# Astronomical tuning of the Aptian Stage from Italian reference sections

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## ABSTRACT

**A high-resolution grayscale series of the pelagic Fucoid Marls (Piobbico core, central Italy) shows strong, pervasive lithological rhythms throughout the Aptian interval. A hierarchy of centimeter- to meter-scale cycles characterizes the rhythms; when calibrating ~1 m cycles to Earth's 405 k.y. orbital eccentricity cycle, these rhythms correspond to the periods of the eccentricity, obliquity, and precession index. Tuning to orbital eccentricity cycles provides a high-resolution time scale for the Aptian. Correlation to the Cismon core (northern Italy) extends the tuning to the Aptian-Barremian boundary. The tuning indicates a minimum duration of 13.42 m.y. for the Aptian Stage, where previous estimates range from 6.4 to 13.8 m.y. The combined Aptian–Albian astronomical tuning of the entire 77-m-long Piobbico core (and part of the Cismon core) provides a 25.85-m.y.-long astronomically calibrated time scale for Earth history.**

## INTRODUCTION

The Early Cretaceous Aptian age was a time of dramatic climate change, global warming, rising sea level, oceanic anoxia, biotic shifts, intensified carbon cycling, increased ocean crust production, onset of a magnetic superchron, and superplume activity (Tarduno et al., 1991; Bralower et al., 1994, 1999; Jahren, 2001; Larson, 1991a, 1991b; Larson and Erba, 1999; Leckie et al., 2002; Jenkyns, 2003; Erba, 2004; Tejada et al., 2009). Important global events include the early Aptian Selli Event, representing Oceanic Anoxic Event 1a (OAE1a) (e.g., Bralower et al., 1994, 1999; Jenkyns, 2003; Erba, 2004), and widespread volcanism that emplaced huge basaltic plateaus in the oceans, impacting marine biology (Erba, 2004). Terrestrial life experienced significant evolutionary change (e.g., angiosperms and birds; Zhou et al., 2003). Other Aptian black shale intervals (Fallot, Jacob, Kilian) have also been described (e.g., Bralower et al., 1999; Leckie et al., 2002), as well as intervening oceanic red beds (ORBs) (Hu et al., 2005). A short-lived magnetic polarity chron "ISEA" occurred within the C34N superchron (e.g., Tarduno et al., 1989).

Despite this rich record, the Aptian Stage has only a roughly defined chronology. GTS2004 assigns 125 ± 1.0 Ma and 112 ± 1.0 Ma to the base and top of the Aptian (Ogg et al., 2004). Radioisotope dates for the early Aptian range between 121.2 and 125.8 Ma (Mahoney et al., 1993; Chambers et al., 2004; He et al., 2008) (see Table DR1 in the GSA Data Repository[1]); the Aptian-Albian boundary is constrained by a high-precision U-Pb date of 113.1 ± 0.3 Ma (Selby et al., 2009). Here, we present a detailed astronomical tuning of the pelagic Fucoid Marls of Italy, using high-resolution grayscale data that sample the sedimentary cyclicity, supported by time-frequency analysis and Early Cretaceous astronomical parameters from Laskar et al. (2004).

## DATA AND METHODS

The Aptian Stage is 33.7 m thick in the Fucoid Marls cored at Piobbico, central Italy (Tornaghi et al., 1989). The core stratigraphy correlates closely with the Aptian GSSP (Global Boundary Stratotype Section and Point) candidate section only 5 km away from Gorgo a Cerbara (Coccioni et al., 1992; Erba, 1996; Channell et al., 2000). A high-resolution (0.81 mm) grayscale scan of the alternating pelagic marls and shales in the core (procedures in Grippo et al., 2004) captures a record of strong, meter- to centimeter-scale lithological rhythms (Fig. 1). This scan was decimated to a 1 mm uniform sample rate for this study.

