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ASTRONOMICAL CALIBRATION OF THE UPPER LANGHIAN/LOWER SERRAVALLIAN RECORD OF RAS IL-PELLEGRIN SECTION (MALTA ISLAND, CENTRAL MEDITERRANEAN)

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Riassunto. Un insieme estremamente dettagliato di dati geochimici e micropaleontologici è stato ottenuto dal campionamento dei sedimenti marnosi, di età Langhiano superiore/Serravalliano inferiore, della sezione Ras il-Pellegrin esposta nella zona nord-occidentale dell'isola di Malta. Lo studio delle alternanze litologiche presenti nella successione, combinato con i risultati dell'analisi spettrale realizzata sui dati geochimici e faunistici, ha messo in evidenza le classiche frequenze di Milankovitch come forzanti astronomiche dominanti del sistema sedimentario in studio. L'applicazione di procedure numeriche di filtraggio (di tipo taglia-banda) ha permesso di selezionare, in maniera differenziale, le periodicità di Milankovitch e di correlarle con le medesime armoniche presenti nel record astronomico. L'affidabilità della sintonizzazione dei segnali geochimici e faunistici con la curva di insolazione è stata confermata dalla comparazione dei cicli di ordine superiore relativi alle due bande di frequenza dell'eccentricità (100.000 e 400.000 anni), presenti nei diversi segnali e dai conseguenti spettri di coerenza.

La calibrazione astronomica ottenuta ha consentito di stimare le età dei cicli sedimentari e dei bioeventi riscontrati nella successione studiata. In particolare, è stata valutata un'età di 13.59 Ma per il livello di scomparsa (LO) di *Sphenolitus heteromorphus* attualmente considerato il più affidabile bioevento per il riconoscimento del limite Langhiano/Serravalliano. Inoltre, è stato possibile datare la prima comparsa (FO) di *Paragloborotalia partimlabiata* a 12.62 Ma.

Abstract. A high-resolution geochemical and micropaleontological data set has been obtained from the uppermost Langhian/lower Serravallian marly sediments of the Ras il-Pellegrin section (Malta Island).

A combination of the recorded stratal organization with the results of spectral analyses performed on $CaCO_3$ data and faunal signals shows a dominance of the classic Milankovitch periodicities as modulating forcing of the studied succession. The application of band-pass filters allowed us to select the different Milankovitch frequencies (precession, obliquity and short- and long-eccentricity) from the original faunal and geochemical signals and to compare them with the same components of the astronomical curve. The reliability of the short-term astronomical tuning has been tested by using the larger-order cyclicity (100-400 kyr) as control. The good match of the different records with the selected insolation curve is consistent with the results of the cross-spectral analysis showing high coherency values in all the considered frequency bands. The calibration provided astronomical ages for the sedimentary cycles and consequently for all the bioevents recorded in the section. In particular, an age of 13.59 Ma has been obtained for the last occurrence (LO) of *Sphenolitus heteromorphus*, at present considered the best bioevent useful for recognizing the Langhian/Serravallian boundary. Moreover, an age of 12.62 Ma has been obtained for the first occurrence (FO) of *Paragloborotalia partimlabiata*.

Introduction

A well established methodology for constructing high-resolution geological time scales is based on the straight correlation between cyclic lithologic patterns of sedimentary records and calculated time series of astronomical-forced insolation changes.

Additionally, cross-spectral techniques have been developed to identify in selected climate-sensitive records (geochemical, isotopic and faunal signals) the cyclic alternations and their (phase) relationships with changes in the insolation. Generally, such an approach is used for the calibration of sedimentary successions characterized by homogeneous lithology in the absence of recognizable cyclic lithologic patterns. On the basis of these two different methodologies, various authors (Hilgen 1991a, 1991b; Hilgen et al. 1995, 2000; Lourens et al. 1996, Shackleton et al. 1995), calibrated a reliable high-resolution astronomical timescale down to about 12.1 Ma.

In this paper, we combine both methodological approaches in order to reconstruct an astronomical time

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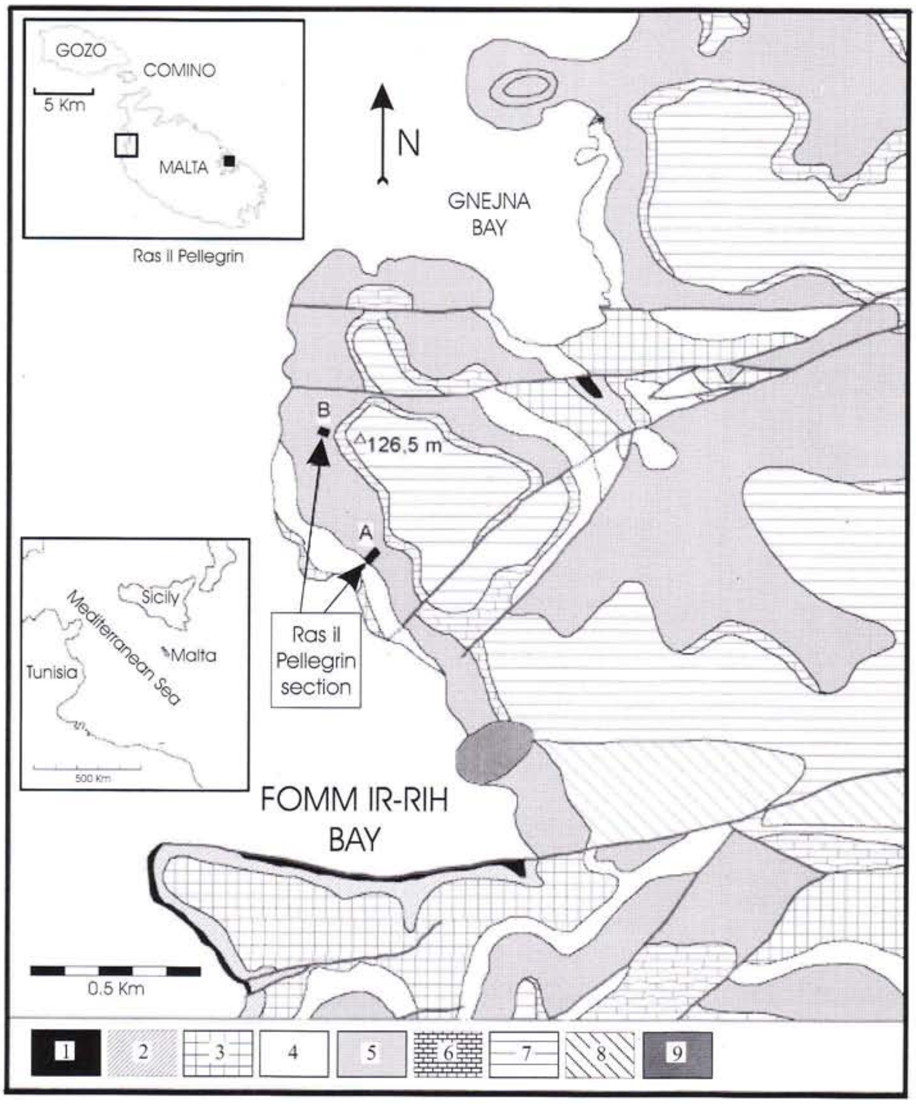

