Newsletters on Stratigraphy, Vol. 53/1 (2020), 19–39 **Stratigraphic News**

Should Unit-Stratotypes and Astrochronozones be formally defined? A dual proposal (including postscriptum)

Frits Hilgen[1]*, Lucas Lourens[1], Heiko Pälike[2] and research support team**

With 5 figures

Abstract. The Global Stratotype Section and Point (GSSP) approach to define stage boundaries leaves the unit or body of the stage undefined. At the same time, previous arguments against the use of unit-stratotypes have been invalidated for the younger Cenozoic part of the geological record through the revolutionary advance in integrated high-resolution stratigraphy and astronomical dating. Combined, these provide unprecedented age control and ensure continuity of sedimentary successions, at least within the time scales of the calibrated astronomical-forced climate oscillations, and offer the possibility to introduce amended unit-stratotypes for global stages. Here we propose that such unit-stratotypes should comprise the entire stage in an astronomically age calibrated deep-marine succession, preferably but not necessarily containing the GSSP. Furthermore, cycles used for the tuning can be formally defined as chronozones, i. e. chronostratigraphic units of either unspecified rank or of a smaller scale than the stage, and independent of the standard hierarchy in global chronostratigraphy. In this way, the standard Geological Time Scale and Global Chronostratigraphic Scale can be brought in line with the progress in integrated high-resolution stratigraphy and astronomical dating. However, the more fundamental formal definition of unit-stratotypes does not depend on the formalization of astrochonozones, and both issues should be separately considered and voted upon.

Key words. Keywords. Astronomical dating, unit-stratotype, global chronostratigraphy, astrochronozones, stages, GSSP

1. Introduction

Following their definition in the 19th century, stages, nowadays the basic building blocks of chronostratigraphy, were regarded in widely different ways with unit-stratotypes being one of them (Walsh et al. 2004). To overcome this unwelcome situation, Hedberg (1958) proposed that boundaries of time stratigraphic units should be formally defined in some type section or area. Initially emphasis was placed on unit-stratotypes (ISST 1961, body stratotype of Harland 1978), i. e. sections in which both the body and the boundaries of a chronostratigraphic unit were defined at the same time. However, this soon changed in favour of the boundary stratotype and, eventually, the GSSP, as it was at that time impossible to define unit-stratotypes as continuous segments of time in the rock record without gaps and/or overlaps (Hedberg 1976, Cowie 1986, Salvador 1994, Remane et al. 1996). In the case of boundary stratotypes and GSSPs, only the boundaries

---

Authors' addresses:
[1] Department of Earth Sciences, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands
[2] MARUM-Center for Marine Environmental Sciences, University of Bremen, Leobener Strasse, 28359 Bremen, Germany
* Corresponding author: F. J.Hilgen@uu.nl
** Research support team: S. J. Batenburg, S. Bohaty, S. Boulila, J. Dinarès-Turell, A. Gale, T. Herbert, L. A. Hinnov, D. Kroon, K. F. Kuiper, M. Martinez, P. R. Renne, U. Röhl, F. J. Sierro, A. C. da Silva, N. Thibault, D. de Vleeschouwer, T. Westerhold, C. Zeeden

DOI: 10.1127/nos/2019/0514
www.borntraeger-cramer.de
0078-0421/2019/0514 $ 5.50

of a chronostratigraphic unit are designated as these best define the time interval, which is its main characteristic (e. g., Walsh et al. 2004). In practice, to avoid time stratigraphic correlation problems, only the lower boundary of a stage is defined by a GSSP, the upper one being automatically defined by the lower boundary of the next younger stage (Salvador 1994).

The switch from unit-stratotypes to boundary stratotypes took place around the same time that the deep-sea drilling project (DSDP) was initiated. DSDP provided crucial data to substantiate theories of sea-floor spreading and plate tectonics. However, an important goal of DSDP was to extend the deep-sea record of the Ice Ages provided by single piston coring for the upcoming paleoceanographic community. Single piston cores had demonstrated that continuous records of Ice Age history could be retrieved from the deep-sea (Emiliani 1955, Ericson et al. 1961). This development eventually culminated in the Hays et al. (1976) milestone paper, which showed that the history of the Ice Ages of the last 450,000 years was paced by variations in the Earth's orbital and inclination parameters.

DSDP and its successors ODP and IODP succeeded to recover continuous successions even though the deep-sea record proved to be punctuated by hiatuses as well (e. g., Keller and Barron 1983, Keller et al. 1987). This was especially achieved by technological innovations combined with the multiple hole drilling strategy to overcome problems at core breaks (Ruddiman et al. 1987). At present, paleoclimate oriented expeditions are able to recover complete if not continuous records of paleoclimate change over many millions of years from carefully selected sites often arranged along preferred drilling transects (e. g., Pälike et al. 2012). Carefully constructed splices provide the base for astronomical tuning of continuous records, providing maximum age control necessary for understanding pre-Pleistocene climate and climate change in detail (e. g., Zachos et al. 2004, Westerhold and Röhl 2005, Holbourn et al. 2013). At the same time, similar high-resolution integrated stratigraphic studies, including astronomical tuning, were carried out on land-based marine sections (Hilgen 1991a, Hilgen 1991b, Lourens et al. 1996, Hüsing et al. 2009).

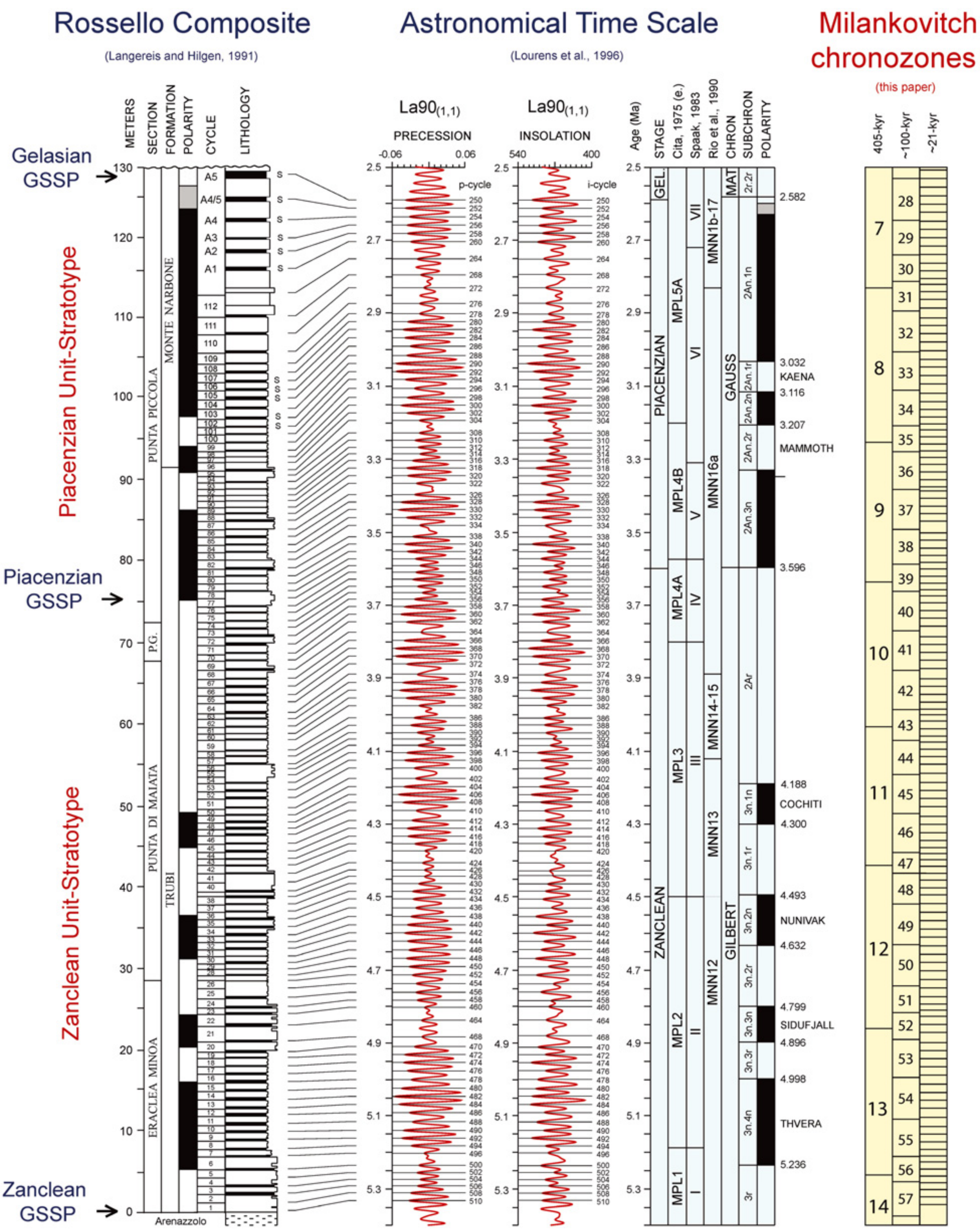
The latter developments were adopted by the Neogene community for defining GSSPs of Neogene stages in tuned deep-marine sections, which had previously been selected as neostratotypes for the less suitable historical stratotypes; they may now serve as unit-stratotype for the pertinent stages (Hilgen et al. 2006). In fact, astronomical tuning has been added as a key requirement to the list of conventional requirements to define remaining Neogene GSSPs (Hilgen et al. 2009).

While high-resolution integrated stratigraphy and astronomical dating are used to build the standard GTS and global chronostratigraphic scale, unit-stratotypes and associated astronomically age calibrated chronozones are not formally defined. Yet, astronomical dating increasingly underlies the age calibration of the GTS and astronomically calibrated cycles are widely applied by the paleoclimate community (e. g., global Marine Isotope Stages of Emiliani (1955) and Lisiecki and Raymo (2005); sapropel layers of Hilgen (1991 a) and Lourens et al. (1996) in the Mediterranean). In the following we will outline our concept of amended unit-stratotypes, give possible examples of such unit-stratotypes and the accompanying astronomically age calibrated chronozones, and discuss why it is logical to formally define these and incorporate them in the standard chronostratigraphic scale.

2. Unit-stratotypes and astrochronozones

The term unit-stratotype is in principal a general term that is not only used in chronostratigraphy, but also for instance in lithostratigraphy (Murphy and Salvador 1999). However, in this proposal, we specifically refer to unit-stratotypes in their chronostratigraphic sense. According to our amended definition, unit-stratotypes should cover the entire range of a chronostratigraphic unit in a demonstrably continuous succession whether in outcrop or deep-sea cores. The ultimate proof for continuity comes from the cyclic variability that is

Fig. 1. The Rossello Composite Section (RCS, Sicily, Italy) as revised unit-stratotype for the Zanclean and Piacenzian Stages of the Pliocene and of the Pliocene Series, showing the orbital tuning of the basic precession-related sedimentary cycles and the resulting astronomical time scale with accurate and precise astronomical ages for sedimentary cycles, calcareous plankton events and magnetic chron boundaries. The Zanclean and Piacenzian GSSPs are both formally defined in the RCS, while the level that time-stratigraphically correlates with the Gelasian GSSP is present in the topmost part of the section. The RCS lies at the base of the Pliocene part of the Neogene Time Scale and the Global Standard Chronostratigraphic Scale. The astronomical indu-



ced cycles in the RCS define Milankovitch chronozones linked to long (405-kyr) and short (~100-kyr) eccentricity, and to precession. The eccentricity related cycles have been numbered by counting eccentricity maxima back from the Recent, but different codification schemes are possible. Precession-related cycles are designated from precession maximum to precession maximum. See further Cita and Gartner (1973), Cita (1975), Langereis and Hilgen (1991), Hilgen (1991 b) and Lourens et al. (1996). Modified after Hilgen et al. (2006).

either expressed in intrinsic (i. e. lithology bound parameters such as colour, etc.) or extrinsic (such as stable isotopes) variables; these should have been calibrated to astronomical target curves of precession, obliquity, eccentricity, or insolation computed by means of an astronomical solution of the Solar System to provide optimal high-resolution age control. This progress paves the way for the formal definition of unit-stratotypes that are based on astronomically age calibrated chronozones, or shortly astrochronozones.

