an important proportion of the spectrum (see Martinez et al., 2016). The effect of the low-density sample distance, and the variations in the sedimentation rate on the spectral analyses were tested on four ETP (Eccentricity e Tilt e Precession)series calculated for the Late Valanginian using the La 2004 (Laskar

Fig. 7. Sensitivity analysis of the impact of the sample step and the fluctuating sedimentation rate on cyclostratigraphic analyses: (AeC) 2p-MTM power spectra of modelled ETPseries representing a Valanginian section with an average sedimentation rate of 14 m/Myr, analogous to the Bersek Quarry section. The three power spectra show the aliasing effect of an increasing (0.05e0.2 m) sample step. The shaded peaks represent the ideal spectrum showing no effect of aliasing. (DeF) 2p-MTM power spectra of the same modelled series

with fluctuating sedimentation rates. The sedimentation rate was set to vary between 9 and 19 m/Myr with maxima coinciding with the long eccentricity maxima.

et al., 2004) solution (Fig. 7). Three modelled ETP series represent a hypothetical section with a sedimentation rate of 14 m/Myr, analogous to the Bersek Quarry section, sampled every 0.05 m, 0.1 m and 0.2 m. A fourth ETP series of the same hypothetical section, sampled every 0.01 m, is regarded to be the ideal representation of the astronomical cycles. On the power spectrum corresponding to the 5-kyr and the 10-kyr sample distances, the peaks associated with the long and the short eccentricity, the obliquity, and the precession cycles are present (Fig. 7AeB). However, on the power spectrum corresponding to the 20-kyr sample distance, the peaks associated with the precession cycles are absent (Fig. 7C). Compared to the power spectrum of the ideal ETP series, the obliquity and eccentricity signals are not impacted by aliasing when analysing the ETP series sampled at a resolution of 5 kyr and 10 kyr. When analysing the ETP series sampled with a resolution of 20 kyr, significant changes in power occur at all Milankovitch-band (Fig. 7C), so that the amplitude of the eccentricity band is affected. The series sampled at 10 kyr thus still allows a correct reconstruct of the amplitude of the eccentricity cycles. The effect of fluctuating sedimentation rate was tested by setting a sedimentation rate cyclically fluctuating from9m/Myr to 19m/Myrwith maxima coinciding with the maxima of the long eccentricity to the previously described ETP series. On the power spectra of the modelled signals, the dispersion of the frequencies is apparent, butte Milankovitch-cyclicities remain detectable (Fig. 7DeF). In particular, at 0.05mand 0.1m, the power spectra do not significantly differ from the power spectrum of the ETP series sampled 0.01 m(Fig. 7DeE). Our test results imply that in a hypothetical section that is analogous with the Bersek Quarry section, a proxy signal sampled with a sample step of 0.1 m is capable of recording the long and the short eccentricity, the obliquity, and the precession. Even with a high variation in the sedimentation rate, our sensitivity analysis demonstrates that the long and the short eccentricity signals remain sufficiently well preserved to support our interpretation that the high-power peaks at the high-frequency end of the power spectrum of the d13C and the magnetic susceptibility signals are feasibly associated with the precession cycles in the lower part of the studied section. A proxy signal sampled with an average sample step of 0.2 representative of the upper 14.4 m section sampling protocol, is capable to record the long and the short eccentricity and the obliquity, with however large disturbances in the amplitude of these cycles compared to the series sampled at 0.01 m (Fig. 7F). These tests show that the interval of the series sampled at 0.1mis suitable for the recognition of the actual amplitude of the eccentricity cycles and thus viable for astronomical tuning.5.6. Origin of the cyclicities in the record
The origin of the observed Milankovitch cyclicities in the measured proxy signals is most likely related to the variation in terrestrially-derived detrital input (e.g., Cotillon, 1987; Mutterlose and Ruffell, 1999; Reboulet et al., 2003; Sagasti, 2005; Martinez et al., 2015; Lukeneder et al., 2016). The intensification of the hydrological cycle typical during more humid periods is likely to correspond to an increase in detrital material. This contributes to the elevated gamma-ray spectroscopy and magnetic susceptibility values, with coinciding maxima and minima, respectively. The increased nutrient availability, resulting from enhanced terrestrial input, supports elevated primary production and subsequently Fig. 8. Conceptual model of cyclic oscillations measured in carbon isotope ratio and magnetic susceptibility and inferred changes in climate and sedimentation. The inverse correlation of the filtered long eccentricity in the d13C and the GRS-MS signals imply an orbitally-forced dilution model for the Bersek Marl Formation. (A) During humid periods, the increase in detrital influx contributes to the elevated sedimentation rate and MS-GRS values, and through the enhanced production rate to the low d13C values. (B) A decrease in detrital influx and hence the MS-GRS values during more arid periods induces an increase in the bulk carbonate d13C values and a decrease in the sedimentation rate. Decreases the bulk carbonate d13C values. Hence, it explains the inverse correlation between the d13C and the MS-GRS signals. The maxima of the sedimentation rate at the studied section concur with the maxima of the long eccentricity in the MS-GRS signals, implying that the sedimentation rate is linked to orbital forcing(Fig. 8). Furthermore, in the “purple marlstone” the d13C values, oscillating with an amplitude of 0.6e0.9‰, and the carbonate content show a positive correlation. Since low carbonate content is characteristic of a humid climate with high runoff rate, a decrease ind13C values agrees with the dilution model (e.g., Fogarasi, 1995b).
The response of the sedimentary record to the climatic variations is similar across the Tethyan realm, and has been observed in the Vocontian Trough (SE France; Cotillon, 1987), in the Lower Saxony Basin (NW Germany; Mutterlose and Ruffell, 1999), and in the Subbetic Domain (SE Spain; Micoud et al., 2012). In these geological settings, the more argillaceous beds were deposited under a humid climate with high continental runoff, whereas the beds with a higher carbonate content indicate a semi-arid climate with a lower continental detrital influx (Mutterlose and Ruffell,1999; Micoud et al., 2012). These variations have been observed at both

