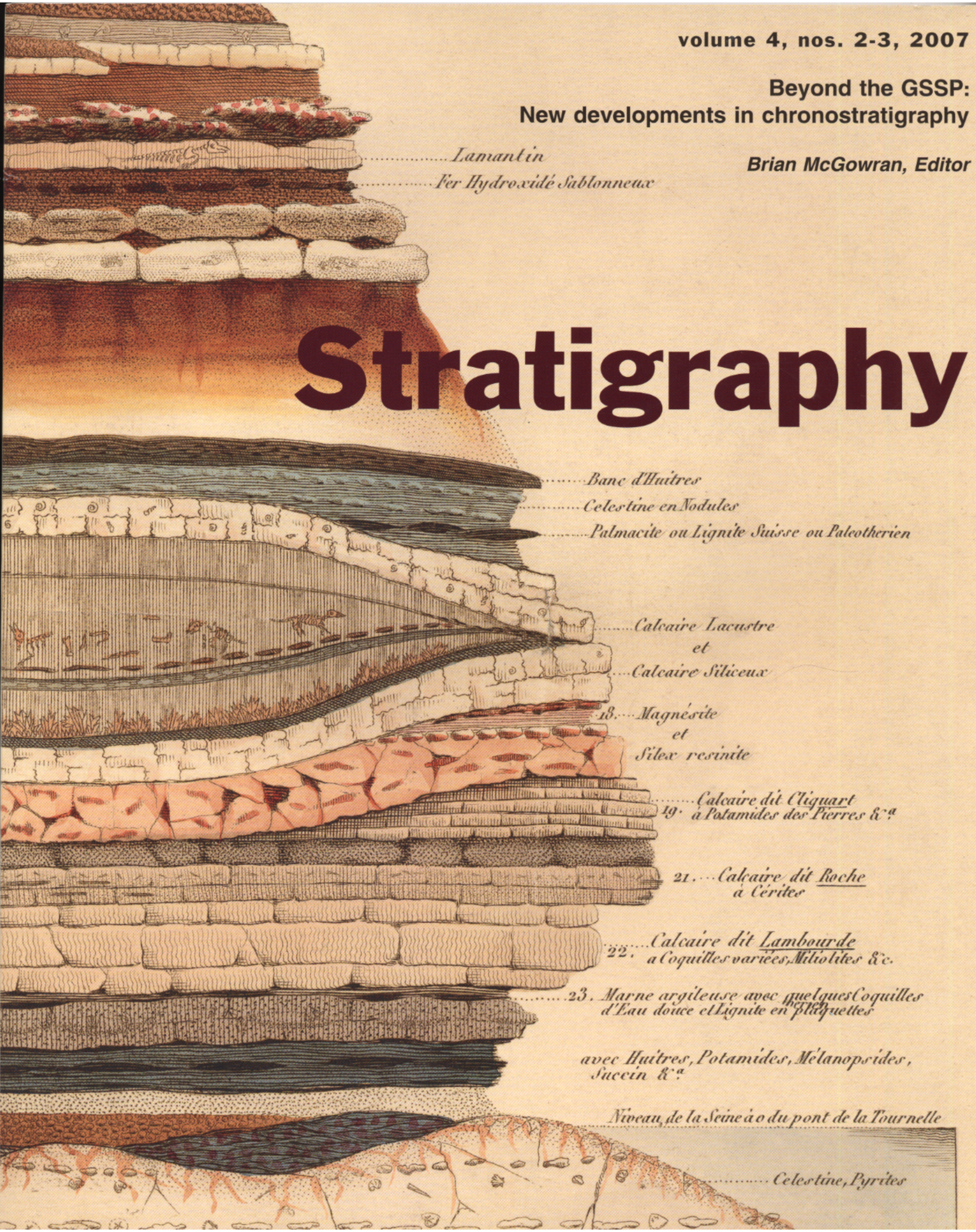
volume 4, nos. 2-3, 2007

Beyond the GSSP: New developments in chronostratigraphy

Brian McGowran, Editor

Stratigraphy



CONTENTS Volume 4 Numbers 2-3 2007

BEYOND THE GSSP: NEW DEVELOPMENTS IN CHRONOSTRATIGRAPHY

Cyclostratigraphy and the Astronomical Time Scale

Linda A. Hinnov[1] **and James G. Ogg**[2]
[1]*Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, Maryland 21218 USA*
email: hinnov@jhu.edu
[2]*Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, Indiana 47907 USA*
email: jogg@purdue.edu

ABSTRACT: An important innovation in the International Geologic Time Scale 2004 is the use of astronomically forced stratigraphy, or cyclostratigraphy, to define geologic time over 0 to 23.03 Ma, much of it at an unprecedented resolution of 0.02 myr. In addition, 'floating' astronomical time scales with 0.10 to 0.40 myr resolution are defined for entire epochs and stages in the Paleogene and all three Mesozoic periods. Some of these calibrations use a new astronomical model with an hypothesized high accuracy over 0-250 Ma. These accomplishments have motivated the International Commission on Stratigraphy to complete a continuous Astronomical Time Scale ('ATS') for the past 250 Ma, and to initiate a coordinated prospecting for astronomical-like signals in Paleozoic cyclostratigraphy. Astronomically calibrated geologic time with a 0.02 to 0.40 myr resolution is a major breakthrough for the geosciences. Chronostratigraphy between widely spaced horizons dated with high-precision radioisotope geochronology suffers total loss in precision and accuracy; a continuous ATS between horizons can restore this hard-won precision and accuracy. Consequently, estimates of rates and magnitudes for a wide range of Earth system processes that can be examined only in the context of Earth history, e.g., paleoclimatology, geochronology, geodynamics, structural geology, geochemical cycles and biotic evolution, will be improved up to an order of magnitude over what is possible today.

INTRODUCTION

Quasi-periodic variations in the Earth's orbit and tilt relative to the Sun produce long-term 'Milankovitch cycles' in seasonal and latitudinal solar insolation. These astronomically forced cycles have a modulating effect on global climate and ocean circulation patterns. The astronomical forcing signal has been recorded in continental and marine sedimentary systems responding to these climate changes over hundreds of millions of years of Earth history. Figure 1 depicts the Earth's astronomical parameters that affect the insolation forcing of climate, and some of the exceptional astronomical signals that have been recovered from Phanerozoic cyclic stratigraphy.

Cyclostratigraphy that is calibrated to 'astronomical target' curves derived from models of solar system dynamics provides a continuous 'Astronomical Time Scale' (ATS). The ATS has a resolution of 0.02-0.4 million years, which is an order of magnitude higher than the current 1-5 million years of the International Geologic Time Scale 2004 (Figure 2). Consequently, the ATS has the potential to transform the study of a wide range of Earth system processes that can be examined only through the context of the geologic record.

Present status of the ATS

A detailed astronomical calibration of Neogene stratigraphy is used in GTS2004 (Lourens et al. 2004). Ages of terrestrial mammal stages, sea-level sequences, and even a proposed recalibration of the ^{40}Ar/^{39}Ar standard, Fish Canyon sanidine (Kuiper et al. 2004, 2005a,b) are now all derived from correlation to this Neogene ATS. Utilization of long-term modulation of the astronomical cycles has enabled accurate calibration of marine oxygen-isotope excursions into the Oligocene (~25 Ma) (Shackleton et al. 1999, 2000). These astronomical calibrations have resulted in significant revisions of earlier estimates of stage boundary ages and oceanic spreading rates, for example, the Paleogene/Neogene boundary is now astronomically calibrated as 23.03 ±0.1 Ma instead of 23.8 ±1.0 Ma. For times prior to the Neogene Period, GTS2004 incorporates 'floating' scales derived from cyclostratigraphy: Early Eocene-Paleocene (Norris and Röhl 1999; Röhl et al. 2000, 2001, 2003; Luterbacher et al. 2004), portions of Cenomanian (Gale 1995, Gale et al. 1999), Albian (Fiet et al. 2001, Grippo et al. 2004), Early Cretaceous (e.g., Giraud et al. 1995, Huang et al. 1993), Toarcian-Aalenian (Hinnov and Park 1999), Pliensbachian (Weedon and Jenkyns 1999), and Late Triassic (Olsen et al. 1996, Kent and Olsen 1999).

In September, 2006, a joint symposium and working session for *'Recent developments in the geologic time scale using orbital tuning'* was convened by the International Association for Mathematical Geology (IAMG) and the International Commission on Stratigraphy (ICS) at the *XIth International Congress for Mathematical Geology* in Liège, Belgium. This unique two-day event brought together astrophysics, orbital-cycle analysis experts, and stratigraphers from Neogene through Permian. It quickly became apparent that a complete Mesozoic-Cenozoic ATS (~250 Ma) is feasible, due to the emergence of the following significant factors:

New astronomical model to 250 Ma: The astronomical solution that enabled the calibration of the Cenozoic ATS (Laskar et al. 2004) has been significantly enhanced to allow astronomical calibrations to the base of the Mesozoic (250 Ma) (Laskar 2006).

New ocean basin data: International Ocean Drilling Program (IODP) Legs 207, 208 and 210 were devoted to recovering high-frequency cyclostratigraphy through the Paleogene-Cretaceous. Data collected from these legs and upcoming IODP 314 (Equatorial Pacific) will provide ATS data for the past 70 Ma

(Röhl and Ogg 2006; Pälike et al. 2006a,b; Westerhold et al. 2007; Westerhold et al., submitted).

New land-based data: Cyclostratigraphic studies are currently underway of Cretaceous, Jurassic, Triassic and Permian sections throughout the Tethys and Boreal provinces of western Europe, northern Africa and North America to enable a direct calibration of microfossil, ammonite and polarity zones (reviewed by Ogg and Hinnov 2006; Weedon and Coe 2006).

Accordingly, the ICS recognized the exciting prospect of compiling an ultra-high resolution time scale for the past quarter-billion years and established a *Task Group for a Cenozoic-Mesozoic Astronomically-Tuned Time Scale.* This task group will coordinate the integration of an array of cyclostratigraphy databases and associated studies into a preliminary composite Cenozoic-Mesozoic time scale for inclusion in the next iteration of the International Geologic Time Scale in 2008. Other goals include constructing a consistent system for cyclostratigraphy, establishing standards for methodology and linkage of databases, and providing calibrations of volcanic ashes that are suitable for radioisotope dating methods.

Uncertainties in the Geologic Time Scale

Figure 2 summarizes the uncertainty in GTS2004. There are intervals where precision is relatively high, e.g., the astronomically tuned Neogene Period, and four critical boundaries (K/T boundary, T/J boundary and basal Cambrian) where multiple radioisotopic dating studies have been conducted (Fig. 2B). Otherwise, the majority of the Phanerozoic time scale has disappointingly high uncertainty that ranges between 1-5 million years. This severely hampers study of deep-time Earth systems interactions.

The advent of high-precision geochronology and astronomically driven cyclostratigraphy has the potential to improve the precision and resolving power of the GTS to less than a 0.5 million year level (bottom of Fig. 2B). A precision limit of ~0. 1% is now routinely accomplished in U-Pb radioisotope dating (Schoene et al. 2006; Bowring et al. 2006). This information, however, is derived from volcanic ash beds that are generally very widely spaced in the stratigraphic record (Fig. 2C); GTS precision is quickly lost in the intervening intervals, which can be up to tens of myr long. The continuity provided by cyclostratigraphy can restore precision to the submyr level through such intervals. Thus, ATS reconstruction is an important priority in Earth history research.

