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Unit stratotypes for global stages: The Neogene perspective

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Abstract

Recent developments in integrated high-resolution stratigraphy and astronomical tuning of continuous deep marine successions invalidate arguments against the designation of unit stratotypes for global stages, the basic building blocks of the standard Global Chronostratigraphic Scale (GCS). For the late Neogene, Global Stratotype Section and Point (GSSP) sections may also serve as unit stratotypes, covering the interval from the base of a stage up to the level that–time-stratigraphically–correlates with the base of the next younger stage in a continuous and well-tuned deep marine succession. The added value of such sections as unit stratotype lies in the integrated high-resolution stratigraphy and astronomical tuning, which combined, provides an excellent age control with an unprecedented resolution, precision and accuracy *within* the entire stage. As such they form the backbone of the new integrated late Neogene time scale and provide the basis for reconstructing Earth's history. In this way a stage is also defined by its *content* and not only by its boundaries. Our unit stratotype concept strengthens the importance of time-rock units by allowing the introduction of astronomically defined chronozones as formal chronostratigraphic units, thereby arguing against the elimination of the dual classification of chronostratigraphy and geochronology.

Extending this concept to older time intervals requires that well-tuned, continuous deep marine sections are employed, thus necessitating the employment of multiple hole (I)ODP sites for defining (remaining) stages and stage boundaries in at least the Cenozoic and Cretaceous and possibly the entire Mesozoic. Evidently the construction of the Geological Time Scale (including the GCS) should be based on the most appropriate sections available while, where possible, taking the historical concept of global stages into account.

Keywords: chronostratigraphy; unit stratotype; GSSP; orbital tuning; chronozone; stage

1. Introduction

Chronostratigraphy, i.e., the temporal ordering of the geological archive, is a baseline requirement for reconstructing Earth's history. Hedberg (1976) believed that the basic chronostratigraphic unit, the *stage*, must be defined in terms of a type section if it was to have any meaning. Hedberg (1958) initially advocated the use of unit stratotypes to define stages of global significance, with the base and top of the stage being designated in the same unit stratotype. In practice, however, it became evident that the designation of unit stratotypes, with both bottom and top of a stage being defined in the same section "… *inevitably creates unresolvable gaps and overlaps between consecutive stages which in turn leads to unproductive arguments about boundaries, or to the definition of useless new ages/stages of very short duration to fill in the gaps*…" (cf. Walsh, 2004). This

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would be particularly so in case the historical stratotype was selected as a formal unit stratotype of that stage. Moreover it was felt that continuous sections covering the entire time interval defined by a stage rarely, if ever, exist (Ager, 1973; Hedberg, 1976; Walsh, 2004; see also Aubry et al., 1999).

It was for these reasons that Hedberg (1976) recommended the use of a single mutual boundary stratotype for two successive stages in the first International Stratigraphic Guide. To avoid the problem of unwanted gaps and/or overlaps between successive stages in their historical stratotypes, the concept of the so-called *topless stage* was already introduced in the 1960s, in which the top of a stage is automatically defined by the base of the next younger stage (George et al., 1967). This, and other developments, eventually led to the 'Global Stratotype Section and Point' (GSSP) concept as formulated in more recent versions of the International Stratigraphic Guide (Salvador, 1994; see also Remane et al., 1996 and Walsh et al., 2004), in which the definition of a stage is restricted to its lower boundary. The GSSP approach thus avoids the problem of correlating top with base of successive (unit) stratotypes located in different geographic areas. It thus acknowledges the fact that, at that time, it was extremely difficult to export a stage boundary–as a time line–away from the historical stratotype, often defined in less suitable and incomplete shallow marine successions. Nevertheless, exportation was exactly why GSSPs are defined in the first place. More importantly, this concept places too much emphasis on boundaries (the so-called *empty stage*), thereby neglecting the body of the stage that actually defines it. The importance of the body has recently also been emphasized by Odin et al. (2004) and Zhamoida (2004).

The abandonment of the unit stratotype approach and the radical preference for defining (lower) stage and even series boundaries–the so-called "golden spikes" or GSSPs–is amply illustrated by Walsh (2004), stating "*In short, the use of unit stratotypes in chronostratigraphy has long been intellectually obsolete, but its persistence testifies to the exasperating ability of a traditional dogma to overwhelm common sense*". The debates on the boundaries *per se*, have drawn attention away from the relevance of the body of the stage as represented by the succession in the single unit stratotype sensu Hedberg (1976).

The focus on the formal definition of chronostratigraphic units and in particular their boundaries resulted in the standard 'Global Chronostratigraphic Scale' (GCS) which is believed to be essentially stable, and will be largely completed by 2008 through the formal designation of most if not all of the remaining GSSPs (Gradstein and Ogg, 2004; Ogg, 2004). Partly independent from the GCS, integrated geological time scales were developed by combining radiometric dating with magnetic reversal histories and (micro)fossil biostratigraphic zonal schemes (e.g., Berggren et al., 1985, 1995). The GCS was logically incorporated in these time scales. The 'Geological Time Scale 2004' (GTS2004) is the most recent version of the integrated geological time scale (Gradstein et al., 2004) and fully integrates the GCS. However, within the framework of an integrated high-resolution stratigraphy, the age-calibration of the youngest Neogene part of this time scale is now based entirely on astronomical tuning, resulting in a time scale with an unprecedented accuracy, resolution and stability (Lourens et al., 2004). This progress in integrated high-resolution stratigraphy in combination with astronomical tuning of cyclic sedimentary successions thus invalidates arguments against unit stratotypes; it argues in favour of a reconsideration of the unit stratotype concept,[1] the introduction of astronomically defined chronozones as formal chronostratigraphic units of lower rank and, as a consequence, a strengthening of the dual classification of chronostratigraphy (time-rock) and geochronology (time).

