Astronomically forced teleconnection between Paratethyan and Mediterranean sediments during the Middle and Late Miocene

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ABSTRACT

A high-resolution correlation between an orbital tuned Middle and early Late Miocene record of the Central Paratethys and an astronomically calibrated Mediterranean deep marine composite record is proposed. The astronomical tuning of the Sarmatian and Pannonian sedimentary record in the Vienna Basin confirms that the beginning of the Pannonian regional stage (lower Tortonian), dated in this work at 11.42 My, is very close to the Miller event Mi5. It coincides with a period of minimum amplitude in the 1.2-Myr obliquity cycle, which in the Mediterranean marine record corresponds with a drastic change in the planktonic foraminiferal fauna. In addition, the warmer period between Mi5 and Mi6—corresponding to a maximum in the long-term 2.3-Myr eccentricity cycle—coincides with a long interval of lignite deposition in the Paratethyan realm. The sedimentation pattern shown by high-frequency cyclicity between lignite and normal sediments reflects a primary influence of 100-kyr eccentricity cycles on the sedimentation system of the Central Paratethys, which corresponds with small- and large-scale sapropel-clusters hierarchical organization in the Mediterranean record.

The Badenian/Sarmatian boundary (astronomically dated at 13.32 Myr) does not coincide with a low-amplitude variation in the 1.2-Myr obliquity cycle and any Mi events. This orbital configuration is supported by the paleoclimatic and paleoecologic data of the Late Badenian and Early Sarmatian, which both represent a warm temperate system with stagnant bottom-water conditions. Finally, the transitional phase from a temperate Early Sarmatian to a warmer Late Sarmatian, associated with predominant carbonate sedimentation, coincides with the glacio-eustatic isotope event Mi4, while the entire Late Sarmatian spans a complete 1.2-Myr obliquity cycle.

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1. Introduction

The rise of the Alpine mountain belt led to a partition of the Tethyan Ocean around the Eocene/Oligocene boundary. This geodynamic process caused the Tethys to disappear as a paleogeographic and paleobiogeographic entity, and two different paleogeographic areas evolved—the (Neogene) Mediterranean Sea and the Paratethys Sea. This geographic separation also resulted in a biogeographic differentiation and necessitated the establishment of different chronostratigraphic/geochronologic scales. Accordingly, within the Paratethys the distinction between Western, Central and Eastern Paratethys reflects internal differentiation and a complex pattern of changing seaways and landbridges between the Paratethys and the Mediterranean as well as the western Indo-Pacific (e.g., Rögl, 1998, 1999).

Times of open connections of the Paratethys with adjacent oceans (e.g., Middle Miocene Badenian regional stage) are reflected by a very low rate of endemism (Harzhauser and Piller, 2007). During these phases, the exchange of plankton allows a biostratigraphic correlation with coeval Mediterranean areas. An example is the *Praeorbulina-Orbulina* lineage as described by Rögl et al. (2002) from the North Alpine Foreland Basin. In contrast, phases of total or partial isolation coincide with considerable endemisms and usually also with a near-complete breakdown of all biostratigraphically relevant planktonic groups. In the Central Paratethys, the Sarmatian and Pannonian regional stages represent phases of apparently complete isolation; their correlation to Mediterranean records has been controversial for decades (see Papp et al., 1974, 1985; Stevanović et al., 1990 for discussions). Nevertheless, a correlation of the Sarmatian with parts of the Serravallian Stage and a correlation of the Pannonian with parts of the Tortonian Stage is generally accepted. Within that system, the upper Middle Miocene Sarmatian stage is outstanding due to its highly endemic marine fauna. At that time, the Paratethys sea formed a huge inland sea which was nearly completely disconnected from the Mediterranean sea. Widespread oolite shoals, unknown from coeval settings in the Mediterranean area, formed in the Central Paratethys and alkaline water

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chemistry prevailed (Piller and Harzhauser, 2005). In contrast, the Upper Miocene Pannonian Stage is characterised by the establishment of an alkaline lake system (Harzhauser et al., 2007) called Lake Pannon. It was diachronously replaced by terrestrial floodplain environments from NW to SE (Magyar et al., 1999a). The timing of the transition from the marine Sarmatian deposits up to the Pannonian continental strata of the Central Paratethys remains a topic of debate.

Milankovitch cyclostratigraphy is nowadays considered one of the best tools to gain high-resolution chronostratigraphy in different depositional environments (continental, marginal marine and deep sea). The presence of high-frequency cycles in deep-sea records and their tuning to the astronomical target curve provides accurate absolute ages for the stratigraphic events recognised through the studied sedimentary successions. This approach assumes a nearly linear response of the sedimentary record (with variations in physical properties, fossil communities, chemical and isotopic characteristics, etc.) to periodic climate variations, ultimately controlled by variations in the shape of the Earth's orbit and the inclination of its rotation axis (e.g., Hilgen et al., 1997). Accordingly, periodic sedimentary cycles can suitably be dated by matching patterns of paleoclimate variability with patterns of varying solar energy input computed from the astronomical model solutions (Hilgen et al., 1999).

Application of cyclostratigraphy resulted in the construction of an accurate Astronomical Tuned Neogene Time Scale (ATNTS 2004) for the Quaternary, Pliocene, Late and Middle Miocene (Hilgen, 1991a,b; Shackleton et al., 1995; Hilgen et al., 1995; Lourens et al., 1996; Shackleton and Crowhurst, 1997; Hilgen et al., 1999, 2000a,b, 2003; Lourens et al., 2004; Hilgen et al., 2006; Hüsing et al., 2007). This has a much higher resolution than the previously generated geological time scales (Berggren et al., 1985; Harland et al., 1990; Berggren et al., 1995). Ongoing researches are focused on an extension of the astronomical time scale to older intervals, even in continental records (Opdyke et al., 1997; van Vugt et al., 1998; Abdul Aziz et al., 2000; van Vugt, 2000; van Vugt et al., 2001; Agustí et al., 2001; Abdul Aziz et al., 2003).

Fig. 1. Geographic position of the investigated sections: Eichhorn 1 well in Austria, Gibliscemi in Sicily and Ras il Pellegrin in Malta. The outline of the Late Miocene Lake Pannon is indicated in the upper inset and the margins of the Vienna Basin are drawn in the inset bottom right.

Though for the Neogene Mediterranean marine records a conceptual model to phase the sedimentary cycles with the astronomical target curves is well defined, in the Paratethys realm only a very short sequence of Middle Miocene deposits has been astronomically tuned (Hohenegger et al., 2007), and a tentative orbital calibration of much longer Upper Miocene depositional sequences has been proposed (Juhász et al., 1999; Sprovieri et al., 2003; Harzhauser and Mandic, 2004; Harzhauser et al., 2004; Sacchi and Muller, 2004).

Extensive hydrocarbon explorations of Middle and Upper Miocene sediments of the Vienna Basin recorded long and characteristic succession of marly and sandy sediments generally used as marker-system for regional correlation of wells. Recently, a large ensemble of geophysical results, collected from several wells drilled in the Vienna Basin, have been discussed by Harzhauser and Piller (2004a) who hypothesised a primary astronomical forcing as driving the fluctuations registered by the different physical/sedimentary parameters.

In this paper, we compare and integrate different stratigraphic data from two selected Middle to Upper Miocene marine deposits, namely from Sicily and Malta (Central Mediterranean), with a high-resolution sedimentary record from the Vienna Basin (Central Paratethys). This paper seeks phase relations between sedimentary cycles (in the two realms) and orbital parameters in order to: (1) provide an astronomical calibration of the base of the Pannonian and Sarmatian regional stages, (2) determine potential correlation with the Mediterranean Serravallian and Tortonian stages and (3) assess the mechanisms which forced the two different sedimentary systems.