Three sources of uncertainty affect the ATS. First, lack of knowledge about Earth's past tidal dissipation and its effect on the precession translates into an accumulating bias in the timing of obliquity and precession cycles back in time (Berger et al. 1992). This effect is noted in Figure 2E as a 'tidal error' in terms of potential deficit of years in the current La2004 precession model (Lourens et al. 2001, 2004). A second uncertainty source lies in chaotic diffusion in the solar system (Laskar 1990; Laskar et al. 1993, 2004). Earth's orbital eccentricity is likely stable throughout most of the Cenozoic; between 50-100 Ma, however, Earth-Mars orbital resonance is thought to have undergone a transition (Laskar et al. 2004). In particular, the 2.4 myr amplitude modulation of the ~100-kyr terms of Earth's orbital eccentricity may have been affected. The precise timing of this latest transition is not known; prior to the transition, orbital behavior cannot be modelled accurately. Fortunately, the 405-kyr orbital eccentricity term, from gravitational interaction between Jupiter and Venus, g_2-g_5, is thought to have remained very stable as well as dominant (due to the great mass of Jupiter) over several hundreds of millions of years, with an estimated uncertainty reaching only 500 kyr at 250 Ma (see 'maximum error', Fig. 2E). Finally, stratigraphic effects related to random depositional events or non-deposition comprise a third source of uncertainty. In many cases, these effects can be accounted for, for example, turbidites by visual inspection (Maurer et al. 2004), and hiatus detection by quantitative biostratigraphy (Cooper et al. 2001), time-frequency analysis (Meyers and Sageman 2004) and/or cyclostratigraphic correlation (Shackleton et al. 1999).

STANDARDS AND METHODS

General considerations

The keystone for the Neogene ATS has been the matching ('tuning') of the predicted orbitally forced insolation cycles, i.e., the classic Milankovitch 65º North summer insolation to the sequence of sedimentary (or climate-proxy) cycles progressively back in time (e.g., Hilgen et al. 1999). The long-term continuity of the orbitally calibrated curves, as for example illustrated in Lourens et al. (2004, Figs. 21.4, 21.5), was achieved by detailed bio-magnetostratigraphic correlation among a set of tuned sections; precision of the timing is on the order of 0.020 myrs.

For the Early Cenozoic ATS, limited knowledge about tidal dissipation (e.g., Berger et al. 1992; Laskar et al. 1993; Néron de Surgy and Laskar 1997) imposes potential inaccuracies approaching 0.5% by 20 Ma (Lourens et al. 2004). Nonetheless, insolation targets have been crucial for the Miocene-Oligocene ATS (e.g., Shackleton et al. 1999, 2000; Zachos et al. 2001). Of pivotal significance, long-period amplitude modulations of the obliquity and precession index (1.2 myr and 2.4 myr, respectively) have enabled an exact age assignment of 23.03 Ma to the Oligocene-Miocene boundary (Pälike et al. 2006a). For the Paleogene ATS, in view of presumed mounting uncertainties in the precession, calibrations rely on an orbital eccentricity target (Westerhold et al. 2007; Westerhold et al., submitted).

For the Mesozoic ATS, measurable effects in Earth's orbital motions from solar system diffusion are likely. Changes in resonance between the orbits of Earth and Mars may cause the 2.4 myr long-term modulation to break down, and alter ~95 to 128-kyr eccentricity terms (Varadi et al. 2003; Laskar et al. 2004). This limits accurate ATS targets to a single mode, g_2-g_5, the 405-kyr orbital eccentricity cycle, although the 2.4 myr amplitude modulation has recently been proposed as viable throughout the Mesozoic (Matthews and Frohlich 2002; Al Husseini and Matthews 2005).

Standards

Global stratigraphic correlation

Attendant stratigraphic information is required for linking the ATS directly to globally significant stratigraphic points/levels, and for providing the geologic framework for duplication studies and splicing. Biostratigraphic and/or magnetic reversal control are essential elements for most contributing data. Nannofossils, foraminifera and ammonites can all be linked to the current Jurassic-Cretaceous global stratigraphic framework set out by the ICS. For the Triassic and older periods, ammonite and conodont stratigraphy comprise principal fossil groups, and a rapidly growing magnetic reversal archive (e.g., Muttoni et al.

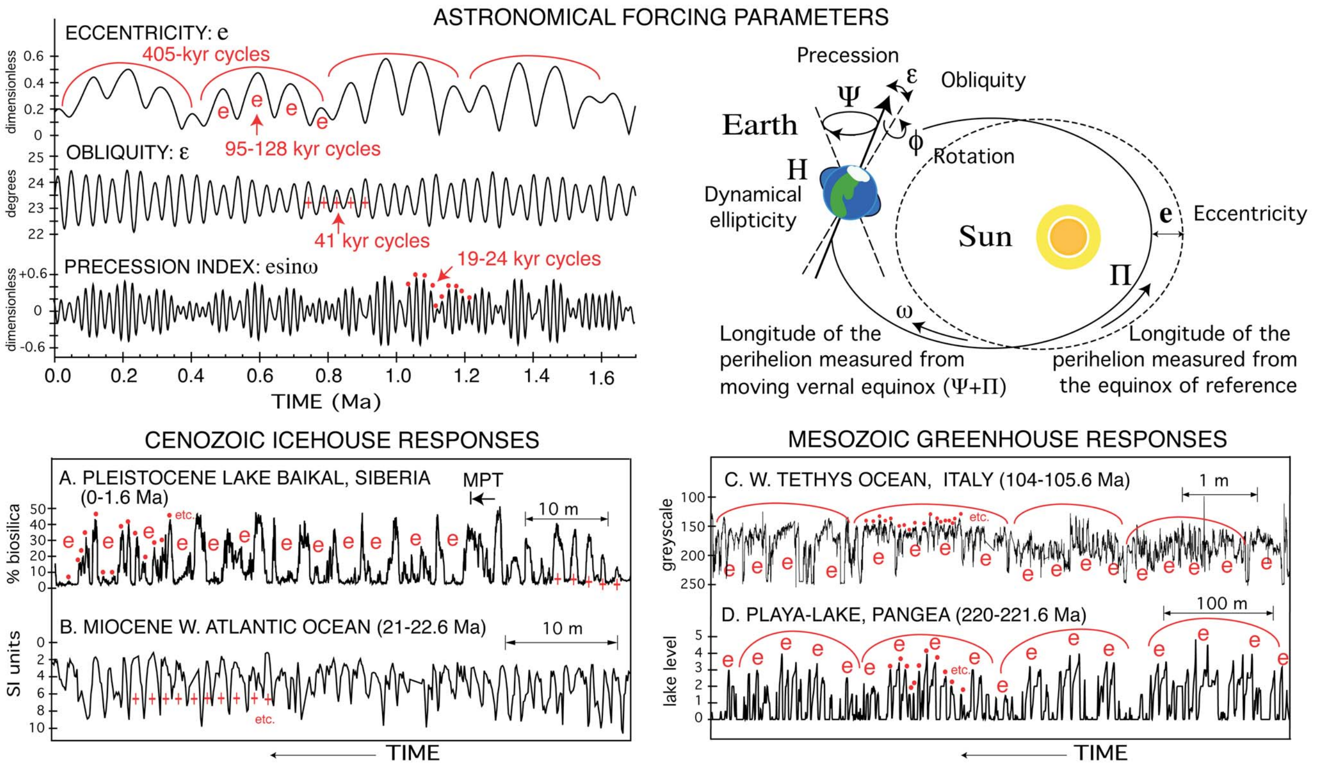


FIGURE 1
Astronomical forcing of the ancient sedimentary record. TOP: Parameters affecting Earth-Sun position (right) undergo 10^4-10^5 year oscillations, shown for the past 1.6 million years (left) (Laskar et al. 2004). Main periodicities are indicated in red. BOTTOM: 1.6 myr-long excerpts from multi-million year-long continental and marine sedimentary sequences showing icehouse (left) and greenhouse (right) climate responses. A–Biogenic silica cycles from a >5 myr-long Lake Baikal core (Prokopenko et al. 2006) reveal a complex response, with the noted 'Mid-Pleistocene Transition' (MPT) from obliquity to major 100-kyr cycling occurring at 1.2 Ma. B–Marine carbonate cycles measured by magnetic susceptibility proxy from the 10 myr-long ODP Site 926B core (Shackleton et al., 1999) exhibits strong obliquity forcing. C–Deep sea carbonate cycles measured by greyscale imaging of a 20 myr-long core through the Fucoid Marls (Grippo et al. 2004). D–A lake depth succession from the 30 myr-long Newark Series (Olsen et al. 1996) shows dominant precession control with responses amplifying the precession index envelope, i.e., the eccentricity. The astronomical periodicity has been documented by time series analysis and modeling; B, C and D have recently been used to calibrate the International Geologic Time Scale 2004 (Gradstein et al. 2004).

2004). In addition, there are numerous, globally significant marine chemostratigraphic patterns that provide well-constrained correlation where biostratigraphy and magnetostratigraphy fail (e.g., the Albian). Finally, high-precision geochronology provides key "tie points" and inter-calibration checks for absolute time along the ATS.

The orbital-climate-sediment link

Understanding the links between sediment, climate and orbital-forced insolation provides crucial support for the ATS. As a rule, the astronomical signal is quite visible in stratigraphy, usually manifested by dark/light lithologic variations. Retrieval of the signal involves fine-scale observations of the vertical sequencing of sedimentary facies and/or dense sampling of sediment geochemistry or other components, e.g., carbonate, iron, TOC, stable isotopes, magnetic susceptibility, color imaging, etc. Such observations need to be interpreted in the context of the sedimentary response to the orbital-climate forcing. This has not always been so forthcoming. For example, the Neogene sapropels have now been matched to the full succession of orbital insolation cycles, but there is still ambiguity of how the insolation came to produce the rhythm-defining sapropelic sediments. To address this issue, the role of terrestrial hydrology in sapropel formation has been investigated with the aid of a coupled climate model (Tuenter et al. 2005; Hilgen et al. 2005). Understanding these linkages raises confidence in the Neogene ATS, and moreover, improves ATS estimated precision, which presently is conservatively limited to ±10 kyrs (Lourens et al. 2004). To maximize confidence in the ATS well-argued orbital-climate models are essential.

METHODS

Time-frequency analysis

Quantitative methods are required for detection of astronomical signal in cyclostratigraphy. Basic methods include: interpolation, statistical time series analysis with hypothesis testing, correlation, tuning, filtering, and demodulation. Evolutionary methods are needed to assess 'time-frequency landscapes' of stratigraphic signals for Milankovitch frequency behavior, variable sedimentation rates, and the presence and durations of hiatuses (e.g., Meyers et al. 2001).

Sedimentological tuning

Excising turbidite and volcaniclastic bed thicknesses, or correcting a geochemical or mineral concentration to a constant value along a section can focus strong astronomical signals (e.g., Kominz et al. 1979; Herterich and Sarnthein 1984; Maurer et al. 2004). Likewise, differential decompaction estimated empirically from magnetic properties in the sediment can sharpen even subtly misaligned astronomical signals (Kodama and Anastasio, in prep.). Recently, a 'depth-derived' strategy was developed that models space-time sediment accumulation across multiple sections as an autocorrelated stochastic process (Huybers and Wunsch 2004). These approaches have strong advantages over astronomical tuning (described next) in that they do not manipulate the recorded astronomical signal directly.