Fig. 1 - Location map of the studied sections. Geology modified after Debono et al. (1993) 1) - Lower Coralline Limestone; 2,3,4) - Lower, Middle and Upper Globigerina Limestone; 5) - Blue Clay Formation; 6-8) - Upper Coralline Limestone: 6 - Mtarfa Member, 7 - Tal-Pitkal Member, 8 - Gebel Imbark Member; 9) - detritus; 10) faults; a) - subsections. The simplified stratigraphic log of the Miocene succession around the studied section is from Giannelli & Salvatorini 1975.

scale for the sedimentary sequence Ras il-Pellegrin, exposed in the central Mediterranean area (Malta island), down to about 13.75 Ma. The astronomical calibration of the studied interval has been achieved using the summer insolation curve $La90_{(1,1)}$ (Laskar et al. 1993), which is considered to be the most appropriate for fitting the geological record from the Pliocene to the early Tortonian (Lourens et al. 1996; Hilgen et al. 1995, 2000). Fluctuations of $CaCO_3$ percentages and *Globigerinoides* spp. abundances have been used as climate-sensitive proxy records for tuning the insolation curve. Additionally, the recognized cyclic patterns have been used as further control of the obtained astronomical calibration.

The studied section

The studied section is located in the north-western margin of the Malta island about 20 km West of Valletta town (Fig. 1). The succession belongs to the Blue Clay Formation and is about 68 m thick. It consists of blue/grey pelagic marls intercalated by thick pale bands (light-grey marls and/or white marls). These sediments conformably overlay the Globigerina Limestone Formation (Giannelli & Salvatorini 1975; Fornaciari et al. 1996). Biostratigraphic results (Giannelli & Salvatorini 1975; Mazzei 1985; Fornaciari et al. 1996) suggest a Langhian/Tortonian age for the deposition of the whole Blue Clay Formation.

The Blue Clay Formation is overlain (unconformably) by the Coralline Limestone Formation, which has a regional thickness varying between 27 and 50 m. It prevalently consists of limestones, wackestones, and packstones with abundant macrofossils. Coralline algae are the most common organogenic remains. Quaternary deposits, consisting of sands and conglomerates interbedded with paleosoils and remains of continental fauna, are present at the top of the sedimentary succession of the Malta island.

From a tectonic point of view, the studied sediments constitute part of the Maltese sedimentary system (Dart et al. 1993) characterized by a graben structure formed by two groups of faults: one with NW-SE direction and the other one with ENE-WSW trend. This graben system lies within the African plate, in the foreland of the Sicilian Apennine-Maghrebian fold and thrust belt. During the Miocene-Pliocene interval this graben system represented the most northern portion of the Pantelleria rift zone.

To obtain the longest and best exposed sedimentary record we have reconstructed a composite section formed by two segments (segments A and B; Fig. 2). These two sedimentary intervals have been correlated on the basis of the common presence of four light-coloured layers (labelled from -1 to -4; Fig. 3) and using the FO of *P. partimlabiata*.

Methods

Quantitative planktonic foraminiferal analysis has been carried out on 451 samples, spaced at a mean interval of 15 cm. Splits of 300-400 specimens from the larger than 125 μm fraction were studied. Counted categories are referred to *Globigerinoides quadrilobatus, Globigerinoides obliquus, Globigerinoides subquadratus, Globigerina bulloides* group, *Globorotalia scitula, Orbulina* spp., *Turborotalita quinqueloba, Globoquadrina* spp., *Paragloborotalia siakensis, Paragloborotalia mayeri, Globorotalia menardii, Globorotalia peripheroronda*.

Carbonate percentage abundance has been determined on 250 samples, spaced at mean intervals of about 30 cm, by means of conventional gas-volumetric methodologies (Husselman 1966).

Spectral analysis and filtering procedures are based on the standard approach of Jenkins & Watts (1968) and Weedon (1991) that enables to show the frequency structure of the studied signals and offers the opportunity to filter the original time series in selected periodicity bands.

Data have been interpolated at 15 cm depth intervals using a Gaussian weighting method. Such a numerical approach ensures that more interpolated data in a given interval than original points are never present.

Calcareous plankton biostratigraphy

Quantitative analyses performed on the planktonic foraminiferal and calcareous nannofossil assemblages obtained by Foresi et al. (2002) enable to recognize the most important biostratigraphic events throughout the succession and the abundance fluctuations of the different species useful for high-resolution correlations among Mediterranean sedimentary sequences. The most important calcareous plankton bioevents recognized in the calcareous nannofossil and planktonic foraminiferal assemblages are reported along with the lithologic column in Fig. 3.

The climate sensitive records

Two climate sensitive records have been used for the astronomical tuning of the section: the *Globigerinoides* spp. and the $CaCO_3$ signals.