The early Aptian Selli Level is 2.3 m thick in the Piobbico core, but 4.75 m thick in the Cismon core (northern Italy, 300 km from Piobbico; Erba et al., 1999). The albedo is a measure of light/dark color derived from spectral reflectance (0%–100%) at 550 nm at high resolution (2.1 cm average sample rate) through the Selli Level at Cismon, providing a high-resolution proxy of lithologic cyclicity, and a means to compare

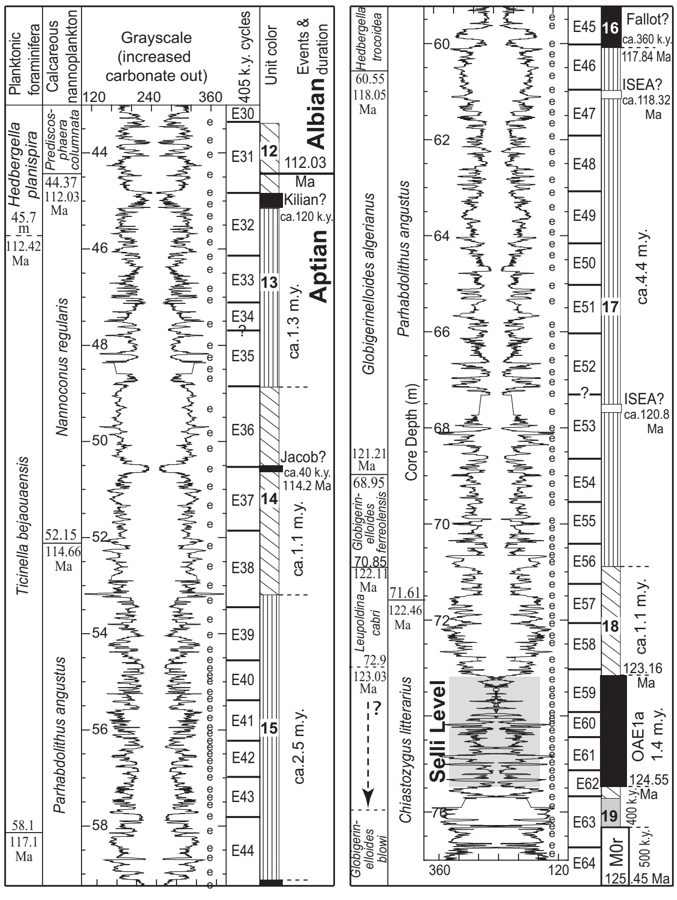


**Figure 1. Aptian Stage integrated stratigraphy of the Piobbico core, central Italy. For location, see Grippo et al. (2004). Grayscale series with increased carbonate outward. Inferred geopolarity, biostratigraphic zones, unit color, and positions of Oceanic Anoxic events (OAEs), chron ISEA, and chron M0r from Larson et al. (1993), Erba (1996), Bralower et al. (1999), Leckie et al. (2002), and GTS2004. Interpreted 100 k.y. ("e") and 405 k.y. ("E") eccentricity cycles and durations are from current study. Dates are based on top Albian age of 99.6 Ma (from GTS2004); see text for further details.**

[1]GSA Data Repository item 2010250, Tables DR1–DR2 and Figures DR1–DR6, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

the Cismon and Piobbico Selli records (Figs. DR1 and DR2 in the Data Repository). The Selli Level in the Cismon core was defined by Erba et al. (1999) between 18.77 and 23.68 m; subsequently, Li et al. (2008) defined the base of the Selli at 23.49 m. For the Selli Level correlation, 18.77 m in the Cismon core was anchored to 73.17 m in the Piobbico core, which marks the top of the black shale interval, and the correlation proceeded downward (Fig. DR1). The results correlate the base of the first black shale at 23.49 m at Cismon (Li et al., 2008, definition) to 75.47 m in the Piobbico core. If the definition of the Selli at Cismon is extended to 23.68 m (Erba et al., 1999, definition), the Selli in the Piobbico core would extend to 75.68 m. However, this additional small segment is carbonate-rich in both cores. Thus, we elected to define the lower limit of the Selli Level at 75.47 m for Piobbico, and at 23.49 m for Cismon.

