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ASTROCHRONOLOGICAL CALIBRATION OF THE UPPER SERRAVALLIAN/LOWER TORTONIAN SEDIMENTARY SEQUENCE AT TREMITI ISLANDS (ADRIATIC SEA, SOUTHERN ITALY)

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Riassunto. Vengono presentati i risultati di uno studio ciclostratigrafico di una sezione composita ubicata nell'Isola di S. Nicola (Isole Tremiti). La successione sedimentaria è costituita da un'alternanza ciclica di marne calcaree biancastre e marne grige, queste ultime talora sostituite da marne rossastre. La diretta correlazione tra i cicli sedimentari, riconosciuti lungo la successione sedimentaria studiata, e le curve astronomiche (eccentricità e precessione) combinata con l'analisi spettrale condotta sui *Globigerinoides* e sul contenuto in $CaCO_3$, hanno portato alla calibrazione astronomica dei cicli sedimentari e alla datazione di alcuni bioeventi nell'intervallo tra 11.12 Ma e 12.60 Ma.

Abstract. A high-resolution cyclostratigraphic study was carried out on a cyclically bedded succession of late Middle Miocene deep marine deposits from the Tremiti Islands, Adriatic sea (Italy). Astronomical calibration of the sedimentary cycles provides absolute ages for different calcareous plankton bioevents, widely used for intra-Mediterranean correlation, in the interval between 11.12 and 12.60 Ma. The sedimentary record of the S. Nicola composite section consists of an alternation of indurated, whitish coloured, $CaCO_3$-rich and grey less indurated, $CaCO_3$-poor marly beds, at times replaced by red coloured, $CaCO_3$-poor marls. Results of direct correlation between the La $90_{(1,1)}$ solution of the insolation curve and the cyclic lithologic patterns occurring in the studied sections, combined with results of spectral methodologies applied on the climate sensitive data ($CaCO_3$ and *Globigerinoides*) showed that the classic Milankovitch periodicity can be represented through the modulation forcing of the studied sedimentary record.

Introduction

Cyclostratigraphy has improved the geological time-scale, and more importantly, our knowledge of climatic changes, but the mechanisms behind the forcing of climatic cycles are not fully understood yet, because the climatic response to the astronomical cycles is often not linear and is affected by oceanic feedback process (Van Vugt 2000). Since astronomical cycles influence climate, and in turn, climate controls the sediment accumulation, it is not surprising that the latter is related to the astronomical influence. Application of cyclostratigraphy has resulted in the construction of a reliable Astronomical Time Scale (ATS) for the Quaternary, Pliocene and the upper Miocene (Hilgen et al. 1999, 2000a, 2000b, Hilgen 1991a, 1991b; Lourens et al. 1996; Shackleton et al. 1995; Shackleton & Crowhurst 1997) that is more accurate and has a much higher resolution than the previous geological time scales. Researchers are now working to extend the astronomical timescales to older intervals, even in continental record, (Augusti et al 2001).

Astronomical calibration of sedimentary cycles or other periodic fluctuations in the geological record to computed insolation curve enabled some authors (Hilgen et al. 1995, 1999, 2000a; Lourens et al. 1996; Krijgsman et al. 1995, 1997, 1999; Krijgsman 1996) to extend the astrochronology of the Mediterranean area back into the Middle Miocene (to about 12 Ma). According to many authors (Lourens 1994; Lourens et al. 1992; Van Vugt 2000; Versteegh 1994) the great advantage of studying sediments from the Mediterranean is that they sensitively record astronomically induced climatic fluctuations, due to the paleo-latitudi-