At present, the best example of this approach are the stage unit-stratotypes defined in the Rossello composite section (Hilgen et al. 2006, Gradstein et al. 2012, Fig. 1). This section contains an entire series, the Pliocene and its constituent stages, the Zanclean and Piacenzian, in a continuous deep marine succession that has been astronomically calibrated and that underlies the – age calibration of the – standard GTS for this interval of time (Lourens et al. 2004, Hilgen et al. 2012). The Zanclean and Piacenzian GSSP have been formally defined in the Rossello composite section (Castradori et al. 1998, Van Couvering et al. 2000), while the Gelasian GSSP, itself being formally defined in the Monte San Nicola section (Rio et al. 1998), can readily be identified on the basis of the correlative sapropel in the topmost part of the section (Fig. 1). Resultant astronomically calibrated ages for bio-events, magnetochrons and stage boundaries in the Rossello composite section were first incorporated in

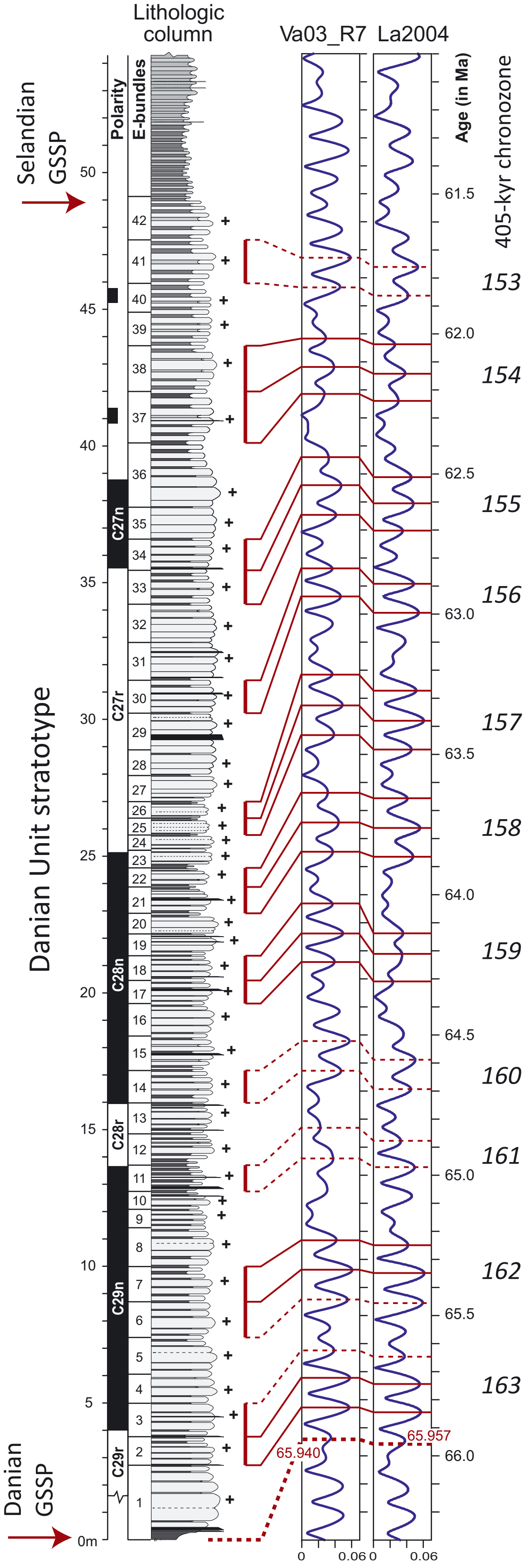


Fig. 2. The Zumaia section as potential unit-stratotype for the Danian (from Gradstein et al. 2012, see also Dinarès-Turell et al. 2014). E-bundles refer to the numbered cycles in the Zumaia section that are related to short ~100-kyr eccentricity (see Dinarès-Turell et al. 2003). The Danian GSSP is formally defined at El Kef in Tunesia, but Zumaia has been designated an auxiliary section for defining the boundary (Molina et al. 2009). The Selandian GSSP is defined at the top of the "Danian" limestones at Zumaia. The sedimentary cycle pattern is tuned to the eccentricity time series of different astronomical solutions. The 405-kyr eccentricity cycles are numbered as 405-kyr chronozones back from the Recent and, once the tuning is confirmed, may serve to define and label correlative 405-kyr limestone-marl cycles as – Milankovitch – chronozones. As a matter of fact, the marly parts of these carbonate cycles, indicated by the vertical red bars next to the lithological column and corresponding to 405-kyr eccentricity maxima, have been labelled. Va03_R7 and La 2004 indicate astronomical solutions from respectively Varadi et al. (2003) and Laskar et al. (2004) used to calculate the eccentricity time series shown in the figure.

the Cande and Kent (1995) and Berggren et al. (1995) time scales. These ages were also adopted in GTS2004 and GTS2012 (Lourens et al. 2004, Hilgen et al. 2012), and essentially remained the same apart from minor changes, as a result of the replacement of the Ber90 solution (Berger and Loutre 1991) by La93 (Laskar et al. 1993, Lourens et al. 1996) and of La93 by La2004 (Laskar et al. 2004, Lourens et al. 2004). This stability is an important advantage of astronomical dating as ages will not change significantly anymore once the underlying tuning is correct.

Other examples now include the Monte dei Corvi section as unit-stratotype for the Tortonian Stage of the Miocene (Hüsing et al. 2009) and the Zumaia section as unit-stratotype for the Danian Stage of the Paleocene (Fig. 2; Gradstein et al. 2012, Dinarès-Turell et al. 2014). The Tortonian GSSP has been defined at Monte dei Corvi (Hilgen et al. 2005), while the base of the next younger stage of the Messinian can be readily identified on the basis of the integrated high-resolution stratigraphy. At Zumaia, the Selandian GSSP has been placed at the top of the Danian limestones (Schmitz et al. 2011), while the Danian base and, thus, per definition Cretaceous-Paleogene (K/Pg) boundary can be recognized by the boundary clay (Bernaola et al. 2006), although the Danian GSSP itself is defined at El Kef in Tunisia (Molina et al. 2006). In 2009, the Zumaia section was selected as an auxiliary boundary stratotype section for the K/Pg boundary (Molina et al. 2009).

In all these sections, sedimentary cycles used for tuning can be formally defined as chronozones (Hilgen et al. 2006). These cycles can be codified back from the Recent using the number of the correlative orbital, inclination or insolation cycle. Sapropels and correlative grey marl layers in precession-related carbonate cycles in the Rossello Composite have been given the number of the correlative summer insolation maximum (Lourens et al. 1996). Further, a strong trend exists already in literature to number eccentricity controlled cycles associated with the short ~100-kyr and in particular the long 405-kyr cycle, albeit informally and in an inconsistent way. For the older part of the Cenozoic and younger part of the Cretaceous, the large-scale 405-kyr eccentricity related cycles are particularly useful, also because the 405-kyr cycle is the only stable cycle left for tuning beyond ~50 Ma, due to the chaotic behaviour of the Solar System (Laskar et al. 2011, Westerhold et al. 2012). Thus, the Danian part of the Zumaia section contains the sedimentary expression of 405-kyr eccentricity cycles nos. 153 to 163 (Fig. 2; Gradstein et al. 2012, Dinarès-Turell et al. 2014), while the Maastrichtian in the Zumaia-Sopelana composite covers cycles 164 to 176 (based on Batenburg et al. 2014). The Rossello Composite holds cycles 7 (partial) to 13, and part of 14, but in this case the ~100-kyr and precession/obliquity-related cycles can be defined and numbered as well (Fig. 1). The same is true for the Monte dei Corvi section, which encompasses 405-kyr cycles nos. 19 to 28. Wade and Pälike (2004) introduced a different codification scheme numbering the 405-kyr minima (for glacial events) back from the Recent and adding a subscription code, which combines the geological epoch with the magnetochron closest to the 405 kyr minimum. Such a scheme was also added to the low-latitude standard planktonic foraminiferal zonation and biochronology for the last 41 million years, while 405-kyr cycles beyond Chron C19 n remained unnamed in anticipation of the uncertainty in and completion of the Paleogene ATS (Wade et al. 2011).

In addition to the 405-kyr eccentricity related cycles, the 100-kyr eccentricity, and precession and obliquity related cycles can be incorporated in such a scheme as well, as long as the astronomical solution is reliable for these parameters. The most recent La2011 solution is reliable back to ~50 Ma for full eccentricity, and ~100-kyr eccentricity related cycles can be numbered back to around this age. The tuning to and codification of 405-kyr cycles can be continued beyond 50 Ma, as this cycle remains stable as mentioned before. For precession and obliquity, the Earth-Moon system has to be solved in the astronomical solution as well, and parameters like tidal dissipation and dynamical ellipticity start to play a role and complicate the accurate computation of both precession and obliquity. Based on a detailed comparison with sedimentary cycle patterns, this limits the reliability of the solution for precession and obliquity at present back to 10–15 Ma (Hüsing et al. 2010, Zeeden et al. 2014).

3. Deep-sea drilling and cores

Shallow-marine and continental successions are less suitable for defining unit-stratotypes and chronozones, as they often contain hiatuses, while cycle patterns related to the combined influence of precession, obliquity and eccentricity are most clearly recorded in deep marine (hemi-)pelagic successions. In principle, lacustrine successions may also be selected, especially in case the tuning approach is extended to the older part

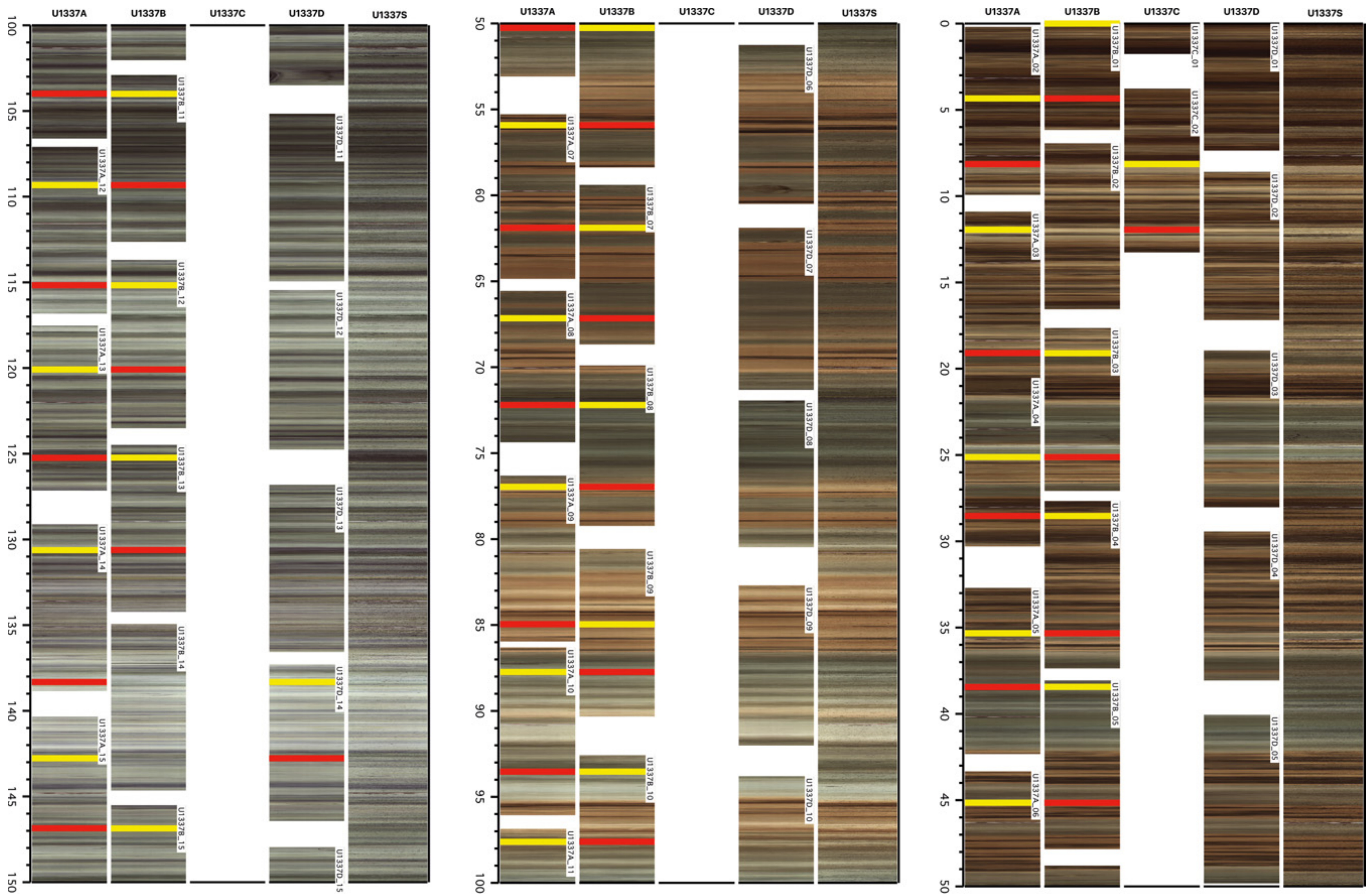


Fig. 3. Sliced core images following the revised composite depth scale for the upper 150 meters of IODP Site U1337 of PEAT Leg 321 (after Wilkins et al. 2013). The panels of the three intervals each show the image of the splice on top followed by images of the cores of the individual holes. For further details the reader is referred to the Wilkins et al. (2013) paper.

of the Mesozoic where truly deep-marine successions become scarce or are no longer available.