2. Astronomical tuning and time scales

2.1. SPECMAP

Astronomical tuning is based on the correlation or tuning of cyclic sedimentary successions to astronomical target curves (precession, obliquity, eccentricity, insolation) computed with the help of astronomical solutions for the Solar System. The first attempt of orbital tuning goes at least back to Köppen and Wegener (1924) who correlated the river terraces of Penck and Brückner (1909) being the expression of the Ice Ages to critical northern Hemisphere insolation curves calculated by Milankovitch (see also Milankovitch, 1941). But the major breakthrough in unravelling the history of the great Ice Ages and their tuning came with

[1] The discussion in this paper is disconnected from the desirability to consider stages as basic chronostratigraphic units of the Global Standard Chronostratigraphic Scale. This usage has recently been discredited by the tendency to define Epoch/Series boundaries prior to their constituent (st)ages, while they should preferably be defined at the same time (see van Couvering et al., 2000 for an example). This procedure even led to the unfortunate proposal to disconnect the hierarchical linkage between global stages and chronostratigraphic units of higher rank.

the recovery of complete and continuous deep-sea successions from the seafloor by piston coring (Kullenberg, 1947). The study of these cores, supported by new proxy developments and dating methods, led to the so-called SPECMAP oxygen isotope stratigraphy and chronology. This time scale was based on tuning well-documented isotope stages, which reflect ice volume, to astronomically derived target curves (Hays et al., 1976; Imbrie et al., 1984). The resulting high-resolution SPECMAP time scale for the last 800,000 years greatly stimulated research into the Ice Ages and served as a global template to which other records, including continental sections and ice cores, could be calibrated.

Following initial attempts (Pisias and Moore, 1981; Ruddiman et al., 1989; Raymo et al., 1989), the astronomical tuning and time scale was extended to the base of the Pliocene, using paleoclimatic records from Ocean Drilling Project (ODP) sites in the eastern equatorial Pacific and North Atlantic (Shackleton et al., 1990) and sedimentary cycle patterns in deep marine successions exposed on dry land in the Mediterranean region (Hilgen, 1991a,b). The orbital tuning in addition provided direct astronomical ages for magnetic reversal and biozonal boundaries since all tuned sections have a good to excellent integrated high-resolution stratigraphy. Astronomical tuning now underlies the age calibration of the new Neogene[2] time scale (ATNTS2004; Lourens et al., 2004) and extension into the Paleogene and even the Mesozoic is well under way (Pälike et al., 2001; Dinares-Turell et al., 2003; Wade and Pälike, 2004).

2.2. ATNTS2004

The 'Astronomical Tuned Neogene Time Scale' (ATNTS2004; Lourens et al., 2004) marks a turning point in time scale development and signifies a major step towards a permanent Neogene time scale. In particular, the late Neogene part of the time scale will not change significantly any more since the tuning has been independently confirmed in different ocean basins. In this respect it can be measured up to the SPECMAP time scale for the late Pleistocene, which is very stable, and will have to undergo only minor changes in the future, if at all.

Also the late Neogene part of the ATNTS2004 will have to be slightly modified, even though the underlying tuning is basically correct. At present the tuning is based on the new numerical solution La2004 of Laskar et al. (2004). As far as eccentricity is concerned, the solution is accurate over the last 40 myr because eccentricity depends on the orbital part of the solution (see also Pälike et al., 2004). But this is different for precession and obliquity because they depend on the Earth–Moon system as well. It is for this reason that Laskar et al. (1993) added two parameters to his solution, namely the dynamical ellipticity of the Earth (E_D) and the tidal dissipation by the Moon (TD). $La93_{(1,1)}$ is the solution with present-day values of E_D and TD set at 1. Changes in either of these parameters, due to for instance the build up of–permanent–ice-caps, will affect precession and obliquity frequencies but not eccentricity.

The ATNTS2004 was constructed using the La2004 solution with present-day values for E_D and TD, hence $La2004_{(1,1)}$. But it is becoming increasingly clear that these values have to be slightly modified as to maintain an excellent fit with the cyclostratigraphic records (Pälike and Shackleton, 2000; Lourens et al., 2001). Hence, the final time scale for the Neogene can only be established with the help of a solution in which the values of TD and/or E_D are adjustable when calculated back in time. However, the resultant changes in absolute age in the order of several kyr are neglectible from a geological time scale perspective in general. But solving the TD/E_D problem is of crucial importance for constructing a time scale that can reliably be used to decipher phase relations between astronomical forcing, climate response and registration in sedimentary archives. Other applications of the new time scale will be discussed below.

2.3. Applications

The combination of orbital tuning and integrated high-resolution stratigraphic records is an extremely powerful tool and has helped to solve numerous problems in Earth Sciences, the most important of which are:

1) the promulgation of geological time scales. GSSPs create stability in the Global Chronostratigraphic Scale but not in the absolute time calibration of that scale. As mentioned before, astronomical tuning results in absolute time scales that are not prone to significant changes and that will remain stable once the underlying tuning is correct. For instance, ages for the Pliocene–Pleistocene part of the ATNTS2004 (Lourens et al., 2004) differ by less than 1 kyr from those in the tuned time scale of Lourens et al. (1996).