2. Materials and methods

2.1. Central Mediterranean

Two sedimentary sections were selected as key marine records: Gibliscemi (southern Sicily, Italy) and Ras il Pellegrin (Malta Island). The Gibliscemi section is exposed along the southern slope of Monte Gibliscemi in southern Sicily (Italy, Fig. 1). The Miocene deep marine succession consists of whitish hemipelagic marls which cyclically alternate with sapropels and/or related grey marl layers (Hilgen et al., 2000b; Turco et al., 2001). The sedimentary record of the Gibliscemi section was astronomically tuned by Hilgen et al. (2000b) and successively revised by Hilgen et al. (2003). Lithostratigraphy, integrated calcareous plankton biostratigraphy, astronomical calibration and stable isotope stratigraphy of the section are based on the previous studies of Hilgen et al. (2000b, 2003) and Turco et al. (2001). The stratigraphic record spans the time interval from 12.5 to 9.5 Myr including the Serravallian/Tortonian boundary (Hilgen et al., 2000b).

The sedimentary record of the Ras il Pellegrin section, cropping out throughout the Blue Clay formation, shows a very distinct and characteristic pattern of homogeneous grey and white marls and contains a transitional bed which separates the yellowish marly limestones of the Globigerina Limestone from the grey clayey marls of the Blue Clay (Foresi et al., 2002). High-resolution planktonic and benthic oxygen isotope records have been generated for the Langhian/Serravallian boundary by Sprovieri et al. (2002) and Abels et al. (2005). Lithostratigraphy, integrated calcareous plankton biostratigraphy, astronomical calibration and stable isotopic stratigraphy of the section are based on previous studies of Sprovieri et al. (2002), Bellanca et al. (2002), Bonaduce and Barra (2002), Foresi et al. (2002) and Abels et al. (2005).

2.2. Central Paratethys

Due to the complex tectonic history, only few areas of the former Central Paratethys Sea provide more or less continuous sedimentary histories. The Vienna Basin, with its very rapid subsidence during the Middle and Late Miocene, is one of such rare target area. The well Eichhorn 1 is situated 40 km NE of Vienna in the northern Vienna Basin (Fig. 1). It is a marginal well near the Matzen oilfield and has the
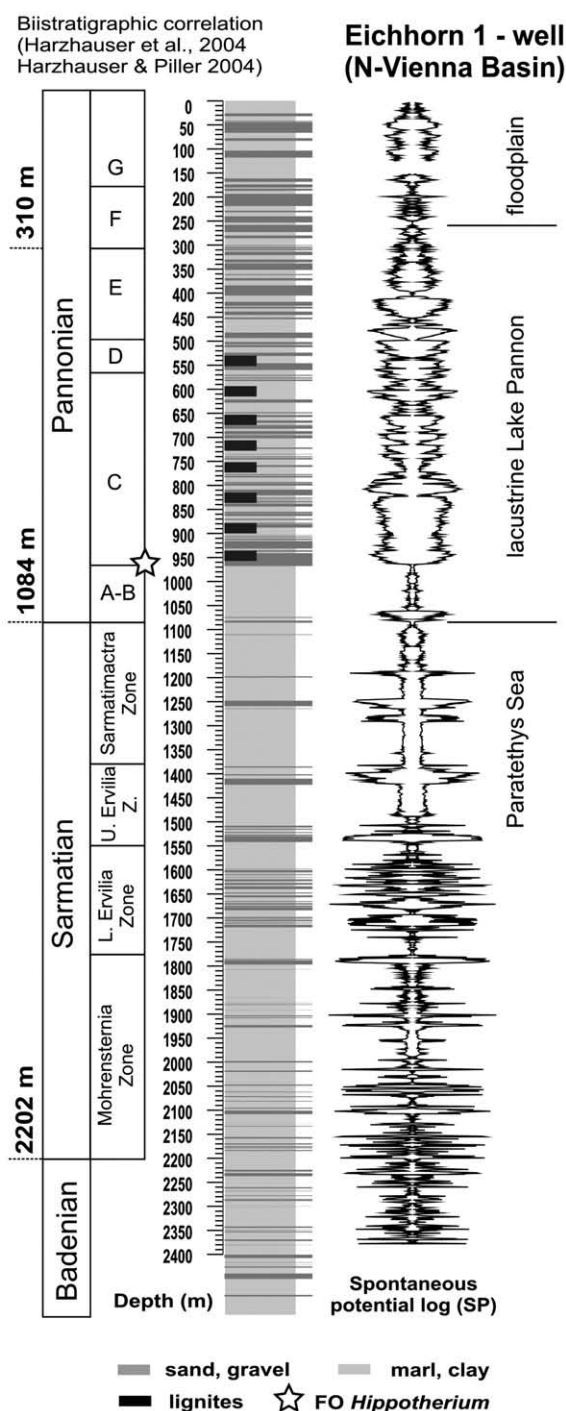

Fig. 2. Simplified lithological log of the Eichhorn 1 well based on drilling reports of the OMV-AG. The spontaneous potential log (SP) is mirrored for better readability. Biostratigraphic correlation follows the papers of Harzhauser et al. (2004), Harzhauser and Piller (2004a,b) and unpublished reports of the OMV oil company. The letter stages A–G are from Papp (1951).

advantage of being, in terms of paleogeography, in a rather basinal position. Most other wells in that area have been drilled along the margin of the Vienna Basin and are characterised by numerous faults and sedimentary gaps. The basinal position of Eichhorn 1 yields a good and continuous sedimentary record, which was further supported by high subsidence of the basin during the Middle and Late Miocene (Wagreich and Schmid, 2002). The well was drilled by the OMV-AG in 1939 and reached a depth of 2535.0 m, stopping in Badenian (Middle

Miocene) sediments. The herein-considered part of the log comprises about 2300 m and covers the Pannonian and Sarmatian deposits (Fig. 2). The biostratigraphic correlation is based on molluscs and benthic foraminifers, which allow a very clear separation of several regional biozones [see Harzhauser et al., 2004 and Harzhauser and Piller, 2004a,b for an extensive review]. The well starts with a c. 335 m thick succession of marls and clayey marls with several sandstone interbeds. The marine mollusc fauna (e.g., turritellids, corbulids, lucinids, turrids) of this part is of Badenian age. Only their uppermost 200 m are integrated in this study. The Sarmatian part of the well starts at c. 2200–2180 m depth. The uncertainty of the exact base is due to the lack of biostratigraphic markers. Marls dominate the Sarmatian lithology. Thicker sandstone intercalations at 1507–1541 m, 1383–1422 m and 1189–1201 m have been used by the OMV as intrabasinal markers. Two thin lignitic beds occur from 1549–1556 m and at 1300 m. At a depth of 1105 m, the occurrence of the bivalve genera *Obsoletiforma* and *Modiolus* indicates the topmost Sarmatian biota. Upsection, the Pannonian succession starts with a characteristic coarser sandy interval between 1064 and 1084 m followed by c. 90 m of marly clay with first Pannonian cardiid bivalves. This unit is characterised in geophysical logs by a continuous shale-line appearance. The main part of the Pannonian core (8–966 m) comprises an intense intercalation of marls and fine to coarse sand sets. In the geophysical logs it is recognised easily by a more or less cylinder-shaped basal part of about 200 m thickness, followed by a succession of broad, funnel-shaped curves passing upwards into serrated, sharply cut, funnel-shaped curves. Lignitic layers (e.g., 707–696 m, 120–116 m) and scattered gravel layers (798–794 m, 178–172 m) occur in these units. The topmost 8 m represent Pleistocene loess. A detailed sequence stratigraphic interpretation of the succession, based on correlation with other wells, is presented by Harzhauser et al. (2004) and Harzhauser and Piller (2004b). The original raw spontaneous potential log (SP) data of well Eichhorn 1 have been described in details Harzhauser et al. (2004) and Harzhauser and Piller (2004a,b) who, by accurate analysis of cuttings, determined a direct correlation between SP response and grain size classes.

