

# Cyclostratigraphy and the Astronomical Time Scale

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**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.

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## 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 <sup>40</sup>Ar/<sup>39</sup>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 65° 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.

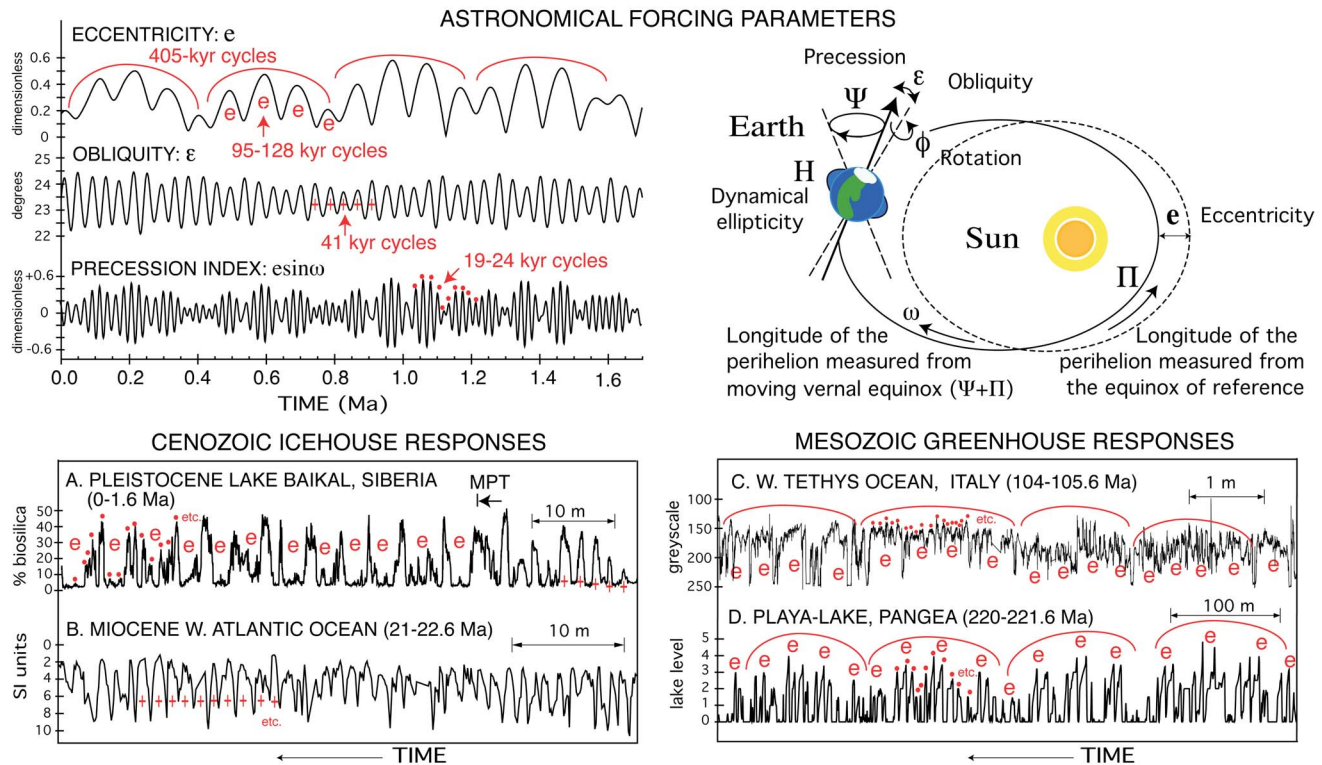


FIGURE 1

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 in-

solation 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  $\pm 10$  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 volcanoclastic 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 Sarthéin 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.