Astronomical tuning

Astronomical (orbital) tuning is the mainstay of ATS calibration. In most cases, starting with a conservative 'minimal tuning' approach is preferable, where only one astronomical frequency is used as the target (Muller and MacDonald 2000). Other astronomical frequencies sharpened in the process constitutes evidence for astronomical forcing, and may be interpreted relative to the tuned frequency. In fact, for the Mesozoic, minimal tuning may be the only option. For this reason, the 405-kyr eccentricity cycle may be the sole reliable astronomical 'target' for the Mesozoic ATS (Kent 1999; Shackleton et al. 1999; Laskar et al. 2004). Using the 405-kyr cycle as the basic astronomical scaling framework will be explored in detail in future ATS development. Examples of Mesozoic stratigraphy with recognizable 405-kyr cycles are shown in Figure 1, and demonstrates the feasibility of this approach; presently, the Albian sequence provides a floating ATS based on 405-kyr tuning for GTS2004.

THE ATS OF THE FUTURE

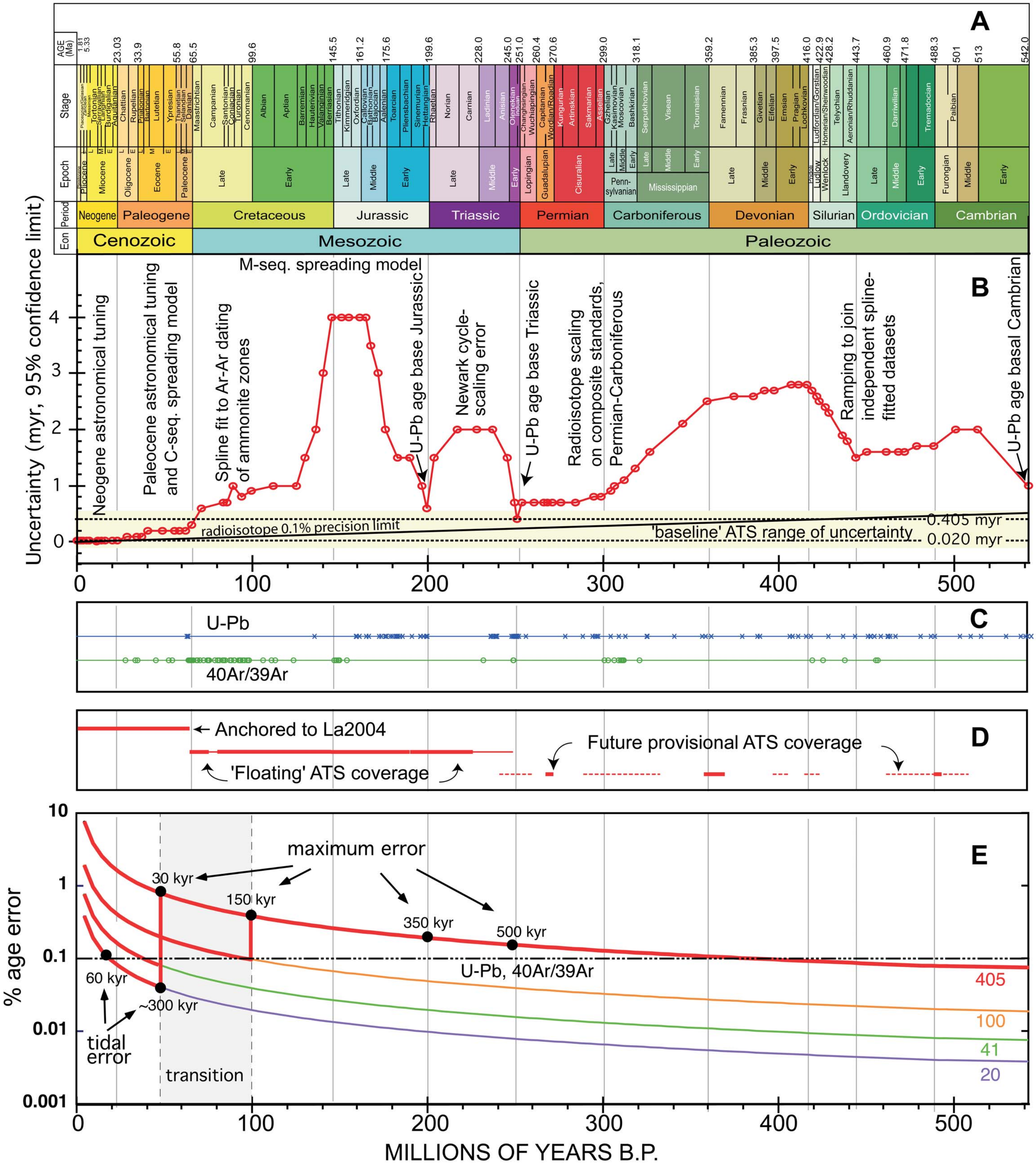
Cyclostratigraphic studies have been published or are in progress for at least one section spanning each geologic stage throughout the Cenozoic and Mesozoic, and there is a steadily growing literature devoted to Paleozoic cyclostratigraphy. Biogenic pelagic sedimentation has proven to be the best recorder of the Cenozoic and Late Mesozoic ATS. In the Triassic and Paleozoic, however, biotically mediated pelagic sediment sources had not yet evolved; much of the evidence occurs in comparatively unexplored cyclic shallow marine facies, and poses a unique set of research challenges (Hinnov 2000). Additionally, for the foreseeable future, a Paleozoic ATS will be restricted to a 'provisional' status, due to lack of an astrodynamical model that can accurately predict planetary motions prior to 250 Ma (Laskar et al. 2004; Laskar 2006). Figure 2D shows the distribution of Phanerozoic cyclostratigraphy that is expected to contribute to the ATS in the near future, summarized as follows.

Cenozoic Era

With its pristine stable isotope record and innumerable facies expressions of an astronomically forced global climate, the Neogene series provides most of our information about astronomical forcing. GTS2004 incorporates an 'absolute' ATS for the Neogene, which is comprised of overlapping signals from stratigraphy from the Mediterranean, Atlantic and Pacific basins (Lourens et al. 2004). The Neogene ATS redefined the ages of major biostratigraphic zones, magnetochron boundaries and major global events; significantly, the base of the Neogene Period was recalibrated from 23.8 Ma to 23.03 Ma. Future work includes marine-continental correlation (e.g., Heslop et al. 2000; Prokopenko et al. 2006), testing geodynamical parameters in the astronomical target (e.g., Lourens et al. 2001), and inter-calibration between the ATS and high-precision radioisotope dates (e.g., Singer et al. 2004; Kuiper et al. 2005a,b).

GTS2004 also incorporated several floating ATS intervals into the Paleogene time scale, for the latest Oligocene and the Danian portion of the Paleocene (Luterbacher et al. 2004). Today, the Paleogene ATS is nearing completion: The Oligocene is defined with an estimated 0.04 myr resolution, due to dominant obliquity forcing (Wade and Pälike 2004; Pälike et al.

FIGURE 2→
Uncertainty in the Phanerozoic International Geologic Time Scale (GTS) 2004 (Gradstein et al. 2004). A–Standard divisions of the GTS. B–Estimated uncertainty (95% confidence level) of stage boundary ages. C–Distribution of U-Pb and $^{40}Ar/^{39}Ar$ dates used in the construction of GTS2004. D–Distribution of astronomically forced cyclostratigraphy in the Phanerozoic. Thick solid lines indicate cyclostratigraphy contributing to the absolute ATS, e.g., anchored to the La2004 astrodynamical model, or to floating ATS segments. Thin solid lines indicate gaps; dashed lines indicate reported cyclostratigraphy with potential to yield ATS information. The Cenozoic ATS is close to complete, anchored to La2004 (Lourens et al. 2004; Wade and Pälike 2004; Pälike et al. 2006a,b; Westerhold et al. 2007, submitted). Some Mesozoic cyclostratigraphy already contributes ATS information to GTS2004 (designated below by *); and the reporting indicates potential future coverage for nearly the entire Era (Ogg and Hinnov 2006; Weedon and Coe 2006): **Cretaceous**: Herbert 1999; Herbert et al. 1995; Herbert and D'Hondt 1990; ten Kate and Sprenger 1993; Bralower et al. 2006; Fischer 1993; Meyers et al. 2001; Gale et al. 1999; Schwarzacher 1994; Fiet et al. 2001; Grippo et al. 2004; see also Figure 1)*; Bellanca et al. 1996; Röhl and Ogg 1998; Fiet 2000; Sprenger and ten Kate 1993; Huang et al. 1993; Giraud et al. 1995; D'Argenio et al. 2004; Ferreri et al. 2004; Herbert 1992. **Jurassic**: Weedon et al. 2004; Weedon et al. 1999)*; Galbrun et al. (in prep.); Weedon (1989); Hinnov and Park 1999*; Weedon and Jenkyns 1999; Gomez and Goy 2000; Colombié and Strasser 2003; Boulila et al. (submitted); Gale (in prep.). **Triassic**: Olsen et al. 1996; see also Figure 1)*; Cozzi et al. 2005; Schwarzacher 2005; Forkner (in prep.); Preto and Hinnov 2003; Lehrmann et al. 2001; Yang and Lehrmann 2003; Szurlies et al. 2003; Szurlies 2004; Menning et al. 2005. For the Paleozoic Era: **Permian**: Rampino et al. 2000; Tong and Yin 1999; Yin et al. 2001; Anderson 1982; Anderson and Dean 1995. **Carboniferous**: Goldhammer et al. 1994; Heckel 2002; Tramp et al. 2004. **Devonian**: Olsen 1990, 1994; Van Tassell 1994a,b; Elrick 1995; Yang et al. 1995; Bai 1995; Anderson and Cross 2001; Chen and Tucker 2003; Algeo et al. 2006. **Silurian**: Crick et al. 2001; Nestor et al. 2001. **Ordovician**: Rodionov et al. 2003. **Cambrian**: Bond et al. 1993; Olseger 1995; Bazykin and Hinnov 2002. E–Lower limit of age error (in %) for the future GTS from by high- precision geochronology (dash-dot line) and cyclostratigraphy (solid lines). Red lines indicate when in the geologic past the different astronomical modeled variations may be used with high confidence. Tidal error refers to the uncertainty in knowledge of past tidal friction and its effect on the Earth's precession and obliquity (Lourens et al. 2004). Maximum error on the 405-kyr term refers to uncertainty estimated from differences in 6 different astronomical models (Laskar et al. 2004). The shaded area labeled "transition" refers to the latest Earth-Mars orbital resonance transition that is predicted to occur during that interval (Laskar et al. 2004). The 405-kyr orbital eccentricity term prior to 250 Ma has not been modeled, and so maximum error has not been carried into the Paleozoic Era.