[2] Neogene is used here in the extended sense of the new Geological Time Scale (GTS2004; Gradstein et al., 2004). It thus includes the Miocene, Pliocene, Pleistocene and Holocene.

These minor differences resulted from retuning paleoclimatic records from La93 to the new full numerical solution La2004 of Laskar et al. (2004).
2) the tuning approach has been successfully applied to Neogene continental records (Van Vugt et al., 1998; Lu et al., 1999; Heslop et al., 2000), allowing high-resolution time-stratigraphic correlations along continental to marine environmental gradients. In fact part of the ATNTS2004, the reversal ages between 11 and 13 Ma, were obtained from tuned continental successions in Spain having a reliable magnetostratigraphy (Abdul Aziz et al., 2003).
3) the problem of the age of mineral dating standards in $^{40}Ar/^{39}Ar$ dating. Full error propagation showed that the total error in $^{40}Ar/^{39}Ar$ ages is much larger by approximately one order of magnitude than the analytical error (Min et al., 2000). Intercalibration of the $^{40}Ar/^{39}Ar$ method with the totally independent absolute astronomical dating method provides a means to significantly reduce the uncertainty by eliminating errors that result from uncertainties in the values of decay constants and the age of the dating standards to a large extent (Kuiper, 2003). Comparison of $^{40}Ar/^{39}Ar$ and astronomical ages for ash layers intercalated in astronomically well tuned sections yielded an astronomical age estimate of 28.21 ± 0.01 and 28.24 ± 0.03 Ma for the Fish Canyon Tuff (FCT) sanidine (Kuiper, 2003; Kuiper et al., 2004) as compared with the at present most widely used age of 28.02 ± 0.32 Ma (Renne et al., 1998). Ongoing studies will provide a very accurate and precise astronomical age for the FCT sanidine and may lead to the introduction of an astronomically dated standard.
4) orbital tuning in addition provides accurate astronomical ages for magnetic polarity reversals leading to the so-called Astronomical Polarity Time Scale (APTS). The approach is particularly useful to solve the problem of the number and age of cryptochrons and short subchrons in the reversal history of the Earth's magnetic field (Langereis et al., 1997; Abdul Aziz and Langereis, 2004). Moreover, the APTS can be used to calculate seafloor-spreading rates more accurately and precisely (Wilson, 1993; Krijgsman et al., 1999).
5) changes on tectonic time scales may be controlled by the long-period orbital cycles of eccentricity (0.4 and 2.4 Myr) and obliquity (1.2 Myr). Solving this issue will have far-reaching consequences for understanding (glacio)eustatic mechanisms behind many third-order sequences in sequence stratigraphy and their potential for global time-stratigraphic correlation (Lourens and Hilgen, 1997; Zachos et al., 2001; Turco et al., 2001; Wade and Pälike, 2004; Lourens et al., 2005).

2.4. Critical notes

Cyclostratigraphy and the cyclostratigraphic approach can certainly be criticized. Recently Miall and Miall (2004) listed three key problems associated with cyclostratigraphy in general and astronomical tuning in particular. Firstly, cyclostratigraphers downplay the probability that orbital frequencies were different in the past. But specialists are aware of these changes and take them into account when studying older cyclic successions (e.g., Hinnov and Park, 1998; Hinnov, 2000) even though the changes themselves are not perfectly known (Berger et al., 1989, 1992). These changes mainly affect precession and obliquity because their frequencies depend on the Earth–Moon system and increase with decreasing Earth-Moon distance and length of day in the geological past. But eccentricity remains unaffected because it is not dependent on the Earth–Moon system, making the prominent and essentially stable 400-kyr eccentricity cycle a prime target for orbital tuning back even into the Mesozoic (Laskar et al., 2004).

Secondly there is the problem of the representation of time in the stratigraphic record due to the occurrence of hiatuses and changes in sedimentation rate. Completeness of the stratigraphic record in tuning studies is usually secured by studying multiple parallel sections, whether land-based marine sections in the Mediterranean or (I)ODP/DSDP cores from the same or even different ocean basins (i.e., oxygen isotope stratigraphy).

The problem of changes in sedimentation rate is realized by most researchers working in the field (Fischer et al., 1991; Herbert, 1994). A constant rate is often used as a first approximation when time series analysis is carried out (in the depth domain) also because sedimentation rates may be fairly constant over prolonged intervals of time in deep marine successions. Wavelet and moving spectral analysis provide powerful statistical tools to detect changes in sedimentation rate through associated changes in cycle thicknesses while astronomical tuning provides an optimal tool to determine changes in sedimentation rate (e.g., Van der Laan et al., 2005). Such changes are often related to the amplitude of the astronomical forcing.

Thirdly, independent age calibration of cyclostratigraphic records is insufficiently precise to provide adequate constraints on astronomical tuning. It is for this reason that we made a rigorous attempt to intercalibrate astronomical and radioisotopic time (see Section 3.3). This intercalibration is critically important for extending the tuning into the Mesozoic although one might argue that it does not provide a fully independent test in this way.