However, apart from land-based deep marine sections, numerous deep-sea cores are available from the DSDP-ODP-IODP archives. Until recently, the stratigraphic community seemed predominantly opposed to the idea of using deep-sea cores for global chronostratigraphic purposes, often with the limited amount of material as main argument against their use. However, current procedures for climate-oriented ODP-IODP drilling legs use a multiple hole drilling strategy per site and multiple sites along climate sensitive transects per leg to reconstruct Earth's climate history in increasing detail. Procedures are directed to recover complete if not continuous records that are suitable for astronomical tuning to generate the necessary high-resolution astrochronologic age models for detailed climate proxy studies. In Fig. 3, the revised splice (to overcome the problem of stratigraphic continuity at the core breaks of the ~9 m long individual cores) of the upper 150 meters of IODP Leg 321 Site U1337 is shown as an example of the potential of this archive (from Wilkins et al. 2013). In our opinion, this archive should be taken into account when unit-stratotypes based on astronomically age calibrated chronozones are to be defined, as only the most suitable ("ideal")

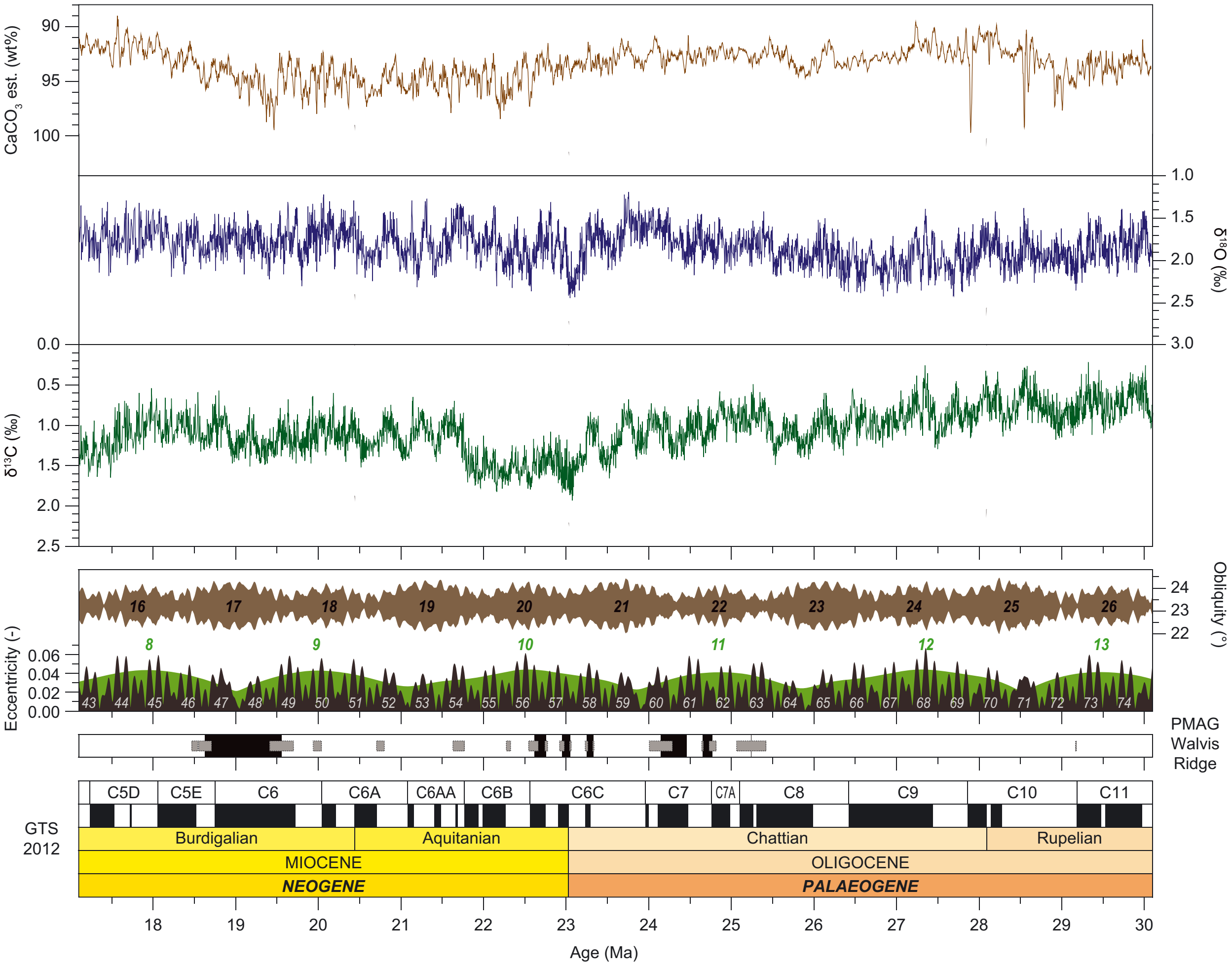


Fig. 4. Astronomically calibrated stable isotope and CaCO$_3$ records of the Oligocene and lower Miocene of ODP Site 1264 at Walvis Ridge, southern Atlantic, for the interval between 17.1 and 30.1 Ma (from Liebrand et al. 2016). The interval covers long 405-kyr eccentricity cycles 43 to 74, as numbered in light blueish in the eccentricity time series of solution La2011_ecc3L (Westerhold et al. 2012) and very long 2.4-Myr eccentricity cycles 16 to 26 (in green). In addition, successive long 1.2 Myr cycles in obliquity amplitude have been numbered in black in the obliquity time series of solution La2004 (Laskar et al. 2004), as they provide in theory alternative astrochronozones. Note that the cyclicity in the climate proxy records is not resolved for higher obliquity and precession related frequencies.

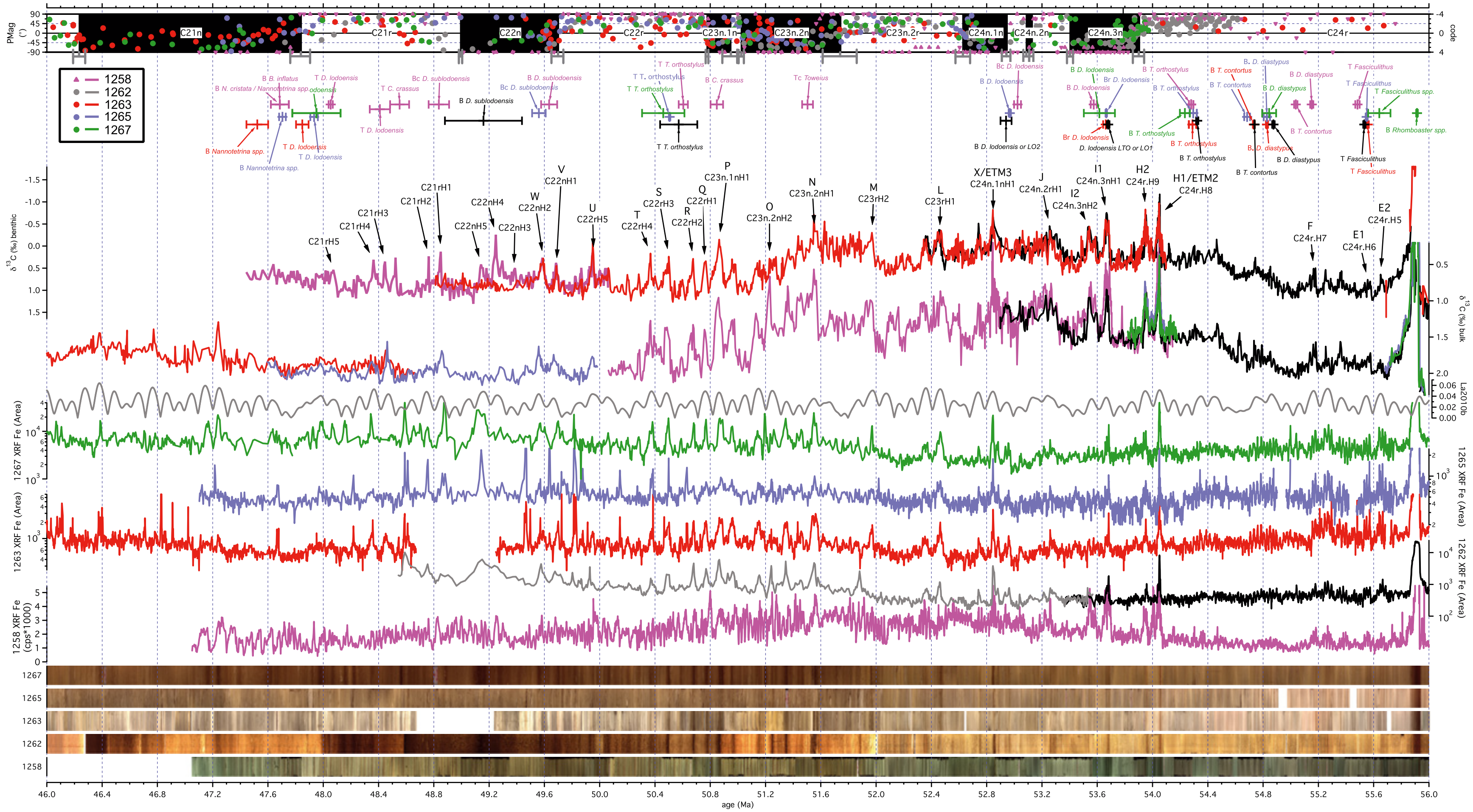


Fig. 5. Integrated stratigraphy and astronomical calibration of deep-sea cores and records for the entire Ypresian (from Westerhold et al. 2017). For details the reader is referred to this paper.

cyclic successions, whether exposed in outcrop or deep-sea cores should be used for this purpose. This deep-sea archive is in many cases superior to that found in time equivalent land-based sections.

Continuous records of the Plio-Pleistocene have been recovered from the deep-sea through single piston coring and deep-sea drilling. These cores have been employed to construct a stacked benthic oxygen isotope record for the last 5.3 Ma astronomically tuned to a modelled ice volume curve (Lisiecki and Raymo 2005). Apart from providing a high-resolution astrochronology, the stack offers an excellent view into the complex history of the Ice Ages. (I)ODP sites have and will continue to produce continuous astronomically calibrated successions for the Miocene and Oligocene. Holbourn and others used a suite of sites from the Indian and Pacific Oceans, including PEAT cores from IODP Legs 320/321, to study the complex climatic history of the Miocene in unprecedented detail (Holbourn et al. 2005, Holbourn et al. 2013, Holbourn et al. 2015). These studies will provide an almost complete Miocene astrochronology, which will likely facilitate defining amended unit-stratotypes and remaining GSSPs in the Neogene. ODP Leg 208 Sites from Walvis Ridge in the southeastern Atlantic have been instrumental in building continuous proxy records for the interval between 19 and 24 Ma, covering 405-kyr cycles 48 to 59 (Liebrand et al. 2011). This record has now been extended back to 30 Ma, or 405-kyr cycle 74, and tuned to 100-kyr eccentricity (Liebrand et al. 2016; Fig. 4). Initially, an astronomical time scale had been developed for the entire Oligocene, using single ODP site 1218 in the equatorial Pacific having an excellent magnetobiostratigraphic age control (Pälike et al. 2006). The latter ODP cores may well serve as candidates for defining Rupelian, Chattian, and Aquitanian unit-stratotypes and GSSPs. In fact, Miller and Wright (2017) already suggested to use deep-sea cores for designating lectostratotypes for the E-O and O-M boundaries, in this case especially for isotopic reference.