A
AGE (Ma)
1.81
5.33
23.03
33.9
55.8
65.5
99.6
145.5
161.2
175.6
199.6
228.0
245.0
251.0
260.4
270.6
299.0
318.1
359.2
385.3
397.5
416.0
422.9
428.2
443.7
460.9
471.8
488.3
501
513
542.0
Stage
Epoch
Period
Eon
Tortonian
Serravallian
Langhian
Burdigalian
Aquitanian
Chattian
Rupelian
Priabonian
Bartonian
Lutetian
Ypresian
Thanetian
Selandian
Danian
Maastrichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
Albian
Aptian
Barremian
Hauterivian
Valanginian
Berriasian
Tithonian
Kimmeridgian
Oxfordian
Callovian
Bathonian
Bajocian
Aalenian
Toarcian
Pliensbachian
Sinemurian
Hettangian
Rhaetian
Norian
Carnian
Ladinian
Anisian
Olenekian
Changhsingian
Wuchiapingian
Capitanian
Wordian/Roadian
Kungurian
Artinskian
Sakmarian
Asselian
Gzhelian
Kasimovian
Moscovian
Bashkirian
Serpukhovian
Visean
Tournaisian
Famennian
Frasnian
Givetian
Eifelian
Emsian
Pragian
Lochkovian
Ludfordian/Gorstian
Homerian/Sheinwoodian
Telychian
Aeronian/Rhuddanian
Darriwilian
Tremadocian
Paibian
Pliocene
Miocene
Oligocene
Eocene
Paleocene
Late
Early
Late
Middle
Early
Late
Middle
Early
Lopingian
Guadalupian
Cisuralian
Late
Middle
Early
Late
Middle
Early
Penn-sylvanian
Mississippian
Late
Middle
Early
Ludlow
Wenlock
Llandovery
Late
Middle
Early
Furongian
Middle
Early
Neogene
Paleogene
Cretaceous
Jurassic
Triassic
Permian
Carboniferous
Devonian
Silurian
Ordovician
Cambrian
Cenozoic
Mesozoic
Paleozoic
B
Uncertainty (myr, 95% confidence limit)
0
1
2
3
4
Neogene astronomical tuning
Paleocene astronomical tuning and C-seq. spreading model
Spline fit to Ar-Ar dating of ammonite zones
M-seq. spreading model
U-Pb age base Jurassic
Newark cycle-scaling error
U-Pb age base Triassic
Radioisotope scaling on composite standards, Permian-Carboniferous
Ramping to join independent spline-fitted datasets
U-Pb age basal Cambrian
radioisotope 0.1% precision limit
'baseline' ATS range of uncertainty
0.405 myr
0.020 myr
0
100
200
300
400
500
C
U-Pb
40Ar/39Ar
D
Anchored to La2004
'Floating' ATS coverage
Future provisional ATS coverage
E
% age error
10
1
0.1
0.01
0.001
maximum error
30 kyr
150 kyr
350 kyr
500 kyr
60 kyr
~300 kyr
tidal error
transition
U-Pb, 40Ar/39Ar
405
100
41
20
0
100
200
300
400
500
MILLIONS OF YEARS B.P.

2006a,b; Jovane et al. 2006). The Eocene-Paleocene cyclostratigraphy of the Atlantic Ocean is tuned to the orbital eccentricity (Westerhold et al. 2007), although there is still ambiguity about the precise age of the K/T boundary (Westerhold et al., submitted). Future work will focus on inter-calibration between the ATS and high-precision radioisotopic dating which thus far indicates disagreement (e.g., the Eocene Green River Formation studies by Smith et al. 2003; Pietras et al. 2003; Machlus et al. 2004; Smith et al. 2006) and testing the astronomical model, which toward the K/T boundary suffers from mounting inaccuracy from unknown changes in the Earth's rotational-orbital parameters (Pälike and Shackleton, 2000; Pälike et al., 2004; Laskar et al., 2004; Laskar, 2006).

Mesozoic Era

The Cretaceous ATS is presently under construction to unite floating sections relative to an astronomical-derived age for the cyclostratigraphy across the Cretaceous/Paleogene boundary (three options in Westerhold et al., submitted). Numerous Maastrichtian-Campanian sequences from both sides of the Atlantic Ocean drilled by ODP Legs 207 and 208 show strong potential for astronomical signal recovery and are currently undergoing analysis. Turonian-Santonian sections still need prospecting to close a significant gap in coverage; this could be accomplished through investigation of the famous Niobrara Chalk cycles, which were an early inspiration for the ATS (Gilbert 1895). The Italian Cenomanian is famously cyclic (e.g., Fischer 1993; Schwarzacher 1994), but still needs to be measured and analyzed. Ubiquitous precession-eccentricity characterizes the bathyal Albian (e.g., Grippo et al. 2004), as well as the Lower Cretaceous platform sequences of Italy (D'Argenio et al. 2004; Ferreri et al. 2004), and 2.4-myr modulations occur as sequences in the shallow marine Cretaceous and Jurassic of Saudi Arabia (e.g., Matthews and Frohlich 2002).

Astronomical-forced cyclicity has been established in ammonite-zoned outcrops spanning a major (~85%) portion of the Jurassic (Weedon and Coe 2006). A full 100% coverage is anticipated within the next five years. The basinal successions of France are promising future ATS targets with excellent ammonite control. This includes the GSSP candidate for the base-Tithonian at Crussol, which contains well-defined magnetic polarity chrons through the entire Kimmeridgian (Ogg and Atrops, in prep.). These European-based studies emphasize an alternating dominance between precession and obliquity signals throughout the Jurassic (Weedon et al. 1999; Hinnov and Park 1999), a theme that has yet to be explained. Other future work will focus on closing gaps in coverage in the Middle Jurassic, inter-calibration between the reconstructed ATS and radioisotope dating, and duplication studies, including marine-continental correlations with Pangean sequences of the USA (e.g., Olsen et al. 2005).

The Late Triassic contains a spectacular record of Milankovitch variations in the Newark lake beds (eastern USA) (e.g., Olsen et al. 1996; Olsen and Kent 1996). Although this unique 30-myr record is calibrated to magnetic polarity zones and overlain by radiometric-dated basalts, there remains uncertainty in its correlation to standard marine-based chronostratigraphy (e.g., two options in Muttoni et al. 2004). Recent U-Pb dating shows excellent agreement with the Newark ATS-determined age for the basal Norian (Furin et al. 2006). The correlation of the eccentricity-cycle-scaled Zechstein-Buntsandstein-Muschelkalk series of the continental upper Permian through middle Triassic of Germany (Szurlies et al. 2003; Szurlies 2004; Menning et al. 2005) to marine stratigraphy is also uncertain. One way to establish reliable correlations is to obtain independent cycle-scaling of polarity zones recorded in fossiliferous marine strata, e.g., to the thick magnetostratigraphic sections of ammonite-zoned basinal facies in former stratotypes of Early Triassic in the Arctic.

The prolific cyclic carbonate platforms of the Late Triassic Dolomites of Italy have been linked to high-frequency eustasy with Milankovitchian characteristics (Preto and Hinnov 2003; Cozzi et al. 2005; Schwarzacher 2005; Forkner, in prep.). However, all of these sequences still need to be correlated to the standard global stratigraphic framework. In the Early Triassic, Milankovitchian eustasy has been invoked to explain Olenekian peritidal carbonate cycles in China (Yang and Lehrmann 2003). On the other hand, the Middle Triassic Latemar cycles of the Dolomites are the subject of controversy: high-precision U-Pb zircon dating indicates that the meter-thick platform cycles were deposited at millennial scales and not Milankovitch scales as originally proposed (e.g., Preto et al. 2001; Mundil et al. 2003; Zühlke et al. 2003). Resolution of this controversy is imperative as zircon geochronology and the ATS are both considered to be leading techniques for improving the future GTS.

Paleozoic Era

Cyclostratigraphy does not contribute an ATS to the Paleozoic GTS2004, despite that cyclic sedimentation is a common theme throughout the Era. Rotational-orbital modeling suggests that the evolution of the solar system and Earth's rotational dynamics likely involved a different Paleozoic astronomical forcing from that of the more recent eras (Laskar et al. 2004). Accordingly, we anticipate development of a 'provisional' ATS for the Paleozoic Era (Fig. 2D). There are reports of cyclic sediments with Milankovitch-like characteristics spanning the Permo-Triassic boundary in Italy (Rampino et al. 2000) and China (Tong and Yin 1999; Yin et al. 2001). The Permian is also host to one of the most remarkable Milankovitch records of the Phanerozoic, i.e., the annually resolved, 250,000 year-long Permian Castile evaporitic varve sequence (Anderson 1982; Anderson and Dean 1995). The Pennsylvanian shelf carbonates of the Paradox Basin, Utah recorded high-frequency sea-level oscillations thought to be astronomically driven (Goldhammer et al. 1994), as did the acclaimed cyclothem sequences of the Midcontinent (Heckel 2002). Devonian, Silurian, Ordovician and Cambrian marine and continental cyclic sequences with intriguing astronomical-like signatures have been reported around the world (short list in Fig. 2 caption). All of these Paleozoic formations require detailed assessment of their depositional signals (see Standards and Methods section above), and many more not cited here need to be prospected and measured in order to link up major spans of continuous geologic time.

SIGNIFICANCE OF THE ATS

Enhancement of the geologic time scale allows for better understanding of the Earth system, e.g., rates and feedbacks of climate change, evolution, tectonic and geochemical processes. Cenozoic-Mesozoic time scales prior to 1990 were generally extrapolated from assumptions of constant rates, e.g., spreading rates of a selected ocean basin, and equal biozone or stage durations. In the 1990's, new orbital stratigraphy and high-precision geochronology for the Cretaceous-Cenozoic revealed major unexplained changes in oceanic spreading rates (e.g., Cande and Kent 1992, 1995), quantified biozone durations and rates of marine evolution (e.g., Berggren et al. 1995), and resolved distortions in the global carbon cycle related to the Paleocene/Eocene Thermal Maximum (e.g., Norris and Röhl 1999). These revelations would not have been possible without astronomical-calibrated stratigraphy. Continued extension the ATS into the Earth's remote past will allow many wide-ranging science themes and problems to be explored, as follows.

Geochronology

In the past few years renewed interest in high-precision calibration of Mesozoic and younger Earth history using an integration of geochronology and biostratigraphy has highlighted systematic differences in ages calculated using different decay schemes. For example, there is an apparent systematic discrepancy of about 1% between ^{40}Ar/^{39}Ar dates and 'older' U-Pb dates derived from the same volcanic ash bed (e.g., Min et al. 2000; Kwon et al. 2002; Schoene et al. 2006; Bowring et al. 2006), thought to be largely from inaccuracies in the K-decay constants. However issues with the U-Pb system such as magmatic residence time and intermediate daughter product corrections must also be taken into account. Most of the current Cretaceous-Paleogene time scale has been calibrated by ^{40}Ar/^{39}Ar geochronology (e.g., Obradovitch 1993), which in some cases may allow precise determination of interval durations but not absolute ages that can be compared with astronomical ages; ^{206}Pb/^{238}U dates are probably closer to absolute (see Schoene et al. 2006). But, before taking ^{238}U-^{206}Pb as the gold standard, much work must be done. An extended ATS with precision/accuracy that is on the same order as radioisotope geochronology will be an important contribution to that effort.

Astrodynamics

A unique collaboration between geoscientists and astronomers has led to the current planetary model for solar system dynamics of the past 250 million years (Laskar et al. 2004). An important outcome of this partnership is the realization that stratigraphic signals may have recorded past transitions in Solar System resonance states (Olsen and Kent 1999; Pälike et al. 2004). One important resonance is expressed in 1.25 myr (s_4-s_3), 2.35 myr (g_4-g_3) modulations expressed in Earth's stratigraphy by obliquity and precession index frequency carriers. The La2004 class of models indicates that by 100 Ma, Earth-Mars resonance should have experienced a transition leading to the current (s_4-s_3)-2(g_4-g_3) resonance (Laskar et al. 2004, their Fig. 23). Detection of this transition in stratigraphy will be extremely significant, because its timing constrains the gravitational model used in the solar system solution. There is tantalizing evidence that the most recent transition occurred after the Albian (post-99 Ma): a strong 1.5 myr modulation affects eccentricity frequencies in Piobbico core stratigraphy, but no 2.4 myr modulation (Hinnov 2005). This evidence, however, seems at odds with new research connecting the 2.4 myr modulation with second order sequences throughout Cretaceous-Jurassic times (see **Sequence Stratigraphy** below).