The *Globigerinoides* spp. is composed by the ensemble of the *Globigerinoides quadrilobatus, Globigerinoides subquadratus,* and *Globigerinoides obliquus* planktonic species. The last two species are not living today and are considered possible ancestors of the *G. ruber* species. It is today abundant in the Mediterranean during the spring-summer seasons (Pujol & Vergnaud-Grazzini 1995) and is therefore considered indicator of warm surface waters.

The abundance curve of the *Globigerinoides* spp. (Fig. 3) shows a decreasing trend (averages from about 50% to about 20%), from the base of the section up to about 50 m. From this point, the curve exhibits an increasing trend up to the top of the succession. Superimposed on these two long trends, the percentages show strong short-term variations ranging in the order of ±20/30%.

The carbonate percentages (Fig. 3) fluctuate throughout the section mostly in the range 20-40%. The

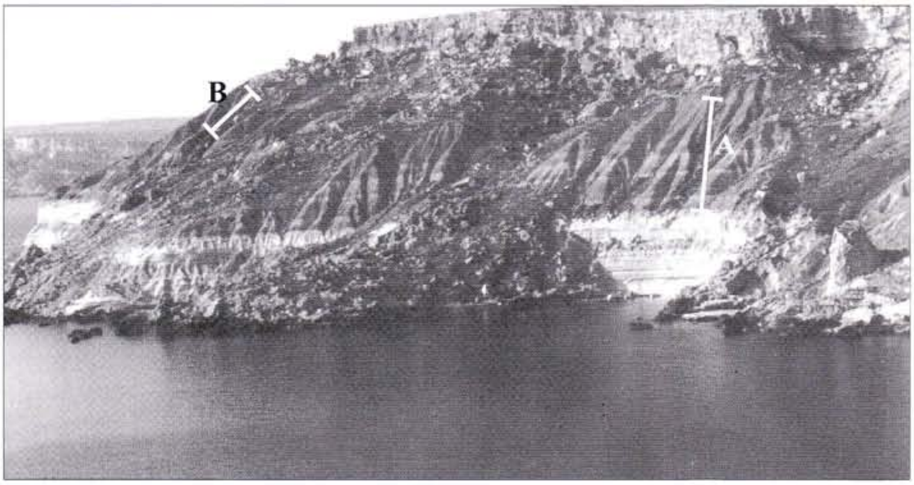

Fig. 2 - A general view of the Ras il-Pellegrin section with included segments A and B indicating the sampled sedimentary intervals.

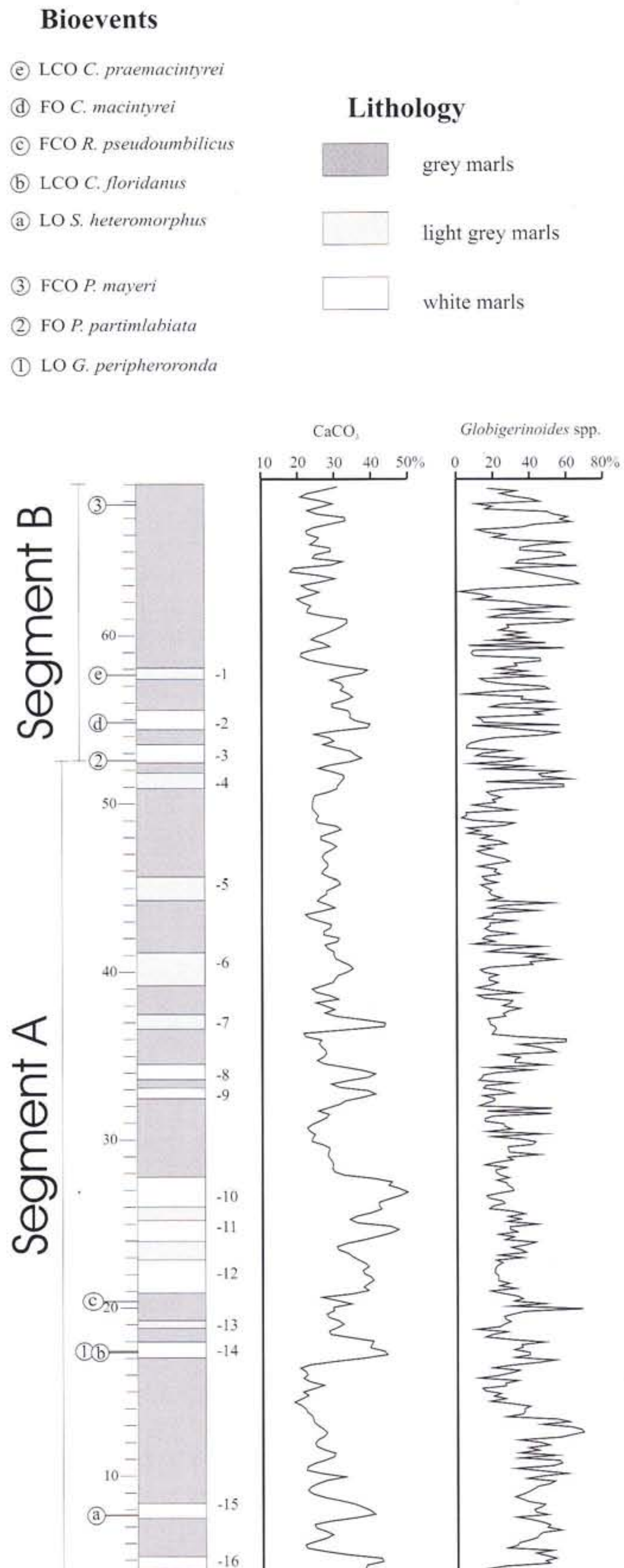

Fig. 3 - $CaCO_3$ and *Globigerinoides* spp. abundance fluctuations throughout the Ras il-Pellegrin section. Calcareous plankton bioevents from Foresi et al. (2002). Numbers to the right of the column mark thick white bands.

carbonate record generally exhibits positive peaks during thick pale intervals and shows an opposite relationship with high abundances of the *Globigerinoides* spp.