the small scale (i.e., precession or obliquity controlled bed couplets) and larger scale (i.e., eccentricity controlled bed bundles).Migration of carbonates from the originally more clay-rich to the more calcareous beds during the early diagenesis processes has been notably invoked to explain the onset of the marl limestone alternations (Munnecke et al., 2001). However, the bundling of the climatic cycles into small and larger scales in the above-mentioned geological settings and the fact that clay minerals (insoluble and related to changes in humidity levels) follow the bundling between the precession and the eccentricity cycles strongly supports an orbital control on the Tethyan marlstone-limestone alternations via humid-arid cycles (Cotillon, 1987; Mutterlose and Ruffell, 1999;Martinez et al., 2015). At the Bersek Quarry, the carbonate content and the total nannoplankton abundance in both the “grey marlstone” and the “purple marlstone” show a strong positive correlation. This implies that the carbonate content is highly dependent on nannoplankton production. Even if carbonate migration might have happened, it did not have a significant effect on the lithology. Conversely, the lithological cycles follow the pattern of the orbital forcing. Even the sedimentation rate appears to follow the filter of the long eccentricity cycle, which support the link between the marl-limestone alternations of the Gerecse Mountains and humid-arid cycles orbitally forced.

6. Conclusions

In this study, a multi-proxy approach was used to assess a local sedimentary record of the globally important Weissert Event. Bulk carbonate carbon and oxygen stable isotope measurements, gammaray spectroscopy and magnetic susceptibility analyses were carried out in a 31.2mthick section at the Bersek Quarry, type locality of the Bersek Marl Formation, in the Gerecse Mountains, Transdanubian Range, Hungary. A Late Valanginian to possibly earliest Hauterivian age of the section is confirmed by ammonoid and calcareous nannoplankton biostratigraphy. Cyclostratigraphic analyses performed on all the studied proxy signals suggest an average sedimentation rate of 14m/Myr. Based on the preservation of Milankovitch-cyclicity and comparison with other Tethyan sections, the values and trend of the d13C signal are considered to reflect a primary signal. The inflexion point of the d13C curve, where the sustained plateau of high values transitions to a decreasing trend, is interpreted as the termination of the plateau phase of the Late Valanginian Weissert Event. The plateau phase of the Weissert Event as recorded in the Bersek Quarry section is at least 1.4 Myr in duration, in agreement with the range of estimates obtained throughout the Tethyan realm. The proxy signals and the sedimentary pattern of the Bersek Marl Formation suggest the presence of dilution cycles which fits the model established for Tethyan realm and argues that orbitally forced humid-arid cycles are major determining factor in the generation of the (hemi-)pelagic marlstone-limestone alternations during the Valanginian-Hauterivian ages.

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