Ciências da Terra (UNL)	Lisboa	Nº 18	pp. 29-34	2013

Cyclostratigraphy and recent developments in the astronomical calibration of the Geological Time Scale

Slah Boulila[1], Bruno Galbrun[1] & Silvia Gardin[2]

[1] Université Pierre et Marie Curie, UMR 7193, Institut des Sciences de la Terre-Paris, Paris, France; slah.boulila@upmc.fr; bruno.galbrun@upmc.fr

[2] Université Pierre et Marie Curie, UMR 7207, Centre de Recherche sur la Paléobiodiversité et les Paléoenvironnements, Paris, France; silvia.gardin@upmc.fr

Summary

Cyclic astronomical variations affect the distribution of solar energy on the Earth's surface, which induces climatic changes detected in the sedimentary records. Such changes have been demonstrated to vary in tune with the classical Milankovitch frequency band (about 10 to 500 kyr). Correlations of high-fidelity stratigraphy with well constrained astronomical models have allowed unprecedented temporal resolution of several intervals of the Cenozoic and Mesozoic eras. Recent studies have highlighted million-year (Myr) to multi-Myr periodic variations in the astronomical and geological time series. These low-frequency cycles mainly result from the interference of the fundamental high-frequency cycles (precession, obliquity, eccentricity); modeling has shown that they have played an important role in paleoclimatic and paleoenvironmental changes. The detection of the astronomical periodicties in the sedimentary records is thus of paramount interest because they provide constraints on geochronology and on how our climate is driven and responds to external forcing. Therefore, multiple efforts have continued to astronomically calibrate the geological time scales for potential implications in understanding rates and velocities of geological processes and events that occurred during Earth's history.

***Keywords*:** Earth's orbital parameters, astronomical models, Milankovitch, cyclostratigraphy, astronomical time scale, long-term orbital periods

The history and principles of the astronomical calibration of the Geological Time Scale have been recently summarized in various publications (Fischer et al., 2004; Hinnov & Ogg, 2007; Hilgen, 2010; Hinnov &Hilgen, 2012). We will recall here the main steps of this discipline, pointing some directions for future research.

Cyclostratigraphy and Earth's orbital parameters

Cyclic variations in Earth's orbital parameters affect the distribution of solar energy (or insolation) on the Earth's surface, which in turn induces climatic changes detected in the geological sedimentary records. Earth's orbital eccentricity is defined by the ratio between the centre-to-focus extent with respect to the semi-major axis. It varies between values close to zero and values close to 0.06, with periodicities of about 100 and 400 kyr. The eccentricity variations have an effect on the global annual mean insolation. Precession of the equinoxes (or axial precession) corresponds to a slow drift of the polar axis with respect to the fixed stars. Its present value is 1.397°

per century (or a periodicity of 25.765 kyr). Precession of the equinoxes is not relevant for climate, however, when the axis is oriented in a different way, the so-called climatic precession corresponds therefore to a drift of the line of equinoxes among the stars in the zodiac. The climatic effect of precession is obtained as a combination of the precession of perihelion and the axial precession. Thus, the precession parameter measures the sine of the angle between vernal equinox and perihelion and scales with the eccentricity. Currently, it has two fundamental periodic components, one at 19 kyr and the other at 23 kyr. Finally, change in the tilt angle (obliquity) between the Earth's axis and the normal to the ecliptic plane has a main present period of 41 kyr. The obliquity affects the meridional distribution of incoming insolation. Today, obliquity is 23°27', which defines the latitude of polar circles (67°33' north and south) and tropics (23°27' north and south). This value oscillates between extremes of 21.9° and 24.5°. Any change in obliquity will have climatic consequences by modifying the extent of these polar and tropical geographic domains.

The resulting change in insolation from Earth's orbital parameters has governed our climate, and first evidences are from the Quaternary ice ages. The first astronomical theory of glacial ages was formulated by Joseph Adhémar (Adhémar, 1842) on the basis of the precession of equinoxes because it was well known since the Antiquity. Adhémar suggested that the fact that today's northern hemisphere winters are close to the Sun, whereas those in southern hemisphere are far from it, may explain why there is no large ice sheet in the north, because of mild and short winters, while there is a large one, Antarctica, in the southern hemisphere. James Croll (Croll, 1875, 1885) strongly insisted on the role of snow accumulation during winters. The new developments of celestial mechanics (in particular by Pierre Simon Laplace and Urbain le Verrier) led Croll to explicitly introduce the effect of the changing eccentricity. According to Croll, large glaciations were therefore associated with maximum eccentricity, which led him to suggest an age of at least 80 ka ago for the last glaciation, with an even greater glacial event about 240 ka ago.