2.3. Methods for spectral analysis

In order to unravel the dominant frequencies and phase relations, from 9.5 back to 14 Myr, between the $\delta^{18}O$ records of the Gibliscemi and Malta sections and the sedimentary record from the Central Parathethys, we applied an ensemble of power spectral methodologies to four different time series. Standard time series analysis for unequally sampled signals was carried out using the CLEAN algorithm and REDFIT program (Lomb-Scargle algorithm) (Schulz and Mudelsee, 2002). In addition, to investigate non-stationary signals, frequency components evolution along the time series was determined using Foster's wavelet analysis algorithm (Foster, 1995, 1996a,b). This technique was developed to identify, in climate sensitive records, cyclic alternations correlatable with variations of the same order recognised in the astronomic target curves of Laskar et al. (2004).

3. Integrated stratigraphy and tentative age modelling of the Eichhorn 1 well

The Sarmatian as a regional stage was defined in the Vienna Basin by Papp and Steininger (1974). The base of the Sarmatian was defined by the occurrence of a highly endemic fauna, particularly molluscs and foraminifers. Both groups allow the establishment of an ecobiostratigraphic subdivision, which comprises, for the lower Sarmatian the *Mohrensternia* Zone and lower *Ervilia* Zone among molluscs and the *Anomalinoides dividens* Zone, *Elphidium reginum* Z. and *Elphidium hauerinum* Zone among benthic foraminifers. The upper Sarmatian contains the *Porosononion granosum* Zone and is subdivided into the upper *Ervilia* Zone and *Sarmatimactra vitaliana* Zone by molluscs. Due to the restricted connection of the Central Parathethys to the Mediterranean and the lack of most stenohaline biota, any possibilities for correlations with records outside the Central Parathethys are highly reduced. While planktic foraminifers in this interval are completely absent (Cicha et al., 1998), calcareous nanoplankton exhibits a restricted inventory generally containing endemic taxa (Steininger et al., 1976; Stradner and Fuchs, 1979). Specifically, the absence of *Sphenolithus heteromorphus* has been
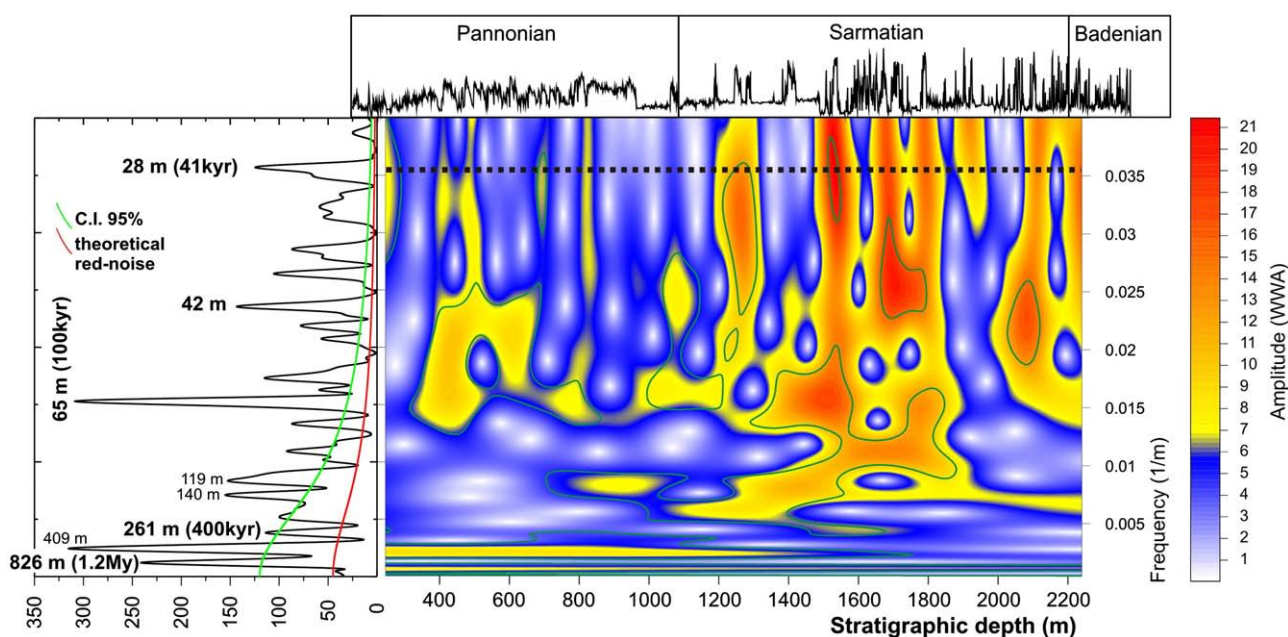

Fig. 3. Wavelet analysis and power spectra of the SP data of Eichhorn 1 in depth domain. In the power spectra, green and red lines indicate the 95% confidence interval and AR(1) theoretical red noise spectrum (Schulz and Mudelsee, 2002), respectively. In Wavelet spectrum (Weighted Wavelet Amplitudes-colour chromatic scale) green line indicates the 95% confidence interval. Power spectra in depth domain reveal prominent peaks at 65 and 261 m and are correlated with 100-kyr and 400-kyr eccentricity cycles. The peaks at 826 and 28 m are interpreted to reflect the 1.2-My obliquity cycle and the 41-kyr obliquity cycle. Note the continuous occurrence of the 100-kyr cycles in contrast to the 41-kyr cycle, which is largely restricted to the Sarmatian (Middle Miocene) part of the log. The thick black dotted line represents the position of 41 kyr periodicity along the Wavelet spectrum. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
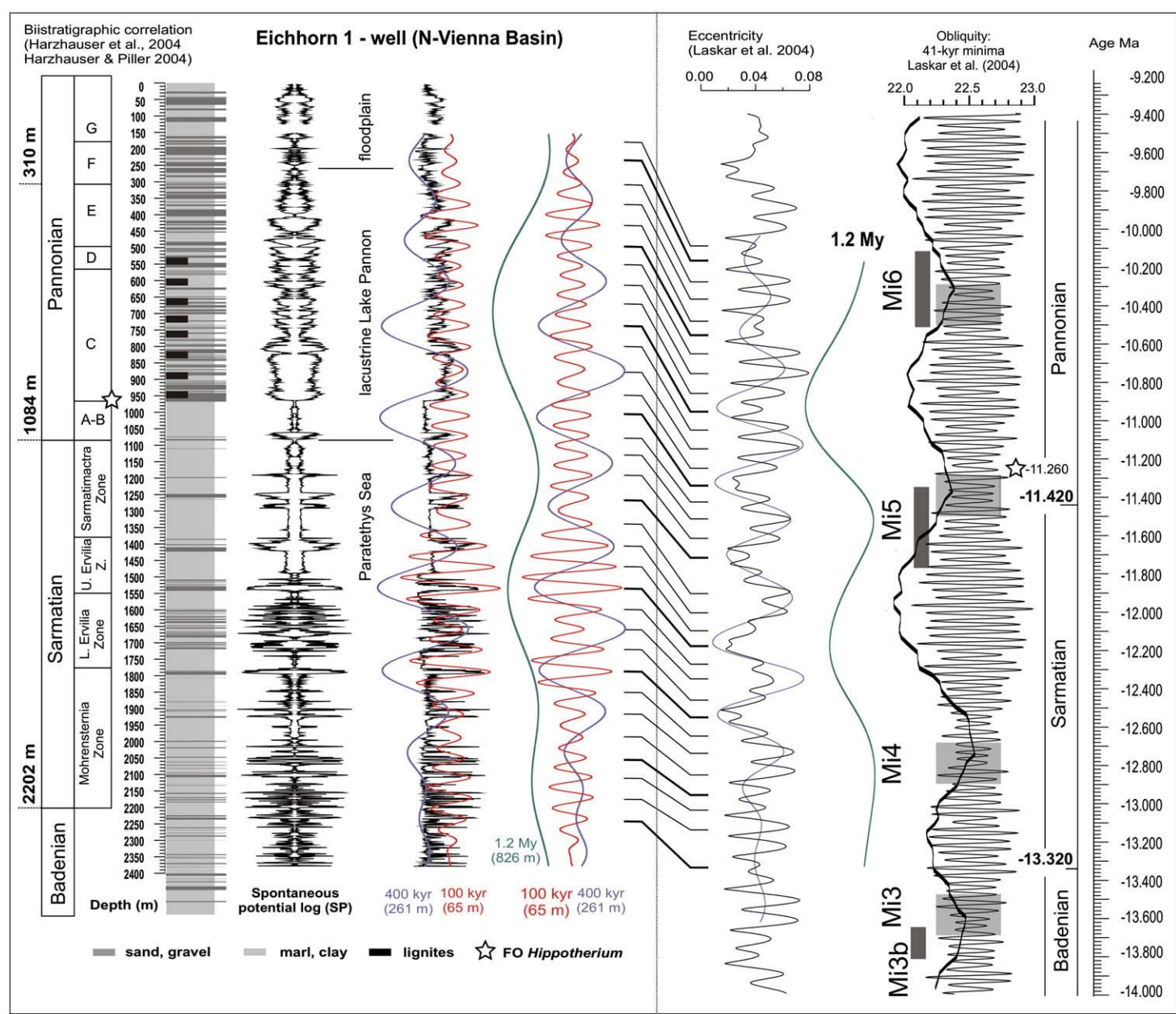
Fig. 4. Simplified lithological log of the Eichhorn 1 well based on drilling reports of the OMV-AG. The spontaneous potential log (SP) is mirrored for better readability. Biostratigraphic correlation follows the papers of Harzhauser et al. (2004), Harzhauser and Piller (2004a,b) and unpublished reports of the OMV oil company. The letter stages A–G are from Papp (1951). The SP-raw data have been filtered at a 400-kyr and 100-kyr filter and plotted on the SP-data for visual comparison. The filtered SP 400-kyr and 100-kyr cycles are then correlated with the eccentricity cycles of Laskar et al. (2004) and to the 1.2 My long-period variation of the obliquity cycles. The thick black line superimposed to the obliquity represents the 5-point moving average of the successive 41 kyr obliquity minima. Note good correlation of the Mi5 event and minimum in the 1.2 My obliquity band with the Sarmatian/Pannonian boundary. Mi4 and Mi6 are also well correlated with major shifts in depositional systems in the Parathethys Sea and Lake Pannon. A decoupling of astronomical forcing, however, is evident for the Badenian/Sarmatian boundary.