Geodynamics

The delay of the Earth's tidal bulge with respect to the tide-raising force of the Moon causes deceleration of the Earth's rotation and acceleration of the Moon in its orbit. These effects act to slow the Earth's precession rate. When projecting back through time, present-day values for these factors imply an Earth-Moon collision ('Roche limit') only 1.5 Ga, which is inconsistent with lunar rock evidence of a 4.5 Ga age (Bills et al. 1999). Thus, tidal dissipation must have varied throughout Earth history, with time intervals during which it was significantly lower than today. Geological evidence for faster Earth rotation, such as tidally influenced growth of coral rings, provide partial constraints on dissipation (e.g., Williams 2000), but modeling the tidal dissipation remains a major challenge. Recovery of the complete recorded sequence of orbital cycles back through time is one way to constrain the astronomical solution. The tidal model of Quinn et al. (1991), when included in La93, resolved numerous misfits between insolation-forced sapropelic deposits from the Mediterranean Pliocene (Lourens et al. 2001). We suggest that a high-resolution tidal dissipation history can be deduced by documenting the 405-kyr cycles through the Mesozoic, then examining the detailed behavior of precession and obliquity that occur within them.

Sequence Stratigraphy

Exxon geologists revolutionized stratigraphy when they revealed a time-scale based upon global sequences of oscillating sea levels (Haq et al. 1987; Vail et al. 1977). Are these sequences truly synchronous, and what drives the apparent major sea-level changes on a non-icehouse world? There is evidence that some of these second- and third-order sequences reflect long-period modulations in the eccentricity (e.g., Lourens and Hilgen 1997; Matthews and Frohlich 2002; Al Husseini and Matthews 2005; Al Husseini et al. 2006). Drilling of carbonate-reef-caps on mid-Pacific guyots have documented that the major "European" lowstands punctuate the ancient reef facies in the Pacific Ocean basin, and that the major and minor sea-level oscillations may carry an orbital signal (e.g., Röhl and Ogg 1998). To test these assertions and decipher how faithfully carbonate platforms record astronomical signals, separate astronomical calibrations to shallow-water facies are required. Indeed, the question of whether the ubiquitous cyclicity in carbonate platforms is Milankovitch-controlled is a hotly debated topic (e.g., the Middle Triassic 'Latemar controversy', e.g., Preto et al. 2001; Mundil et al. 2003), which must be resolved before utilizing shallow-marine cycles in the ATS.

Global Tectonics

At present, it is impossible to use marine magnetic anomalies to determine if the rate of spreading in the Pacific basin (or any other ocean) has changed during Late Jurassic (170 Ma) through Early Cretaceous (120 Ma). This is because that portion of the time scale is based on assumptions of constant spreading (e.g., Larson and Hilde 1975; Kent and Gradstein 1983; Ogg 2004). Our understanding of Cenozoic plate tectonic rates was similarly hampered prior to the independent astronomical calibration. Only when durations of geomagnetic polarity zones and corresponding marine magnetic anomalies are freed from the straightjacket of constant-spreading assumptions can we begin to understand potential feedbacks between global spreading rates, long-term climate/sea-level, atmospheric CO_2, weathering rates, continental margin tectonics, and other postulated relationships (e.g., Sheridan 1987; Larson 1991; Hardie 1996).

Biological Evolution

Recently, van Dam et al. (2006) found a correlation between Neogene mammalian extinctions and the long-term 2.4 myr modulation of Earth's orbital eccentricity. Does this pattern carry through into the Mesozoic, possibly in other animal groups? Rates of finer-scale evolution within and among fossil groups can be quantified only if there is a time scale with much higher accuracy and resolution than the fastest evolutionary processes. The ATS will constrain these questions, as well as molecular clocks for divergence of major biological families.

CONCLUSIONS

The assembly of the ATS finally puts into place what Milankovitch (1941) campaigned for throughout his life, namely, using the insolation canon as a geochronometer. In the next five years, astronomical calibration of cyclostratigraphy and integration of the ATS into the geologic time scale should afford an order of magnitude improvement to the resolving power of the time scale through much of the Phanerozoic Eon. The status of the ATS is summarized as follows:

The Cenozoic ATS is nearly complete. The scale is constructed from overlapping paleoclimate proxy records from the Mediterranean, Atlantic and Pacific basins, tied to the geomagnetic polarity sequence and global biostratigraphic zones. The records were tuned to the new La2004 model of Earth's rotational-orbital influences on insolation, to a 0.02 myr resolution over the Neogene Period, 0.04 myr resolution over the Oligocene, and 0.1 myr resolution for the Eocene and Paleocene. Effects from tidal dissipation are not yet well understood, and a precise astronomical age for the K/T boundary remains ambiguous. Inter-calibration studies between the ATS and radioisotope-derived ages show excellent agreement in the Neogene, but show mixed results in the Paleogene.

The Mesozoic ATS is evolving rapidly in the form of extended cyclostratigraphic sequences interpreted as 'floating' ATS segments and tied to the global integrated stratigraphic framework. Resolution is limited to 0.4 myr due to uncertainties from solar system diffusion. The number of reliable paleoclimate proxies is limited by rock diagenesis. Presently, there is ~80% time coverage of the Era; 100% coverage is anticipated within the next five years. In a number of cases obliquity-only forcing appears to dominate the cyclostratigraphy, which poses a challenge in terms of discovering an accurate model of Earth's long-term rotation and precession. Inter-calibration studies thus far range from good to irreconcilable.

The Paleozoic ATS has not yet been realized. Cyclostratigraphy is in abundant supply, but a specific astrodynamical model that can be used as a time framework is not available, with the possible exception of the 405-kyr eccentricity (g_2-g_5) term. Thus, study of Paleozoic cyclic sequences will continue to be limited to generalized comparisons with Cenozoic models, and the resulting ATS will be provisional. There is some potential for the Paleozoic record to guide the rotational-orbital modeling.

The development of a stable ATS stands to improve the resolution of geologic time by an order of magnitude or better. Consequently, long-standing questions can be newly addressed in fields as far ranging as plate tectonics, global geochemical cycles, paleoclimate, sea level change, and biotic evolution. Did seafloor spreading rates slow during the Late Jurassic? How rapid was the dramatic atmospheric CO_2 buildup leading to the Paleocene/Eocene Thermal Maximum? Are the ubiquitous sea-level oscillations through Earth history caused by astronomical forcing? The ATS will help solve these and many other puzzles in the history of our planet.

ACKNOWLEDGMENTS

We thank the convenors of the Penrose conference in Seggau, Austria for the opportunity to discuss the emerging role of cyclostratigraphy in the geologic time scale. This work was supported by National Science Foundation Grant EAR-0718905.

REFERENCES

AL-HUSSEINI, M.I. and MATTHEWS, R.K., 2005. Arabian orbital stratigraphy: Periodic second-order sequence boundaries. *GeoArabia,* 10(2): 165-184.

AL-HUSSEINI, M., MATTHEWS, R.K. and MATTNER, J. 2006. Stratigraphic Note: Orbital-forcing calibration of the Late Jurassic (Oxfordian-early Kimmeridgian) Hanifa Formation, Saudi Arabia. *GeoArabia*, 11(3): 145-149.

ALGEO, T.J., HINNOV, L.A. and OVER, D. J., 2006. Milankovitch cyclicity in the Ohio and Sunbury shales: astronomical calibration of the Late Devonian-Early Mississippian timescale, *Geological Society of America Annual Meeting Abstracts,* Philadelphia, PA.

ANDERSON, D.S. and CROSS, T.A., 2001. Large-Scale Cycle Architecture in Continental Strata, Hornelen Basin (Devonian), Norway. *Journal of Sedimentary Research,* 71: 255-271

ANDERSON, R.Y. and DEAN, W.E., 1995. Filling the Delaware Basin: hydrologic and climatic controls on the Upper Permian Castile Formation varved evaporite. In: Scholle, P.A., Peryt, T.M. and Ulmer-Scholle, D.S., Eds., *The Permian of North Pangea*, 61-78. Springer-Verlag, Sedimentary basins and economic resources.

ANDERSON, R.Y., 1982. A long geoclimatic record from the Permian. *Journal of Geophysical Research*, 87: 7285-7294.

BAI, S. L., 1995. Milankovitch cyclicity and time scale of the middle and upper Devonian, *International Geological Review*, 37: 1109-1114.

BAZYKIN, D.A. and HINNOV, L.A, 2002. Orbitally-driven depositional cyclicity of the Lower Paleozoic Aisha-Bibi seamount (Malyi Karatau, Kazakstan): integrated sedimentological and time series study, in Zempolich, W.G. and Cook, H.E., Eds., *Paleozoic carbonates of the Commonwealth of Independent States (CIS): Subsurface reservoirs and outcrop analogs*, 19-41. SEPM Special Publication No. 75.

BELLANCA, A., CLAPS, M., ERBA, E., NERI, R. PREMOLI-SILVA, I. and VENEZIA, F., 1996. Orbitally induced limestone/marlstone rhythms in the Albian-Cenomanian Cismon section (Venetian region, northern Italy): sedimentology, calcareous and silicieous plankton distribution, elemental and isostope geochemistry. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 126: 227-260.

BERGER, A., LOUTRE, M.-F. and LASKAR, J., 1992. Stability of the astronomical frequencies over the Earth's history for paleoclimate studies. *Science*, 255: 560-566.

BERGGREN, W.A., KENT, D.V., SWISHER, C.C., III and AUBRY, M.-P., 1995. A revised Cenozoic geochronology and chronostratigraphy. In: Berggren, W.A., Kent, D.V., Aubry, M.-P. and Hardenbol, J., Eds., *Geochronology, time scales and global stratigraphic correlation*, 129-212. Tulsa: SEPM Special Publication, 54

BILLS, B.G. and RAY, R.D., 1999. Lunar orbital evolution: A synthesis of recent results. *Geophysical Research Letters*, 26: 3045-3048.

BOND, G.C., W.J. DEVLIN, KOMINZ, M.A., BEAVAN, J. and MCMANUS, J., 1993. Evidence of astronomical forcing of the Earth's climate in Cretaceous and Cambrian times. *Tectonophysics*, 222: 295-315.

BOULILA, S., GALBRUN, B., HINNOV, L.A. and COLLIN, P.-Y., submitted. High-resolution cyclostratigraphic analysis from magnetic susceptibility in an Early Kimmeridgian marl-limestone succession, La Méouge, Vocontian Basin, France), *Sedimentary Geology.*

BOWRING, S.A. , SCHOENE, B., CROWLEY, J.L, RAMEZANI, J. and CONDON, D.J., 2006. High-precision U-Pb geochronology and the stratigraphic record: progress and promise. In: Olszewski, T.D., Ed., *Geochronology, emerging opportunities*, 25-46. New Haven, CT: The Paleontological Society Special Publication, 12,

BRALOWER, T.J., PREMOLI SILVA, I. and MALONE, M.J., 2006. Leg 198 Synthesis: A remarkable 120-m.y. record of climate and oceanography from Shatsky Rise, Northwest Pacific Ocean. In: Bralower, T. J., Premoli Silva, I., Malone, M., Eds., *Proceeding of the ODP, Scientific Results*, volume 198, 1-4. College Station, TX: Ocean Drilling Program.

CANDE, S.C. and 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.

———, 1992. A new geomagnetic polarity time scale for the Late Cretaceous and Cenozoic, *Journal of Geophysical Research*, 97: 13917-13951.

CHEN, D. and TUCKER, M.E., 2003. The Frasnian-Famennian mass extinction: insights from high-resolution sequence stratigraphy and cyclostratigraphy in South China. *Palaeogeography, Palaeoclimatology, Palaeoecology* 193: 87-111.