A further objection is that astronomical frequencies are introduced in the paleoclimatic time series as a consequence of the tuning (Shackleton et al., 1995a,b; Huybers, 2001). This is realized but is unavoidable whereby the gain by far compensates the drawbacks. However, it stresses again the importance of a correct tuning. As far as the orbital tuning itself is concerned, independent testing comes from additional statistical techniques such as amplitude demodulation (e.g., Shackleton et al., 1995a; Shackleton and Crowhurst, 1997) or from tuning to precession while separately analyzing the obliquity signal (e.g., Hilgen et al., 1993).

Final points of criticism include the claim of supremacy of cyclostratigraphy above other stratigraphic disciplines and adopting "the truth is manifest" attitude (Miall and Miall, 2004). The former is not the case because we always place emphasis on the importance of a high-resolution integrated stratigraphy before cyclostratigraphy and astronomical tuning can be performed in providing optimal age control. However, we do indeed claim that the astronomical tuning for major parts of the late Neogene is certain and stable, and will not have to be modified apart from minor changes related to adjustments in the values for the tidal dissipation and/or dynamical ellipticity parameters. We realize that this attitude may be difficult to accept for stratigraphers working in older parts of the geological records and/or in less ideal successions while for paleoclimatologists who extend the SPECMAP type of approach to the pre-Pleistocene it appears the logical outcome of developments in science (e.g., astronomical solutions) and technology (e.g., multiple offset advanced piston corer (APC) drilling).

By now it has become clear that the astronomical climate forcing signal has been accurately recorded in pre-Pleistocene sediments, allowing unambiguous tuning of cyclic successions. It is equally evident that similar signals have been recorded back into the Mesozoic and there is no obvious reason why astronomical tuning cannot be extended that far back in time even in view of present limitations such as the accuracy of the astronomical solutions. Twenty years ago, only few researchers believed that tuning of the pre-Pleistocene would ever be achieved.

3. Unit stratotypes

3.1. Neogene

All late Neogene stage boundaries are by now defined in tuned land-based marine sections in the Mediterranean that together form the backbone for the younger part of the ATNTS2004. Originally most of these Neogene stages were defined in less suitable sections in northern Italy. In fact, we witnessed already a radical shift in chronostratigraphic thinking before cyclostratigraphy started to play a role by replacing the often incomplete and discontinuous historical stratotypes defined in relatively shallow marine successions in northern Italy by hypostratotypes in deeper marine successions in southern Italy or by stages already defined in these successions. The Zanclean has therefore been given priority over the Tabianian with the erection of a Zanclean neostratotype (Cita and Gartner, 1973), and a new stage, the Gelasian (Rio et al., 1998), has been introduced for the Upper Pliocene to replace the obsolete Astian.

As a consequence all late Neogene GSSPs are by now defined in land-based deep marine sections. All these sections have an integrated high-resolution stratigraphy, uniting detailed cyclo-, magneto- and biostratigraphies and have been astronomically tuned. Moreover, they cover the entire interval of the stage in a demonstrable continuous succession. As such, the sections perfectly embody the concept of a stage and may serve as unit stratotype for that stage in addition to accommodating its GSSP. The modified concept of the unit stratotype will be illustrated here on the basis of the standard stages for the late Neogene from older to younger, starting with the Tortonian Stage.

The base of the Tortonian Stage is defined at the sapropel (dark organic-rich layer) mid-point of small-scale precession controlled cycle 76 in the deep marine section of Monte dei Corvi, with an astronomical age of 11.608 Ma (northern Italy; Hilgen et al., 2003). The section is continuous, has a good to excellent integrated high-resolution stratigraphy and is astronomically well tuned up to the level that correlates with the Messinian GSSP formally defined at the base of cycle 15 in section Oued Akrech located on the Atlantic side of Morocco (Bou Regreg area) and dated astronomically at 7.251 Ma (Hilgen et al., 2000). Hence the Monte dei Corvi section may serve as unit stratotype for the Tortonian.

The cyclic open marine succession of the Blue Marls in the Bou Regreg area covers the entire Messinian but the succession is incompletely exposed in the tuned sections of Oued Akrech, Ain el Beida and Loulja (Hilgen et al., 2000; Van der Laan et al., 2005, in press). The time-correlative level of the Zanclean base and, hence, the Miocene/Pliocene boundary is identified in the Loulja section (Van der Laan et al., in press). The Messinian succession is completed with the core drilled at the base of Ainel Beida (Hodell et al., 1994). Moreover a complete Messinian succession has been drilled at Salé, some 5 km north of AEB, but the cores have not been tuned in detail (Hodell et al., 2001; Van der Laan et al., 2005, in press).

The GSSP of the Lower Pliocene Zanclean Stage is formally designated at the base of the deep marine Trubi marls in the Eraclea Minoa partial section of the Rossello Composite exposed in the natural cliffs along the south coast of Sicily (Fig. 1) and dated astronomically at 5.332 Ma (Van Couvering et al., 2000). The base of the superjacent Middle Pliocene Piacenzian Stage is defined at the base of the beige marls of small-scale cycle 77 in the Punta Piccola partial section of the same composite with an astronomical age of 3.600 Ma (Castradori et al., 1998). The Rossello Composite Section has been astronomically tuned (Hilgen, 1991b; Lourens et al., 1996) and is demonstrably continuous up to the level that is time-equivalent with the base of the Upper Pliocene Gelasian Stage formally defined at the top of sapropel A5 at San Nicola, located some 30 km east of Punta Piccola, and dated astronomically at 2.588 Ma (Rio et al., 1998). Consequently the Rossello Composite Section constitutes unit stratotypes of both the Zanclean and Piacenzian stages, having an excellent magnetostratigraphy and calcareous plankton biostratigraphy in addition to the tuned cyclostratigraphy (see Fig. 2; Rio et al., 1984; Langereis and Hilgen, 1991; Hilgen, 1991b).