considered by Schütz et al. (2007) as suitable marker of the calcareous nannofossil biozone NN6, while the occurrence of *Discoaster kugleri* indicates the biozone NN7. On the other hand, the passage from the Sarmatian to the Pannonian is generally identified by a drastic extinction rate (over 90%) in the gastropods and foraminifers assemblages termed by Harzhauser and Piller (2007) as the "Sarmatian–Pannonian-Extinction-Event" (SPEE). The mollusc fauna recorded during the Pannonian regional stage (the letter stages A–G reported in the figures are from Papp, 1951) is characterised by a high degree of endemism and fast evolutionary radiations (Müller et al., 1999) reflecting the evolution of a long-lived lake system called Lake Pannon.

The integrated stratigraphy of the Eichhorn 1 well is firstly based on recognition of the above reported mollusc and foraminiferal stratigraphic events (Fig. 2). Additional information have been deduced from correlations with other adjacent wells and land based outcrops as described in detail by Harzhauser et al. (2004) for the Pannonian succession and by Harzhauser and Piller (2004a,b) for the Sarmatian. In particular, the lower Pannonian strata in the Eichhorn 1 well (c. 1000–900 m) were correlated to land based outcrops which yield the first occurrence of the three-toed horse *Hippotherium*, which defines the base of mammal zone MN9 (Crusafont-Pairo, 1950). The estimated age of this event is not younger than 11.1 Myr and not older than 11.5 Myr (Garcés et al., 1997). Specifically, Bernor et al. (1988) dated the first occurrence of *Hippotherium* in Central Europe at 11.1–11.2 Myr.

In their in-depth review of the stratigraphy of the Central Paratethys, Piller et al. (2007), pointed out the strong relationship between the onset of Pannonian Lake deposits with the base of the Tortonian (astronomically dated at 11.60 Myr; Lourens et al., 2004) although Vasiliev (2006) assumed, based on detailed results from Transylvanian basin, an age younger than 11.4–11.5 Myr for Sarmatian–Pannonian boundary.

Finally, direct correlation proposed by Harzhauser et al. (2004) and Harzhauser and Piller (2004a,b) with well data reported by Daxner-Höck (1993, 1996) and Magyar et al. (1999b) restricts the upper part of the Eichhorn 1 well to a time interval between 9.7 Myr and 9.9 Myr (Magyar et al., 1999b).

Further information helpful to support the chronostratigraphic framework of the studied record are based on the interpretation of regional sequence stratigraphy proposed by Harzhauser and Piller (2004b) Kováč et al. (2004) and Schreilechner and Sachsenhofer (2007). The authors suggested that entire Sarmatian is part of a 3rd order sea level cycle correlated to the TB 2.6 of Haq et al. (1988). The lowstand at the end of the Sarmatian, representing the Sarmatian/Pannonian boundary, is correlated to the Ser 4/Tor 1 sequence boundary of Hardenbol et al. (1998), which coincides with the Serravallian/Tortonian boundary at 11.60 Myr (Lourens et al., 2004) and at 11.5 Myr as proposed by Rögl et al. (1993) and Kováč et al. (1998). The lower to middle Pannonial lake deposits have been proposed by Harzhauser et al. (2004) to represent a single cycle (TB 3.1. of Haq et al., 1988) starting at the Middle Miocene/Upper Miocene (Serravallian/Tortonian) boundary due to the influence of the glacio-eustatic sea level lowstand Ser 4/Tor 1 of Hardenbol et al. (1998) (Harzhauser and Piller, 2004b; Strauss et al., 2006). Finally, the upper Pannonian sediments belong to two 3rd order cycles (TB 3.2. and 3.3. of Haq et al., 1988) starting with the Tor 2 lowstand of Hardenbol et al. (1998).