Sites from ODP Leg 208 in addition provided complete and (near-)continuous records of late Eocene and Paleocene age (Lourens et al. 2005, Westerhold et al. 2007, Littler et al. 2014). However, the targeted early Paleogene ATS is still in a state of flux, due to the presence of the Eocene gap in the ATS (Pälike and Hilgen 2008), which resulted in different tuning options (Westerhold et al. 2008 2012, Kuiper et al. 2008, Hilgen et al. 2010). These issues are currently being addressed and the Eocene gap will eventually be closed and a final ATS for the Early Paleogene be established (Dinarès-Turell et al. 2014, Hilgen et al. 2015, Westerhold et al. 2015). Already, a fully tuned integrated stratigraphic framework based on multiple ODP-IODP sites has been presented for the Ypresian Stage of the Eocene (Fig. 5 from Westerhold et al. 2017), again showing the excellent quality of this archive. As mentioned before, unit-stratotypes and Milankovitch chronozones for global chronostratigraphic purposes should be based on the most suitable archive that is available to us.

4. The Quaternary and Mesozoic/ Paleozoic

It is not feasible to employ the proposed unit-stratotype approach in the same way throughout the geological record. In the first place, it will likely never be possible to extend the approach beyond the Phanerozoic. In fact, it already becomes increasingly problematical in the Paleozoic and older part of the Mesozoic, due to scarcity of suitable open marine successions. However, at the end, the approach might well be achievable for this time interval (see below). Currently the approach is tailored in particular for the Cenozoic and late Cretaceous, although problems may arise at the younger end of the time scale due to the increasing resolution and time control.

4.1. Quaternary

A logical first thought is to use the existing LR04 benthic oxygen isotope stack for the purpose of defining unit-stratotypes in the Pliocene-Pleistocene. However, a serious drawback from using a stack is that adding new records will immediately affect the stack itself. In addition, the stack is composed of many individual records coming from different localities so that differences will unavoidably arise both from diachroneity in recording the same astronomical controlled signal as well as from added contributions associated with regional/local processes. However, this problem is not limited to the LR04 stack, but holds for all cyclic records as soon as stacking procedures are included. For instance sapropel formation may locally start earlier or later as a consequence of differences in thresholds that arise from differences in (sub)basin configuration. A stacked sapropel record will thus encounter essentially the same problems as

LR04, and the same also holds for instance for carbonate dissolution cycles along paleo-water depth transects on submarine highs (e. g. Kroon et al. 2007). As this issue is a consequence of the stacking itself, one may only select the most suitable individual oxygen isotope or sapropel record for defining global chronostratigraphy. A Mediterranean based composite unit-stratotype for the Plio-Pleistocene will also be advantageous, as a benthic isotope record is now directly attached to it, which allows identification of all the Marine Isotope Stages of the LR04 isotope stack (unpublished). Such a Mediterranean unit-stratotype is further appropriate as the position of GSSPs defined outside the Mediterranean can (as) accurately (as possible) be transferred to the unit-stratotype, using an integrated stratigraphic approach. This implies that it is not necessary to redefine existing GSSPs, which are not already defined in the unit-stratotype, even though this might be favoured in case new boundaries are defined in the future. However, the application of auxiliary or lectoboundary stratotypes in addition to the unit-stratotype might become a normal procedure in global chronostratigraphic procedures (see also Miller and Wright 2017).

The differences and uncertainties in age of cyclic signals recorded in individual records that result from uncertainties and differences in the phasing relative to the astronomical forcing are in the order of only several kyr. Such departures start to play an increasing role in the late Quaternary, but are essentially negligible in older time intervals, also because Cenozoic GSSPs cannot be dated better and correlated more accurately as time line away from the GSSP. This uncertainty has to be compared with the substantial differences between successive conventional time scales in the past (and now still present in the Mesozoic and Paleozoic parts of our GTS). By contrast, the recent developments in integrated high-resolution stratigraphy and astrochronology have the clear prospect to provide a stable GTS for at least the last 100 million years. Such a time scale only has to undergo minor changes when a new improved astronomical solution is published, but differences will likely be small, in the order of tens of thousands of years. At present the maximum uncertainty in the age of the 405-kyr eccentricity cycle is estimated to be 150 kyr at 100 Ma for solution La2004 (Hinnov and Hilgen 2012). The maximum difference between La2004 and the La2010 solutions is one full 405-kyr cycle at 250 Ma (Laskar et al. 2011).

4.2. Mesozoic/Paleozoic

Extension of the proposed unit-stratotype approach back into the Mesozoic and Paleozoic will be difficult, but is certainly feasible. The problems are partly due to the increasing scarcity to non-existence of truly deep marine pelagic successions, but are also related to less research efforts in this direction. Nevertheless, a tuned integrated stratigraphic framework has already been constructed for the Maastrichtian, the youngest stage of the Cretaceous, based on a combination of deep-sea cores and land-based marine sections (Husson et al. 2011, Thibault et al. 2012, Batenburg et al. 2012, Batenburg et al. 2014). Moreover, several cyclic sections and cores provide good candidates for unit-stratotypes in the Mesozoic, such as St. Audries Bay in the UK for the Hettangian (Ruhl et al. 2010, Hüsing et al. 2014), the Piobbico-Cismon cores in Italy for the Aptian and Albian (Grippo et al. 2004), the Libsack core in the Western Interior Basin of the US for the Coniacian and Santonian (Sageman et al. 2014) and Seaford Head in the UK for the Santonian (Thibault et al. 2016). Also for the Paleozoic, potential unit-stratotypes are already available for the Frasnian, Givetian and Pragian Stages of the Devonian (De Vleeschouwer et al. 2012, De Vleeschouwer et al. 2015, Da Silva et al. 2016) and for the Wuchiapingian and Changhsingian Stages and, thus, the Lopingian Series of the Permian (Wu et al. 2013), but such results need to be independently confirmed in other sections and/or cores. Clearly aiming at the ultimate goal of designing unit-stratotypes for the entire Mesozoic and Paleozoic will help to identify suitable sections. In addition, continental drilling such as the Mochras drilling project for the Lower Jurassic (Hesselbo et al. 2013, Ruhl et al. 2016) will play a crucial role in accomplishing this goal, especially when linked to natural outcrops.

5. Application of the ATS

The need for formally defining unit-stratotypes and associated astronomically calibrated chronozones also depends on the applicability of the ATS in solving fundamental problems in Earth history. In fact, the construction of the ATS has largely been driven by the aspiration to solve such problems, which are generally, but not exclusively related to paleoclimatology. Thus astrochronology played and continues to play a critical role in unravelling among others the complex history of human and mammal evolution and dispersal (e. g., van Dam et al. 2006, Joordens et al. 2011, Larrasoaña et al. 2013), Cenozoic ice ages (e. g., Hays et al. 1976, Holbourn et al. 2013) and hyperthermals (e. g., Zachos et al. 2010, Littler et al. 2014), the global carbon cycle (e. g., Pälike et al. 2006), and the Messinian Salinity Crisis (Krijgsman et al. 1999, Hilgen et al. 2007, Hüsing et al. 2009, Manzi et al. 2013, Roveri et al. 2014), and in detecting the signature of the chaotic behaviour of the Solar System (e. g. Olsen and Kent 1999). As far as the Eocene hyperthermals are concerned, the astrochronologic framework already starts to include the terrestrial record (Abdul-Aziz et al. 2008, Abels et al. 2012, Abels et al. 2013) as well as the East Greenland flood basalts, based on single crystal U/Pb zircon dating (Wotzlaw et al. 2012). The latter is made possible through the intercomparison between and intercalibration of the most important numerical dating methods of astronomical tuning, and Ar/Ar and U/Pb radio-isotopic dating. This intercomparison and intercalibration (Kuiper et al. 2008, Wotzlaw et al. 2013, Wotzlaw et al. 2014) guarantees that astronomical dating is consistent with both single crystal ^{40}Ar/^{39}Ar sanidine and U/Pb zircon dating and that these independent dating methods will in principal produce the same age when dating the same geological event (e. g. Wotzlaw et al. 2014). This is important as in that case radio-isotopic ages can be employed as constraints for extending the tuning back in time, even in case gaps are present in the ATS (Kuiper et al. 2008, Pälike and Hilgen 2008). Furthermore, it guarantees that the Cenozoic ATS can be smoothly linked to older parts of the standard GTS that mainly use radio-isotopic dating for age calibration.

6. Discussion

6.1. The empty stage GSSP

In Gradstein et al. (2012), the question was raised whether chronostratigraphy would "*not be served best if suitable sedimentary sections could be identified on Earth that harbour both the complete body of rock and the upper and lower boundaries of stages in one and the same section*". They state that this is now within reach due to the recent developments in astronomical tuning and integrated high-resolution stratigraphy, and argue that "*astrochronology invalidates arguments against unit-stratotypes*", and "*At the same time, due to the geochronologic quality of the tuned cycle units, it elegantly combines chronostratigraphy with geochronology. It argues in favour of a reconsideration of the unit-stratotype concept, and, as a consequence, a strengthening of the dual classification of chronostratigraphy (time-rock) and geochronology (time*)". Gradstein et al. (2012) thus follow the line of reasoning outlined in Hilgen et al. (2006), which opposes proposals against a separate set of terms for the time-rock domain (Harland et al. 1990, Walsh 2001, Zalasiewicz et al. 2004, but see also Zalasiewicz et al. 2013), and forms the basis of the current proposal.

Our concern about the so-called *empty* stage is also shared by Aubry (2007), who states that there is more to stratigraphy than the conventional chronostratigraphic boundaries. She specifically argues that GSSPs should be inserted in a global framework of correlation with reference sections in both neritic and terrestrial settings and that complementary chronohorizons should be selected between GSSPs. In practice, astrochronology in combination with integrated high-resolution stratigraphy already provides such a detailed 4-D stratigraphic framework, as part of the ATS, in which stratigraphic information can be incorporated as accurately as possible, pending on the quality of that information. As stated before, such frameworks have been or are currently being developed, both for the Neogene and Paleogene, and into the Mesozoic (Hilgen et al. 2015). Moreover, they already incorporate or start to incorporate shallow marine and continental successions (e. g., Naish et al. 1998, van Vugt et al. 1998, Abdul-Aziz et al. 2003, Abdul-Aziz et al. 2008, Prokopenko et al. 2006, Abels et al. 2012, Abels et al. 2013, see further Hilgen et al. 2015).

6.2. Fallibility and genetic connotations

The need for revision of chronostratigraphic concepts and the definition of existing GSSPs has further been discussed in some detail by Walsh et al. (2004). They are sceptical about the necessity of relocating existing GSSPs in astronomically tuned sections, arguing that "*all means of correlation are potentially fallible, because all such methods depend on assumptions that, no matter how reasonable and productive at present, may be overturned or modified in the future with additional evidence*". Indeed, one may argue that genetic connotations should be avoided, but this is not necessary if a concept and its application are widely accepted by a community. Pertinent examples are the tree ring chronology used for the numerical calibration of the radiocarbon curve (e. g., Stuiver et al. 1986, Friedrich et al. 2004, Reimer et al. 2013) and the Swedish Time Scale of de Geer (1912), based on annual varves. Especially the comparison with dendrochronology is illustrative in the way we may proceed with astrochronology based on astronomical climate forcing in the future, as outlined in the present proposal. In the case of astronomically controlled cycles in the stratigraphic record, their presence, in particular in deep-marine sediments, and their application in building high-resolution time scales are widely, but not unanimously, accepted by the stratigraphic community. In our opinion, the fact that the age calibration of the standard Geological Time Scale of the Cenozoic is largely based on astronomical dating would not have been possible without such a broad acceptance by our community.

Walsh et al. (2004) are apparently unaware of the implications of astrochronology, especially in combination with integrated high-resolution stratigraphy, for chronostratigraphy and thereby Earth history. The Pliocene ATS was published more than 20 years ago, but has remained unchallenged, apart from a recent attempt that was proven wrong (Colleoni et al. 2012, Colleoni et al. 2014, Hilgen et al. 2014), and ages remained basically the same. Further, it is preferable to have the GSSP defined in the tuned unit-stratotype of the stage, but this is not strictly necessary, and astrochronology should not simply be regarded as just any other means of correlation; it is directly numerically dated and intercalibrated with independent radioisotopic dating methods, and underlies the age calibration of the standard GTS. Finally, Walsh et al. (2004) agree with the suggestion of Carter et al. (1999) that astrochronologic criteria should be added to the list of conventional criteria for defining GSSPs, but this was already common practice within the Neogene community for defining GSSPs at that time.