Multitaper spectral analysis with robust red noise modeling (Ghil et al., 2002; SSA-MTM [Singular Spectrum Analysis–MultiTaper Method] Toolkit) was used to assess the lithologic cycles as a possible record of astronomically forced sedimentation. The series were pre-whitened by subtracting a 35% weighted average (in Kaleidagraph™; Cleveland, 1979); the Piobbico series was smoothed using a 9-point (~1 cm) moving average (Analyseries; Paillard et al., 1996) to suppress very high frequencies. “E” and “e” cycles representing 405 k.y. and ~100 k.y. orbital eccentricity variations were visually assessed and used to tune the series (Fig. 1); Gaussian band-pass filtering (Analyseries) aided in the recognition of “e” cycles. The tuned sedimentary rhythms are compared to the La2004 astronomical model (Laskar et al., 2004).

## RESULTS

The untuned Piobbico spectrum (Fig. DR3) shows prominent wavelengths at 4 m, ~1 m, and ~0.26 m, and weaker ones at ~0.1 m and 0.04 m. These stratigraphic cycles correspond to ~1.6 m.y., ~400 k.y., ~100 k.y., ~40 k.y., and ~20 k.y. periods when calibrating the ~1 m cycles to the 405 k.y. eccentricity cycle.

The 405 k.y. tuned Piobbico spectrum has significant spectral peaks at 405 k.y. (tuned), 100 k.y., 37 k.y., 22 k.y., 20 k.y., and 18 k.y. (Fig. 2A; see Table DR2 for time table). A strong peak occurs at ~1.6 m.y., bifurcated between 2.6–1.76 m.y. and 1.28–1.03 m.y. The upper part of the series exhibits relatively strong 405 k.y. cyclicity; the lower part of the series has stronger ~100 k.y. cyclicity (Figs. 2B and 2C; Fig. DR4).

The 100 k.y. tuned Piobbico spectrum has significant peaks at ~1.6 m.y., 405 k.y., and 100 k.y. (tuned), and weaker (but significant) peaks in the obliquity and precession bands (Figs. 2D and DR5; see Table DR2 for time table). Two significant periods in the obliquity band (40 k.y. and 33 k.y.) may be the consequence of tuning the series to a single 100 k.y. component, whereas ~100 k.y. eccentricity has multiple components, causing the single obliquity component to split. The spectrum of the upper part of the series has similarly scaled 1.6 m.y., ~400 k.y., and 100 k.y. peaks, but the middle and lower parts show a strong 100 k.y. peak, one at ~1.6 m.y., and a lesser peak at 405 k.y. (Figs. 2E and 2F).

The tuned spectra compare closely with the La2004 astronomical model (Fig. 2G), for which the eccentricity, tilt, and precession (ETP) spectrum shows eccentricity (405 k.y.; 95–132 k.y.), and dissipation-adjusted obliquity (37 k.y.) and precession index (18–22 k.y.) (Laskar et al., 2004). La2004 predicts a 2 m.y. eccentricity component, which may be reflected by the ~1.6 m.y. cycle (see “Discussion”).

The Piobbico series provides a high-resolution astronomical time scale for OAE1a and compares closely with the much expanded Selli Level in the Cismon core. The spectra of the untuned Piobbico and Cismon series show significant ~12 cm and ~46 cm peaks, respectively (Figs. DR1C and DR1D). We assumed that ~12 cm cycles in the Piobbico core and ~46 cm cycles at Cismon represent ~100 k.y. cycles (Figs. 3A and 3B).

The spectra of both 100 k.y. tuned Selli Level series reveal all of the astronomical frequencies (Figs. 3C and 3D). The Piobbico spectrum shows a strong 100 k.y. peak (tuned), one at 350 k.y., peaks at 38 k.y. (obliquity), 25 k.y., and very weak 19 k.y. and 17 k.y. (precession) peaks (Fig. 3C). In the Cismon spectrum, there is a strong 100 k.y. peak (tuned), one at 400 k.y., and peaks at 36 k.y. (obliquity) and 20 k.y. (precession) (Fig. 3D). Both tuned series indicate a 1.40 m.y. duration.