4. Astronomical tuning of the Eichhorn 1 well

A stepwise methodological approach has been adopted to calibrate the sedimentary record of Eichhorn 1 well. The original raw spontaneous potential logs (SP) data have been processed by spectral analysis. Power spectrum performed in depth domain revealed prominent peaks at 826, 261, 65, and 28 m (Fig. 3). The calculated ratios among those frequencies (1, ~3, ~12, and ~29) are absolutely comparable to the proportions among the classic Milankovitch periodicities of the 1.2 My long-obliquity cycles, long- and short-eccentricity and 41-ky obliquity cycles (Fig. 3).
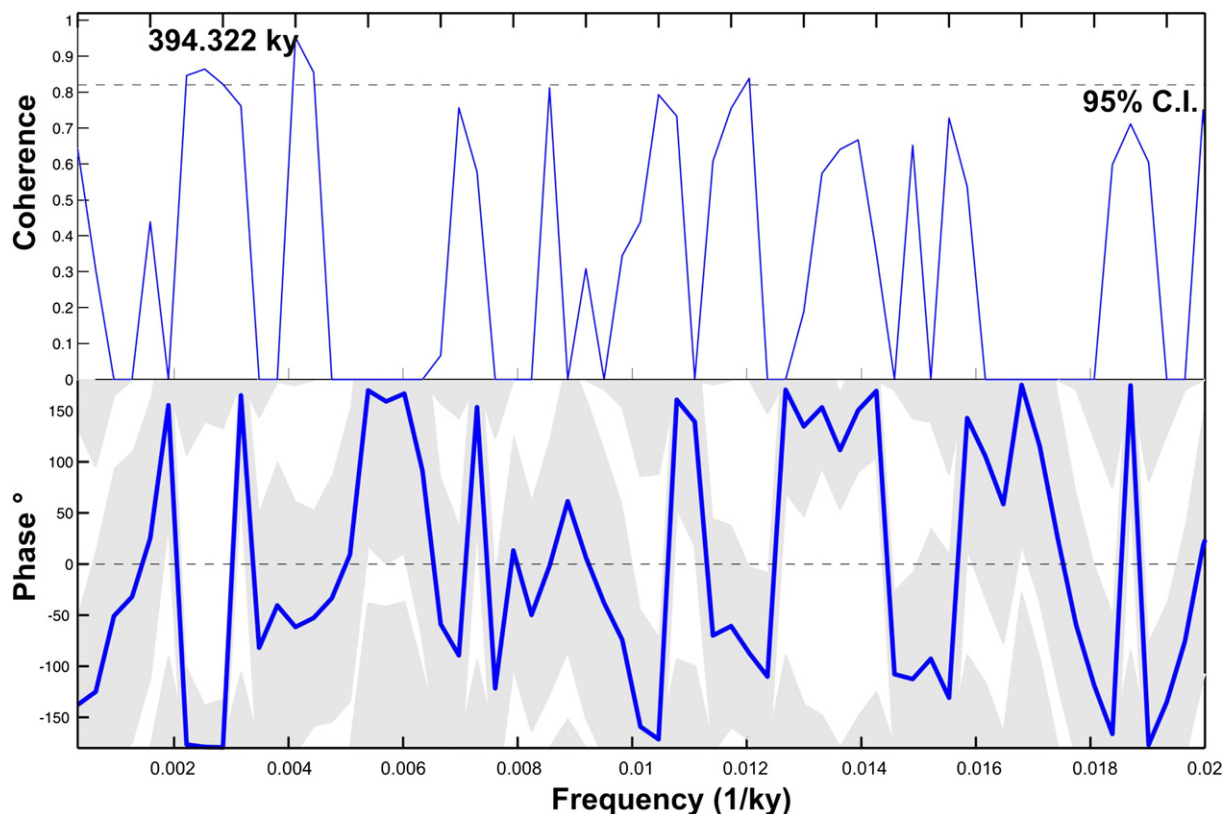

Fig. 5. Coherence and phase lag between SP data of Eichhorn 1 in time domain and the eccentricity curves of La04$_{(1:1)}$. Coherence and phase spectra were measured by multitaper method estimates, using adaptive weighting and correcting for the inherent bias. Coherence values are plotted on a linear scale. The 95% phase confidence level is estimated with a built-in Monte Carlo procedure (P. Huybers m-files).

Moreover, the average sedimentation rate calculated between the stratigraphic level correlated to the first occurrence of the three-toed horse *Hippotherium* (at 970 m; 11.1–11.2 Myr) and the Sarmatian–Pannonian boundary (at 1090 m; 11.4 Myr) is about 0.65 m/kyr thus confirming the attribution to Milankovitch periodicities of the dominant peaks recorded in the power spectrum of Fig. 3. Wavelet analysis (Fig. 3) indicates that the periodicity associated with 65 m is clearly present on the entire studied record, while the periodicity of 261 m is recorded only in the upper part of the studied record (Fig. 3). The periodicity of 28 m is statistically significant only in the lower part of the record (base of the section up to ~1200 m) (Fig. 3). Finally, the long-term 1.2 Myr obliquity cycle is present along the whole succession (Fig. 3).

As far as the phase relation between SP record and insolation curve is concerned, we assume, according to Sprovieri et al. (2003) and Sacchi and Muller (2004), that sedimentary intervals characterised by coarser grain size correspond to intervals of stronger insolation and, *vice versa*, marly sediments deposited during relatively weaker astronomical forcing.

The original SP data have been filtered in the 400 kyr and 100 kyr periodicity bands and compared with the astronomical eccentricity curve La04$_{(1,1)}$ of Laskar et al. (2004) (Fig. 4). Visual comparison between the eccentricity curve with the lithologic record evidences a systematic distribution of long marly intervals during minima of 400-kyr (Fig. 4) alternated to high-frequency sand/gravel cycles mainly distributed during periods of highs of the 400-kyr eccentricity curve.

Coherence and phase spectra calculated for the SP time-series-record and the astronomic target curve reveals high coherence values (>0.7) for all the detected Milankovitch frequencies that confirms the appropriateness of the achieved tuning (Fig. 5) and a nearly linear of the Central Paratethys sedimentary system to astronomical forcing.

Based on the achieved astronomical tuning an age of 11.42 Myr is proposed for the Sarmatian/Pannonian boundary and an age of 11.26 Myr for the first occurrence of *Hippotherium* in the Vienna Basin (Fig. 4). Consequently, the base of the Pannonian regional stage is younger than the base of the standard Tortonian stage (dated at 11.6 Myr, Lourens et al., 2004). The correlation of the Sarmatian/Pannonian boundary with the Serravallian/Tortonian boundary at 11.6 Myr (Hilgen et al., 2000a,b; Lourens et al., 2004), as proposed by Harzhauser et al. (2004), was a conceptual approach which expected a synchronous sea-level drop in the hydrologically connected basins of the Mediterranean Sea and the Central Paratethys. As this sea-level drop was proven by Turco et al. (2001) to predate the Serravallian/Tortonian boundary, the concept-based dating has to be adapted as well. Thus, the herein proposed dating of the Sarmatian/Pannonian boundary is still in agreement with the sequence-stratigraphical signal (Miller event Mi5 = Haq-cycle boundary TB 3.1).

The new calibrated age for the Badenian/Sarmatian is 13.32 Myr older than that data proposed by Harzhauser and Piller (2007) who correlated that boundary to the sea level drop between the TB 2.5 and TB 2.6 cycles of Haq et al. (1988) at c. 12.7 (corresponding to the Mi4 event of Miller et al., 1991 dated by Turco et al., 2001 at 12.9 Myr). The herein proposed Badenian/Sarmatian boundary has to be treated as a preliminary solution. There is a widespread discordance in the Central Paratethys at the Badenian/Sarmatian transition and a change in sedimentary environments took place. We cannot exclude that the well-data are obscured by a hiatus at that crucial level. The basinal position of the well is expected to reduce the amount information-loss. In any case, the tuning suggests a distinct shift of the boundary from the previously reported dating at 12.7 as proposed by Harzhauser and Piller (2004a,b). Moreover, the tuning links the up to now unexplained drastic shift in water chemistry and lithologies at the Early/Late Sarmatian boundary with the Mi4 event.

5. Mediterranean–Central Paratethys correlation

Spectral analysis has been performed on the oxygen isotope record of benthic foraminifers (*Cibicidoides kullenbergi* or *C. wuellerstorfi*,

$\delta^{18}O_{benthic}$) collected from the Mediterranean Gibliscemi section (12.6–9.8 Myr) by Turco et al. (2001) and on the oxygen isotope records of planktonic foraminifers (*Globigerinoides quadrilobatus*, $\delta^{18}O_{G. quadrilobatus}$) from the composite Mediterranean record Gibliscemi-Ras il Pellegrin sections (between 9.8 and 13.6 Myr) reported by Turco et al. (2001) and Sprovieri et al. (2002).

Power spectral analysis performed on the $\delta^{18}O_{G. quadrilobatus}$ signal shows two distinct peaks at 19 and 23.6 kyr (associated with the precession forcing) and a prominent peak at ~1.37 Myr which well-fits the long-period 1.2 Myr obliquity cycle (Fig. 6a). The slight discrepancy between the obtained 1.37 Myr and the periodicity associated to the 1.2 Myr long-term obliquity cycle could be related to an algorithm artefact related to the interval of lacking data between 12.1 and 12.5 Myr.

Power spectrum calculated on the $\delta^{18}O_{benthic}$ record of Gibliscemi section reveals a maximum concentration of variance around 1.25 Myr (Fig. 6b).