The Monte San Nicola section contains the interval from the base of the Gelasian Stage up to above the level that time-stratigraphically correlates with the Pliocene/Pleistocene boundary (no formal stage name has yet been selected for the oldest Pleistocene stage) formally defined at the top of the “e” sapropel in section Vrica (northern Calabria, Italy; Aguirre and Pasini, 1985) with an astronomical age of 1.808 Ma (Lourens et al., 1996). The Monte San Nicola section has not yet been tuned entirely but may well serve as unit stratotype for the Gelasian Stage despite some structural deformation. The well-tuned Singa section (southern Calabria, Italy) provides an alternative land-based section for the Gelasian unit stratotype. This section has the additional advantage of having a reliable magnetostratigraphy and excellent stable isotope stratigraphy (Zijderveld et al., 1991; Lourens et al., 1992).

Summarizing a series of tuned deep marine sections containing all late Miocene and Pliocene GSSPs form the backbone of the standard geological time

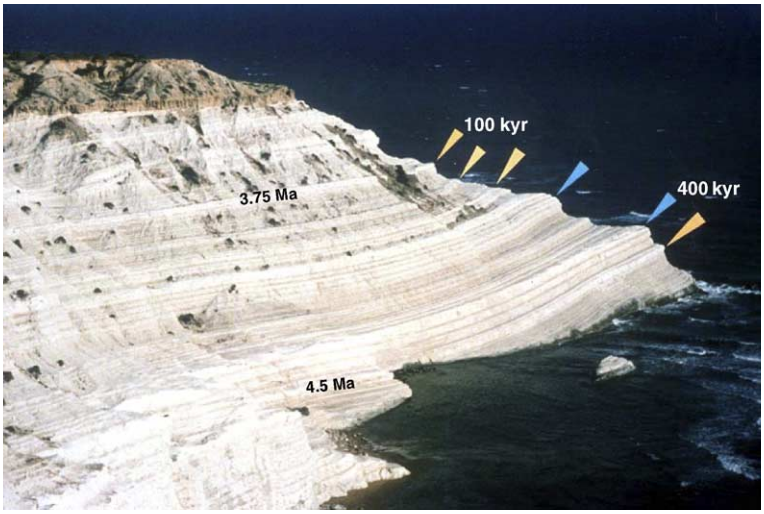

Fig. 1. Color photo of the Punta di Maiata section on Sicily. Punta di Maiata is the middle partial section of the Rossello Composite and part of the potential Zanclean unit stratotype. Larger-scale eccentricity-related cycles are clearly visible in the weathering profile of the cape. Small-scale quadripartite cycles are precession-related; precession-obliquity interference patterns are present in particular in the older 400-kyr carbonate maximum indicated in blue. All cycles have been tuned in detail and the section has an excellent magnetostratigraphy, calcareous plankton biostratigraphy and stable isotope stratigraphy (Langereis and Hilgen, 1991; Hilgen, 1991b; Lourens et al., 1996).