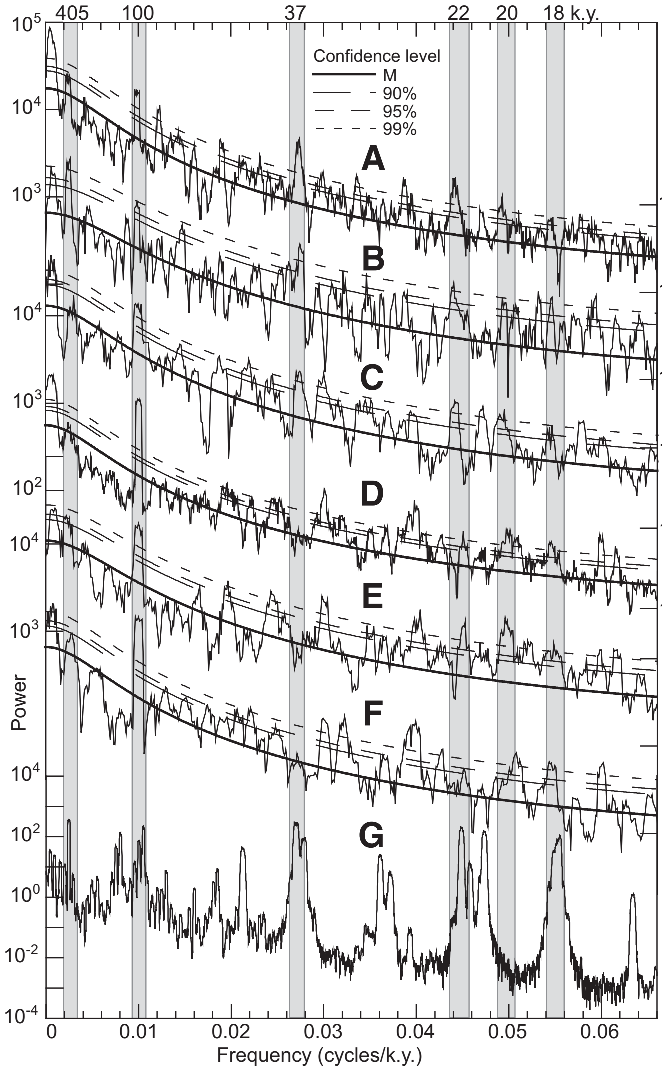


**Figure 2. Multitaper spectral analysis of the Piobbico core grayscale series with robust red noise modeling (linear fit). Power is in units of variance/frequency. A–C: 405 k.y. tuned spectra. 5π power spectrum of entire tuned series (A); 3π power spectra of the upper (B) and lower (C) parts of the tuned series. D–F: 100 k.y. tuned spectra. 5π power spectrum of entire tuned series (D); 3π power spectra of the upper (E) and lower (F) parts of the tuned series. G: ETP 3π power spectrum of the La2004 astronomical parameters over 108–130 Ma. ETP is as in Mitchell et al. (2008).**

## DISCUSSION

The spectral analysis shows that the Piobbico succession was driven by astronomical variations. Eccentricity-scale cyclicity is prominent in the upper Aptian; ~100 k.y. power is stronger than 405 k.y. power in the lower Aptian, especially in the ORBs (units 13, 15, and 17). Units 14 and 18 and the upper parts of unit 17 are dominated by obliquity-scale cycles. In general, obliquity predominates in black shales and adjacent stratigraphy. The eccentricity signal dominates the rhythms through rectification of the precession index (Weedon, 2003). The precession index band confirms the presence of an eccentricity modulator (Fig. DR6). La2004 eccentricity

