Rivista Italiana di Paleontologia e Stratigrafia	volume 108	numero 2	pagine 179-182	Luglio 2002

CYCLOSTRATIGRAPHY: A METHODOLOGICAL APPROACH

MARIO SPROVIERI [1], ANGELO BONANNO [2a], SALVATORE MAZZOLA [2b] & BERNARDO PATTI [2c]

Received July 15, 2001; accepted Juanuary 9, 2002

Keywords: Cyclostratigraphy, insolation curve, spectral analysis, astronomical calibration.

Riassunto. In questo lavoro vengono descritte e commentate sinteticamente le metodologie più usate di analisi ciclostratigrafica per la calibrazione astronomica di sequenze sedimentarie. Dapprima sono descritte diverse soluzioni numeriche della curva di insolazione e, in particolare, della più nota curva astronomica $La90_{(1,1)}$. Vengono quindi, in ordine, descritte le metodologie di calibrazione astronomica i) su base lito-ciclostratigrafica e ii) sulla base di metodologie di analisi spettrale applicate a segnali faunistici e geochimici che rispondono in fase alle diverse forzanti astronomiche.

Abstract. Aim of this study is a synthetic description of the most used methodologies of cyclostratigraphic analysis for the astronomical calibration of sedimentary sequences. The different numerical solutions of the insolation curve and, in particular, the most used astronomic curve $La90_{(1,1)}$ are analyzed. Then, a detailed description of the methodologies for the astronomic calibration of different sedimentary sequences i) on the basis of a litho-cyclostratigraphic approach and ii) on the basis of spectral analysis applied to faunal and geochemical climate-sensitive records, is proposed.

Introduction

An important part of this volume is dedicated to the reconstruction of an astronomically calibrated time scale from about 11 Ma to about 13.7 Ma, on the basis of cyclostratigraphic analyses of different land-based sections.

In the last years, a restricted group of researchers provided to the international scientific community a reliable astronomical calibration of the late Neogene geological record (e.g. Hilgen 1991a, 1991b; Hilgen et al. 1995; Shackleton et al. 1995; Lourens et al. 1996; Hilgen et al. 2000). They also developed the procedures to tune sedimentary sequences, characterised either by homogeneous or cyclically-repeated lithologies, to different numerical solutions of the insolation curve.

The most used numerical and cyclostratigraphic techniques applied for calibration of sedimentary records are here synthesized.

Two different kinds of sedimentary records are generally used for astronomical calibration: i) sequences characterised by lithologic alternations organised in well-recognisable cluster patterns and ii) sequences characterised by homogeneous lithology and studied by means of spectral methodologies applied to selected climate-sensitive records.

When possible, the combination of these two cyclostratigraphic approaches represents the most reliable system to calibrate geological time series with the astronomical curves.

The insolation curve

The insolation on the Earth depends on its orbital parameters. Until 1988, the solution adopted for paleoclimate computation consisted of the orbital elements of the Earth, complemented by the computation of its precession and obliquity (Berger 1978, 1988). In 1988, Laskar proposed a solution for orbital elements of the Earth, which was obtained in a new manner, making use of vast analytical computation and numerical integration (Laskar 1988). In this solution the precession and obliquity parameters, necessary for paleoclimate computations, were integrated at the same time, insuring a good consistency of the solutions. Unfortunately, for various reasons, this latter solution for the precession and obliquity was considered reliable only for the last 3 Ma (Berger & Loutre, 1991). Later on, Laskar et al. (1993) produced a new solution (hereafter named La 90) that is a slight improvement of the previous one. This solution allows evaluation of orbital parameters, precession and obliquity, up to the last 20 Ma.