COLOMBIÉ, C. and STRASSER, A., 2003. Depositional sequences in the Kimmeridgian of the Vocontian Basin (France) controlled by carbonate export from shallow-water platforms. *Geobios*, 36: 675-683.

COOPER, R.A., CRAMPTON, J.S., RAINE, J.I., GRADSTEIN, F.M., MORGANS, H.E.G., SADLER, P.M., STRONG, C.P., WAGHORN D. and WILSON, G.J., 2001. Quantitative biostratigraphy of the Taranaki Basin, New Zealand - a deterministic and probabilistic approach. *Bulletin of the American Association of Petroleum Geologists*, 85: 1469-1498.

COZZI, A., HINNOV, L.A. and HARDIE, L.A., 2005. Orbitally forced Lofer cycles in the Dachstein Limestone of the Julian Alps (NE Italy). *Geology*, 33: 789-792.

CRICK, R.E., ELLWOOD, B.B., HLADIL, J., EL HASSANI, A., HROUDRA, F. and CHLUPÁC, I., 2001. Magnetostratigraphy susceptibility of the Pridolian-Lochkovian (Silurian-Devonian) GSSP (Klonk, Czech Republic) and a coeval sequence in Anti-Atlas Morocco. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 167: 73-100.

D'ARGENIO, B., FERRERI, V., WEISSERT, H., AMODIO, S., BUONOCUNTO, F.P. and WISSLER, L., 2004. Carbonate platforms: a multidisciplinary approach to global correlation and geochronology. The Cretaceous shallow-water carbonates of southern Apennines, Italy. In: D'Argenio, B., Fischer, A.G., Premoli Silva, I., Weissert, H. and Ferreri, V., Eds., *Cyclostratigraphy: Approaches and case histories*, 103-122. Tulsa: SEPM Special Publication No. 81.

ELRICK, M., 1995. Cyclostratigraphy of Middle Devonian carbonates in the eastern Great Basin. *Journal of Sedimentary Research*, B65: 61-79.

FERRERI V., D'ARGENIO B., AMODIO S. and SANDULLI R., 2004. Orbital chronostratigraphy of the Valanginian-Hauterivian boundary. A cyclostratigraphic approach, In: D'Argenio B., Fischer A.G., Premoli Silva I., Weissert H. and Ferreri V., Eds., *Cyclostratigraphy: Approaches and case histories*, 15 1-166. Tulsa: SEPM Special Publication No. 81.

FIET, N., 2000. Calibrage temporal de l'Aptien et des sous-etages associes par une approach cyclostratigraphique appliquee a la serie pelagique de Marches-Ombrie (Italie centrale). *Bulletin, Societé Géologique de France*, 171(1): 103-113.

FIET, N., BEAUDOIN, B. and PARIZE, O., 2001. Lithostratigraphic analysis of Milankovitch cyclicity in pelagic Albian deposits of central Italy: implications for the duration of the stage and substages. *Cretaceous Research*, 22: 265-275.

FISCHER, A.G., 1993. Cyclostratigraphy of Cretaceous chalk-marl sequences. In: Caldwell, W.G.E. and Kauffman, E.G., Eds., *Evolution of the Western Interior Basin*, 283-293. Geological Association of Canada Special Paper 39.

FURIN, S., PRETO, N., RIGO, M., ROGHI, G., GIANOLLA, P., CROWLEY, J. and BOWRING, S.A., 2006. A high-precision U/Pb zircon age from the Triassic of Italy—implications for the Carnian rise of calcareous nannoplankton and dinosaurs. *Geology*, 34: 1009-1012.

GALE, A.S., 1995. Cyclostratigraphy and correlation of the Cenomanian stage in Europe. In: House, M.R. and Gale, A.S., Eds., *Orbital forcing timescales and cyclostratigraphy*, 177-197. Geological Society of London, Special Publication, 85.

GALE, A.S., YOUNG, J.R., SHACKLETON, N.J., CROWHURST, S.J. and WRAY, D.S., 1999. Orbital tuning of Cenomanian marly chalk successions: towards a Milankovitch time-scale for the Late Cretaceous, *Philosophical Transactions of the Royal Society, London, Series A*, 357: 1815-1829.

GILBERT, G.K., 1895. Sedimentary measurement of geological time, *Journal of Geology,* 3: 121-127.

GIRAUD, F., L. BEAUFORT, L. and P. COTILLON, 1995. Periodicities of carbonate cycles in the Valanginian of the Vocontian Trough: a strong obliquity control. In: House, M.R. and Gale, A.S., Eds., *Orbital forcing time-scales and cyclostratigraphy*, 143-164. Geological Society of London Special Publication, 85.

GOLDHAMMER, R. K., OSWALD, E. J. and DUNN, P. A., 1994. High-frequency glacio-eustatic cyclicity in the Middle Pennsylvanian of the Paradox Basin: an evaluation of Milankovitch forcing. In: De Boer, P. L. and Smith, D. G., Eds., *Orbital forcing and cyclic sequences*, 243-283. International Association of Sedimentologists Special Publication no. 19.

GOMEZ, J. and GOY, A., 2000. Sequential analysis of the Toarcian in the northern central-eastern part of the Iberian Sub-plate (Spain). In: Hall, R.L. and Smith, P.L., Eds., *Advances in Jurassic research 2000*, 301–309. Zurich: Trans Tech Publications, 6.

GRADSTEIN, F., OGG, J. and SMITH, A., Editors, 2004. *A Geologic Time Scale 2004.* Cambridge: Cambridge University Press, 589 p.

GRIPPO, A., FISCHER, A.G., HINNOV, L.A., HERBERT, T.D. and 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. and Ferreri, V., Eds., *Cyclostratigraphy: Approaches and case histories,* 57-81. Tulsa: SEPM Special Publication No. 81.

HAQ, B.U., HARDENBOL, J. and VAIL, P.R., 1987. Chronology of fluctuating sea levels since the Triassic. *Science*, 235: 1156-1167.

HARDIE, L.A., 1996. Secular variation in seawater chemistry: An explanation for the coupled secular variation in the mineralogies of marine limestones and potash evaporites over the past 600 m.y. *Geology*, 24: 279-284.

HECKEL, P.H., 2002. Overview of cyclothems in Midcontinent North America and brief summary of those elsewhere in the world. In: Hills, L.V., Henderson, C.M. and Bamber, E.W., Eds., *The Carboniferous and Permian of the World*, p. 79-98. Canadian Society of Petroleum Geologists Memoir 19.

HERBERT, T.D., 1999. Toward a composite orbital chronology for the late Cretaceous and early Palaeocene GPTS, *Philosophical Transactions of the Royal Society, London, Series A*, 357: 189 1-1905.

———, 1992. Paleomagnetic calibration of Milankovitch cyclicity in Lower Cretaceous sediments, *Earth and Planetary Sciences Letters*, 112: 15-28.

HERBERT, T.D., PREMOLI SILVA, I., ERBA, E. and FISCHER, A.G., 1995. Orbital chronology of Cretaceous-Paleogene marine strata, in D.V. Kent and W.A. Berggren, eds.), *Geochronology, time scales and global stratigraphic correlation*, 81-93. Tulsa: SEPM Special Publication no. 54.

HERBERT, T.D. and D'HONDT, S.L., 1990. Precessional climate cyclicity in late Cretaceous- early Tertiary marine sediments: a high resolution chronometer of Cretaceous-Tertiary boundary events. *Earth and Planetary Science Letters*, 99: 263-275.

HERTERICH, K. and SARNTHEIN, M., 1984. Brunhes time scale: tuning by rates of calcium-carbonate dissolution and cross spectral analysis with solar insolation. In:, Berger, A., Imbrie, J., Hays, J. Kukla, G. and Saltzman, B., Eds., *Milankovitch and climate, Part 1*, 447-466., Dordrecht: NATO ASI Series, D. Reidel Pub. Co.

HESLOP, D., LANGEREIS, C.G. and DEKKERS, M.J., 2000. A new astronomical timescale for the loess deposits of Northern China, *Earth and Planetary Science Letters*, 184: 125-139.

HILGEN, F.J., ABDUL AZIZ, H., ABELS, H.A., BECKER, J., KUIPER, K.F., LOURENS, L.J., MEIJER, P.TH., STEENBRINK, E., TUENTER, E., LAAN, E. VAN DER and WEBER, N., 2005. Mediterranean Neogene cyclostratigraphy and astrochronology: Recent progress and new developments. In: Berger, A., Ercegovac, M. and Mesinger, F., Eds., *Milutin Milankovitch 125th Anniversary Symposium: Paleoclimate and the earth climate system*, 89-100. Belgrade, Serbia: Proceedings of the Serbian Academy of Sciences and Arts.

HILGEN, F.J., ABDUL AZIZ, H., KRIJGSMAN, W., LANGEREIS, C.G., LOURENS, L.J., MEULENKAMP, J.E., RAFFI, I., STEENBRINK, J., TURCO, E., VAN VUGT, N., WIJBRANS, J.R. and ZACHACHRIASSE, W.J., 1999. Present status of the astronomical (polarity) time-scale for the Mediterranean Late Neogene, *Philosophical Transactions of the Royal Society, London, Series A*, 357: 1931-1947.

HINNOV, L.A., 2000. New perspectives on orbitally forced stratigraphy. *Annual Review of Earth and Planetary Sciences*, 28: 419-475.

———, 2005. Astronomical signals from Pre-Cenozoic eras. In: Berger, A. and Ercegovac, M., Eds., *Milutin Milankovitch 125th Anniversary Symposium: Paleoclimate and the earth climate system*, 63-78. Belgrade, Serbia: Proceedings of the Serbian Academy of Sciences and Arts.

HINNOV, L.A. and PARK, J., 1999. Strategies for assessing Early-Middle (Pliensbachian-Aalenian) Jurassic cyclochronologies. *Philosophical Transactions of the Royal Society, London, Series A*, 357: 1831-1859.

HUANG, Z., OGG, J.G. and GRADSTEIN, F.M., 1993. A quantitative study of Lower Cretaceous cyclic sequences from the Atlantic Ocean and Vocontian Basin (SE France). *Paleoceanography,* 8: 275-291.

HUYBERS, P. and WUNSCH, C., 2004. A depth-derived Pleistocene age model: uncertainty estimates, sedimentation variability and nonlinear climate changes. *Paleoceangraphy,* 19, PA1028, doi: 10.1 029/2002PA000857,

JOVANE, L., FLORINDO, F., SPROVIERI, M. and PÄLIKE, H., 2006. Astronomic calibration of the late Eocene/early Oligocene Massignano section (Central Italy), *Geochemistry, Geophysiscs and Geosystems*, 7(7), doi: 10.1029/2005GC001 195.

KENT, D.V., 1999. Orbital tuning of geomagnetic polarity time-scales, *Philosophical Transactions of the Royal Society, London, Series A,* 357: 1995-2007.

KENT, D. V. and OLSEN, P. E., 1999. Astronomically tuned geomagnetic polarity time scale for the Late Trias sic. *Journal of Geophysical Research,* 104: 12831-12841.

KENT, D.V. and GRADSTEIN, F., 1983. A Jurassic and Cretaceous geochronology. *Geological Society of America Bulletin*, 96: 1419-1427.

KODAMA, K.P., ANASTASIO, D.J., in prep. "A new decompaction technique for marine sedimentary rocks: Using remanence anisotropy to determine the amount of volume lost during burial compaction."

KOMINZ, M. A., HEATH, G. R., KU, T. L., PISIAS, N. G., 1979. Brunhes time scales and the interpretation of climatic change, *Earth and Planetary Science Letters*, 45: 394-410.