After the attempts of Adhémar (1842) and Croll (1875, 1885), the Serbian mathematician M. Milankovitch (1941) was the first to calculate in detail the effects of the three astronomical parameters on insolation to explain the astronomical theory of the ice ages. The second half of the 20th century would see the confirmation of the astronomical theory of paleoclimate.

The irrefutable validation of this theory would come from the marine record and the oxygen isotope proxy. The work of Hays *et al.* (1976) was then considered as the final confirmation of the astroclimate theory through the link with ice-volume proxies; this was owing to the CLIMAP (Climate Long-Range Investigation Mapping and Prediction) international project, and then came the SPECMAP (Mapping Spectral Variability in Global Climate) international project for marine isotope chronology (e.g., Imbrie *et al*., 1984).

The seminal study that had tested the potential use of astronomical periodicities in the measurements of geologic time refers in fact to Gilbert (1895), who published a paper entitled "Sedimentary measurement of geologic time" (Gilbert, 1895). He was the first to suggest the link between the Upper Cretaceous limestone/shale alternations of the Colorado (USA) and the orbital forcing. He was able to estimate a duration of 20 myr for the Late Cretaceous, but his visionary analysis was too inconsistent with the end 19th century concepts over the duration of geological time.

In the first half of the 20th century cyclostratigraphic studies and attempts to correlate astronomically calculated insolation and paleoclimatic proxies were quite scarce. Since then, there has been an increase of cyclostratigraphic studies of various orbital origin sedimentary successions. Among the most important works of the '50s and '60s, special attention must be paid to the cyclostratigraphic analysis of Triassic Alpine limestones (Schwarzacher, 1947, 1957; Fischer, 1964). Astronomical cyclicities (precession, obliquity, short eccentricity) were recognized in these marine platform deposits suggesting that low amplitude eustatic oscillations were driven by periodic glaciations. Because glaciations are unknown for the Triassic, the debate on the origin of these shallow marine successions is still relevant.

Despite important progress in cyclostratigraphic studies in phanerozoic strata, in icehouse and greenhouse periods, in marine and continental domains, using multiple climatic proxies,… outstanding questions remain opened: how does our climate respond to the astronomical driving force? Has astronomical forcing changed through time or does the expression or the impact of astronomical forcing vary as a function of continent and ocean mass distribution? What is the "mystery" that caused the switch from a 41 kyr obliquity cycle mode in the Pliocene-early Pleistocene to a 100 kyr cycle mode in the last ~800 kyr? What about the early Cenozoic hyperthermal events (and other Mesozoic events) that match timing of orbital cycle extrema? Is it a coincidence or a real trigger? etc. Thus, a highly resolved timescale and confrontation of several proxies with high-fidelity stratigraphy are becoming increasingly critical in studies of paleoclimate and paleoceanography. Determination of the rates at which Earth processes take place and how these rates change are key to developing our understanding of Earth history.

The astronomical calibration of the Cenozoic and Mesozoic eras

The validation of the astronomical theory of paleoclimate would allow to undertake the astronomical calibration of the geological time scale in the early ‘90s. This was made possible by the connection between high resolution cyclostratigraphic studies and the development of astronomical models. The first step is to recognize astronomical cycles in the sedimentary records via time series analysis of climatic proxies (stable oxygen or carbon isotopes, magnetic susceptibility, carbonate content, sedimentary facies…). The second step is to correlate these cyclostratigraphic signals to a target astronomical curve (e.g., insolation, precession, sum of the orbital parameters). Numerous studies for the Neogene were carried out in the Mediterranean area (e.g. Hilgen *et al.,* 1995). The astronomical model La2004 (Laskar *et al.*, 2004) has allowed the establishment of the first Astronomically Tuned Neogene Time Scale in 2004 (ATNTS2004), owing to the validity of the La2004 astronomical solution over this time coupled with high-fidelity climatic proxies (Lourens *et al.*, 2004). A new ATNTS 2012 was recently established, not really different from its predecessor (Hilgen *et al.*, 2012). Age calibration to full astronomical solution is now established back to the Oligocene/Eocene boundary (34 Ma) (Vandenberghe *et al.*, 2012).

The new astronomical solution La2010 extends back the accuracy of orbital eccentricity model from 40 to 50 Ma (Laskar *et al.*, 2011a). The validity of such model however, rapidly diminishes back in time and no hope is allowed to have an accurate model beyond 60 Ma.