Cyclostratighaphy

The absence of well-recognizable (high-frequency) lithologic alternations in the Ras il-Pellegrin section, stimulated us to use the fluctuations in the $CaCO_3$ and *Globigerinoides* spp. records to reconstruct an astronomical time scale using the methodological approach proposed by Shackleton et al. (1995). The insolation curve used for the tuning of the section is the solution of Laskar et al. (1993), with present-day values for the dynamic ellipticity of the Earth and tidal dissipation by the Sun and Moon ($La90_{1,1}$) calculated at 65°N for the summer season. Hilgen et al. (1995), Lourens et al. (1996), and Hilgen et al. (2000) demonstrated that this is the most accurate solution for the calibration of Miocene-Plio-Pleistocene sedimentary records.

Firstly, we estimated a mean sedimentation rate for the sedimentary interval between the FCO of *P. mayeri* and the LCO of *C. premacintyrei* (67.80 and 57.80 m, respectively) calibrated by Lirer et al. (2002) in the lower part of S. Nicola composite section (Tremiti Islands) at 12.34 Ma and 12.52 Ma, respectively. Extrapolation of the obtained value to the whole section allowed us to transform in time the *Globigerinoides* spp. and carbonate signals. Power spectra (Fig. 4) estimated for the two time series highlight the presence of the 400 and 100-kyr eccentricity cycles in both the signals, while the precession forcing has been recorded only in the *Globigerinoides* spp. signal. Since the samples analyzed for the carbonate curve are more spaced, at an approximate time interval of about 9 kyr, they do not allow a reliable registration of the 19-23 kyr cyclicity in this signal.

The original time series have been filtered in the 400 and 100-kyr periodicity bands and directly compared with the astronomic eccentricity curve. The comparison (Fig. 5) highlights an evident mismatch between the astronomic eccentricity curve and the two filtered time series, probably due to the assumption of a constant sedimentation rate for the whole section. Then, we tried to tune the two climate sensitive records to the eccentricity curve, imposing that highs in the eccentricity curve (400 and 100 kyr cycles) coincide with relative lows in the carbonate curve (following Shackleton et al. 1995) and relative highs in the *Globigerinoides* spp. signal (following Sprovieri et al. 1999) (Fig. 6). Re-calculated power spectra for the tuned time series (Fig. 7) show again the same dominance of the primary Milankovitch cyclicities in the two signals.

Cross-spectral analysis of the insolation curve and of the two time series shows high values of coherency in the 400 and 100-kyr periodicity bands and, only for the

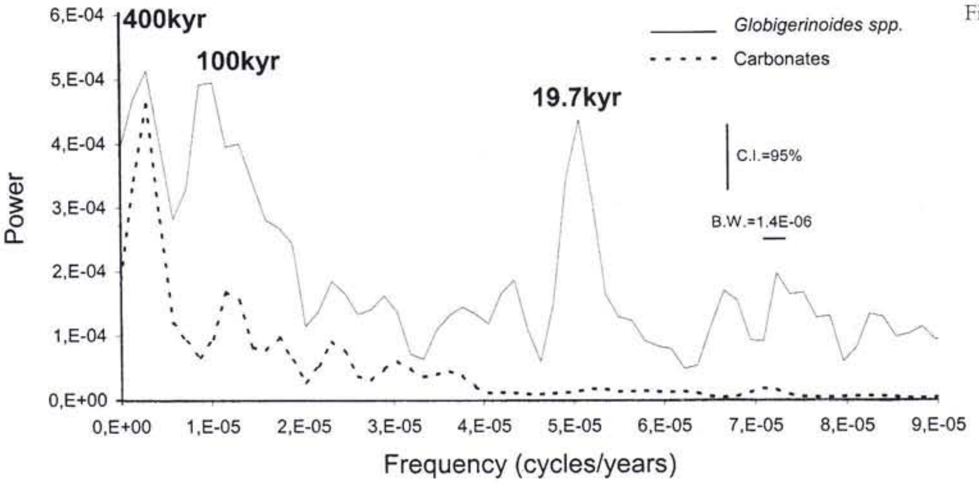

Fig. 4 - Power spectra of $CaCO_3$ (dashed line) and *Globigerinoides* spp. (solid thin line) signals. B.W: bandwidth, C.I.: Confidence Interval.

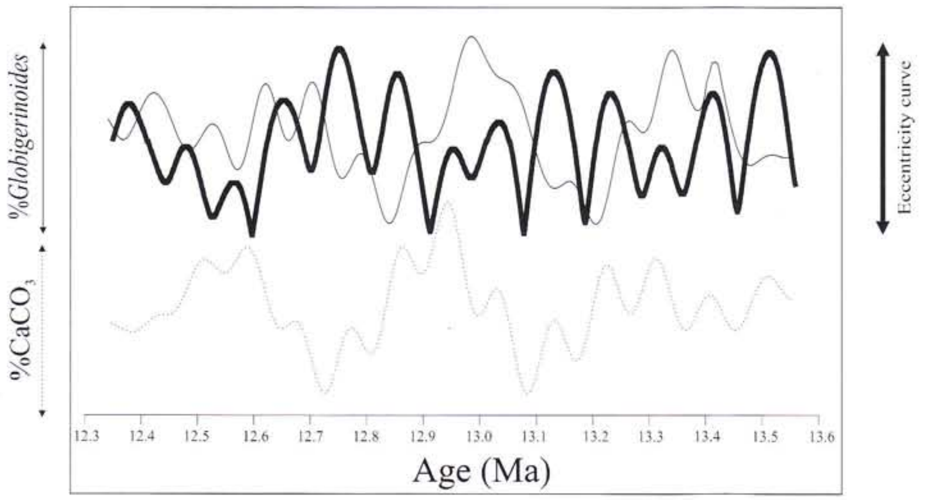

Fig. 5 - Comparison between the short- and long-eccentricity periodicities recognized in the insolation curve (thick line) and in the $CaCO_3$ (dashed line) and faunal (solid thin line) signals.