KUIPER, K.F., DEINO, A.D., HILGEN, F.J., KRIJGSMAN, W. and RENNE, P., 2005b. Intercalibration of astronomical and radioisotopic time. *Geochimica et Cosmochimica Acta*, 69: A316.

KUIPER, K.F., HILGEN, F.J., STEENBRINK, J. and WIJBRANS, J.R., 2004. ^{40}Ar/^{39}Ar ages of tephras intercalated in astronomically tuned Neogene sedimentary sequences in the eastern Mediterranean. *Earth and Planetary Science Letters*, 222: 583-597.

KUIPER, K.F., WIJBRANS, J.R. and F.J. HILGEN, 2005a. Radioisotopic dating of the Tortonian Global Stratotype Section and Point: implications for intercalibration of ^{40}Ar/^{39}Ar and astronomical dating methods. *Terra Nova*, 17: 385-398.

KWON J., MIN K., BICKEL P.J. and RENNE P.R., 2002. Statistical methods for jointly estimating decay constant of 40K and age of a dating standard. *Mathematical Geology*, 34: 457-474.

LARSON, R.L., 1991. Latest pulse of the Earth: Evidence for a mid Cretaceous super plume. *Geology*, 19: 547-550.

LARSON, R.L. and HILDE, T.W.C., 1975. A revised time scale of magnetic reversals for the Early Cretaceous and Late Jurassic. *Journal of Geophysical Research*, 80: 2586-2594.

LASKAR, J., 1990. The chaotic motion of the solar system: A numerical estimate of the chaotic zones. *Icarus*, 88: 266-291.

———, 2006. Astronomical limits in using orbital tuning methodology for the geologic time scale. *International Association of Mathematical Geology: Meeting on quantitative geology from multiple sources, 3-8 September*. Liège, Belgium.

LASKAR, J., JOUTEL, F. and BOUDIN, F., 1993. Orbital, precessional and insolation quantities for the Earth from -20 myr yo +10 myr. *Astronomy and Astrophysics*, 270: 522-533.

LASKAR, J., ROBUTEL, P., JOUTEL, F., GASTINEAU, M., CORREIA, A.C.M. and LEVRARD, B., 2004. A long-term numerical solution for the insolation quantities of the Earth. *Astronomy and Astrophysics*, 428: 261-285.

LEHRMANN, D.J., YANG, W., WEI, J. YU, Y.Y. and XIAO, J., 2001. Lower Triassic peritidal cyclic limestone: an example of anachronistic carbonate facies from the Great Bank of Guizhou, Nanpanjiang Basin, Guizhou Province, South China. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 173: 103-123.

LOURENS, L.J. and HILGEN, F., 1997. Long-periodic variations in the Earth's obliquity and their relation to third order eustatic cycles and late Neogene glaciations. *Quaternary International*, 40: 43-52.

LOURENS, L., HILGEN, F., SHACKLETON, N.J., LASKAR, J. and WILSON, D., 2004. Chapter 21: The Neogene Period. In: Gradstein, F., Ogg, J. and Smith, A., Eds., *A Geologic Time Scale 2004,* 409-440. Cambridge*:* Cambridge University Press.

LOURENS, L.J., WEHAUSEN, R. and BRUMSACK, H.J., 2001. Geological constraints on tidal dissipation and dynamical ellipticity of the Earth over the past three million years. *Nature*, 409: 1029-1033

LUTERBACHER, H.P., ALI, J.R., BRINKUIS, H., GRADSTEIN, F.M., HOOKER, J.J., MONECHI, S., OGG, J.G., OWELL, J., ROHL, U., SANFILIPPO, A. and SCHMITZ, B., 2004. Chapter 20: The Paleogene Period. In: Gradstein, F., Ogg, J. and Smith, A., Eds., *A Geologic Time Scale 2004*, 384-408. Cambridge: Cambridge University Press.

MACHLUS, M., HEMMING, S.R., OLSEN, P.E. and CHRISTIE-BLICK, N., 2004. Eocene calibration of geomagnetic polarity time scale reevaluated: evidence from the Green River Formation of Wyoming, *Geology*, 32: 137-140.

MATTHEWS, R.K. and FROHLICH, C., 2002. Maximum flooding surfaces and sequence boundaries: comparisons between observations and orbital forcing in the Cretaceous and Jurassic (65-190 Ma), *GeoArabia*, 7: 503-538.

MAURER, F., HINNOV, L.A. and SCHLAGER, W., 2004. Statistical time series analysis and sedimentological tuning of bedding rhythms in a Triassic basinal succession (S. Alps, Italy). In: D'Argenio, B., Fischer, A.G., Premoli Silva, I., Weissert, H. and Ferreri, V., Eds., *Cyclostratigraphy: Approaches and case histories*, 83-99. SEPM Special Publication No. 81.

MENNING, M., GAST, R., HAGDORN, H., KÄDING,, K.-C., SIMON, T., SZURLIES, M. and NITSCH, E., 2005. Zeitskala für Perm und Trias in der Stratigraphischen Tabelle von Deutschland 2002, zyklostratigraphische Kalibrierung der höheren Dyas und Germanischen Trias und das Alter der Stufen Roadium bis Rhaetium 2005. *Newsletters in Stratigraphy*, 41: 173-2 10.

MEYERS, S.R. and SAGEMAN, B. B., 2004. Detection, quantification and significance of hiatuses in pelagic and hemipelagic strata, *Earth and Planetary Science Letters*, 224: 55-72.

MEYERS, S., SAGEMAN, B. and HINNOV, L.A., 2001. Integrated quantitative stratigraphy of the Cenomanian-Turonian Bridge Creek Limestone member using evolutive harmonic analysis and stratigraphic modeling. *Journal of Sedimentary Research*, 71: 627-643.

MILANKOVITCH, M., 1941. *Canon of Insolation and the Ice-Age Problem.* Belgrade: Serbian Academy of Sciences and Arts, Special Publication 132, Section of Mathematical and Natural Sciences, 39 3/4, YU, 634 p. (1998 English Translation.)

MIN K., MUNDIL R., RENNE P. R. and LUDWIG K. R., 2000. A test for systematic errors in ^{40}Ar/^{39}Ar geochronology through comparison with U-Pb analysis of a 1.1 Ga rhyolite. *Geochimica et Cosmochimica Acta*, 64: 73-98.

MULLER, R.A. and MACDONALD, G.J., 2000. *Ice Ages and astronomical causes: Data, spectral analysis and mechanisms.* Berlin: Springer-Verlag, 318 p.

MUNDIL, R., ZÜHLKE, R. BECHSTÄDT, T. PETERHÄNSEL, A. EGENHOFF, S., OBERLI, F., MEIER, M., BRACK, P. and RIEBER, H., 2003. Cyclicities in Triassic platform carbonates: synchronizing radio-isotopic and orbital clocks. *Terra Nova,* 15: 8 1-87.

MUTTONI, G., KENT, D.V., OLSEN, P.E., DI STEFANO, P., LOWRIE, W., BERNASCONI, S.M. and HERANDEZ, F.M., 2004. Tethyan magnetostratigraphy from Pizzo Mondello (Sicily) and correlation to the Late Triassic Newark astrochronological polarity time scale. *GSA Bulletin*, 116: 1043–1058.

NÉRON DE SURGY, O. and LASKAR, J., 1997. On the long term evolution of the spin of the Earth. *Astronomy and Astrophysics*, 318: 975-989.

NESTOR, H., EINASTO, R., NESTOR, V., MARSS, T. and VIIRA, V., 2001. Description of the type section, cyclicity and correlation of the Riksu Formation (Wenlock, Estonia). *Proceedings of the Estonian Academy of Sciences, Geology*, 50: 149-173.

NORRIS, R.D. and RÖHL, U., 1999. Astronomical chronology for the Paleocene/Eocene transient global warming and carbon isotope anomaly. *Nature*, 401: 775-778.

OBRADOVICH, J.D., 1993. A Cretaceous time scale, in Caldwell, .G.E. and Kaufmann, E.G., Eds., *Evolution of the Western Interior Basin,* 379-396. Geological Society of America Special Paper 39.

OGG, J.G., 2004. Status of divisions of the International Geologic Time Scale. *Lethaia*, 37: 183-199.

OGG, J.G. and HINNOV, L.A., 2006. Astronomical Scaling of Stages within the Cretaceous and Triassic, *International Association of Mathematical Geology: Meeting on quantitative geology from multiple sources,* 3-8 September, Liège, Belgium

OLSEN, H., 1994. Orbital forcing on continental depositional systems—lacustrine and fluvial cyclicity in the Devonian of East Greenland. In: De Boer, P.L. and Smith, D.G., Eds., *Orbital forcing and cyclic sequences*, 429-438. International Association of Sedimentologists Special Publication 19.

———, 1990. Astronomical forcing of meandering river behavior: Milankovitch cycles in Devonian of East Greenland, *Palaeogeography, Palaeoclimatology, Palaeoecology*, 79: 99-115.

OLSEN, P. E. and KENT, D. V., 1996. Milankovitch climate forcing in the tropics of Pangea during the Late Triassic. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 122: 1-26.

———, 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 of London, Series A*, 357, 1761-1786.

OLSEN, P. E., KENT, D V., CORNET, B., WITTE, W. K. and SCHLISCHE, R. W., 1996. High-resolution stratigraphy of the Newark rift basin (Early Mesozoic, Eastern North America). *Geological Society of America Bulletin*, 108: 40-77.

OLSEN, P.E., WHITESIDE, J.H., LETOURNEAU, P.M. and HUBER, P., 2005. Jurassic cyclostratigraphy and paleontology of the Hartford basin. In: B.J. Skinner and A.R. Philpotts, Eds., *97th New England Intercollegiate Geological Conference,* A4-A51. New Haven, Connecticut: Department of Geology and Geophysics, Yale University.

OSLEGER, D.A., 1995. Depositional sequences on Upper Cambrian carbonate platforms: variable sedimentologic responses to allogenic forcing. In: Haq, B.U., *Sequence stratigraphy and depositional responses to eustatic, tectonic and climate forcing*, 247-276. Dordrecht: Kluwer Academic Publishers.

PÄLIKE, H. and SHACKLETON, N.J., 2000. Constraints on astronomical parameters from the geological record for the last 25 My. *Earth and Planetary Science Letters*, 182: 1-14.

PÄLIKE, H., FRAZIER, J. and ZACHOS, J.C., 2006a. Extended orbitally forced palaeoclimate records from the equatorial Atlantic Ceara Rise. *Quaternary Science Reviews*, 25: 3138-3149.

PÄLIKE, H., LASKAR, J. and SHACKLETON, N.J., 2004. Geological constraints on the chaotic diffusion of the Solar System. *Geology,* 32: 929-932.

PÄLIKE, H., NORRIS, R.D., HERRLE, J.O., WILSON, P.A., COXALL, H.K., LEAR, C.H., SHACKLETON, N.J., TRIPATI, A.K. and WADE, B.S., 2006b. The heartbeat of the Oligocene climate system. *Science*, 314: 1894-1898.

PIETRAS, J.P., CARROLL, A.R., SINGER, B.S. and SMITH, M.E., 2003. 10 K.Y. depositional cyclicity in the early Eocene: stratigraphic and ^{40}Ar/^{39}Ar evidence from the lacustrine Green River Formation. *Geology*, 31: 593-596.

PRETO, N. and HINNOV, L.A., 2003. Unravelling the origin of carbonate platform cyclothems in the Upper Triassic Dürrenstein Fm. (Dolomites, Italy). *Journal of Sedimentary Research*, 73(5): 774-789.