The last 10 years numerous studies have been undertaken on the Paleogene which is tentatively calibrated to full eccentricity solution. This gave rise to several controversies mainly due to the identification and counting of the eccentricity cycles (i.e., Dinarès-Turell *et al.*, 2007; Westerhold *et al.*, 2008; Hilgen *et al.*, 2010). These discussions have highlighted the need for an astrochronology-geochronology intercalibration. An example is represented by the dating of the Cretaceous-Paleogene boundary. Considering the astronomical calibrations carried out on Paleogene successions, this boundary was dated at 65.3, 65.7, 65.9, 66.1 Ma… On the other hand, studies of the Maastrichtian successions suggested an age of 66 Ma (Husson *et al.*, 2011) and very recent new radioisotopic data confirmed this result (66 Ma; Renne *et al.*, 2013).

Because the chaotic behavior of the solar system (Laskar, 1989, 1990) only the 405 kyr eccentricity term is stable at least over the last 250 Ma – the 405 kyr metronome - can be used for astronomical calibration of Mesozoic and Paleozoic strat. Since the pioneering works of Schwarzacher and Fischer on the Alpine Triassic sediments in the '50s and '60s, there have been many cyclostratigraphic studies of Mesozoic successions (listed in Hinnov and Hilgen, 2012). These “floating” astrochronologies allow to cover 75% of the Mesozoic time. The challenge of the coming years will be to complete the gaps and to establish an Astronomically Tuned Mesozoic Time Scale (ATMTS?) using the 405 kyr eccentricity metronome.

The long-term orbital periods: geologic evidences

An important feature of the Earth's orbital parameter variations is that they display modulations in amplitude and frequency. The modulation terms arise through the interference of individual cycles to produce **“**resultants**”**, with periods ranging from hundreds of thousands to millions of years. The significance of certain amplitude modulation cycles was first described by Laskar (Laskar, 1990; 1999; Laskar *et al*., 1993), and an extensive review was also given by Hinnov (2000). The best known long-period modulation cycles are those of eccentricity (~2.4 myr) and obliquity (~1.2 myr). The ~1.2 and ~2.4 Myr periods could derive from the interfering terms ~41 kyr (p+s3) and ~39 kyr (p+s4), and ~95 kyr (g4 – g5) and ~99 kyr (g3–g5), respectively (where p is the Earth's axial precession frequency; s3, s4 are related to the precession of nodes of the Earth and Mars, g3, g4 and g5 are related to the precession of perihelions of the Earth, Mars and Jupiter, respectively). Thus, the ~1.2- and ~2.4-myr cycles correspond to the fundamental secular frequencies (s3–s4) and (g4–g3), respectively.

Increasing evidence from high-resolution sediment records in a parallel development of well-constrained astronomical models (Laskar *et al*., 2004, 2011a,b) suggests that significant astroclimatic variability is present at million year (Myr) to multi-Myr timescales (e.g., Zachos *et al.*, 2001a,b; Pälike *et al*., 2004, 2006a,b; Wade & Pälike, 2004; Lirer *et al*., 2009; Boulila *et al*., 2011, 2012). The study of the influence of these low-frequency astronomical cycles on Earth's climate change is of considerable value in deciphering biological turnover (e.g., van Dam *et al*., 2006), carbon-cycle variations (Pälike *et al.*, 2006a, Boulila *et al.*, 2012), ice-sheet events (Zachos *et al.*, 2001a; Pälike *et al*., 2006a), sea-level fluctuations (Boulila *et al.*, 2011), etc.

The orbital motion in the solar system has been demonstrated to be chaotic because of the presence of multiple secular resonances in the inner solar system (Laskar, 1989, 1990). As a result, the orbits of planets undergo slow but non-regular variations. Nevertheless, the 405 kyr periodicity was demonstrated to be relatively stable (Laskar *et al.,* 2004) because it is caused by the gravitational interaction of Jupiter and Venus (i.e., g2 – g5), and Jupiter has an extremely stable orbit. However, the ~1.2 and ~2.4 Myr periodicities are not stable, because they result from the motions of the inner planets (the Earth and Mars), which are less regular. An important resonance in this interaction between the motions of perihelions and nodes in the orbital relation of Mars and the Earth is related to a transition from (s4 – s3) – 2(g4 – g3) to (s4 – s3) – (g4 – g3) secular resonance (Laskar, 1990), that links the ~1.2 Myr obliquity (s4 – s3) to the ~2.4 Myr eccentricity (g4 – g3) modulation cycles.