6.3. Climatostratigraphic rather than chronostratigraphic units?

Another possible point of criticism is that astronomical-induced variations in the stratigraphic record, such as marine isotope stages, should be considered climatostratigraphic units rather than chronostratigraphic units (Railsback et al. 2015). However, due to their inherent nature, they also have a chronostratigraphic connotation, and not only in a relative, but also in a numerical sense, as such variations have been calibrated to astronomical target curves (of precession, obliquity, eccentricity or insolation) derived from an astronomical solution of the Solar System. One may argue that a strict temporal significance is not correct as e. g. response times of different parts of the climate system and mixing times of the ocean have to be taken into account. Such a delayed response is not only relevant for the Quaternary, but also for the Neogene, for instance when assumptions have to be made about phase relations between astronomical forcing and climate response in order to employ cyclostratigraphic details to constrain tidal dissipation/dynamical ellipticity in the astronomical solution (e. g., Zeeden et al. 2014). However, on geological time scales, astronomically controlled cyclicity in the stratigraphic record is so close to a strict temporal meaning that they can be used for that purpose without problem. Thus, we do not consider the exact phase relation with the astronomical forcing an issue, especially not for the pre-Quaternary part of the Cenozoic, as the potential differences in age (with a quarter of the period as the maximum for the response time) are small compared to uncertainties in exporting a global (chronostratigraphic) stage boundaries away from their GSSP as a time line.

The comparison with magnetostratigraphy and magnetozones (or magnetostratigraphic polarity zones) by Railsback et al. (2015, p. 102) as argument to name Marine Isotope Stages zones rather than stages is interesting, as the term magnetochronozone is used for the chronostratigraphic equivalent of magnetozones recorded in the rock record and magnetochrons for their geochronologic equivalent (Murphy and Salvador 1999). As with cyclostratigraphy, similar problems with a minor degree of diachroneity are encountered when magnetic reversal boundaries are studied in detail, partly due to the recording process (i. e., delayed acquisition), but also due to true diachroneity in the process of reversing the Earth’s magnetic field. However, the position and age of magnetic chron boundaries in the polarity time scale are always based on the rock record, whether derived from astronomically dated magnetostratigraphy or radio-isotopically dated seafloor anomaly profiles.

By contrast, the proposed labelling scheme for astrochronozones starts from the astronomical solution and the numbering of successive orbital, inclination or insolation cycles in that solution. These numbers and the corresponding ages are then transferred to the correlative cycle in Earth´s climatic archives, irrespective of the relative small uncertainties in response times outline above. Thus, although the expression of these cycles in the stratigraphic record may be labelled as zones, their correlation to astronomical target curves identifies them as chronozones in a chronostratigraphic sense (within the uncertainties in e. g. the phase) and chrons in a geochronologic sense. At present, such astrochronozones form the foundation for the age calibration of the standard GTS and the unit-stratotype approach that we propose. Note that the ages and possibly even the labelling of the chronozones may slightly change if new astronomical solutions become available and that such a numbering scheme can only be applied as long as the pertinent astronomical parameter is reliable in the solution. In that respect, the publication of new solutions is not fundamentally different from revising the age of a standard or the value of a decay constant or any other physical parameter that underlies the age determination in radio-isotopic dating.

6.4. Do we really need unit-stratotypes and astrochronozones?

Nevertheless, the question that remains is whether we need to formally define unit-stratotypes based on astrochronozones, even though it seems fully justified to do so. Odin et al. (2004) separates the Pliocene-Pleistocene from the older part of the rock record because of its excellent archives, both marine as well as continental, and the large number of stratigraphic tools available for reconstructing its history. They further state that there is no principal stratigraphic tool to record Plio-Pleistocene history, although in our opinion marine isotope stages (MIS) provide the most detailed astrochronologic framework. Odin et al. (2004) then continue to argue that the different integrated stratigraphic scales (e. g., δ^{18}O, magnetostratigraphy) have accurate and precise numerical ages attached to them so that reference sections and GSSPs are not needed. And: "*This simplifies the establishment of pertinent conventions, for they are replaced by detailed knowledge about most scales. Among possible units, we admit the traditional and often used subdivisions: Pliocene and Quaternary*". In practice, the paleoclimate community, which is familiar with applying 4D integrated high-resolution and astronomically calibrated stratigraphic frameworks often prefer to use Marine Isotope Stages rather than stages (Shackleton 2006), or use chronostratigraphic terms on the scale of the (sub)series (e. g. Holbourn et al. 2013). In the latter case, one may still prefer to designate unit-stratotypes for series, such as the Rossello Composite for the Pliocene. Once more, this argues for the incorporation of deep-sea cores in constructing such integrated high-resolution frameworks not only for the Pliocene-Pleistocene, but for the entire Cenozoic, and possibly beyond. A final argument in favour of formalization is that it would provide a means to decide on the best possible astrochronology, unit-stratotypes and astrochronozones, underlying our standard GTS. In that respect, the comparison with dendrochronology and varve chronology, and the way these have been applied to radically improve the youngest part of our time scale is particularly illuminating.

Finally, it should be made clear that the more fundamental issue of the formal definition of unit-stratotypes does not depend on the formalization of astrochronozones, as these can also be labelled informally. Thus, the two issues of the formal definition of unit-stratotypes and astrochronozones should be considered separately and voted upon.

7. Conclusions

Astronomical dating in combination with integrated high-resolution stratigraphy validates reappraisal of the unit-stratotype. In this view and the fact that the age calibration of the standard GTS for the Cenozoic will be almost entirely based on astronomical dating, it seems a logical next step to formally define unit-stratotypes and associated astronomically age calibrated chronozones. This would bring the standard GTS and the underlying global chronostratigraphic scale in harmony with the revolution in stratigraphy brought about by astrochronology in combination with integrated high-resolution stratigraphy. Another reason for this substantial revision of standard formal chronostratigraphic procedures is the prospect that the Cenozoic astronomical time scale (ATS2020) will be completed in the coming years by solving the remaining geological (i. e., cyclostratigraphic) and astronomical uncertainties. This concept further strengthens the dual nomenclature of chronostratigraphy (time/rock) and geochronology (time), as high-resolution relative and numerical dating is in this case directly/intrinsically linked to the rock record itself. In theory, ATS2020 will not change significantly anymore once the underlying astronomical age calibration proves correct. However, the more fundamental formal definition of unit-stratotypes does not rely on the formalization of astrochronozones, and both issues should be separately voted upon.

References

Abdul Aziz, H., Hilgen, F. J., Krijgsman, W., Calvo, J. P., 2003. An astronomical polarity time scale for the late middle Miocene based on cyclic continental sequences. Journal of Geophysical Research B: Solid Earth 108, EPM 5-1-16.

Abdul Aziz, H., Hilgen, F. J., Luijk, G. M., Sluijs, A., Kraus, M. J., Pares, J. M., Gingerich, P. D., 2008. Astronomical climate control on paleosol stacking patterns in the Upper Paleocene-Lower Eocene Willwood Formation, Bighorn Basin, Wyoming. Geology 36, 531–534.

Abels, H. A., Clyde, W. C., Gingerich, P. D., Hilgen, F. J., Fricke, H. C., Bowen, G. J., Lourens, L. J., 2012. Terrestrial carbon isotope excursions and biotic change during Palaeogene hyperthermals. Nature Geoscience 5, 326–329.

Abels, H. A., Kraus, M., Gingerich, P. D., 2013. Orbital climate cycles triggering river avulsion in the lower Eocene Willwood Formation, Bighorn Basin, Wyoming (USA). Sedimentology 60, 1467–1483.

Aubry, M.-P., 2007. Chronostratigraphy beyond the GSSP. Stratigraphy 4, 127–137.

Batenburg, S. J., Sprovieri, M., Gale, A. S., Hilgen, F. J., Hüsing, S., Laskar, J., Liebrand, D., Lirer, F., Orue-Etxebarria, X., Pelosi, N., Smit, J., 2012. Cyclostratigraphy and astronomical tuning of the Late Maastrichtian at Zumaia (Basque country, northern Spain). Earth and Planetary Science Letters 359–360, 264–278.

Batenburg, S. J., Gale, A. S., Sprovieri, M., Hilgen, F. J., Thibault, N., Boussaha, M., Orueetxebarria, X., 2014. An astronomical time scale for the Maastrichtian based on the Zumaia and Sopelana sections (Basque country, northern Spain). Journal of the Geological Society 171, 165–180.

Berger, A., Loutre, M. F., 1991. Insolation values for the climate of the last 10 million years. Quaternary Science Reviews 10, 297–317.

Berggren, W. A., Kent, D. V., Swisher III, C. C., Aubry, M.-P., 1995. A revised Cenozoic geochronology and chronostratigraphy. In: Berggren, W. A., Kent, D. V., Hardenbol, J. (Eds.), Geochronology, Time Scales and Global Stratigraphic Correlations: A Unified Temporal Framework for an Historical Geology. Society of Economic Paleontologists and Mineralogists, Special Publication 54, 129–212.

Bernaola, G., Baceta, J. I., Payros, A., Orue-Etxebarria, X., 2006. The Paleocene and lower Eocene of the Zumaia section (Basque Basin). Climate and Biota of the Early Paleogene 2006. Post conference Field Trip Guidebook, Bilbao, 82 pp.

Cande, S. C., Kent, D. V., 1995. Revised calibration of the Geomagnetic Polarity Time Scale for the Late Cretaceous and Cenozoic. Journal of Geophysical Research 100, 6093–6095.

Carter, R. M., Abbott, S. T., Naish, T. R., 1999. Plio-Pleistocene cyclothems from Wanganui basin, New Zealand: type locality for an astrochronologic time-scale, or template for recognizing ancient glacio-eustasy? Philosophical Transactions of Royal Society of London A 357, 1861–1872.

Castradori, D., Rio, D., Hilgen, F. J., Lourens, L. J., 1998. The Global Standard Stratotype-section and Point (GSSP) of the Piacenzian stage (middle Pliocene). Episodes 21, 88–93.

Cita, M. B., 1975. The Miocene-Pliocene boundary: history and definition. In: Saito, T., Burckle, L. (Eds.), Late Neogene Epoch Boundaries. Micropaleontology Press, New York, Special Publication, 1–30.

Cita, M. B., Gartner, S., 1973. Studi sul Pliocene e gli strati di passagio dal Miocene al Pliocene, IV. The stratotype Zanclean foraminiferal and nannofossil biostratigraphy. Rivista Italiana di Paleontologia e Stratigrafia 79, 503–558.

Colleoni, F., Masina, S., Negri, A., Marzocchi, A., 2012. Plio-Pleistocene high-low latitude climate interplay: A Mediterranean point of view. Earth and Planetary Science Letters 319–320, 35–44.

Colleoni, F., Masina, S., Negri, A., Marzocchi, A., 2014. Response to comment by Hilgen et al.: Integrated stratigraphy and pitfalls of automated tuning. Earth and Planetary Science Letters 387, 25–26.

Cowie, J. W., 1986. Guidelines for boundary stratotypes. Episodes 9, 78–82.

Da, Silva, A. C., Hladil, J., Chadimová, L., Slavík, L., Hilgen, F. J., Bábek, O., Dekkers, M. J., 2016. Refining the Early Devonian time scale using Milankovitch cyclicity in Lochkovian–Pragian sediments (Prague Synform, Czech Republic). Earth and Planetary Science Letters 455, 125–139.

De Geer, G., 1912. A geochronology of the last 12,000 years. Proceedings of the XIth International Geological Congress Stockholm (1910) 1, 241–257.

De Vleeschouwer, D., Boulvain, F., Da Silva, A.-C., Pas, D., Labaye, C., Claeys, P., 2015. The astronomical calibration of the Givetian (Middle Devonian) timescale (Dinant Synclinorium, Belgium). Geological Society of London, Special Publications 414, 245–256.

De Vleeschouwer, D., Whalen, M. T., Day, J. E., Claeys, P., 2012. Cyclostratigraphic calibration of the Frasnian (late Devonian) time scale (western Alberta, Canada). Bulletin of the Geological Society of America 124, 928–942.

Dinarès-Turell, J., Baceta, J. I., Pujalte, V., Orue-Etxebarria, X., Bernaola, G., Lorito, S., 2003. Untangling the Palaeocene climatic rhythm: an astronomically calibrated Early Palaeocene magnetostratigraphy and biostratigraphy at Zumaia (Basque basin, northern Spain). Earth and Planetary Science Letters 216, 483–500.