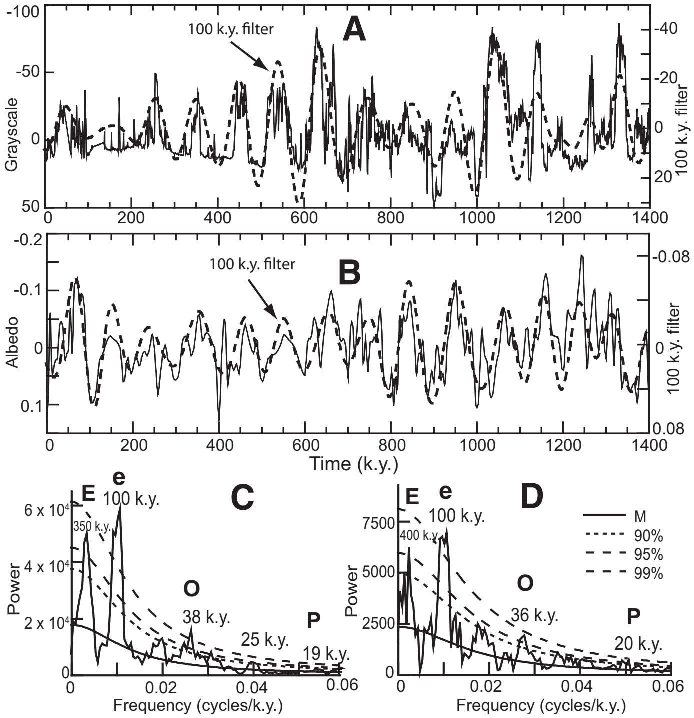


**Figure 3. 100 k.y. tuned Piobbico grayscale (A) and Cismon albedo (B) series with 100 k.y. filtered output. Power is in units of variance/frequency. C–D: 2π multitaper spectra of the tuned series. Tuning details are in Table DR2 (see footnote 1). E—405 k.y. eccentricity; e—100 k.y. eccentricity; O—obliquity; P—precession.**

predicts a 2 m.y. periodicity, from $g_4$-$g_3$, the secular frequencies of Mars and Earth. The Piobbico eccentricity spectrum, however, indicates a shorter, and somewhat unstable (but persistent) 1.6 m.y. term. This could represent the actual evolution of $g_4$-$g_3$ during the Aptian, which modeling indicates was a time during which Mars and Earth may have experienced chaotic motions (Laskar et al., 2004).

Recalibrating Grippo et al.'s (2004) Albian cyclostratigraphy based on E = 405 k.y. (instead of 406 k.y.), and assuming the base of the Albian at the first occurrence of *Prediscosphaera columnata*, gives a duration of 12.43 m.y. for the Albian Stage and an age of 99.6 Ma + 12.43 m.y. = 112.03 Ma (Fig. 1). If this is adjusted to the recently proposed Fish Canyon sanidine monitor of 28.293 Ma (Renne et al., 2009), the top of the Albian Stage recalibrates to 100.62 Ma, i.e., 1.02 m.y. older than the GTS2004 argon-based age of 99.6 Ma (details in Table DR1). The Albian-Aptian boundary age thus increases from 112.03 Ma to 113.05 Ma, which is statistically indistinguishable from the U-Pb age of 113.1 ± 0.3 Ma by Selby et al. (2009), taken just below the first occurrence of *P. columnata*, at the top of the *Hypacanthoplites jacobi* ammonite zone.

Our tuning indicates a duration for the Aptian above chron M0r of 12.7 m.y. (100 k.y. tuning) or 12.9 m.y. (405 k.y. tuning); the top of the Selli Level is at 123.16 Ma and the base at 124.55 Ma (405 k.y. tuning) (Fig. 1). The duration from the base of the Selli to the top of chron M0r is 400 k.y., and the estimated duration of M0r is 500 k.y., based on 100 k.y. tuning of the Cismon core (Fig. 3; Fig. DR1), which is consistent with Herbert et al. (1992, 1995). Therefore, the top of chron M0r is 124.95 Ma, the base of M0r, i.e., the base of the Aptian, is 125.45 Ma, and the duration of the Aptian Stage is 13.42 m.y. (405 k.y. tuning). If the new Fish Canyon sanidine monitor is used (see above), the basal Aptian age will increase to 126.47 Ma. The Piobbico-Cismon correlation suggests that the Piobbico core penetrates chron M0r over a 360 k.y. interval. Evidence for disrupted intervals (Fig. DR3) could signify an even longer duration for the stage.