The s4–s3 and g4–g3 terms have mean periodicities of ~1.2 and ~2.4 Myr in the Cenozoic, but in the Mesozoic their values are not constrained by the astronomical models. The only possible way to constrain their periodicities in the astronomical models is from the geological record. For instance, Laskar *et al.* (2004) recommended tuning Mesozoic sedimentary records to the 405 kyr stable period (g2–g5), then infer the mean period of the g4–g3 component from long-period sedimentary cycles. Only five cyclostratigraphic studies have dealt with g4–g3 period estimates in Mesozoic strata. Olsen & Kent (1999) estimated a period of 1.75 Myr from Late Triassic sequences. Similarly, Ikeda *et al.* (2010) found a 1.8 Myr term in the Late Triassic Inuyama deep-sea chert sequence of Japan. Boulila *et al.* (2010), and Huang *et al.* (2010a) assigned a period of ~2 Myr to Oxfordian-Kimmeridgian (Late Jurassic) sequences. Finally, Huang *et al.* (2010b) detected a period of 1.6 Myr in the Aptian (Early Cretaceous). These results converge towards a shortened g4–g3 periodicity in the Mesozoic, and supports astronomical modeling for the instability in the g4–g3 eccentricity term.

Recently, studies have even shown very long-period (8 to 10 Myr) cycles in the geological record, likely related to long-eccentricity modulation cycles (Boulila *et al.*, 2012; Ikeda and Tada, 2013; Sprovieri *et al*. 2013). Multi-Myr-long sedimentary records are in fact needed to look for these long-period cycles, their impact on climate and sea-level changes, and reciprocally, what their studies could provide in terms of constraints on Solar system modeling. Another potential interest of the study of (s4 – s3) and (g4 – g3) terms is that the differential expression of one to the detriment of the other may indirectly indicate the importance of ice sheets, and thus provide idea about icehouse *versus* greenhouse during poorly known epochs. For example, the s4–s3 related obliquity period is well expressed in sea-level depositional sequences via ice-volume change (glacioeustasy, Boulila *et al.,* 2011). Sprovieri *et al.* (2013) highlighted the s4–s3 cyclicity in $\delta^{13}C$ record in the Turonian-Coniacian (Umbria-Marche Basin, central Italy) suggesting the important role of glacioeustasy on the carbon cycle during this so-called Turonian-Coniacian super-greenhouse.

References

ADHEMAR J. A. (1842) – *Révolutions de la mer, déluges périodiques*. Private edition, Paris, 184 p.

BOULILA S., GALBRUN B., HINNOV L. A., COLLIN P. Y., OGG J. G., FORTWENGLER D. & MARCHAND D. (2010) – Milankovitch and sub-Milankovitch forcing of the Oxfordian (Late Jurassic) Terres Noires Formation (SE France) and global implications. *Basin Research* 22 (5), 717-732.

BOULILA S., GALBRUN B., LASKAR J. & PÄLIKE H. (2012) – A ~9 myr cycle in Cenozoic ?13C record and long-term orbital eccentricity modulation: Is there a link? *Earth Planet. Sc. Lett*. 317-318, 273-281.

BOULILA S., GALBRUN B., MILLER K. G., PEKAR S. F., BROWNING J. V., LASKAR J. & WRIGHT J. D. (2011) – On the origin of Cenozoic and Mesozoic "third-order" eustatic sequences. *Earth-Science Reviews* 109, 94-112.

CROLL J. (1875) – *Climate and time in their geological relations: A Theory of Secular Changes of the Earth's ClimateDaldy*. Isbister & Co, London, 577 p.

CROLL J. (1885) – *Discussions on Climate and Cosmology*. Adam & Charles Black, Edinburgh, 327 p.

DINARES-TURELL J., BACETA J. I., BERNAOLA G., ORUE-ETXEBARRIA X. & PUJALTE V. (2007) – Closing the Mid-Palaeocene gap: toward a complete astronomically tuned Palaeocene Epoch and Selandian and Thanetian GSSPs at Zumaia (Basque Basin, W Pyrenees). *Earth Planet. Sci. Lett*. 262, 450–467.

FISCHER A. G. (1964) – The Lofer cyclothems of the Alpine Triassic. *Kansas Geological Survey Bulletin* 169, 107–149.