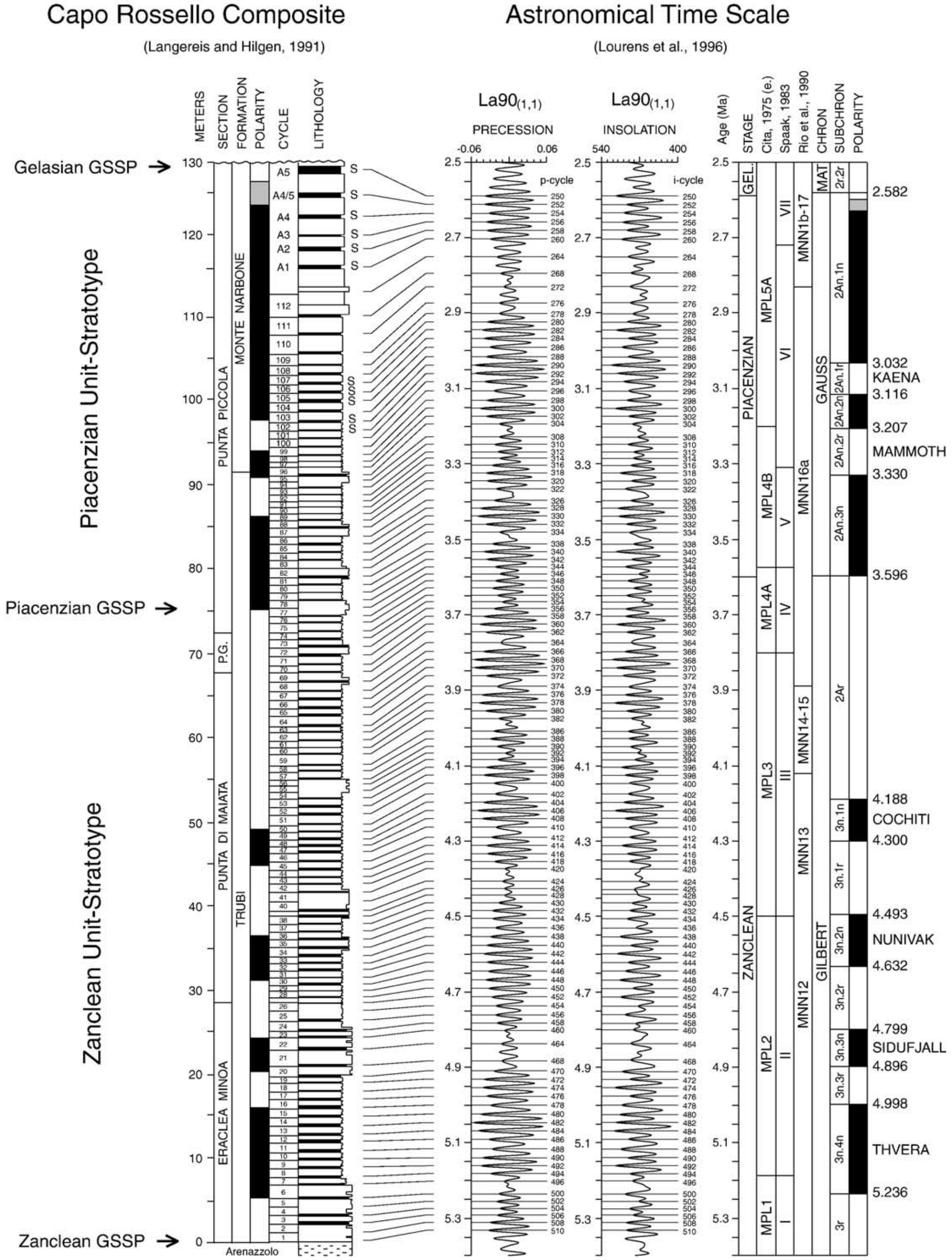

Fig. 2. The Rossello Composite Section (RCS, Sicily, Italy) as prime example of the modified unit stratotype approach showing the orbital tuning of the basic precession-controlled sedimentary cycles and the resulting astronomical time scale with accurate and precise astronomical ages for sedimentary cycles, calcareous plankton events and magnetic reversal boundaries. The Zanclean and Piacenzian GSSPs are formally defined in the RCS while the level that time-stratigraphically correlates with the Gelasian GSSP is found in the topmost part of the section. The well tuned RCS lies at the base of the Early–Middle Pliocene part of the ATNTS2004 and the Global Standard Chronostratigraphic Scale and as such could serve as unit stratotype for both the Zanclean and Piacenzian Stage.

scale, the ATNTS2004. As a consequence all GSSPs are directly tied via first-order calibrations to this new time scale. Evidently the highly accurate and precise astronomical dating of the GSSPs could not have been made without the cyclostratigraphic content of the stages as exposed in their potential unit stratotypes which in addition provides excellent age control with an unprecedented resolution and accuracy *within* the stage (compare Walsh, 2004, p.138–139). Evidently the latter is of crucial importance if one argues that the final goal of chronostratigraphy is to provide a calendar to reliably reconstruct Earth's history.

However, unit stratotypes of global Neogene stages do not have to be necessarily defined in the Mediterranean sections listed above. Other well tuned sections (or ODP cores, see also Section 3.2) may be considered as well because of their excellent stable isotope records or the fact that the standard low-latitude calcareous plankton zonal schemes are directly tied to them. On the other hand, all GSSPs are defined in the Mediterranean sections which have a good-to-excellent calcareous plankton biostratigraphy and magnetostratigraphy in addition to the tuned cyclostratigraphy.

3.2. Paleogene, Mesozoic and Paleozoic

It is for all the above reasons that we propose the same approach in defining the remaining stage boundaries in at least the Neogene, Paleogene and Cretaceous and possibly in the entire Mesozoic (i.e., to place golden spikes in continuous deep marine sections that have an excellent integrated high-resolution stratigraphy, are astronomically tuned and serve as unit stratotype for that particular interval). It is only a matter of time before the astronomical time scale is extended into the Cretaceous and serious attempts are already made in this direction (Shackleton et al., 1999; Pälike et al., 2001; Dinares-Turell et al., 2003; Wade and Pälike, 2004). The new numerical solutions of Varadi et al. (2003) and Laskar et al. (2004) are accurate over the last 40 million years as far as eccentricity is concerned. The most stable 400-kyr eccentricity component can reliably be used to establish a tuning for the entire Mesozoic (Laskar et al., 2004). Despite the existing uncertainty in E_D and *TD* values, tuning to precession and obliquity (and insolation) is still possible due to additional constraints provided by the amplitude modulation (which is eccentricity for precession). For the Paleozoic, direct astronomical tuning is beyond reach at least for the moment but a Milankovitch based unit stratotype approach will be particularly useful to demonstrate continuity and completeness of the stratigraphic record and to provide a high-resolution integrated stratigraphy and accurate estimate for the astronomical *duration* (not *age*) of a stage (e.g., House, 1995).