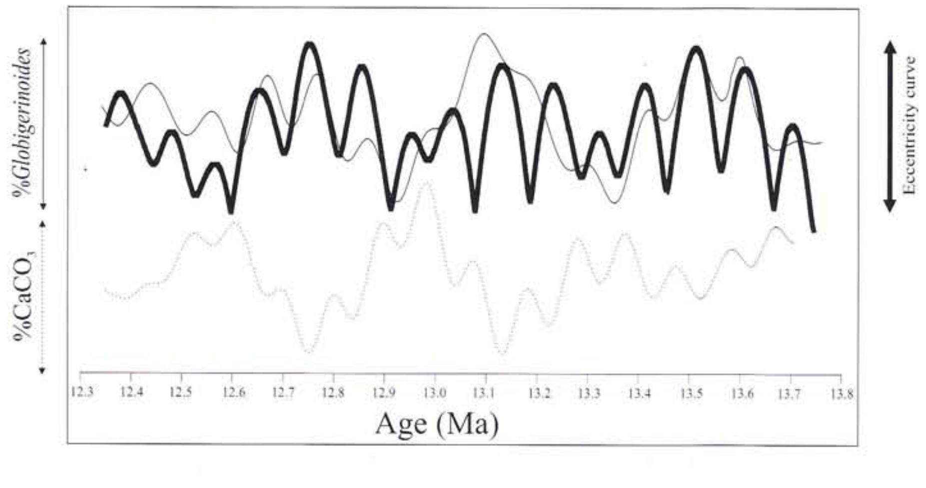

Fig. 6 - Comparison between the short- and long-eccentricity periodicities in the insolation curve (thick line), in the $CaCO_3$ (dashed line) and faunal (solid thin line) signals.

Globigerinoides spp. curve, in the precession periodicity band. This confirms that the obtained calibration is appropriate (Fig. 8).

Based on this first order tuning, the *Globigerinoides* spp. time series has been filtered in the precession frequency bands and then tuned to the precession index of Laskar et al. (1993) (Fig. 9) again associating highs in the insolation curve to highs in the precession filtered *Globigerinoides* spp. curve. With reference to the precessional cycle coincident with the FCO of *P. mayeri* in the Tremiti composite section and labelled with number 90, we numbered down-section all the consecutive precession cycles recognized in the Malta section. The cycle-to-cycle correlation with the insolation curve allowed us to attribute an astronomical age to all the biostratigraphic events recognized throughout the succession.

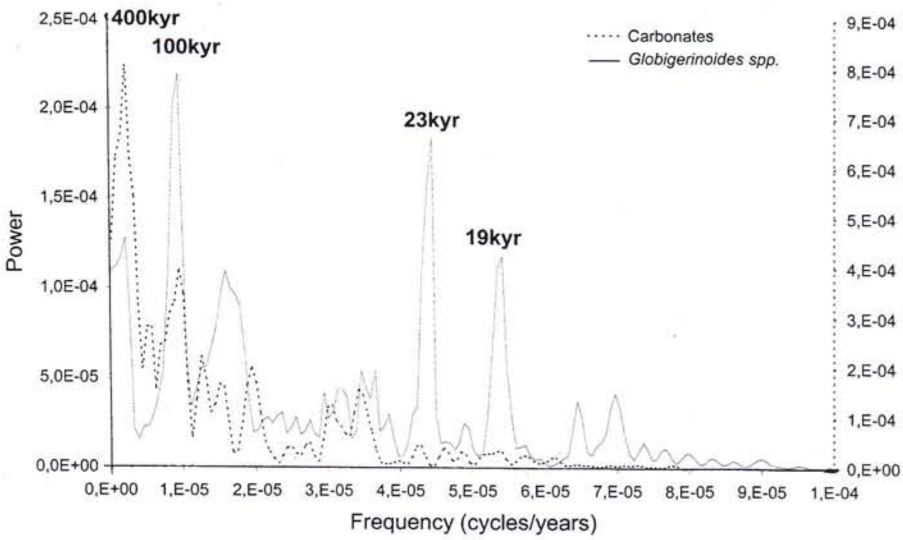

Fig. 7 - Power spectra of $CaCO_3$ (dashed line) and *Globigerinoides* spp. (continuous line) signals after tuning. B.W: bandwidth, C.I.: Confidence Interval.

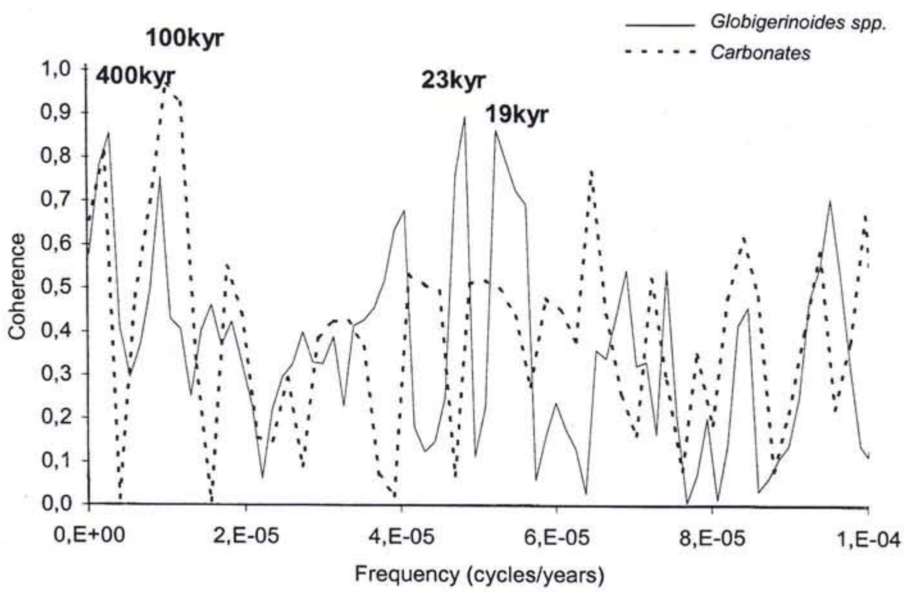

Fig. 8 - Coherence spectra between the insolation curve La $90_{1,1}$ and the $CaCO_3$ (dashed line) and *Globigerinoides* spp. (continuous line) signals.