FISCHER A. G., D'ARGENIO B., PREMOLI SILVA I., WEISSERT H. & FERRERI V. (2004) – Cyclostratigraphic approach to Earth's history: an introduction. *In* D'ARGENIO B. *et al.* (Eds.), Cyclostratigraphy: approaches and case histories. *S.E.P.M. Special Publication* 81, 5-13.

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

HAYS J. D., IMBRIE J. & SHACKLETON J. (1976) – Variations in the Earth's orbit: pacemaker of the ice ages. *Science* 194, 1121–1132.

HILGEN F. J. (2010) – Astronomical dating in the 19th century. *Earth-Science Reviews* 98, 65–80.

HILGEN F. J., KRIJGSMAN W., LANGEREIS C. G., LOURENS L. J., SANTARELLI A. & ZACHARIASSE W. J. (1995) – Extending the astronomical (polarity) time scale into the Miocene. *Earth Planet. Sci. Lett*. 136, 495-510.

HILGEN J. J., KUIPER K. F. & LOURENS L. J. (2010) – Evaluation of the astronomical time scale for the Paleocene and earliest Eocene. *Earth Planet. Sci. Lett.* 300, 139–151.

HILGEN F. J., LOURENS L. J. & VAN DAM J. A. (2012) – Chapter 29: The Neogene Period. *In* GRADSTEIN F. M., OGG J. G., SCHMITZ M. D. & OGG G. M. (Eds.), *The Geologic Time Scale 2012*. Elsevier, vol. 1, 923-978.

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

HINNOV L. A. & HILGEN F. J. (2012) – Chapter 4: Cyclostratigraphy and astrochronology. *In* GRADSTEIN F. M., OGG J. G., SCHMITZ M. D. & OGG G. M. (Eds.), *The Geologic Time Scale 2012*. Elsevier, vol. 1, 63-83.

HINNOV L. A. & OGG J. (2007) – Cyclostratigraphy and the astronomical time scale. *Stratigraphy* 4, 239-251.

HUANG C., HESSELBO S. P. & HINNOV L. A. (2010a) – Astrochronology of the Late Jurassic Kimmeridge Clay (Dorset, England) and implications for Earth system processes. *Earth Planet. Sci. Lett.* 289, 242–255.

HUANG C., HINNOV L. A., FISCHER A. G., GRIPPO A. & HERBERT T. (2010b) – Astronomical tuning of the Aptian Stage from Italian reference sections. *Geology* 38, 899–902.

HUSSON D., GALBRUN B., LASKAR J, HINNOV L. A., THIBAULT N., GARDIN S. & LOCKLAIR R. E. (2011) – Astronomical calibration of the Maastrichtian (Late Cretaceous). *Earth Planet. Sc. Lett.* 305, 328-340.

IKEDA M. & TADA R. (2013) – Long period astronomical cycles from the Triassic to Jurassic bedded chert sequence (Inuyama, Japan), Geologic evidences for the chaotic behavior of solar planets. *Earth Planets Space* 65, 1–10.

IKEDA M., TADA R., KARASUDA A. & SAKUMA H. (2010) – Long period astronomical cycles from the Upper Triassic to Lower Jurassic Bedded Chert sequence: Implications for Jurassic Cyclostratigraphy. *Earth Sci. Front*. 17, 112–113.

IMBRIE J., HAYS J. D., MARTINSON D. G., MCINTYRE A., MIX A. C., MORLEY J. J., PISIAS N. G., PRELL W. L. & SHACKLETON N. J. (1984) – The orbital theory of Pleistocene climate: support from a revised chronology of the marine ?18O record. *In* Berger A. (Ed.), *Milankovitch and ClimateD*. Reidel, Norwell, Mass, 269–305.

LASKAR J. (1989) – A numerical experiment on the chaotic behaviour of the Solar System. *Nature* 338, 237–238.

LASKAR J. (1990) – The chaotic motion of the solar system:Anumerical estimate of the chaotic zones. *Icarus* 88, 266-291.

LASKAR J. (1999) – The limits of Earth orbital calculations for geological time-scale use. *Phil. Trans. R. Soc. Lond.* 357, 1735–1759.

LASKAR J., FIENGA A., GASTINEAU M. & MANCHE H. (2011a) – La2010: A new orbital solution for the long term motion of the Earth. *Astronomy and Astrophysics,* 532, A89, doi:10.1051/0004-6361/201116836.

LASKAR J., GASTINEAU M., DELISLE J. B., FARRES A. & FIENGA A. (2011b) – Strong chaos induced by close encounters with Ceres and Vesta. *Astronomy and Astrophysics,* 532, L4, doi:10.1051/0004-6361/201117504.