The orbital solution La90 is obtained by numerical

[1] Dipartimento (CFTA) - Via Archirafi 36, 90123 Palermo, Italy, e-mail: marios@unipa.it
[2] Istituto IRMA CNR - Via Luigi Vaccara, 61, 91026 Mazara del Vallo, Italy, e-mail: [2a] bonanno@irma.pa.cnr.it; [2b] mazzola@irma.pa.cnr.it; [2b] patti@irma.pa.cnr.it

integration of an extended averaged system that represents the mean evolution of the orbits of the planets. All the 8 main planets of the solar system are taken into account, as well as the main lunar and relativistic perturbations. The use of numerical integration for computing the solution of the secular system is one of the reasons for the good quality of this solution, which was checked by comparing with the ephemeris over a short time scale (Laskar 1988). The La 90 solution is in quasi-periodic form over 10 Mr, but these representations are slowly convergent, which prevents good accuracy of the solution. The reason for this slow convergence is due to the presence of multiple resonance in secular periodicity of the inner solar system (Laskar 1990). Because of these resonance the motion of the solar system is chaotic in the long term, and not quasi-periodic. The Lyapunov exponents of the solar system, that quantify the average grow of small initial error in the calculation, was estimated to $1/5yr^{-1}$. This implies that it is not possible to give any precise solution for the motion of the Earth over more than about 10 Mr, and most probably, ephemerids can only be given with good precision for no more than 20 Mr.

The solution of Laskar et al. (1993) can be "recalibrated" at different ages because it gives the possibility to vary the values of the dynamical ellipticity and total dissipation by the Sun and Moon.

Lourens et al. (1996) carried out a careful correlation between Plio-Pleistocene Mediterranean land-based sedimentary sequences characterised by well-recognisable lithologic rhythms and well calibrated from a cyclostratigraphic point of view, and the different solutions of the insolation curve La 90. The best fit between the geological record and the insolation curve has been obtained using the numerical solution of Laskar et al. (1993) with unitary values of both the dynamical ellipticity and the total dissipation by the Sun and moon $La90_{(1,1)}$.

Successive works (Hilgen et al. 1995; Sprovieri et al. 1999; Hilgen et al. 2000) confirmed these results for the Neogene stratigraphic records.

In the papers of Iaccarino (2002), the $La90_{(1,1)}$ solution has been used to calibrate the studied sedimentary records.

Astronomical calibration of cyclic land-based sedimentary sequences

The studies of Hilgen and co-workers (e.g., Hilgen 1991a, 1991b; Hilgen et al. 1995, 2000) on Mediterranean sections demonstrated that the high frequency alternations of different lithologies, recognised throughout several land-based sedimentary sequences, can be directly related to the precessional forcing and that the alternation of longer sedimentary intervals characterised by absence/presence of high frequency lithologic cycles can be related to the eccentricity periods of about 100 and 400 kyr.

These papers demonstrated that the same kind of cyclic pattern - with clusters on different scales superimposed on the basic sedimentary cycle - can be recognised in the Mediterranean from the Tortonian up to the Plio-Pleistocene.

Alternation of homogeneous grey marls and sapropelitic layers represents the classic high frequency cyclicity recognised in most of the Mediterranean records. Alternatively, these two lithologies can be substituted by similar variants (e.g., grey marls tone /carbonate layers, light coloured/grey coloured marls tone, etc.). Individual sapropelitic layers or substitutive sedimentary expressions correspond to precession minima or the equivalent summer insolation maxima, while small- and large-scale lithologic clusters can be related to the 100.000 and 400.000 years eccentricity maxima cycles.

This simple sedimentary response to insolation forcing remained in practical identical over the last 10 Myr, with the same phase relations between sedimentary and orbital cycles described for the Plio-Pleistocene.

The assumption of a constant phase relationship between lithological cycles and astronomic forcing for all the Neogene, allow us to identify a rigorous stepwise methodological approach for calibrating sedimentary sequences, characterised by lithological alternated records.

Firstly, a detailed lithologic description of the studied sections allows the identification and the characterization of the sedimentary rhythms along the records.

Secondly, the studied successions must be accurately dated with classic bio-magnetostratigraphy. In particular, polarity chrons must be identified on the basis of Cande & Kent (1995; CK95). Then, the ages of CK95 and Shackleton et al. (1995a; SCHPS95) for the polarity reversals, and especially for the youngest ones, have to be adopted as starting point for the actual tuning.

Thirdly, a first-order tuning between the sedimentary records and the insolation curve is obtained by a first-order correlation of large-scale sapropel clusters to the 400,000-year eccentricity maxima and a direct correlation of the small-scale sapropel clusters to the 100.000-year insolation cycles maxima.

Fourthly, the astronomical calibration is completed by tuning individual sapropels to precession minima and the corresponding summer insolation maxima. According to Hilgen (1991a, 1991b) and Lourens et al. (1996), a phase lag of ~3 ky between mid-summer Northern Hemisphere insolation and lithologic cycles has to be considered for the final tuning.