BIOEVENT	PRECESSION CYCLE	AGE (MA)
Planktonic foraminifera		
LO *G. peripheroronda*	142/143	13,39
FO *P. partimlabiata*	104	12,62
FCO *P. mayeri*	90	12,34
Calcareous nannofossils		
LO *S. heteromorphus*	152	13,59
LCO C. *floridanus*	142/143	13,39
FCO *R. pseudoumbilicus*	139	13,33
FO *C. macintyrei*	101	12,56
LCO *C. praemacintyrei*	98/99	12,52

Tab. 1 - Estimated ages for the most important bioevents recognized throughout the studied section.

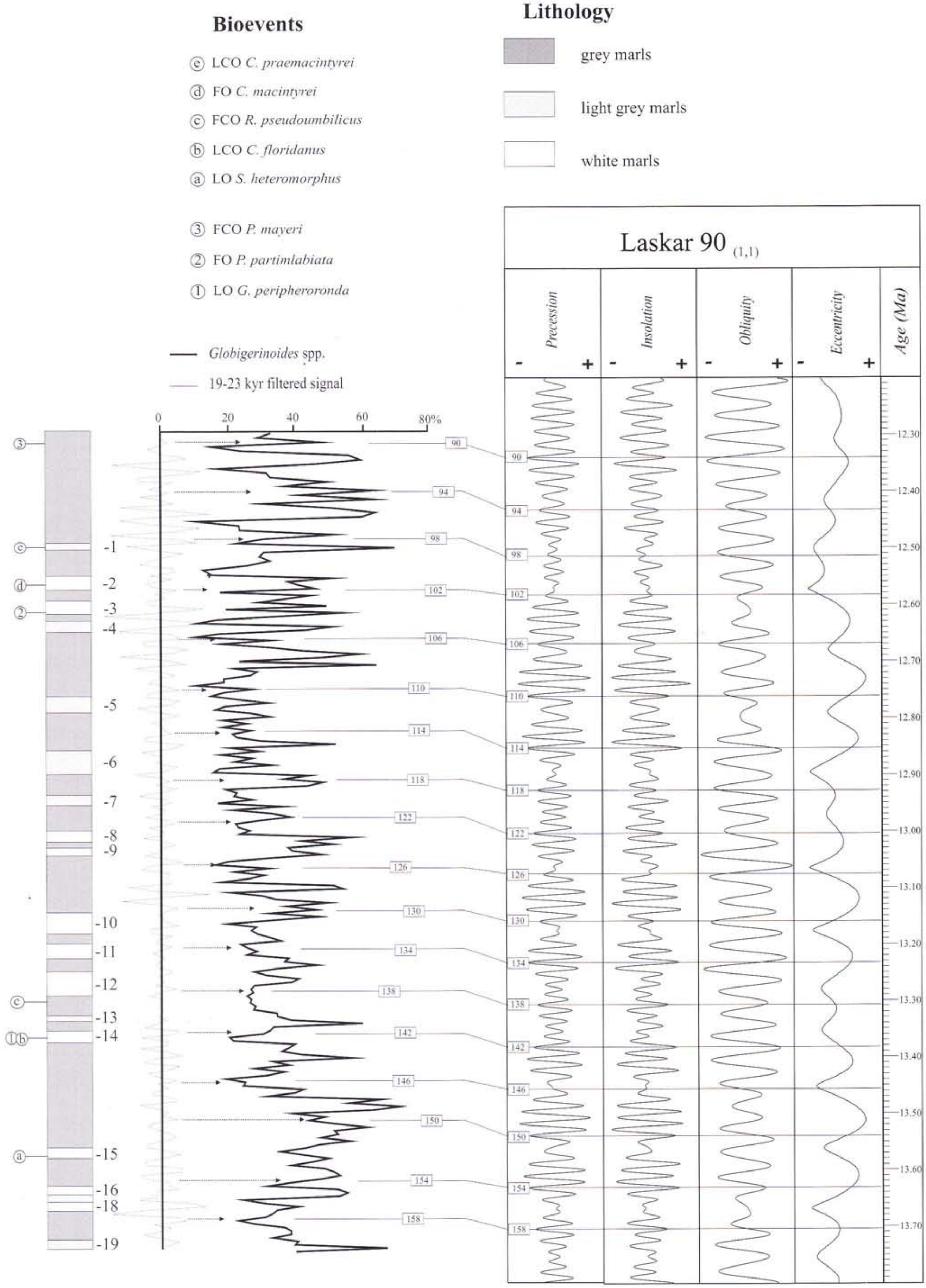

Fig. 9 - Comparison between original and filtered (in the precession frequency bands) *Globigerinoides* spp. signals and correlation with the insolation curve La90$_{(1,1)}$. See text for the cycle labelling.