LASKAR J., JOUTEL F. & 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. & LEVRARD B. (2004) – A long term numerical solution for the insolation quantities of the Earth. *Astronomy and Astrophysics* 428, 261-285.

LIRER F., HARZHAUSER M., PELOSI N., PILLER W. E., SCHMID H. P. & SPROVIERI M. (2009) – Astronomically forced teleconnection between Paratethyan and Mediterranean sediments during the Middle and Late Miocene. *Palaeogeo. Palaeoclim. Palaeoecol*. 275, 1–13.

LOURENS L., HILGEN F., SHACKLETON N. J., LASKAR J. & WILSON D. (2004) – The Neogene Period. *In* GRADSTEIN F., OGG J. G. & SMITH A. G. (Eds.), *A Geologic Time Scale 2004*. Cambridge University Press, Cambridge, 409-440.

MILANKOVITCH M. (1941) – Kanon der Erdbestrahlung und seine Auswirkung auf das Eiszeitenproblem. *Königlich Serbische Akademie, Belgrad*, Edit. spec. 133, 633 p.

OLSEN P. E. & KENT D. V. (1999) – Long period Milankovitch cycles from the Late Triassic and Early Jurassic of eastern North America and their implications for the calibration of the early Mesozoic timescale and the long-term behavior of the planets. *Phil. Trans. R. Soc. London* A 357, 1761–1786.

PALIKE H., FRAZIER J. & ZACHOS J. C. (2006a) – Extended orbitally forced palaeoclimate records from the equatorial Atlantic Ceara Rise. *Quaternary Science Reviews* 25, 3138-3149.

PALIKE H., LASKAR J. & SHACKLETON N. J. (2004) – Geologic constraints on the chaotic diffusion of the Solar System. *Geology* 32, 929–932.

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

RENNE P. R., DEINO A. L., HILGEN F. J., KUIPER K. F., MARK D. F., MITCHELL W. S., MORGAN L. E., MUNDIL R. & SMIT J. (2013) – Time scales of critical events around the Cretaceous-Paleogene boundary. *Science* 339, 684-687.

SCHWARZACHER W. (1947) – *Uber die sedimentare Rhythmik des Dachstein Kalkes von Lofer*. Verh. Geol. Bundesanst. Vienna, 175–188.

SCHWARZACHER W. (1954) – Die Grossrhytmik des Dachsteinkalkes von Lofer. *Tschermaks mineral. petrogr. Mitt*. 4, 44–54.

SPROVIERI M., SABATINO N., PELOSI N., BATENBURG S. J., COCCIONI R., IAVARONE M. & MAZZOLA S. (2013) – Late Cretaceous orbitally-paced carbon isotope stratigraphy from the Bottaccione Gorge (Italy). *Palaeogeo. Palaeoclim. Palaeoecol*. 379–380, 81–94.

VAN DAM J. A., ABDUL A. H., ANGELES A. S., HILGEN F. J., VAN DEN H. O., LOURENS L. J., MEIN P., VAN DER MEULEN A. L. & PELAEZ-CAMPOMANES P. (2006) – Long-period astronomical forcing of mammal turnover. *Nature* 443, 687–691.

VANDENBERGHE N., HILGEN F. J. & SPEIJER R. P. (2012) – Chapter 28: The Paleogene Period. *In* GRADSTEIN F. M., OGG J. G., SCHMITZ M. D. & OGG G. M. (Eds.), *The Geologic Time Scale 2012*. Elsevier, vol. 1, 855-921.

WADE B. S. & PALIKE H. (2004) – Oligocene climate dynamics. *Paleoceanography* 19, PA4019. doi: 10.1029/2004PA001042.

WESTERHOLD T., RÖHL U., RAFFI I., FORNACIARI E., MONECHI S., REALE V., BOWLES J. & EVANS H. F. (2008) – Astronomical calibration of the Paleocene time. *Palaeogeo. Palaeoclim. Palaeoecol*. 257, 377-403.

ZACHOS J. C., PAGANI M., SLOAN S., THOMAS E. & BILLUPS K. (2001a) – Trends, rhythms, aberrations in global climate 65 Ma to Present. *Science* 292, 686–693.

ZACHOS J. C., SHACKLETON N. J., REVENAUGH J. S., PALIKE H. & FLOWER B. P. (2001b) – Climate response to orbital forcing across the Oligocene–Miocene boundary. *Science* 292, (5515), 274–278.