PRETO, N., HINNOV, L.A., HARDIE, L.A. and De ZANCHE, V., 2001. A Middle Triassic orbital signal recorded in the shallow marine Latemar carbonate buildup (Dolomites, Italy). *Geology*, 29: 1123-1128.

PROKOPENKO, A.A., HINNOV, L.A., WILLIAMS, D.F. and 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.

QUINN, T.R., TREMAINE, S. and DUNCAN, M., 1991. A three million year integration of the Earth's orbit. *Astronomical Journal*, 101: 2287-2305.

RAMPINO, M.R., PROKOPH, A. and ADLER, A., 2000. Tempo of the end-Permian event: High-resolution cyclostratigraphy at the Permian-Triassic boundary. *Geology*, 28: 643-646.

RODIONOV, V.P., DEKKERS, M.J., KHRAMOV, A.N., GUREVICH, E.L., KRUGSMAN, W., DUERMEUER, C.E. and HESLOP, D., 2003. Paleomagnetism and cyclostratigraphy of the Middle Ordovician Krivolutsky Suite, Krivaya Luka section, S. Siberian Platform: record of non-synchronous NRM-components or a non-axial geomagnetic field? *Studies in Geophysics and Geodesy*, 47: 255-274.

RÖHL, U. and OGG, J.G., 1998. Aptian-Albian eustatic sea-levels: *Special Publication of the International Association of Sedimentologists*, 25: 95-136.

———, 2006. Astronomical-scaling of the Early Paleogene: Integrative stratigraphy for the Paleocene-Eocene. *International Association of Mathematical Geology: Meeting on quantitative geology from multiple sources, 3-8 September*. Liège, Belgium.

RÖHL, U., BRALOWER, T.J., NORRIS, R.D. and WEFER, G., 2000. New chronology for the late Paleocene thermal maximum and its environmental implications. *Geology*, 28: 927-930.

RÖHL, U., NORRIS, R. D. and OGG, J. G., 2003. Cyclostratigraphy of upper Paleocene and lower Eocene sediments at Blake Nose Site 1051 (western North Atlantic). In: Wing, S., Gingerich, P. D. and Schmitz, B., Eds., *Causes and consequences of globally warm climates in the early Paleogene*, 567-588. Geological Society of America Special Paper 369.

RÖHL, U., OGG, J.G., GEIB, T.L. and WEFER, G., 2001. Astronomical calibration of the Danian time scale. *Geological Society, Special Publication*, 183: 163-183.

SCHOENE, B., CROWLEY, J.L., CONDON, D.J., SCHMITZ, M.D. and BOWRING, S.A., 2006. Reassessing the uranium decay constants for geochronology using ID-TIMS U-Pb data. *Geochimica Cosmochimica Acta*, 70:, 426445.

SCHWARZACHER, W., 2005. The stratification and cyclicity of the Dachstein Limestone in Lofer, Leogang and Steinerndes Meer (Northern Calcareous Alps, Austria). *Sedimentary Geology*, 181: 93-106.

———, 1994. Cyclostratigraphy of the Cenomanian in the Gubbio district, Italy: a field study. In: De Boer, P.L. and Smith, D.G., Eds., *Orbital forcing and cyclic sequences*, 87-98. IAS Special Publication 19. Oxford UK: Blackwell Scientific.

SHACKLETON, N.J., CROWHURST, S.J., WEEDON, G. and LASKAR, J., 1999. Astronomical calibration of Oligocene-Miocene time. *Royal Society of London Philosophical Transactions, Series A*, 357: 1909–1927.

SHACKLETON, N.J., HALL, M.A., RAFFI, I., TAUXE, L. and ZACHOS, J.C., 2000. Astronomical calibration of the Oligocene-Miocene boundary. *Geology*, 28: 447-450.

SHERIDAN, R.E., 1987. Pulsation tectonics as the control of long-term stratigraphic cycles. *Paleoceanography*, 2: 97-118.

SINGER, B.S., BROWN, L.L., RABASSA, J.O. and GUILLOU, H., 2004. ^{40}Ar/^{39}Ar chronology of Late Pliocene and early Pleistocene geomagnetic and glacial events in southern Argentina. in: Channell, J.E.T., Lowrie, W. and Meert J., Eds., *Timescales of the Internal Geomagnetic Field*, p. 320. American Geophysical Union, Geophysical Monograph 145.

SMITH, M.E., SINGER, B.S. and CARROLL, A.R., 2003. ^{40}Ar/^{39}Ar geochronology of the Eocene Green River Formation, Wyoming. *Geological Society of America Bulletin*, 115: 549-565.

SMITH, M.E., SINGER, B.S., CARROLL, A.R. and FOURNELLE, J.H., 2006. High-resolution calibration of Eocene strata: ^{40}Ar/^{39}Ar geochronology of biotite in the Green River Formation. *Geology*, 34: 393-396.

SPRENGER, A. and TEN KATE, W.G., 1993. Orbital forcing of calcilutite-marl cycles in southeast Spain and an estimate for the duration of the Berriasian stage. *Geological Society of America Bulletin,* 105: 808-818.

SZURLIES, M., 2004. Magnetostratigraphy: the key to a global correlation of the classic Germanic Trias-case study Volpriehausen Formation (Middle Buntsandstein), Central Germany. *Earth and Planetary Science Letters*, 227: 395-410.

SZURLIES, M., BACHMANN, G.H., MENNING, M., NOWACZYK, N.R. and KADING, K.-C., 2003. Magnetostratigraphy and high-resolution lithostratigraphy of the Permian-Triassic boundary interval in central Germany. *Earth and Planetary Science Letters,* 212: 263-278.

TEN KATE, W.G.H. and SPRENGER, A., 1993. Orbital cyclicities above and below the Cretaceous/Paleogene boundary at Zumaya (N. Spain), Agost and Relleu (SE Spain). *Sedimentary Geology*, 87: 69-101.

TONG, J. and YIN, J., 1999. A study on the Griesbachian cyclostratigraphy of Meishan Section, Changxing, Zhejiang Province. *Journal of Stratigraphy*, 23: 130-135 (in Chinese with English abstract).

TRAMP, K.L., SOREGHAN, G.S. and ELMORE, R.D., 2004. Paleoclimatic inferences from paleopedology and magnetism of the Permian Maroon Formation loessite (Colorado, USA). *Geological Society of America Bulletin*, 116: 671-686.

TUENTER, E., WEBER, S.L., HILGEN, F.J., LOURENS, L.J. and GANOPOLSKI, A., 2005. Simulation of climate phase lags in response to precession and obliquity forcing and the role of vegetation. *Climate Dynamics*, 24: 279-295.

VAIL, P.R., MITCHUM, JR., R.M., TODD, R.G., et al., 1977. Seismic stratigraphy and global changes in sea level. In: Payton, C.E., Ed., *Seismic Stratigraphy-Applications to Hydrocarbon Exploration,* 49-212. AAPG Memoir 26.

VAN DAM, J.A., ABDUL AZIZ, H., ANGELES ALVAREZ SIERRA, M., HILGEN, F.J., VAN DEN HOEK OSTENDE, L.W., LOURENS, L.J., MEIN, P., VAN DER MEULEN, A.J. and PELAEZ-CAMPOMANES, P., 2006. Long-period astronomical forcing of mammal turnover. *Nature*, 443: 687-691.

VAN TASSELL, J., 1994a. Evidence for orbitally-driven sedimentary cycles in the Devonian Catskill Delta Complex. In: Dennison, J.M., Ettensohn, F.R., Eds., *Tectonic and eustatic controls of sedimentary cycles*, 121-131., SEPM Concepts in Sedimentology and Paleontology, 4.

———, 1994b. Cyclic deposition of the Devonian Catskill Delta of the Appalachians, USA. In: De Boer, P.L. and Smith, D.G., Eds., *Orbital forcing and cyclic sequences*, 395-411. International Association of Sedimentologists Special Publication, 19.

VARADI, F., RUNNEGAR, B. and M. GHIL, 2003. Successive refinements in long-term integrations of planetary orbits. *Astrophysical Journal*, 592: 620-630.

WADE, B. S. and PÄLIKE, H., 2004. Oligocene climate dynamics. *Paleoceanography*, 19: PA4019, doi: 10.1029/2004PA001042.

WEEDON, G.P., 1989. The detection and illustration of regular sedimentary cycles using Walsh power spectra and filtering, with examples from the Lias of Switzerland. *Journal of the Geological Society, London*, 146: 133-144.

WEEDON, G.P. and COE, A.L., 2006. Jurassic cyclostratigraphy: recent advances, implications and problems. *International Association of Mathematical Geology: Meeting on quantitative geology from multiple sources, 3-8 September.* Liège, Belgium.

WEEDON, G.P. and JENKYNS, H.C., 1999. Cyclostratigraphy and the Early Jurassic timescale: data from the Belemnite Marls, Dorset, southern England. *Geological Society of America Bulletin*, 111: 1823-1840.

WEEDON, G.P., COE, A.L. and GALLOIS, R.W., 2004. Cyclostratigraphy, orbital tuning and inferred productivity for the type Kimmeridgian Clay (Late Jurassic), southern England. *Journal of the Geological Society, London*, 161: 655-666.

WEEDON, G.P., JENKYNS, H.C., COE, A.L. and HESSELBO, S.P., 1999. Astronomical calibration of the Jurassic time-scale from cyclostratigraphy in British mudrock formations. *Philosophical Transactions of the Royal Society of London, Series A*, 357: 1787-1814.

WESTERHOLD, T., RÖHL, U., LASKAR, J., RAFFI, I., BOWLES, J., LOURENS, L. J. and ZACHOS, J. C., 2007. On the duration of Magnetochrons C24r and C25n and the timing of early Eocene global warming events: Implications from the ODP Leg 208 Walvis Ridge depth transect. *Paleoceanography*, 22: PA2201 10.1 029/2006P A001 322

WESTERHOLD, T., RÖHL, U., RAFFI, I., FORNACIARI, E., MONECHI, S., REALE, V., BOWLES, J., EVANS, H.F., submitted. The first comprehensive orbital chronology for the Paleocene: Implications for the Geomagnetic Polarity Time Scale and the age of the K/Pg boundary. *Palaeogeography, Palaeoclimatology, Palaeoecology.*

WILLIAMS, G.E., 2000. Geological constraints on the Precambrian history of Earth's rotation and the Moon's Orbit. *Reviews of Geophysics*, 38: 37-59.

YANG, W. and LEHRMANN, D.J., 2003. Milankovitch climate signals in Lower Triassic (Olenekian) peritidal carbonate successions, Nanpanjiang Basin, South China. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 201: 283-306.

YANG, W., HARMSEN, F. and KOMINZ, M., 1995. Depositional cyclicity of the Middle and Late Devonian Lost Burro Formation, Death Valley, California—a possible record of Milankovitch climatic cycles. *Journal of Sedimentary Research*, B65: 306-322.

YIN, H., ZHANG, K., TONG, J., YANG, Z. and WU, S., 2001. The Global Stratotype Section and Point (GSSP) of the Permo-Triassic boundary. *Episodes*, 24: 102-114.

ZACHOS, J.C., SHACKLETON, N.J., REVENAUGH, J.S., PÄLIKE, H. and FLOWERS, B.P., 2001. Climate response to orbital forcing across the Oligocene-Miocene boundary. *Science*, 292: 474-478.

ZÜHLKE, R., BECHSTÄDT, T. and MUNDIL, R., 2003. Sub-Milankovitch and Milankovitch forcing on a model Mesozoic carbonate platform – the Latemar (Middle Triassic, Italy). *Terra Nova*, 15: 69-80.