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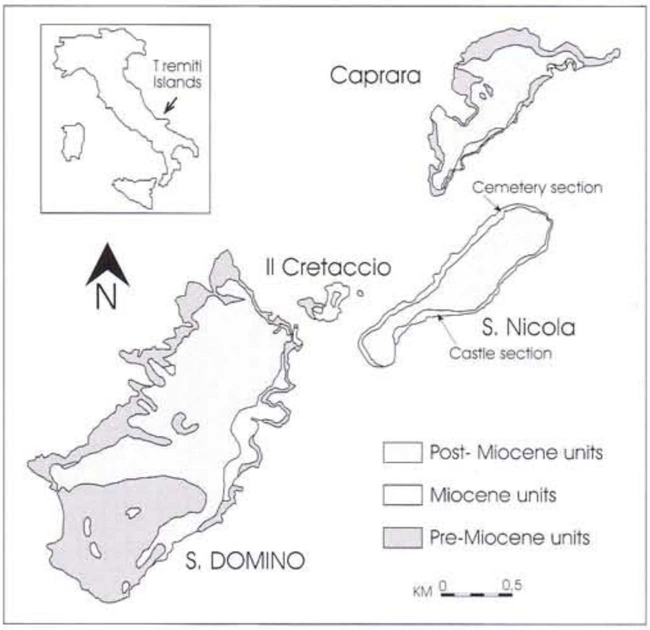


Fig. 1 - S. Nicola island: Location map of Cemetery and Castle sections.

nal position of the Mediterranean in combination with its semienclosed, land-locked configuration. In the Mediterranean area, the extension of the astrochronological time scale back to 12.098 Ma was based on different Miocene sections outcropping in Metochia (Crete, Greece) and Faneromeni (Greece) and in Sicily (Hilgen et al. 2000b; Krijgsman et al. 1995; Postma & Ten Veen 1999; Ten Veen & Postma 1993). At the Tremiti Islands, cyclically bedded sediments are exposed (Foresi et al. 1998; Iaccarino et al. 2001) and offer the possibility of extending the scale back to the middle part of the Serravallian stage.

Accurate calibration of Plio-Pleistocene and Miocene series obtained by Lourens et al. (1996) and Hilgen et al. (1995, 2000) demonstrated that the La $90_{(1,1)}$ solution represents the best tuning between the geological and the astronomical record for the last 12 My. In this paper we used this astronomical solution to correlate the Serravallian-early Tortonian sedimentation record with the astronomical insolation curve of Laskar et al. (1993) and to calibrate precise ages for all the sedimentary cycles and biostratigraphic datum planes recorded in the studied Mediterranean sections. The investigated time interval includes the Serravallian/Tortonian (S/T) boundary (Foresi et al. 1998; Iaccarino et al. 2001) which hystorically is recognised as coincident with the FO of *Neogloboquadrina acostaensis* in the Mediterranean area (Cita & Blow 1969 and others).

Geological setting and studied sections

The Tremiti Islands (S. Domino, S. Nicola, Cretaccio, Caprara and Pianosa), located in the southern part of Adriatic sea (Fig. 1), belong to the Adria microplate that is bounded by west verging Hellenides to the West, and east verging Apennines, to the East (Channell et al. 1979; Gambini & Tozzi 1996; Platt et al. 1989). The sedimentary sequences, cropping out on the Tremiti Islands, span from the upper Paleocene to the Quaternary (Iaccarino et al. 2001, and others). The Neogene sequence belongs to the Cretaccio Formation (Iaccarino et al. 2001; Pampaloni 1988; Selli 1971) and outcrops mainly on the Cretaccio and S. Nicola islands.

The investigated sections (Castle and Cemetery) are located on S. Nicola island and both consist of deep-marine cyclically bedded hemipelagic sediments of Middle to early Late Miocene age and are transgressive on the pre-Neogene sediments.

The present study focuses on the S. Nicola composite section which consists of two different sections: the Cemetery (N 42°07'41.6"; E15°30'47.9") and Castle (N 42°07'18.3"; E 15°30'26") sections which are located in the NW and SE parts respectively of the S. Nicola island (Fig. 1). Both sections have been sampled and logged along different trajectories because of small faults (Fig. 2). The detailed logging provides a continuous record for the entire investigated sequence(Fig. 3). Sedimentary cycles are not equally distinct and visible in the two sections due to lateral changes, different weathering and bad exposure. Correlation between the two sections was established on the base of calcareous plankton bioevents and comparing the pattern of relative abundance fluctuations of selected planktonic foraminifera.