Once compared to the astronomical long-period 1.2 Myr obliquity record, the ~1.2 Myr filtered $\delta^{18}O_{G. quadrilobatus}$ and $\delta^{18}O_{benthic}$ records clearly evidence that the Mi6, Mi5 and Mi4 Miller events (at 10.4, 11.4 and ~12.8 Myr, respectively) coincide with periods of low-amplitude in the long-term obliquity forcing (Fig. 7).
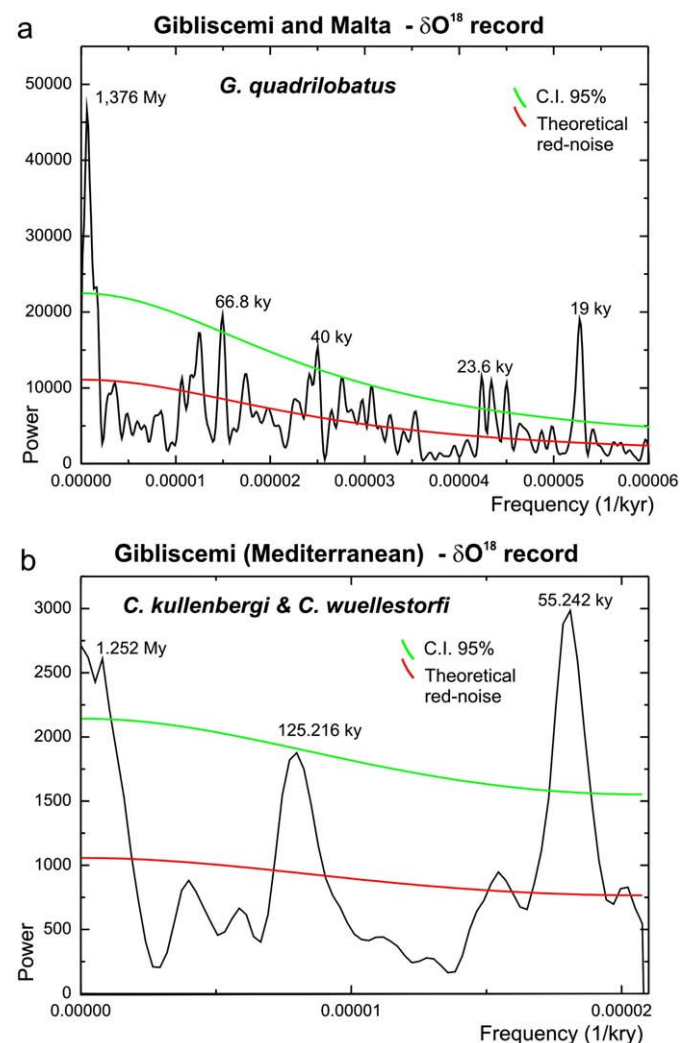

Fig. 6. Lomb-Scargle power spectra performed on the *G. quadrilobatus* $\delta^{18}O$ record from the Mediterranean integrated record (Gibliscemi and Malta sections) (a), and *C. kullenbergi-C. wuellstorfi* $\delta^{18}O$ record from the Gibliscemi section (b). Green line in Lomb-Scargle power spectra indicates the 95% confidence level. Red solid line indicates the AR(1) theoretical red noise spectrum (Schulz and Mudelsee, 2002). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The comparison of the astronomically calibrated well Eichhorn 1 with the astronomically tuned Mediterranean record (Fig. 8) points towards a significant relationship with glacio-eustatic sea level oscillations classically associated to 1.2 Myr long-periodic oscillations in the orbital obliquity band (e.g., Lourens and Hilgen, 1997; Zachos et al., 2001; Wade and Palike, 2004; Westerhold et al., 2005). Actually, the phased Central Paratethys and Mediterranean 1.2 Myr filtered records (Fig. 8) suggests a linear response of the sedimentary systems in the two realms to major nodes of the 1.2 Myr obliquity cycle. Particularly, the astronomically tuned 11.42 Myr age for the Sarmatian/
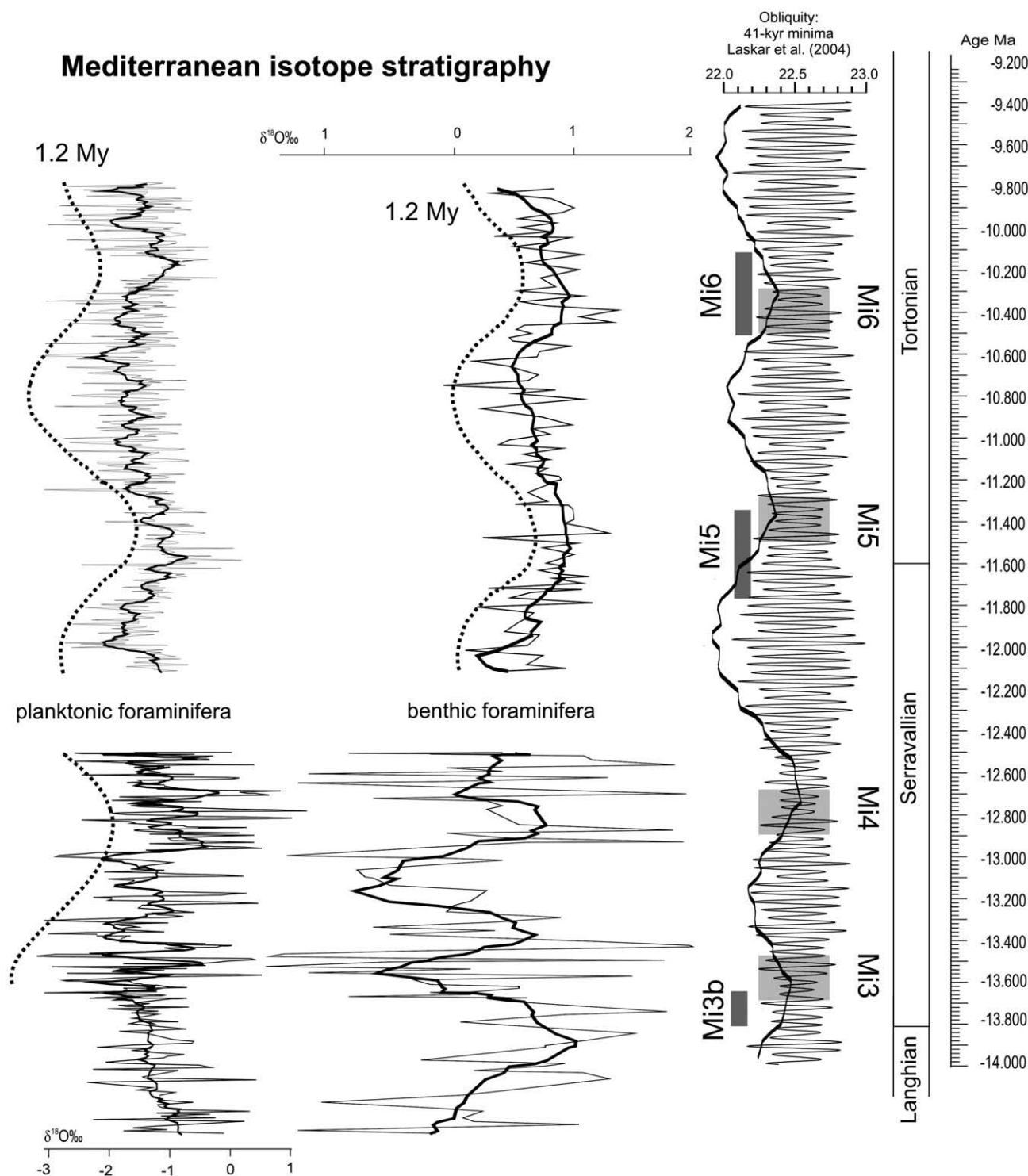