During the tuning exercise, larger-scale eccentricity cycle patterns must be taken into account, because they provide a direct check on the validity of the calibration and prevent accumulations of errors due to tuning of the individual cycles (i.e., several 20 kyr cycles could be missing or not recognisable). The resulting tuning is probably accurate to the level of the individual precession/insolation cycle in certain intervals but may be off by one cycle in others. The final calibration provides astronomical ages for the sedimentary cycles, as well as for the bio-events recognised throughout the studied record. It should also provide refinement of duration of individual polarity chrons.

Astronomical calibration of homogeneous sedimentary sequences

When lithological rhythms are not present in a sedimentary sequence, the acquisition of detailed time series of climate sensitive records (oxygen isotopes, geochemical elements, planktonic and benthic foraminifera species, nannofossils species, etc.), known to be forced by astronomic periodicities, can be used to calibrate the studied sequence. In this case application of spectral analysis allows the recognition of a set of periodicity directly correlatable to astronomic parameters. The first step for comparing proxy records to the insolation curve is an appropriate sampling rate of the section (selected for a proper analytical resolution of the highest frequency band) and the selection of the tuning strategy that enables the establishment of the phase relationships among the different chosen signals and the astronomic record for the different frequency bands (generally the three Milankovitch frequencies of precession, obliquity and short and long-eccentricity).

The different records have to be converted in the time domain using the classic procedures suggested by Martinson et al. (1982) and the numerical algorithms of the inverse conjugate.

Identification of a set of tie points (already independent dated biohorizons and/or magnetostratigraphic intervals recognized along the section) allows the definition of a first approximation of the sedimentation rate of the studied succession. It is necessary to transform the available signals from the space- to the time-domain and to identify in the power spectra, estimated for the selected signals, the classic Milankovitch periodicities.

The filtering of the original signals in the long- and short-eccentricity frequency bands and the direct comparison with the same cyclicity of the insolation curve allows a first-order astronomical calibration of the sequence.

Then, filtering of the signals in the precession frequency bands and correlating them with the 19-23 kyr cycles present in the astronomic curve, produces a detailed short-time calibration of the studied record. Cross-spectral analysis between the paleoclimate signals and insolation should confirm with high coherency values for the Milankovitch frequency bands the correctness of the obtained calibration. At this point all the stratigraphic events recognised throughout the succession can be dated.

Shackleton et al. (1997) suggested that application of numerical techniques of complex demodulation could be used as useful tool for calibrating sedimentary sequences, characterised by high variance concentrated in the precession frequency band. The complex demodulation method is a tool for examining the instantaneous amplitude and phase of that portion of the variability that is in a particular frequency band of the signal spectrum. For the mathematical procedure, reader is referred to Shackleton et al. (1995b) and Pisias & Moore (1981).

There are several applications of such a method for investigating the amplitude modulation in the precession band, or in the obliquity band (Pisias & Moore 1981).

The complex demodulation can be used as a method to assess the correctness of a timescale. Shackleton et al. (1995b) pointed out that it is extremely difficult to use cross-spectral analysis to investigate whether signal and forcing share the same amplitude modulation (e.g., the eccentricity modulation of the precession signal), so that this aspect of the validity of a timescale must be evaluated by complex demodulation or other means like band-pass filtering, etc. However, demodulation works only if the paleoclimatic record is modulated (as the insolation curve). Then, application of this numerical technique must be proceeded by a verification of the temporal relationship between the selected climate sensitive-record and the primary forcing. In the following papers we preferred to use the similar method of the band-pass filtering technique. In the papers presented in Iaccarino (2002), the SPAGEOS software package (Bonanno et al. 1996) has been used for application of all the above-described methodologies of spectral analysis.

Acknowledgments. We thank E. Erba and L. Lanci for their helpful critical comments. This research has been supported by Murst Cofin 98.

REFERENCES

Berger A.L. (1978) - A simple algorithm to compute long-term variations of daily or monthly insolation. *Contrib., Inst. Astr. Geophys. Geogr. Lemaitre, Univ. Cathol. De Louvain*, V.18, 17 pp., Louvaine.