Most ideally, tuning of unit stratotypes underlies the age calibration of the geological time scale, including the GCS, for that particular time interval, as is the case for the late Neogene. Selecting the most suitable deep marine sections implies that deep-sea cores should not be excluded beforehand. Drilling of multiple offset holes per single ODP site in combination with the Advanced Piston Corer (APC) technique already ensured the recovery of some of the most complete, continuous and relatively undisturbed cyclic deep marine successions that are presently available (e.g., Pälike et al., 2001; Cramer et al., 2003; Röhl et al., 2003; Lourens et al., 2005; Zachos et al., 2005). Moreover, redrilling of the sites in question can now easily compensate depletion of materials and such locations do not suffer from anthropogenic changes, weathering or other erosional processes. Such cores are in our view thus perfectly suitable for extending the astronomical time scale and, hence, the modified unit stratotype approach back into the Mesozoic. In fact the use of (I)ODP cores (like e.g., those of Leg 199 for the Oligocene, and of Legs 171, 189, 208 for the Eocene) seems inevitable in defining Paleogene and Cretaceous stages, although land-based sections are available as alternatives in certain intervals (e.g., sections in the Vocontian Basin, southern France and in northern Italy). Initially attention was mainly on calculating the (cycle) duration of stages and chrons (e.g., Herbert et al., 1995; Giraud et al., 1995; Gale, 1995; Fiet et al., 2001; Röhl et al., 2003; Grippo et al., 2004; Wissler et al., 2004) but focus will soon shift towards direct tuning of the cyclic successions (Dinares-Turell et al., 2003). But, if one accepts the modified unit stratotype concept[3] and define the remaining GSSPs of the Cenozoic and Cretaceous in an astronomical tuned integrated stratigraphic framework of deep marine sections, it is clear that it takes time (at least 5 to 10 years) to develop such a framework. In that case the deadline set by the International Commission on Stratigraphy to have all GSSPs defined

[3] Following the formulation of the GSSP concept, unit stratotypes for global stages may be named GUSS (Global Unit Stratotype Section), or GUSSP (Global Unit Stratotype Section and Point) in case the (lower) boundary of that stage is defined in the same section, to distinguish them from unit stratotypes in general. Such sections represent an hypostratotype of the original historical stratotype section.

by 2008 will not be met.[4] In fact one might even consider to relocate some of the existing GSSPs to sections that are more suitable for the purpose.

For GSSPs that have already been defined, auxiliary boundary stratotypes that act as unit stratotype can be defined. For instance the Oligocene–Miocene boundary formally defined in the less suitable Lemme–Carrioso section (Steininger et al., 1997) is now astronomically dated at Ceara Rise (ODP Leg 154 Sites) in the equatorial Atlantic (Shackleton et al., 1999, 2000). ODP Leg 154 sites can act as auxiliary stratotype for the Oligocene–Miocene boundary and as unit stratotype for the oldest Miocene stage, the Aquitanian.

3.3. Astronomical-defined chronozones

Astronomical tuning resulted in a new generation of geological time scales with an unprecedented accuracy, resolution and stability. In this respect it is worth considering the introduction of a formal codification scheme for astronomical controlled variations in the stratigraphic record (see Hilgen et al., 2004). At present different informal schemes exist in the literature for sedimentary cycles and cyclic variations in oxygen-isotope records that have been tuned to the astronomical record. Oxygen-isotope stages have been numbered back from the Recent with even numbers indicating glacial stages (e.g., Emiliani, 1955; Raymo et al., 1989) or have been given a code linked to the magnetic Chron nomenclature via magnetostratigraphic calibration (Shackleton et al., 1995b). Sedimentary cycles in the Mediterranean Pliocene and Pleistocene have been coded after the correlative peak in the precession or insolation time-series numbered back from the Recent (Hilgen, 1991a,b; Lourens et al., 1996). However, probably the most suitable cycle for defining astronomically calibrated variations is the 400-kyr eccentricity cycle because it is the longer-term orbital cycle that is most stable over prolonged intervals of time making it an excellent target for extending the astronomical time scale (Hilgen et al., 2004; Laskar et al., 2004). Wade and Pälike (2004) recently used this approach to informally label cyclic variations in stable isotope records of Oligocene age from ODP Site 1218, while they maintained a link to the Chron nomenclature.

It can even be argued whether these 400-kyr packages should be given a formal status. In that case, type sections, preferably the unit stratotypes, should be designated where the 400-kyr cycles are well-developed and astronomically tuned, and are directly linked to other stratigraphic scales. Such formal astronomically calibrated time-stratigraphic units can even be incorporated in the standard Global Chronostratigraphic Scale. The latter would be a logical consequence if the age calibration of the Chronostratigraphic Scale is based on astronomical tuning of these units. In practice this prerequisite is already met for the younger part of the Neogene.

Astronomically controlled climatostratigraphic units would fall under the category of the Chronozone, being a non-hierarchical formal chronostratigraphic unit, according to the second edition of the International Stratigraphic Guide (Salvador, 1994). Non-hierarchical means that they are not part of the hierarchy of conventional chronostratigraphic units and, hence, that their boundaries do not necessarily coincide with the boundaries of conventional units. However, astronomically controlled units differ from other chronozones in several ways, not in the first place because they possess direct and absolute time significance. As such they not only represent chronostratigraphic units (of minor rank) but are also used to age calibrate the Global Chronostratigraphic Scale through orbital tuning. Following the Stratigraphic Guide (Salvador, 1994), the (cyclo)stratigraphic unit on which the Chronozone is based extends geographically only as far as its diagnostic properties (f.i., $\delta^{18}O$, sapropels) can be recognized. However, the influence of the underlying insolation forcing through variations in the Earth's orbital parameters is global.