Fig. 7. Integrated Mediterranean (Gibliscemi and Malta sections) planktonic and benthic δ¹⁸O records compared with the long-periodic 1.2-My obliquity cycle. The black boxes indicate the position of Mi5 and Mi6 (Turco et al., 2001) and the position of Mi3b (Abels et al., 2005). The light grey boxes superimposed on the obliquity records indicate the position of the Miller events in correspondence to the 1.2-My obliquity nodes (van Dam et al., 2006). The thick black line superimposed to the obliquity represents the 5-point moving average of the successive 41 kyr obliquity minima. The planktonic δ¹⁸O record is smoothed with a 40 kyr average (solid line). The benthic δ¹⁸O record is smoothed with a 150 kyr average (solid line). The filtered 1.2 My component of obliquity (thick dotted line) in the integrated Mediterranean (Gibliscemi and Malta sections) planktonic δ¹⁸O record is superimposed on the planktonic δ¹⁸O original signal; the filtered 1.2 My component of obliquity (thick dotted line) in the Mediterranean (Gibliscemi section) benthic δ¹⁸O record is superimposed on the benthic δ¹⁸O original signal.
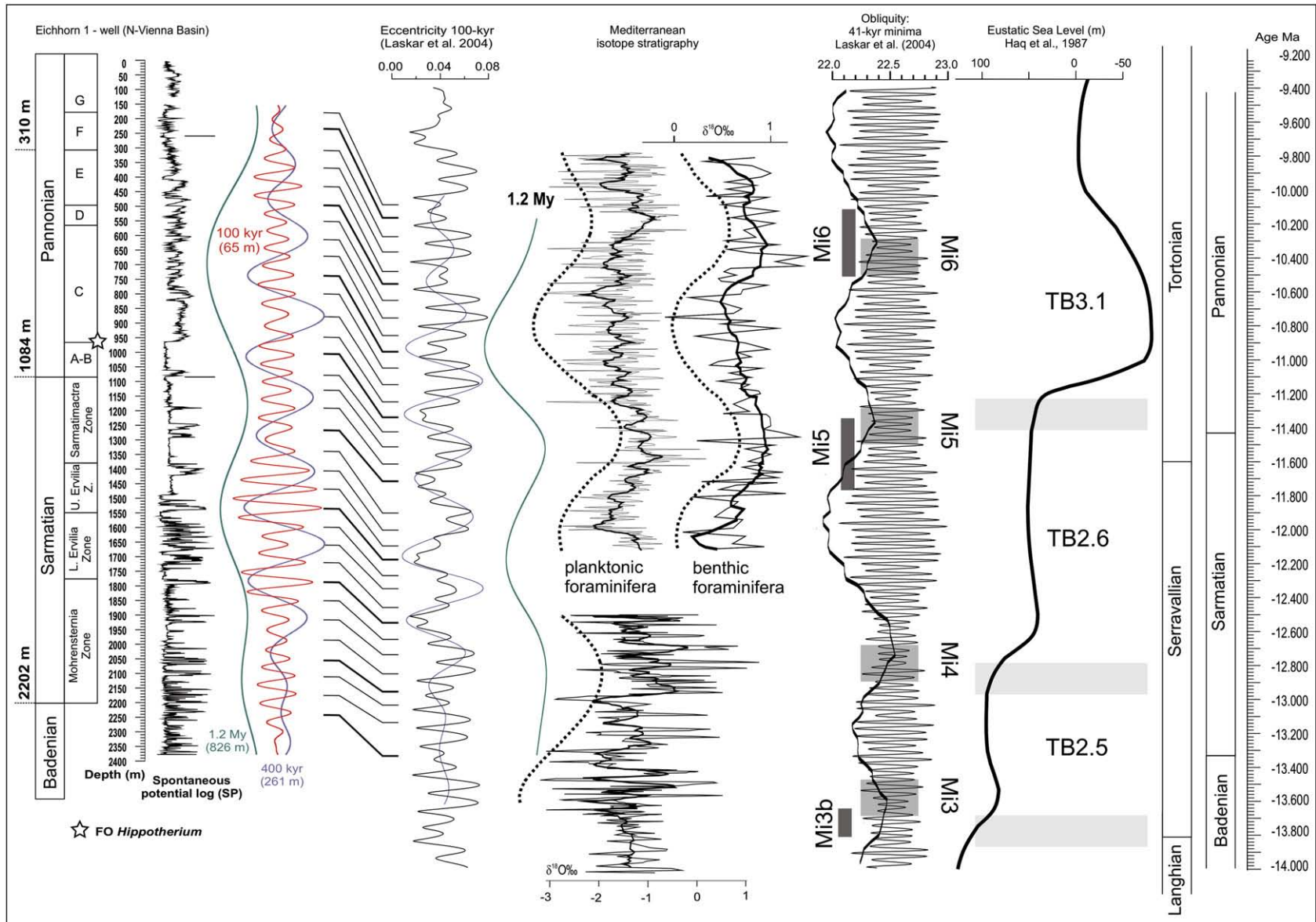
Fig. 8. Integrated stratigraphy of the Eichhorn 1 well based on Harzhauser et al. (2004), Harzhauser and Piller (2004a,b) and unpublished reports of the OMV. The letter stages A–G are from Papp (1951). In depth domain: the SP-raw data have been filtered at the 400-kyr (blue line), 100-kyr (red line) and 1.2 My (green line) frequency bands and superimposed on the SP original data. In time domain: the filtered SP 400-kyr band converted into time domain is compared with the same harmonic component (long eccentricity component) of Laskar et al. (2004). The filtered SP 1.2 My long-period variation of the obliquity cycles (green line) is compared with the 1.2 My filtered component of integrated Mediterranean planktonic δ^{18}O record (Gibliscemi and Malta sections; thick black dotted line), with the 1.2 My filtered component of the benthic δ^{18}O record (Gibliscemi section; thick black dotted line), with the long-period 1.2-My obliquity cycle of Laskar et al. (2004) and with the third-order eustatic sea level curve of Haq et al. (1988) recalibrated by Turco et al. (2001). The thick black line superimposed to the obliquity represents the 5-point moving average of the successive 41 kyr obliquity minima. The black boxes close to the obliquity signal of Laskar et al. (2004) indicate the position of the Mi5 and Mi6 events (Turco et al., 2001) and the position of the Mi3b event (Abels et al., 2005). The light grey boxes superimposed on the obliquity records indicate the position on the Miller events in correspondence with the 1.2-My obliquity nodes (van Dam et al., 2006). The grey bands close to the sea level curve indicate the position of the boundaries between the TB 2.5/TB 2.6/TB 3.1 cycles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
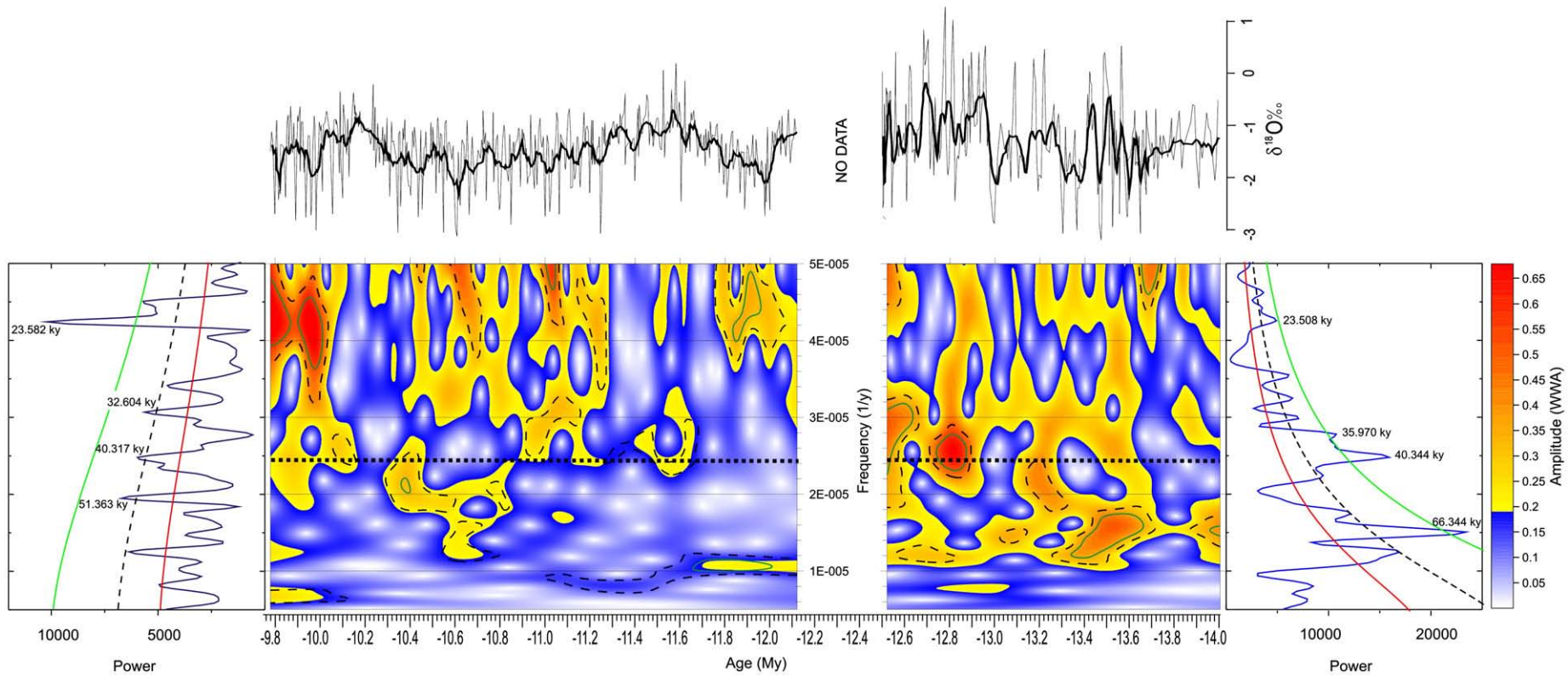
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Fig. 9. Wavelet analysis and power spectra of the integrated Mediterranean planktonic $\delta^{18}O$ record performed of *G. quadrilobatus* (Gibliscemi and Malta sections). Green and black lines in Lomb-Scargle power spectra indicate the 95% and 85% confidence level, respectively. Red solid line indicates the AR(1) theoretical red noise spectrum (Schulz and Mudelsee, 2002). In Wavelet spectrum (Weighted Wavelet Amplitudes-colour chromatic scale) green and black dotted lines indicate the 95% and 85% confidence interval, respectively. The integrated Mediterranean planktonic ^{18}O record (Gibliscemi and Malta sections) is smoothed with a 40 kyr average (solid line). The thick black dotted line represents the position of 41 kyr periodicity along the Wavelet spectrum. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Pannonian boundary (Figs. 4 and 8) well corresponds to the glacio-eustatic event recorded in the Mediterranean by Turco et al. (2001) close to the Mi5 event and associated to a major node of low-amplitude variations in orbital obliquity. It is in excellent agreement with results of Rögl (1998), Harzhauser et al. (2004) and Piller et al. (2007) who correlated the Sarmatian/Pannonian boundary with the 3rd order sea level fall between the Haq cycles TB 2.6. and TB 3.1. It is worth noting that the major extinction event (the "Sarmatian–Pannonian-Extinction-Event" (SPEE) of Harzhauser and Piller, 2007) occurs near to the Sarmatian/Pannonian boundary when the coeval Mediterranean marine record documents drastic changes in the planktonic foraminiferal fauna with the important influxes of neogloboquadrinids from the Atlantic Ocean (Turco et al., 2001; Lirer et al., 2004; Lirer and Iaccarino, 2005). This drastic climatic change is recently recorded also in other Mediterranean sections by a strong decrease in Nd isotope composition measured on calcareous fossils (Kocsis et al., 2008).