Berger A. (1988) - Milankovitch theory and climate. *Rev. Geophys.*, 26: 624-657.

Berger A. & Loutre M.F. (1991) - Insolation values for the climate of the last 10 m.y. *Quat. Sci. Rev.*, 10: 297-317, Amsterdam.

Bonanno A., Mazzola S., Sprovieri M. & Patti B. (1996) - SPAGEOS, a system for the analysis in time-and in frequency-domain of paleoceanographic and sedimentological data. *Paleopelagos*, 6: 371-384, Roma.

Cande S.C. & Kent D.V. (1995) - Revised calibration of the geomagnetic polarity timescale for the late Cretaceous and Cenozoic. *J. Geophys. Res.*, 100 (B4): 6093-6095, Washington D.C.

Hilgen F.J. (1991a) - Astronomical calibration of Gauss to Matuyama sapropels in the Mediterranean and implication for the Geomagnetic Polarity Time Scale. *Earth Planet. Sc. Letters*, 104: 226-244, Amsterdam..

Hilgen F.J. (1991b) - Extension of the astronomically calibrated (polarity) time scale to the Miocene/Pliocene boundary. *Earth Planet. Sc. Letters*, 107: 349-368, Amsterdam.

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. Sc. Letters*, 136: 495-510, Amsterdam.

Hilgen F.J., Krijgsman W., Raffi I., Turco E. & Zachariasse W.J. (2000) - Integrated stratigraphy and astronomical calibration of the Serravallian/Tortonian boundary section at Monte Gibliscemi (Sicily, Italy). *Mar. Micropal.*, 38: 181-211, Amsterdam.

Iaccarino S.M. (ed.) (2002) - Integrated Stratigraphy and Paleoceanography of the Mediterranean Middle Miocene. *Riv. It. Paleont. Strat.*, 108: 175-353, Milano.

Laskar J. (1988) - Secular evolution of the solar system over 10 million years. *Astron. Astrophys.*, 198: 341-362, Washington D.C.

Laskar J. (1990) - The chaotic motion of the solar system: a numerical estimate of the size of the chaotic zone. *Icarus*, 88: 266-291, Orlando.

Laskar J., Joutel F. & Boudin F. (1993) - Orbital, precessional, and insolation quantities for the Earth from -20 Myr to +10 Myr. *Astron. Astrophys.*, 270: 522-533, Washington D.C.

Lourens L.J., Antonarakou A., Hilgen F.J., Van Hoof A.A.M., Vergnaud-Grazzini C. & Zachariasse W.J. (1996) - Evaluation of the Plio-Pleistocene astronomical timescale. *Paleoceanography*, 11: 391-413, Washington D.C.

Martinson D.G., Menke W. & Stoffa P. (1982) - An inverse approach to signal correlation. *J. Geophys. Res.*, 87: 4807-4818, Washington D.C.

Pisias N.G. & Moore T.C. (1981) - The evolution of the Pleistocene climate: a time series approach. *Earth Planet. Sc. Letters.*, 52: 450-458, Amsterdam.

Shackleton N.J., Crowhrust S., Hagelberg T., Pisias N.G. & Schneider D.A. (1995a) - A new late Neogene timescale. Application to leg 138 sites. *Proc. ODP Results*, 138: 73-101, College Station (TX)

Shackleton, N.J., Hagelberg, T.D. & Crowhurst, S.J. (1995b) - Evaluating the success of astronomical tuning: pitfalls of using coherence as a criterion for assessing pre-Pleistocene timescales. *Paleoceanography*, 10: 693-697, Washington D.C.

Shackleton N.J. & Crowhrust S. (1997) - Sediment fluxes based on an orbitally tuned time scale 5 Ma to 14 Ma, site 926: Application to ODP leg 154 sites. In: Shackleton N.J., Curry W.B., Richter C. and Bralower T.J. (Eds.) *Proc. ODP Results.*, 154: 69-82, College Station (TX).

Sprovieri M., Bellanca A., Neri R., Mazzola S., Bonanno A., Patti B., & Sorgente R. (1999) - Astronomical calibration of Late Miocene stratigraphic events and analysis of precessionally driver paleoceanographic changes in the Mediterranean basin. *Mem. Soc. Geol. It.*, 54: 7-24, Roma.