Dinarès-Turell, J., Westerhold, T., Pujalte, V., Röhl, U., Kroon, D., 2014. Astronomical calibration of the Danian stage (Early Paleocene) revisited: Settling chronologies of sedimentary records across the Atlantic and Pacific Oceans. Earth and Planetary Science Letters 405, 119–131.

Emiliani, C., 1955. Pleistocene temperatures. Journal of Geology 63, 538–578.

20200624-132426
A17159/31141/83D30C0B

Ericson, D. B., Ewing, M., Wollin, G., Heezen, B. C., 1961. Atlantic Deep-Sea Sediment Cores. Bulletin of the Geological Society of America 72, 193–286.

Friedrich, M., Remmele, S., Kromer, B., Hofmann, J., Spurk, M., Kaiser, K. F., Orcel, C., Küppers, M., 2004. The 12,460-year Hohenheim oak and pine tree-ring chronology from central Europe – A unique annual record for radiocarbon calibration and paleoenvironment reconstructions. Radiocarbon 46, 1111–1122.

Gradstein, F. M., Ogg, J. G., Hilgen, F. J., 2012. On the Geologic Time Scale. Newsletters on Stratigraphy 45, 171–188.

Grippo, A., Fischer, A. G., Hinnov, L. A., Herbert, T. D., Premoli Silva, I., 2004. Cyclostratigraphy and chronology of the Albian stage (Piobbico core, Italy). In: d'Argenio, B., Fischer, A. G., Premoli Silva, I., Weissert, H., Ferreri, V. (Eds.), Cyclostratigraphy: Approaches and case histories. SEPM Special Publication 81, 57–81.

Harland, W. B., 1978. Geochronologic scales. In: Cohee, G. V., Glaessner, M. F., Hedberg, H. D. (Eds.), Contributions to the Geological Time Scale. American Association of Petroleum Geologists, Studies in Geology 6, 9–31.

Harland, W. B., Armstrong, R. L., Cox, A. V., Craig, L. A., Smith, A. G., Smith, D. G., 1990. A Geologic Time Scale 1989, Cambridge University Press, Cambridge, 263 pp.

Hays, J. D., Imbrie, J., Shackleton, N. J., 1976. Variations in the Earth's orbit: pacemaker of the ice ages. Science 194, 1121–1132.

Hedberg, H. D., 1958. Stratigraphic classification and terminology. Bulletin of the American Association of Petroleum Geologists 42, 1881–1896.

Hedberg, H. D., 1976. International stratigraphic guide – A guide to stratigraphic classification, terminology and procedure, New York, John Wiley and Sons, 200 pp.

Hesselbo, S. P., Bjerrum, C. J., Hinnov, L. A., MacNiocaill, C., Miller, K. G., Riding, J. B., van de Schootbrugge, B., 2013. and the Mochras Revisited Science Team. Mochras borehole revisited: a new global standard for Early Jurassic Earth history. Scientific Drilling 16, 81–91.

Hilgen, F., Brinkhuis, H., Zachariasse, W.-J., 2006. Unit-stratotypes for global stages: The Neogene perspective. Earth-Science Reviews 74, 113–125.

Hilgen, F., Zeeden, C., Lourens, L., 2014. Comment on Colleoni et al., 2012. Integrated stratigraphy and pitfalls of automated tuning. Earth and Planetary Science Letters 387, 22–24.

Hilgen, F. J., 1991a. Astronomical calibration of Gauss to Matuyama sapropels in the Mediterranean and implication for the Geomagnetic Polarity Time Scale. Earth and Planetary Science Letters 104, 226–244.

Hilgen, F. J., 1991b. Extension of the astronomically calibrated (polarity) time scale to the Miocene–Pliocene boundary. Earth and Planetary Science Letters 107, 349–368.

Hilgen, F. J., Abels, H. A., Iaccarino, S., Krijgsman, W., Raffi, I., Sprovieri, R., Turco, E., Zachariasse, W. J., 2009. The Global Stratotype Section and Point (GSSP) of the Serravallian stage (Middle Miocene). Episodes 32, 152–166.

Hilgen, F. J., Bice, J., Iaccarino, S., Krijgsman, W., Montanari, A., Raffi, I., Turco, E., Zachariasse, W. J., 2005. The Global Stratotype Section and Point (GSSP) of the Tortonian Stage (Upper Miocene) at Monte dei Corvi. Episodes 28, 6–17.

Hilgen, F. J., Hinnov, L. A., Aziz, H. A., Abels, H. A., Batenburg, S., Bosmans, J. H. C., de Boer, B., Hüsing, S. K., Kuiper, K. F., Lourens, L. J., Rivera, T., Tuenter, E., Van de Wal, R. S. W., Wotzlaw, J.-F., Zeeden, C., 2015. Stratigraphic continuity and fragmentary sedimentation: the success of cyclostratigraphy as part of integrated stratigraphy. In: Smith, D. G., Bailey, R. J., Burgess, P. M., Fraser, A. J. (Eds.), Strata and time: Probing the Gaps in Our Understanding. Geological Society, London, Special Publications 404, 157–197.

Hilgen, F. J., Kuiper, K., Krijgsman, W., Snel, E., van der Laan, E., 2007. Astronomical tuning as the basis for high resolution chronostratigraphy: the intricate history of the Messinian Salinity Crisis. Stratigraphy 4, 231–238.

Hilgen, F. J., Kuiper, K. F., Lourens, L. J., 2010. Evaluation of the Astronomical Time Scale for the Paleocene and earliest Eocene. Earth and Planetary Science Letters 300, 139–151.

Hilgen, F. J., Lourens, L. J., van Dam, J. A., 2012. The Neogene Period. In: Gradstein, F., Ogg, J. G., Schmitz, Ogg, G. (Eds.), The Geological Time Scale 2012, Elsevier, 923–978.

Hinnov, L. A., Hilgen, F. J., 2012. Cyclostratigraphy and Astrochronology. In: Gradstein, F., Ogg, J. G., Schmitz, Ogg, G. (Eds.), The Geological Time Scale 2012, Elsevier, 63–83.

Holbourn, A., Kuhnt, W., Clemens, S., Prell, W., Andersen, N., 2013. Middle to late Miocene stepwise climate cooling: Evidence from a high-resolution deep water isotope curve spanning 8 million years. Paleoceanography 28, 688–699.

Holbourn, A., Kuhnt, W., Kochhann, K. G. D., Andersen, N., Sebastian Meier, K. J., 2015. Global perturbation of the carbon cycle at the onset of the Miocene Climatic Optimum. Geology 43, 123–126.

Holbourn, A., Kuhnt, W., Schulz, M., Erlenkeuser, H., 2005. Impacts of orbital forcing and atmospheric carbon dioxide on Miocene ice-sheet expansion. Nature 438, 483–487.

Hüsing, S. K., Beniest, A., van der Boon, A., Abels, H. A., Deenen, M. H. L., Ruhl, M., Krijgsman, W., 2014. Astronomically-calibrated magnetostratigraphy of the Lower Jurassic marine successions at St. Audrie's Bay and East Quantoxhead (Hettangian–Sinemurian; Somerset, UK). Palaeogeography, Palaeoclimatology, Palaeoecology 403, 43–56.

Hüsing, S. K., Cascella, A., Hilgen, F. J., Krijgsman, W., Kuiper, K. F., Turco, E., Wilson, D., 2010. Astrochronology of the Mediterranean Langhian between 15.29 and 14.17 Ma. Earth and Planetary Science Letters 290, 254–269.

Hüsing, S. K., Kuiper, K. F., Link, W., Hilgen, F. J., Krijgsman, W., 2009. The upper Tortonian-lower Messinian at Monte dei Corvi (northern Apennines, Italy): Completing a Mediterranean reference section for the Tortonian stage. Earth and Planetary Science Letters 282, 140–157.

Husson, D., Galbrun, B., Laskar, J., Hinnov, L. A., Thibault, N., Gardin, S., Locklair, R. E., 2011. Astronomical calibration of the Maastrichtian (Late Cretaceous). Earth and Planetary Science Letters 305, 328–340.

International Subcommission on Stratigraphic Terminology, 1961. Statement of principles of stratigraphic classification and terminology, 21st International Geological Congress, Copenhagen, Part XXV, 1–38.

Joordens, J. C. A., Vonhof, H. B., Feibel, C. S., Lourens, L. J., Dupont-Nivet, G., van der Lubbe, J. H. J. L., Sier, M. J., Davies, G. R., Kroon, D., 2011. An astronomically-tuned climate framework for hominins in the Turkana basin. Earth and Planetary Science Letters 307, 1–8.

Keller, G., Barron, J. A., 1983. Paleoceanographic implications of Miocene deep-sea hiatuses. Geological Society of America Bulletin 94, 590–613.

Keller, G., Herbert, T., Dorsey, R., d'Hondt, S., Johnsson, M., Chi, W. R., 1987. Global distribution of late Paleogene hiatuses. Geology 15, 199–203.

Krijgsman, W., Hilgen, F. J., Raffi, I., Sierro, F. J., Wilson, D. S., 1999. Chronology, causes and progression of the Messinian salinity crisis. Nature 400, 652–655.

Kroon, D., Zachos, J. C., 2007. Leg 208 Scientific Party. Leg 208 synthesis: Cenozoic climate cycles and excursions. In: Kroon, D., Zachos, J. C., Richter, C. (Eds.), Proceedings ODP, Scientific Results, 208: College Station, TX (Ocean Drilling Program), 1–55.

Kuiper, K. F., Deino, A., Hilgen, F. J., Krijgsman, W., Renne, P. R., Wijbrans, J. R., 2008. Synchronizing the rock clocks of Earth history. Science 320, 500–504.

Langereis, C. G., Hilgen, F. J., 1991. The Rossello composite: A Mediterranean and global reference section for the Early to early Late Pliocene. Earth and Planetary Science Letters 104, 211–225.

Larrasoaña, J. C., Roberts, A. P., Rohling, E. J., 2013. Dynamics of green Sahara periods and their role in hominin evolution. PLoS ONE 8, e76514.

Laskar, J., Fienga, A., Gastineau, M., Manche, H., 2011. La2010: A new orbital solution for the long-term motion of the Earth. Astronomy & Astrophysics 532, A89.

Laskar, J., Joutel, F., Boudin, F., 1993. Orbital, precessional, and insolation quantities for the Earth from –20 Myr to + 10 Myr. Astronomy & Astrophysics 270, 522–533.

Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A. C. M., Levrard, B., 2004. A long term numerical solution for the insolation quantities of the Earth. Astronomy & Astrophysics 428, 261–285.

Liebrand, D., Beddow, H., Lourens, L., Pälike, H., Raffi, I., Bohaty, S. M., Hilgen, F. J., Saes, M. J. M., Wilson, P. A., van Dijk, A. E., Hodell, D. A., Kroon, D., Huck, C. E., Batenburg, S. J., 2016. Cyclostratigraphy and eccentricity tuning of the early Oligocene through early Miocene (30.1–17.1 Ma): *Cibicides mundulus* stable oxygen and carbon isotope records from Walvis Ridge Site 1264. Earth and Planetary Science Letters 450, 392–405.

Liebrand, D., Lourens, L. J., Hodell, D. A., De Boer, B., van de Wal, R. S. W., Pälike, H., 2011. Antarctic ice sheet and oceanographic response to eccentricity forcing during the early Miocene. Climate of the Past 7, 869–880.

Lisiecki, L. E., Raymo, M. E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic δ^{18}O records. Paleoceanography 20, 1–17.

Littler, K., Röhl, U., Westerhold, T., Zachos, J. C., 2014. A high-resolution benthic stable-isotope record for the South Atlantic: Implications for orbital-scale changes in Late Paleocene-Early Eocene climate and carbon cycling. Earth and Planetary Science Letters 401, 18–30.

Lourens, L., Hilgen, F. J., Shackleton, N. J., Laskar, J., Wilson, D., 2004. The Neogene Period. In: Gradstein, F. M., Ogg, J.G, Smith, A. G. (Eds.), A Geological Time Scale 2004, Cambridge University Press, 409–440.

Lourens, L. J., Hilgen, F. J., Zachariasse, W. J., van Hoof, A. A. M., Antonarakou, A., Vergnaud-Grazzini, C., 1996. Evaluation of the Plio-Pleistocene astronomical time scale. Paleoceanography 11, 391–413.