The duration of the Aptian according to GTS2004 is 13.0 ± 0.5 Ma (Ogg et al., 2004). Herbert et al. (1995) estimated a duration of 10.6 m.y. for the Aptian Stage based on the combined cycle count from the Piobbico core and outcrop studies. In a separate interpretation of outcrops near Piobbico, Fiet (2000) obtained a 6.4 ± 0.2 m.y. duration for the Aptian. However, their outcrop ensemble likely contains significant gaps from tectonics and/or nondeposition. Most recently, a 405 k.y. "straton" chronology based on Arabian sequence stratigraphy indicates a total duration for the Aptian Stage of 13.8 m.y. (Al-Husseini and Matthews, 2010).

The Selli Level is relatively thin at Piobbico; nonetheless, the Piobbico series exhibits bundles that correlate to the doubly thick Selli Level at Cismon. The estimated duration of 1.40 m.y. for the event (Fig. 3) is close to previous estimates of 1.0–1.3 m.y. (Herbert, 1992; Li et al., 2008; Malinverno et al., 2010). Kuhnt and Moullade (2007) estimated a 760 k.y. duration for the *Globigerinelloides ferreolensis* zone in a section at Marcouline, France, based on 33 precessional cycles, somewhat less than our 900 k.y. at Piobbico. GTS2004 assigned a 1.7 m.y. duration for the zone, but with low confidence.

A brief magnetic reversal, ISEA (M"-1r"), occurred soon after the start of the C34N superchron, within the *G. algerianus* foraminifera zone (e.g., Tarduno et al., 1991; Erba, 2004; Ogg et al., 2004). At Piobbico, ISEA was not detected but assumed to be at the top of the *G. algerianus* zone (Larson et al., 1993), which astronomically dates it at 118.32 Ma (Fig. 1). If instead chron ISEA is at the base of the *G. algerianus* zone (as in GTS2004), then the astronomical age would be 120.8 Ma. Our results cannot determine the stratigraphic position of chron ISEA, but once its position can be firmly established, an age can be assigned to it. A robustly dated chron ISEA will provide a key global tie point for the Aptian time scale; with its occurrence within the C34N superchron, it can inform models of long-term quiescence in the geodynamo.

The 405 k.y. tuning indicates durations of 360 k.y., 40 k.y., and 120 k.y. for the Fallot, Jacob, and Kilian Events, respectively; 7.2 m.y. and 1.3 m.y. for ORB1 and ORB2; and 2.58, 0.36, 1.1, and 0.4 m.y. for green units 18, 16, 14, and 12 (Fig. 1). Thus, ORBs and green beds are associated with relatively high accumulation rates (2–6 m/m.y.) and long durations, whereas the black shale intervals have lower rates (1–3 m/m.y.) and short durations (Table DR2).

## CONCLUSIONS

Spectral analysis of a high-resolution grayscale scan of the Aptian Fucoid Marls (Piobbico core, Italy) indicates that pelagic sedimentation in the bathyal Tethys realm was strongly influenced by astronomical forcing. Basic results are as follows:

- Eccentricity-scale (~100 k.y. and 405 k.y.) cyclicity dominates most of the succession by rectification of the precession index.
- Prominent ~1.6 m.y. cyclicity occurs throughout the core, possibly a manifestation of Cretaceous astronomical secular frequencies $g_4$-$g_3$.
- ORBs have unusually strong ~100 k.y. eccentricity cycles.
- Black shale intervals and adjacent stratigraphy exhibit strong obliquity-scale cyclicity.
- Precession-scale cyclicity is weakly preserved due to low accumulation rates.

The astronomical calibration is as follows (Fig. 1):

- 405 k.y. tuning indicates a duration of 12.9 m.y. for the Aptian above chron M0r.
- 100 k.y. tuning indicates a duration of 1.40 m.y. for the Selli Event in both Piobbico and Cismon cores; the duration of chron M0r is 500 k.y.
- The combined tuning of the Piobbico and Cismon cores indicates a 13.42 m.y. duration for the Aptian Stage, and assuming a 99.6 Ma age for the Albian-Cenomanian boundary, places the base of the Aptian Stage at 125.45 Ma.

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