Upward, the major regression recorded in the Lake Pannon starting at c. 10.3 Myr with development of floodplains in the Vienna Basin, well corresponds to the interval of Mi6 event with associated another major low-amplitude 1.2 Myr obliquity cycle.

Interestingly, the long warm period, between Mi5 and Mi6, coincides with a maximum in the long-term 2.3 Myr eccentricity cycle, that could have favoured extreme climate conditions, mainly in terms of changes in the evaporation/precipitation budget of the basin, and development of high-frequency alternations between highly stratified water column and reducing bottom environments (with deposition of lignite) and normal oxic sediments (with deposition marly intervals) (Figs. 4 and 8).

The new astronomical age proposed for the Badenian/Sarmatian boundary does not coincide neither with minima in the 1.2 Myr obliquity curve nor any Miller event (Fig. 8). This contrasts with the interpretation of Harzhauser and Piller (2007) who correlated the Badenian/Sarmatian boundary with the sea level drop between the TB 2.5 and TB 2.6 cycles of Haq et al. (1988) at c. 12.7 Myr close to the Mi4 event of Miller et al. (1991), dated by Turco et al. (2001) at 12.9 Myr.

Nevertheless, the new calibrated age of the Badenian/Sarmatian boundary and direct correlation with the insolation curve supports paleoclimatic and paleoecologic data (Harzhauser and Piller, 2007) that indicate temperate climates for this time interval, while the transitional phase from a cooler Early Sarmatian to a warmer Late Sarmatian clearly coincides, based on the new astronomical tuning of the record, with the glacio-eustatic isotope event Mi4 with the entire Late Sarmatian spanning a complete entire 1.2 Myr obliquity cycle.

Last but not least wavelet analyses of the $\delta^{18}O$ records from Mediterranean and of SP Central Paratethys data indicate that the 41 kyr Milankovitch periodicity is lacking in the Eichhorn 1 succession during the lower Pannonian interval (Fig. 3) while in the Mediterranean it is continuously present for all the coeval early Tortonian–Serravallian time interval (Fig. 9). This supports the view of a primary sea level control on the relationship between the Mediterranean and Central Paratethys realms and suggests a more definitive separation among them at about 11.4 Myr when sea-level 41 kyr cyclicity, globally controlled by variations in the ice volume, did not influence any more the continental record.

6. Conclusions

Astronomical tuning of the Eichhorn 1 well Paratethyan record in the Vienna Basin definitively confirms an age of 11.42 Myr for the Sarmatian/Pannonian boundary, close to the global marine isotope Mi5 event. It coincides with a period of minimum in the 1.2 Myr obliquity cycle, which corresponds in the Mediterranean marine record to a drastic change in the planktonic foraminiferal fauna. Similarly, the change from lacustrine to floodplain deposits in the Vienna Basin, triggered by a retreat of Lake Pannon, coincides with the global marine isotope Mi6 event and an other minimum in the 1.2 Myr

obliquity cycle. Once again, the minimum in the 1.2 Myr obliquity cycle during the Sarmatian Stage (in coincidence with the global marine Mi4 event) corresponds to a major change in the environmental system of the Central Paratethys from a temperate siliciclastic depositional (characteristic of Early Sarmatian deposits) to the warmer carbonate of the Late Sarmatian (Piller and Harzhauser, 2005). Finally, the Badenian/Sarmatian boundary seems not to coincide with any global glacio-eustatic event suggesting a regional geodynamical control on the isolation of the Paratethys Sea from the global ocean.

Although characterised by very different sedimentary environments, the Central Paratethys realm appears strongly influenced by glacio-eustatic sea level oscillations and directly forced, in terms of environmental responses, by the classic Milankovitch frequencies that allows accurate correlations with marine records. A more definitive break in the communications between Central Paratethys and Mediterranean realms at the base of the Pannonian stage is clearly reflected by the loss of obliquity control on the sedimentary variability of the continental record, although eccentricity forcing maintains its significant influence on that.

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