It should be noted that a formal subdivision of stages into Standard Chronozones defined by "golden spikes" has been proposed before although from a somewhat different perspective (George et al., 1967; Holland, 1986; see also Walsh et al., 2004). In our case it is a logical consequence of the much improved resolution and age control that has been achieved during the last decades with integrated high-resolution stratigraphy combined with orbital tuning.

3.4. Unit stratotypes and GSSPs

The recent advance in tuning sedimentary cycles argues for the reintroduction of the unit stratotype concept. Main arguments against unit stratotypes ini-

[4] The discussion above also depends on the definition of chronostratigraphy. In a narrow sense chronostratigraphy remains restricted to the philosophy and procedures involved in the formal definition of standard chronostratigraphic units of the geological time scale (Whittaker et al., 1991; Walsh, 2004). In our view chronostratighraphy is the temporal ordening of the stratigraphic record thus providing the means to reliably reconstruct Earth history while the restricted definition refers to chronostratigraphic classification only. Our preferred definition links up directly with the modified unit stratotype approach.

tially preferred by Hedberg were uncertainties in time-stratigraphic correlations between potentially overlapping historical stratotypes and, secondly, the perception that no ideal (i.e., continuous) successions exist (e.g., Ager, 1973; Hedberg, 1976; Walsh et al., 2004). Consequently a stage was best defined by its boundary stratotypes (Hedberg, 1976, p.71). These arguments were probably valid at the time that cyclostratigraphy and deep-sea drilling were still in their infancy but do not hold today. Both deep-sea cores as well as land-based sections do contain deep marine Neogene records that are continuous and allow orbital tuning for absolute age calibration with an unprecedented resolution and accuracy. It is also clear that uncertainties in time-stratigraphic correlations between successively younger (neo)stratotype sections have been eliminated. Consequently, the counterarguments against the designation of unit stratotypes outlined above are no longer valid.

The unit stratotype concept also touches upon the debate whether the dual classification scheme for time-rock units (chronostratigraphy) and equivalent time units (geochronology) should be continued or abandoned as proposed by Harland et al. (1990) and, more recently, by Zalasiewicz et al. (2004). In fact the tendency exists to limit the use of time-rock units to GSSPs of global chronostratigraphic units and equating them with specific moments in time (e.g., Zalasiewicz et al., 2004). With all GSSPs expected to be defined by 2008, the time might seem ripe to abandon the dual system of time-rock and time units by dropping the time-rock units. This approach however downgrades the importance of time-rock units, being the basic building blocks of the GCS, while it is the rock record from which the scale is ultimately derived. Moreover, it is in contrast with the concept of the (modified) unit stratotype and the introduction of formally defined orbitally controlled chronozones. In fact the modified unit stratotype concept in combination with astronomical tuning once more stresses the importance of time-rock units and thus provides a strong argument against the elimination of the dual classification system despite the fact that the astronomical tuning of orbital-forced climate change results in a very tight and intimate link between the rock record (in the unit stratotypes) and absolute geological time. The concept however reduces the necessity to distinguish between chronostratigraphy/geochronology (relative time) and geochronometry (absolute time), as expressed for instance by the Chronostratigraphic and Geochronometric Scales of Harland et al. (1990). The reason for this is that highly accurate and precise absolute astronomical ages are now directly assigned to the tuned cyclic succession in the unit stratotype and, hence, to stage boundaries, magnetic polarity reversals and bioevents that are *directly* tied to it via first-order calibrations.

Of course, it can be argued to leave the GCS as it is, with GSSPs defined in boundary stratotype sections that are not always the most suitable available and that are not underlain by astronomical tuning. In this case, the GSSPs will provide a stable albeit admittedly rough time frame sufficient for mapping and the reconstruction of the general history of our planet. Accordingly there is no need for the re-introduction of the unit stratotype concept and the formal designation of astronomically controlled units as chronozones. But much higher resolution integrated time scales are needed in particular–but not exclusively–for paleoclimate studies; they will be developed independent from the potential use of the underlying cyclic sections as unit stratotype for global stages. Such time scales are in that case based on tuned marine sequences which only occasionally will contain golden spikes, providing direct astronomical ages for these stage boundaries only.

4. Conclusions

Recent progress in integrated high-resolution stratigraphy in combination with astronomical tuning heralds a revolution in Earth Sciences, allowing the construction of time scales with unprecedented resolution, precision, accuracy and stability. It started already to revolutionize our understanding of the Cenozoic and Cretaceous in the same way as the SPECMAP time scale changed our perception of the late Pleistocene.

Basic chronostratigraphic units, the stages, should be defined using the most suitable sections available (i.e., sections that are continuous, deep marine and cyclic), allowing astronomical tuning and underlying the standard geological time scale for that time interval. We recommend that these sections may serve as unit stratotype for that particular stage, while orbital tuned cycles, in particular the 400-kyr cycle, may be formally defined as chronozones, i.e., non-hierarchical chronostratigraphic units of lower rank.

A basic chronostratigraphic unit such as the stage should not just be defined by its boundaries; the temporal resolution and accuracy *within* that unit is of great importance for the detailed reconstruction of Earth's history. Moreover, although a point (or "golden spike") may define a stage boundary, it does not define a stage as envisaged by Hedberg and, e.g., suggested by Aubry et al. (1999). As such the (modified) unit stratotype approach as advocated here strengthens the rationale for time-rock units and argues against the elimination of the dual classification of chronostratigraphy (time-rock) and geochronology (time).

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