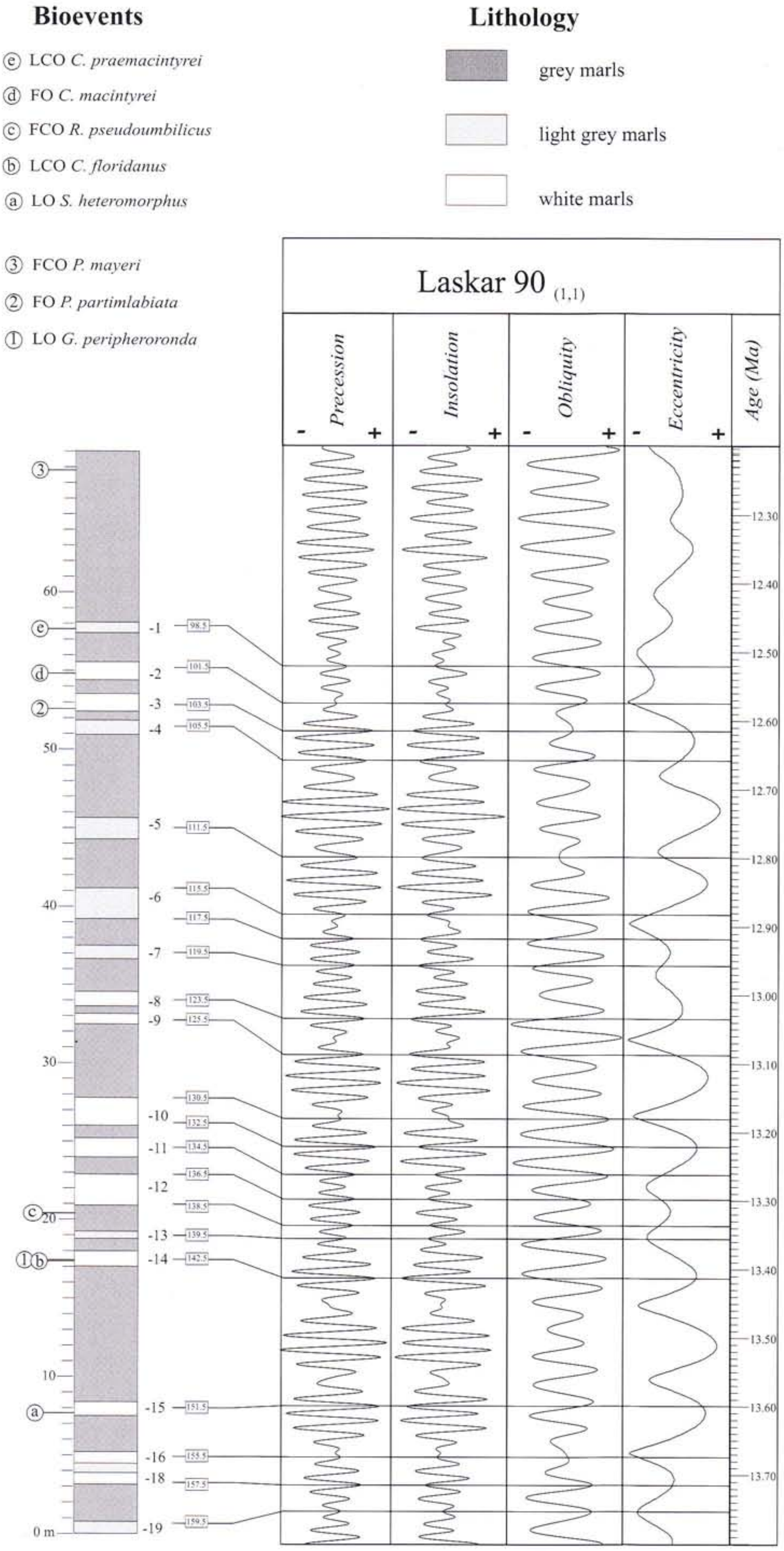

Fig. 10 - Calibration of the lithological cycles recognized throughout the Ras il-Pellegrin section with the insolation curve $La90_{(1,1)}$.

Astronomical ages for the most important biostratigraphic events present in the Ras il-Pellegrin sequence are reported in Tab. 1. The obtained calibration can be considered accurate to the level of the individual precession/insolation cycle for all the studied interval. Unfortunately, a direct comparison with other timescales is complicated because of the presently absence of detailed magnetostratigraphic data from the Ras il-Pellegrin section.

An age of 13.59 Ma has been estimated for the LO of *S. heteromorphus*, in our section. It is well comparable with the age of 13.52 0.11 Ma reported for this bioevent by Backman & Raffi (1997) in the equatoral Atlantic Ocean (Leg 154) and with the age of 13.57 Ma reported by Raffy & Flores (1995) and Raffi et al. (1995) for the equatoral Pacific Ocean (Legs 115, 130 and 138). These results suggest that the biohorizon of LO of *S. heteromorphus* has a high potential for biostratigraphic correlations among different basins.

Lithologic patterns

Colour modulations from grey to white have been previously described to alternate throughout the studied succession. The most evident colour bands (the above-mentioned thick pale bands) have been reported in the lithologic column. They have been progressively labelled in descending order -1 to -19 from the top to the base of the section.