Lourens, L. J., Sluijs, A., Kroon, D., Zachos, J. C., Thomas, E., Röhl, U., Bowles, J., Raffi, I., 2005. Astronomical pacing of late Palaeocene to early Eocene global warming events. Nature 435, 1083–1087.

Manzi, V., Gennari, R., Hilgen, F., Krijgsman, W., Lugli, S., Roveri, M., Sierro, F. J., 2013. Age refinement of the Messinian salinity crisis onset in the Mediterranean. Terra Nova 25, 315–322.

Miller, K.G, Wright, J. D., 2017. Success and failure in Cenozoic global correlations using golden spikes: A geochemical and magnetostratigraphic perspective. Episodes 40, 8–21.

Molina, E., Alegret, L., Arenillas, I., Arz, J. A., Gallala, N., Grajales-Nishimura, J. M., Murillo-Muñetón, G., Zaghbib-Turki, D., 2009. The Global Boundary Stratotype Section and Point for the base of the Danian Stage (Paleocene, Paleogene, "Tertiary", Cenozoic): Auxiliary sections and correlation. Episodes 32, 84–95.

Molina, E., Alegret, L., Arenillas, I., Arz, J. A., Gallala, N., Hardenbol, J., von Salis, K., Steurbaut, E., Vandenberghe, N., Zaghbib-Turki, D., 2006. The Global Boundary Stratotype Section and Point for the base of the Danian Stage (Paleocene, Paleogene, "Tertiary", Cenozoic) at El Kef, Tunisia – Original definition and revision. Episodes 29, 263–273.

Murphy, M. A., Salvador, A. (Eds.), 1999. International Stratigraphic Guide – An abridged version. Episodes 22, 255–271.

Naish, T. R., Abbott, S. T., Alloway, V. B., Beu, A. G., Carter, M. R., Edwards, A. R., Journeaux, D. T., Kamp, P. J. J., Pillans, B. J., Saul, G., Woolfe, K. J., 1998. Astronomical calibration of a Southern Hemisphere Plio-Pleistocene reference section, Wanganui Basin, New Zealand. Quaternary Science Reviews 17, 695–710.

Odin, G. S., Robaszynski, F., Thierry, J., 2004. Stage boundaries, global stratigraphy, and the time scale: towards a simplification. Carnets de Géologie/Notebooks on Geology, CG2004_A02.

Olsen, P. E., Kent, D. V., 1999. Long-period Milankovitch cycles from the Late Triassic and Early Jurassic of eastern North America and their implications for the calibration of the Early Mesozoic time-scale and the long-term behaviour of the planets. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 357, 1761–1786.

Pälike, H., Hilgen, F., 2008. Rock clock synchronization. Nature Geoscience 1, 282 pp.

Pälike, H., Lyle, M. W., Nishi, H., Raffi, I., Ridgwell, A., Gamage, K., Klaus, A., Acton, G., Anderson, L., Backman, J., Baldauf, J., Beltran, C., Bohaty, S. M., Bown, P., Busch, W., Channell, J. E. T., Chun, C. O. J., Delaney, M., Dewangan, P., Dunkley Jones, T., Edgar, K. M., Evans, H., Fitch, P., Foster, G. L., Gussone, N., Hasegawa, H., Hathorne, E. C., Hayashi, H., Herrle, J. O., Holbourn, A., Hovan, S., Hyeong, K., Iijima, K., Ito, T., Kamikuri, S.-I., Kimoto, K., Kuroda, J., Leon-Rodriguez, L., Malinverno, A., Moore, Jr, T. C., Murphy, B. H., Murphy, D. P., Nakamura, H., Ogane, K., Ohneiser, C., Richter, C., Robinson, R., Rohling, E. J., Romero, O., Sawada, K., Scher, H., Schneider, L., Sluijs, A., Takata, H., Tian, J., Tsujimoto, A., Wade, B. S., Westerhold, T., Wilkens, R., Williams, T., Wilson, P. A., Yamamoto, Y., Yamamoto, S., Yamazaki, T., Zeebe, R. E., 2012. A Cenozoic record of the equatorial Pacific carbonate compensation depth. Nature 488, 609–614.

Pälike, H., Norris, R. D., Herrle, J. O., Wilson, P. A., Coxall, H. K., Lear, C. H., Shackleton, N. J., Tripati, A. K., Wade, B. S., 2006. The heartbeat of the Oligocene climate system. Science 314, 1894–1898.

Prokopenko, A. A., Hinnov, L. A., Williams, D. F., Kuzmin, M. I., 2006. Orbital forcing of continental climate during the Pleistocene: a complete astronomically tuned climatic record from Lake Baikal, SE Siberia. Quaternary Science Reviews 25, 3431–3457.

Railsback, L. B., Gibbard, P. L., Head, M. J., Voarintsoa, N. R. G., Toucanne, S., 2015. An optimized scheme of lettered marine isotope substages for the last 1.0 million years, and the climatostratigraphic nature of isotope stages and substages. Quaternary Science Reviews 111, 94–106.

Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Bronk, Ramsey, C., Buck, C. E., Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T. J., Hoffmann, D. L., Hogg, A. G., Hughen, K. A., Kaiser, K. F., Kromer, B., Manning, S. W., Niu, M., Reimer, R. W., Richards, D. A., Scott, E. M., Southon, J. R., Staff, R. A., Turney, C. S. M., van der Plicht, J., 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55, 1869–1887.

Remane, J., Bassett, M. G., Cowie, J. W., Gohrbandt, K. H., Lane, H. R., Michelson, O., Naiwen, W., 1996. Revised guidelines for the establishment of global chronostratigraphic standards by the International Commission on Stratigraphy (ICS). Episodes 19, 77–81.

Rio, D., Sprovieri, R., Castradori, D., Di Stefano, E., 1998. The Gelasian Stage (Upper Pliocene): A new unit of the global standard chronostratigraphic scale. Episodes 21, 82–87.

Roveri, M., Flecker, R., Krijgsman, W., Lofi, J., Lugli, S., Manzi, V., Sierro, F. J., Bertini, A., Camerlenghi, A., de Lange, G., Govers, R., Hilgen, F. J., Hübscher, C., Meijer, P. T., Stoica, M., 2014. The Messinian Salinity Crisis: Past and future of a great challenge for marine sciences. Marine Geology 352, 25–58.

Ruddiman, W. F., Cameron, D., Clement, B. M., 1987. Sediment disturbance and correlation of offset holes drilled with the hydraulic piston corer: Leg 94.. Initial Reports of the Deep Sea Drilling Program, Leg 94, Part 2, 615–634.

Ruhl, M., Deenen, M. H. L., Abels, H. A., Bonis, N. R., Krijgsman, W., Kürschner, W. M., 2010. Astronomical constraints on the duration of the early Jurassic Hettangian stage and recovery rates following the end-Triassic mass extinction (St. Audrie's Bay/East Quantoxhead, UK). Earth and Planetary Science Letters 295, 262–276.

Ruhl, M., Hesselbo, S. P., Hinnov, L., Jenkyns, H. C., Xu, W., Riding, J. B., Storm, M., Minisini, D., Ullmann, C. V., Leng, M. J., 2016. Astronomical constraints on the duration of the early Jurassic Pliensbachian Stage and global climatic fluctuations. Earth and Planetary Science Letters 455, 149–165.

Sageman, B. B., Singer, B. S., Meyers, S. R., Siewert, S. E., Walaszczyk, I., Condon, D. J., Jicha, B. R., Obradovich, J. D., Sawyer, D. A., 2014. Integrating ^{40}Ar/^{39}Ar, U-Pb, and astronomical clocks in the Cretaceous Niobrara Formation, Western Interior Basin, USA. Bulletin of the Geological Society of America 126, 956–973.

Salvador, A. (Ed.), 1994. International Stratigraphic Guide: A Guide to Stratigraphic Classification, Terminology and Procedure: 2nd Edition, International Union of Geologists Scientists and Geological Society of America, Trondheim, Norway and Boulder, CO, iiixix+214.

Schmitz, B., Pujalte, V., Molina, E., Monechi, S., Orue-Etxebarria, X., Speijer, R. P., Alegret, L., Apellaniz, E., Arenillas, I., Aubry, M.-P., Baceta, J.-I., Berggren, W. A., Bernaola, G., Caballero, F., Clemmensen, A., Dinarès-Turell, J., Dupuis, C., Heilmann-Clausen, C., Orús, A. H., Knox, R., Martín-Rubio, M., Ortiz, S., Payros, A., Petrizzo, M. R., Von Salis, K., Sprong, J., Steurbaut, E., Thomsen, E., 2011. The global stratotype sections and points for the bases of the Selandian (Middle Paleocene) and Thanetian (Upper Paleocene) stages at Zumaia, Spain. Episodes 34, 220–243.

Shackleton, N. J., 2006. Formal Quaternary stratigraphy – What do we expect and need? Quaternary Science Reviews 25, 3458–3462.

Stuiver, M., Kromer, B., Becker, B., Ferguson, C. W., 1986. Radiocarbon age calibration back to 13,300 years BP and the ^{14}C age matching of the German oak and US bristlecone pine chronologies. Radiocarbon 28, 969–979.

Thibault, N., Husson, D., Harlou, R., Gardin, S., Galbrun, B., Huret, E., Minoletti, F., 2012. Astronomical calibration of upper Campanian-Maastrichtian carbon isotope events and calcareous plankton biostratigraphy in the Indian Ocean (ODP hole 762C): implication for the age of the

Campanian-Maastrichtian boundary. Palaeogeography, Palaeoclimatology, Palaeoecology 337–338, 52–71.

Thibault, N., Jarvis, I., Voigt, S., Gale, A. S., Attree, K., Jenkyns, H. C., 2016. Astronomical calibration and global correlation of the Santonian (Cretaceous) based on the marine carbon isotope record. Paleoceanography 31, 847–865.

Van Couvering, J. A., Castradori, D., Cita, M. B., Hilgen, F. J., Rio, D., 2000. The base of the Zanclean Stage and of the Pliocene Series. Episodes 23, 179–187.

Van Dam, J. A., Abdul Aziz, H., Sierra, M. A. A., Hilgen, F. J., van de Hoek Ostende, L. W., Lourens, L. J., Mein, P., van der Meulen, A. J., Pelaez-Campomanes, P., 2006. Long-period astronomical forcing of mammal turnover. Nature 443, 687–691.

Van Vugt, N., Steenbrink, J., Langereis, C. G., Hilgen, F. J., Meulenkamp, J. E., 1998. Magnetostratigraphy-based astronomical tuning of the early Pliocene lacustrine sediments of Ptolemais (NW Greece) and bed-to-bed correlation to the marine record. Earth and Planetary Science Letters 164, 535–551.

Varadi, F., Runnegar, B., Ghil, M., 2003. Successive refinements in long-term integrations of planetary orbits. The Astrophysical Journal 592, 620–630.

Wade, B. S., Pälike, H., 2004. Oligocene climate dynamics. Paleoceanography 19, 1–16.

Wade, B. S., Pearson, P. N., Berggren, W. A., Pälike, H., 2011. Review and revision of Cenozoic tropical planktonic foraminiferal biostratigraphy and calibration to the geomagnetic polarity and astronomical time scale. Earth-Science Reviews 104, 111–142.

Walsh, S. L., 2001. Notes on geochronologic and chronostratigraphic units. Bulletin of the Geological Society of America 113, 704–713.

Walsh, S. L., Gradstein, F. M., Ogg, J. G., 2004. History, philosophy, and application of the Global Stratotype Section and Point (GSSP). Lethaia 37, 201–218.

Westerhold, T., Röhl, U., 2005. Data report: Revised composite depth records for Shatsky Rise Sites 1209, 1210, and 1211. Proceedings of the Ocean Drilling Program, Scientific Results, v. 198.

Westerhold, T., Röhl, U., Frederichs, T., Agnini, C., Raffi, I., Zachos, J. C., Wilkens, R. H., 2017. Astronomical calibration of the Ypresian time scale: Implications for seafloor spreading rates and the chaotic behavior of the Solar System? Climate of the Past 13, 1129–1152.

Westerhold, T., Röhl, U., Frederichs, T., Bohaty, S. M., Zachos, J. C., 2015. Astronomical calibration of the geological timescale: Closing the middle Eocene gap. Climate of the Past 11, 1181–1195.

Westerhold, T., Röhl, U., Laskar, J., 2012. Time scale controversy: Accurate orbital calibration of the early Paleogene. Geochemistry Geophysics Geosystems 13, Q06015.