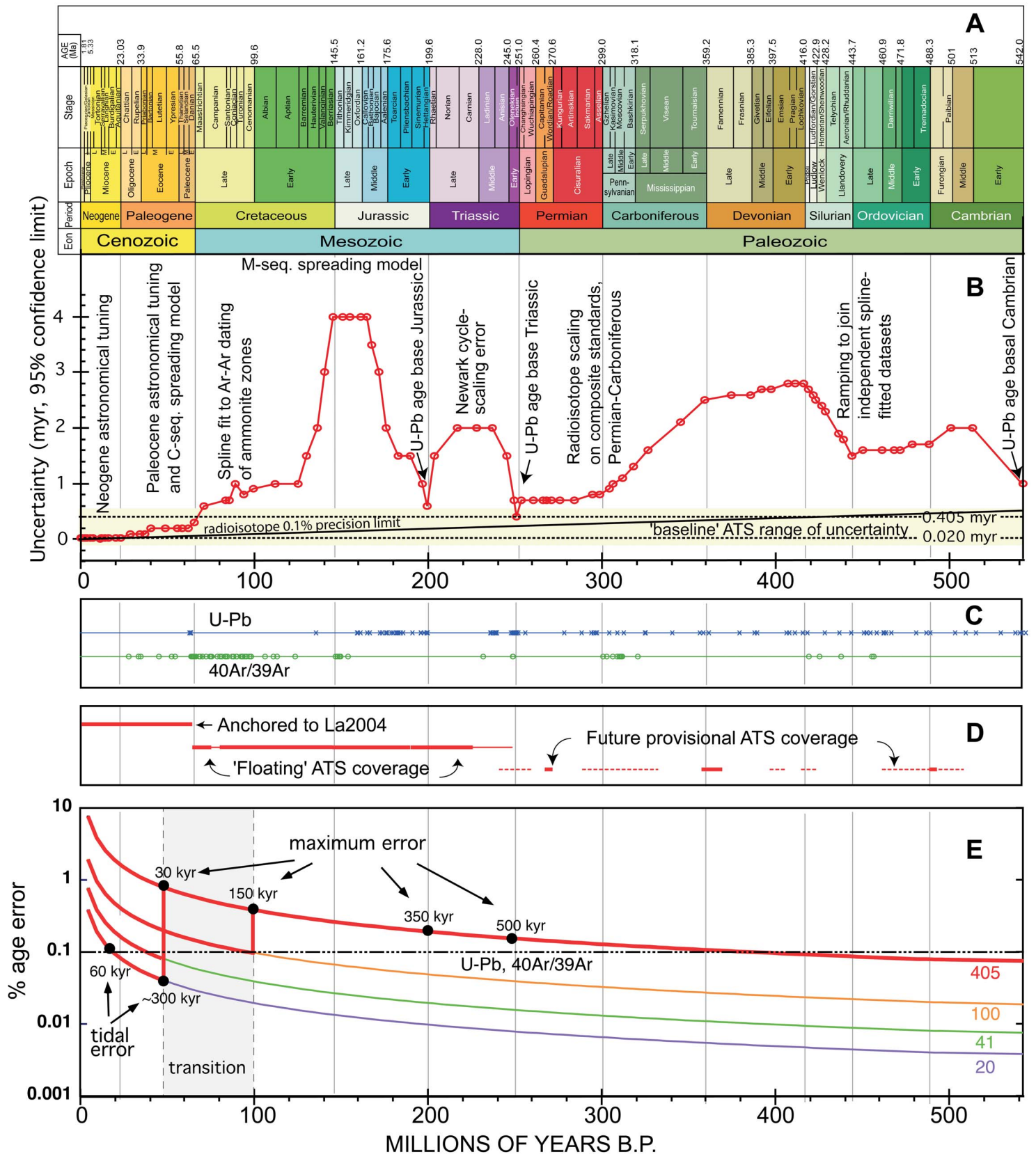
### Cenozoic Era

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  $^{40}\text{Ar}/^{39}\text{Ar}$  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; Grippio 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; Lehmann et al. 2001; Yang and Lehmann 2003; Szurles et al. 2003; Szurles 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:** Goldammer 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.



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-myrr 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-myrr 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 (Szurliés et al. 2003; Szurliés 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 ma-



rine 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  $^{40}\text{Ar}/^{39}\text{Ar}$  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  $^{40}\text{Ar}/^{39}\text{Ar}$  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;  $^{206}\text{Pb}/^{238}\text{U}$  dates are probably closer to absolute (see Schoene et al. 2006). But, before taking  $^{238}\text{U}$ - $^{206}\text{Pb}$  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 Hussein and Matthews 2005; Al Hussein 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  $\text{CO}_2$ , 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<sub>2</sub> 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.

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