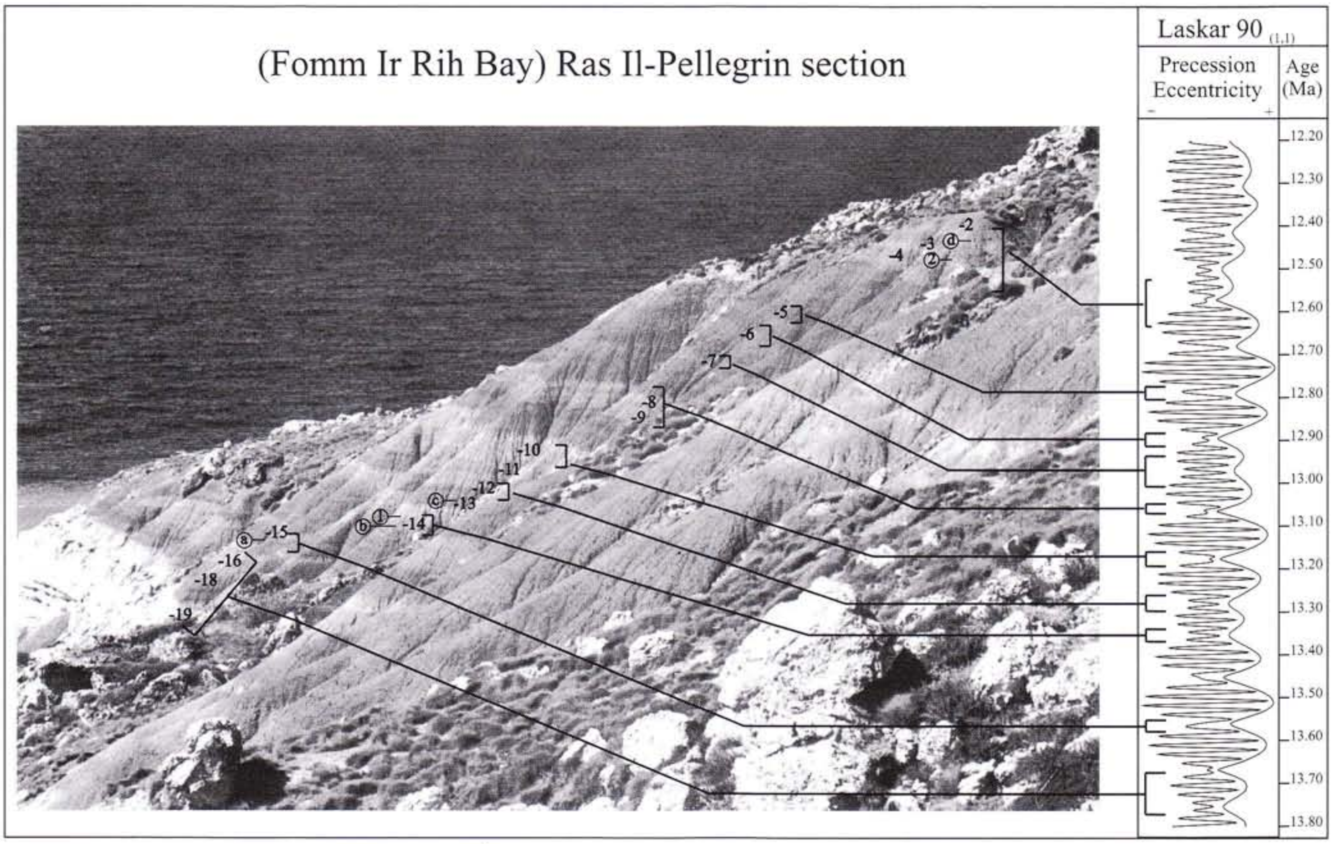

Fig. 11 - Comparison between the lithological cycles recognized throughout the Ras il-Pellegrin section and the insolation curve $La90_{1,1}$. Calcareous plankton bioevents (circled) and numbers marking thick white bands as in Figure 3.

WHITE MARLS	PRECESSION CYCLE	AGE (MA)
-1	98,5	12,54
-2	101,5	12,57
-3	103,5	12,64
-4	105,5	12,75
-5	111,5	12,80
-6 top	115,5	12,88
-6 base	117,5	12,92
-7	119,5	12,98
-8	123,5	13,06
-9	125,5	13,07
-10 top	130,5	13,17
-10 base	132,5	13,20
-11	134,5	13,24
-12 top	136,5	13,28
-12 base	138,5	13,32
-13	140,5	13,55
-14	142,5	13,39
-15	151,5	13,58
-16	155,5	13,66
-18	157,5	13,68
-19	159,5	13,73

Tab. 2 - Age of the recognized lithologic alternation throughout the Ras il-Pellegrin section.

These white bands, generally characterized by higher carbonate content, have been recognized to correlate with the 100 and 400 kyr eccentricity minima cycles (Fig. 10).

Use of very contrasted photos of the sedimentary succession (Fig. 10 and 11) and field work with many different sunlight conditions allowed us to recognize a lighter colour differentiation along the sequence that we, tentatively, attributed to high frequency (19-23 kyr) lithologic changes. Nonetheless, because of the difficulty to recognize the precession cycles in the sedimentary record, we consider reliable the calibration to the 400-100 kyr scale (thick pale horizons) obtained using lithology, whereas the calibration to the 19-23 kyr time scale is considered less straightforward at the moment. In Tab. 2 the ages for each of the thick pale horizons are reported.

A detailed analysis of other sedimentary sequences, with a clearer exposition of high-frequency cycle patterns, could allow a more accurate comparison between climate-sensitive records and lithological distribution patterns for the same stratigraphic interval.

Conclusive remarks

The sedimentary record of the Ras il-Pellegrin section has been astronomically tuned to the insolation curve of Laskar et al. (1993), La90$_{(1,1)}$ solution, producing a reliable calibration of the geological time scale from 12.32 Ma down to about 13.75 Ma.

The combination of the lithologic pattern distribution with spectral and filtering results applied to two selected climate-sensitive records obtained from the studied sequence, $CaCO_3$-content and *Globogerinoides* spp. abundance, produced an astronomical calibration accurate to the level of individual precession cycle.

All the bioevents recognized throughout the record have been dated. In particular, the age of 13.59 Ma has been obtained for the LO of *S. heteromorphus*. Such a biostratigraphic event is one of the most easily determined Middle Miocene biohorizons both in the Mediterranean region (Muller 1978; Ellis & Lohman 1979; Theodoridis 1984) and on a global scale (Fornaciari et al. 1996; Olafsson 1989, 1991; Backman & Raffi 1997). At present, such a biostratigraphic event is considered an excellent and easily detectable biohorizon with high chronostratigraphic correlation potential between Mediterranean (Muller 1978; Ellis & Lohman 1979; Theodoridis 1984) and oceanic global record (Fornaciari et al. 1996; Olafsson 1989, 1991; Backman & Raffi 1997). On the basis of a study of numerous Mediterranean sections, Fornaciari et al. (1996) suggested that the LO of *S. heteromorphus* is close to the top of the Langhian stratotype and that this bioevent can be considered the best approximation to individuate the Langhian/Serravallian boundary. The extremely similar astronomical age obtained for this bioevent in the Ras il-Pellegrin section and in the equatorial Atlantic and Pacific (see in the text above) confirms the reliability of this biohorizon for global correlation.

The FO of *G. peripheroronda* is the planktonic foraminiferal bioevent closest to the LO of *S. heteromorphus*. The astronomical age of this biohorizon in the Ras il-Pellegrin section is 13.39 Ma. Such a result suggests that on the basis of plankton foraminiferal biostratigraphy the best approximation for dating the Langhian/Serravallian boundary can be achieved with an error of about 200 kyr.

Two other important events have been recognized throughout the studied section, useful for regional and local correlations. The FO of *Paragloborotalia partimlabiata* useful for large-scale Mediterranean correlations, has an astronomically calibrated age of 12.62 Ma. Finally, the top and the base of the studied section have an estimated astronomical age of 12.32 and 13.75 Ma, respectively.

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