Westerhold, T., Röhl, U., Laskar, J., Raffi, I., Bowles, J., Lourens, L. J., Zachos, J. C., 2007. On the duration of magnetochrons C24 r and C25 n and the timing of early Eocene global warming events: implications from the Ocean Drilling Program Leg 208 Walvis Ridge depth transect. Paleoceanography 22, PA2201.

Westerhold, T., Röhl, U., Raffi, I., Fornaciari, E., Monechi, S., Reale, V., Bowles, J., Evans, H. F., 2008. Astronomical calibration of the Paleocene time. Palaeogeography, Palaeoclimatology, Palaeoecology 257, 377–403.

Wilkens, R. H., Dickens, G. R., Tian, J., Backman, J.and the Expedition 320/321 Scientists, 2013. Data report: revised composite depth scales for Sites U1336, U1337, and U1338. In: Pälike, H., Lyle, M., Nishi, H., Raffi, I., Gamage, K., Klaus, A.and the Expedition 320/321 Scientists (Eds.), Proc. IODP, 320/321, Tokyo.

Wotzlaw, J.-F., Bindeman, I. N., Schaltegger, U., Brooks, C. K., Naslund, H. R., 2012. High-resolution insights into episodes of crystallization, hydrothermal alteration and remelting in the Skaergaard intrusive complex. Earth and Planetary Science Letters 355–356, 199–212.

Wotzlaw, J.-F., Hüsing, S. K., Hilgen, F. J., Schaltegger, U., 2014. High-precision zircon U-Pb geochronology of astronomically dated volcanic ash beds from the Mediterranean Miocene. Earth and Planetary Science Letters 407, 19–34.

Wotzlaw, J. F., Schaltegger, U., Frick, D. A., Dungan, M. A., Gerdes, A., Günther, D., 2013. Tracking the evolution of large-volume silicic magma reservoirs from assembly to super-eruption. Geology 41, 867–870.

Wu, H., Zhang, S., Hinnov, L. A., Jiang, G., Feng, Q., Li, H., Yang, T., 2013. Time-calibrated Milankovitch cycles for the late Permian: Nature Communications 4, art. no. 2452.

Zachos, J. C., Kroon, D., Blum, P., 2004. ODP leg 208: The early Cenozoic extreme climates transect along Walvis Ridge. JOIDES Journal 30, 8–13.

Zachos, J. C., McCarren, H., Murphy, B., Röhl, U., Westerhold, T., 2010. Tempo and scale of late Paleocene and early Eocene carbon isotope cycles: Implications for the origin of hyperthermals. Earth and Planetary Science Letters 299, 242–249.

Zalasiewicz, J., Cita, M. B., Hilgen, F., Pratt, B. R., Strasser, A., Thierry, J., Weissert, H., 2013. Chronostratigraphy and geochronology: A proposed realignment. GSA Today 23, 4–8.

Zalasiewicz, J., Smith, A., Brenchley, P., Evans, J., Knox, R., Riley, N., Gale, A., Gregory, F. J., Rushton, A., Gibbard, P., Hesselbo, S., Marshall, J., Oates, M., Rawson, P., Trewin, N., 2004. Simplifying the stratigraphy of time. Geology 32, 1–4.

Zeeden, C., Hilgen, F. J., Hüsing, S. K., Lourens, L. J., 2014. The Miocene astronomical time scale 9–12 Ma: new constraints on tidal dissipation and their implications for paleoclimatic investigations. Paleoceanography 29, 296–307.

Manuscript received: October 19, 2018
Revisions required: October 31, 2018
Revised version received: January 02, 2019
Manuscript accepted: January 18, 2019

Appendix

7.1. Research support team affiliations:

Batenburg, Sietske: Department of Earth Sciences, University of Oxford, South Parks Road, Oxford OX1 3AN, United Kingdom;
Bohaty, Steve: National Oceanography Centre Southampton, University of Southampton, Waterfront Campus, European Way, Southampton, United Kingdom;
Boulila, Sla: Sorbonne Universités, University of Paris 06, 4 place Jussieu, Paris, and IMCCE, Observatoire de Paris, 77 avenue Denfert-Rochereau, Paris, France;
Da Silva, Anne-Christine: Paleomagnetic Lab. 'Fort Hoofddijk', Department of Earth Sciences, Utrecht University, Netherlands, and/now at: Sedimentary Petrology Laboratory, Liège University, Liège, 4000, Belgium
De Vleeschouwer, David: MARUM – Center for Marine Environmental Science, University of Bremen, Bremen, Germany;
Dinarès-Turell, Jaume: Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata, 605, Rome, Italy;
Gale, Andy: School of Earth and Environmental Sciences, University of Portsmouth, Burnaby Road, Burnaby Building, Portsmouth PO1 3QL, United Kingdom;
Herbert, Timothy: Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI, United States;
Hinnov, Linda: Department of Atmospheric, Oceanic and Earth Sciences, George Mason University, Fairfax, VA, United States;
Kroon, Dick: School of GeoSciences, Grant Institute, University of Edinburgh, King's Buildings, James Hutton Road, Edinburgh, United Kingdom;
Kuiper, Klaudia: Institute of Earth Sciences, Vrije Universiteit Amsterdam, De Boelelaan 1085, Amsterdam, Netherlands;
Martinez, Matthieu: MARUM – Center for Marine Environmental Sciences, University of Bremen, Leobenerstrasse, Bremen, Germany, now at: Géosciences Rennes, Université de Rennes 1, 350423 Rennes, France;
Renne, Paul: Berkeley Geochronology Center, 2455 Ridge Road, Berkeley, CA 94709, USA.
Röhl, Ursula: MARUM – Center for Marine Environmental Sciences, University of Bremen, Germany;
Sierro, Francisco: Department of Geology, University of Salamanca, Salamanca, 37008, Spain
Thibault, Nicolas: Department of Geosciences and Natural Resource Management, University of Copenhagen, Øster Voldgade 10, Copenhagen K, Denmark
Westerhold, Thomas: MARUM – Center for Marine Environmental Sciences, University of Bremen, Germany,
Zeeden, Christian: PSL, IMCCE, Observatoire de Paris, 77 Avenue Denfert-Rochereau, 75014 Paris, France, now at: LIAG – Leibniz Institute for Applied Geophysics, Geozentrum Hannover, Hannover, Germany.

7.2. Postscriptum

The proposal was submitted to ISSC for voting after several rounds of internal discussion with ISSC members and one informal round of discussion with members of the Research Support team. The final revised proposal was send to ISSC voting members on February 23 last year with the deadline one month later. The outcome of the voting was circulated to ISSC members on April 30 and later to ICS:
Voting members = 19; Votes received = 15, which is 78.95 %, so the quorum is reached (>60 %).
Unit-Stratotypes: Yes 8 votes; No 6 votes, Abstention 1 vote. "Yes" received 57.14 %. As the needed majority of 60 % is not reached, **Unit-Stratotypes, as suggested in Hilgen et al.'s proposal, will be declined by the ISSC.**
Astrochronozones: Yes 9 votes; No 5 votes , Abstention 1 vote. "Yes" received 64.29 %. As the needed majority of 60 % is reached, **Astrochronozones, as suggested in Hilgen et al.'s proposal, are accepted by the ISSC.**

The final proposal with separate voting on unit-stratotypes and astrochronozones was a revised version of the initial proposal which did not have this dual structure. This structure was added following the discussions in an attempt to reduce the risk that the voting on the more fundamental and important issue of the unit-stratotype would be compromised by the potentially less appealing formalization of the astrochronozone. Unfortunately the outcome of the voting show the reverse.

Looking at the outcome of the vote, we could have continued with a separate proposal on the astrochronozone part for voting in ICS. However, the astrochronozone is intimately linked to the unit-stratotype concept and an exclusive vote on it would be less relevant as a consequence. Note that this would not have been the case if the results of the ISSC vote would have been opposite, as the formalization of unit-stratotypes would have implied a much more fundamental change in global chronostratigraphic procedures and thinking than that of astrochronozones. Moreover, the most important astrochronozones associated with the stable 405-kyr eccentricity cycle will anyway be numbered from the Recent back in time, although in an informal rather than a formal way (e. g., Liebrand et al. 2016, Westerhold et al. 2017).

Of course we are disappointed by the outcome of the vote, but also feel strengthened by the fact that a proposal about such a far-reaching issue as the unit-stratotype received a majority, but not the required supermajority of votes, and was thus nearly accepted by ISSC, and that the part of the proposal on the astrochronozone was accepted. However, looking at the discussions that were held before the actual voting, several critical questions were raised. These have largely been addressed in the final proposal, but we return shortly to some of them below.

In the first place, several members expressed scepticism about the key application of cyclostratigraphy in astrochronology, which is not seldomly regarded as circular reasoning. This misunderstanding may be explained by the fact that not all members have followed the remarkable developments in cyclostratigraphy and astrochronology over the last decades in detail. As such, they may not have realized that the age calibration of the standard Cenozoic Time Scale is already largely based on astronomical dating (rather than radio-isotopic dating), and that the duration of many stages in the Mesozoic is now obtained through cyclostratigraphy.

A second issue that played a role in the discussion was the idea that the unit-stratotype would replace the GSSP, while it is in fact defined in addition to the GSSP, delimiting the interval between two successive GSSPs as unit-stratotype. However, this point was discussed and clarified in the proposal and, hence, likely did not play a significant role during the actual voting.

Another argument against the unit-stratotype is the impossibility to correlate the top of a stage with the base of the next younger stage as a time stratigraphic horizon. Indeed exact time correlations cannot be made: age uncertainties in precession scale correlations between different sections worldwide will be in the order of thousands of years, even in case the origin of the cycles and thus their phase relation with the correlative astronomical parameter or insolation are perfectly understood. A practical solution is that the base and thus the GSSP of the younger stage defines the exact position and age of the boundary (as is already the case for the GSSP approach) with the boundary pinpointed as precisely as possible at the top of the unit-stratotype of the preceding older stage.

A further issue that was raised but not fully discussed concerned the naming of such a stratigraphic unit, as there was not unanimous agreement on the use of the term unit-stratotype. In principle, unit-stratotype is a general term often regarded to include an entire stratigraphic unit of any stratigraphic subdivision/discipline. However, the use of unit-stratotype in the proposal harks back to its application in chronostratigraphy, as outlined in the proposal, covering the entire body of a chronostratigraphic unit (see also Walsh 2004). However, at that time, the stratigraphic means were simply not available to realize unit-stratotypes in chronostratigraphy.

The question further is whether we really need unit-stratotypes in addition to GSSPs. This point is addressed to some extend in the final version of the proposal. The principal reason for the unit-stratotype approach in chronostratigraphy is that they define both the body and the boundaries of a stage in the best possible way. Critical arguments initially raised against unit-stratotypes for stages, which resulted in their demise and our current preference for defining stage boundaries, have been eliminated by the building of integrated high-resolution astrochronologic frameworks (see Westerhold et al. 2017 for the Ypresian as an example), which provide unprecedented age control, not only for the stage boundaries, but also within the stage itself. Defining only the boundaries would leave an “empty” stage. The introduction of unit-stratotypes, in addition to GSSPs, and of astrochronozones is required to facilitate the much higher resolution, accuracy and precision needed in stratigraphy today. For example, astronomical age models have been instrumental in addressing fundamental issues in Earth Sciences, such as the Messinian Salinity Crisis in the Mediterranean and Eocene hyperthermals as greenhouse counterparts of glacial cycles in the late Cenozoic. A final consideration for writing the proposal is that our standard GTS should not become a black-box and that we have to make clear to students, colleagues and laymen how it is constructed.

Discussion with ISC and ISSC board members made clear that a moratorium of 10 years does not hold for our unit-stratotype proposal. Hence, we aim to resubmit the proposal, although likely after the Strati 2019 congress and the publication of GTS2020, as these are expected to underpin the increasingly important role of astrochronology in building global chronostratigraphy and our standard geological time scale, and in understanding Earth history. As such, it is anticipated that the Cenozoic part of the time scale will for the first time be entirely underlain by astronomical dating. In our opinion, it would be a missed opportunity if our standard global chronostratigraphic framework remains at the low resolution of the GSSP only and becomes isolated from the remarkable progress made in high-resolution integrated stratigraphy and astrochronology over the last decades.

Finally, note that the present published version of the proposal deviates slightly from the version that was voted upon by ISSC as some inconsistencies in the use of unit-stratotype versus unit stratotype have been removed, and some figure captions have been lengthened to better explain the figures.