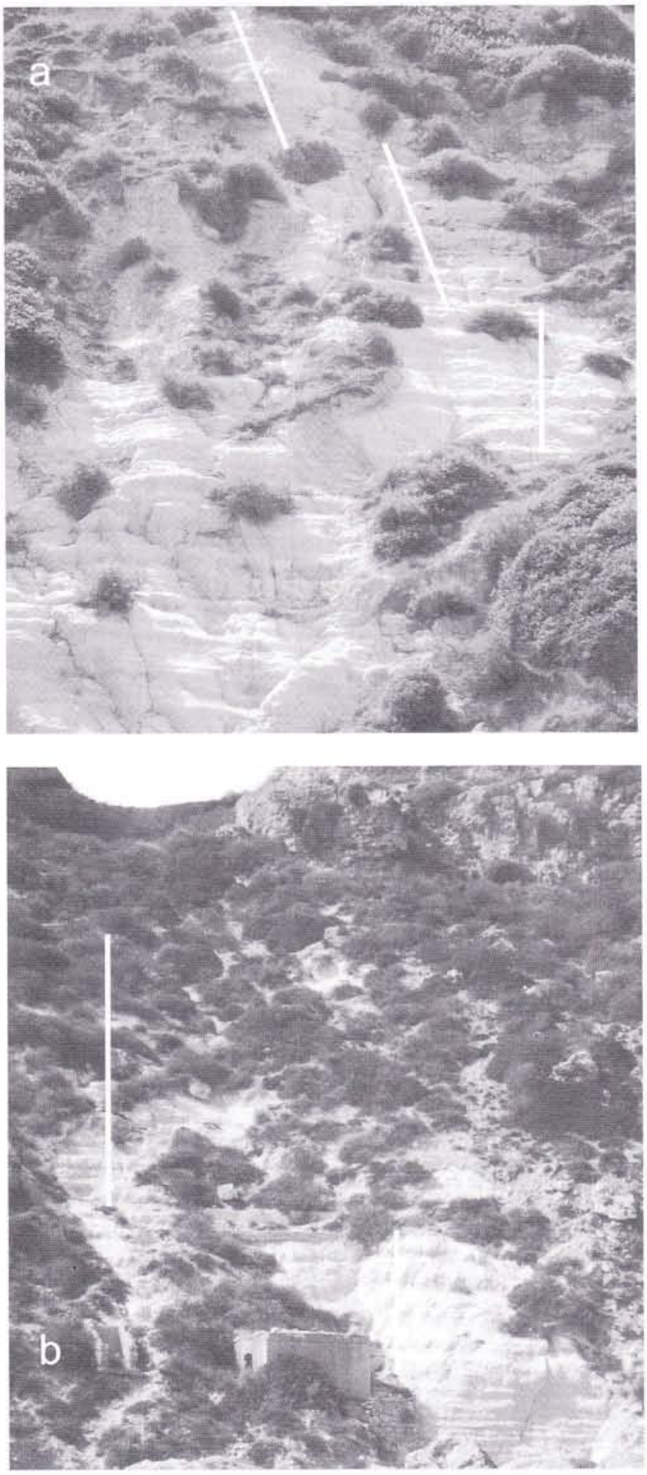
Cemetery section

The Cemetery section is 19 meters thick, and shows a quasi-regular rhythmic alternation of red-grey coloured less indurated, $CaCO_3$-poor marly beds and whitish coloured, $CaCO_3$-rich marly limestones (Fig. 3). The cyclic pattern in this section, consists of an evident alternation of clusters which are distinguishable for the colour of the marly beds (Fig. 3).

The lower part of the section, 6.5 m thick consists of couplets of grey marls and white prominent carbonate beds. They are followed above (from 6.5 to 9.5 m) by cycles, showing distinct red marly beds, of variable thickness (between 0.20 and 0.70 m), and white marly limestones ranging in thickness from 0.20 to 0.40 m. The interval from 9.5 to 16 m, is again characterised by an alternation of grey marls and white carbonate beds, which become progressively thicker upwards. In the uppermost part of the Cemetery section, from 16 to 19 m a regular alternation of red marls and white carbonate is present.

Castle section

The thickness of the Castle section is 26.03 m and



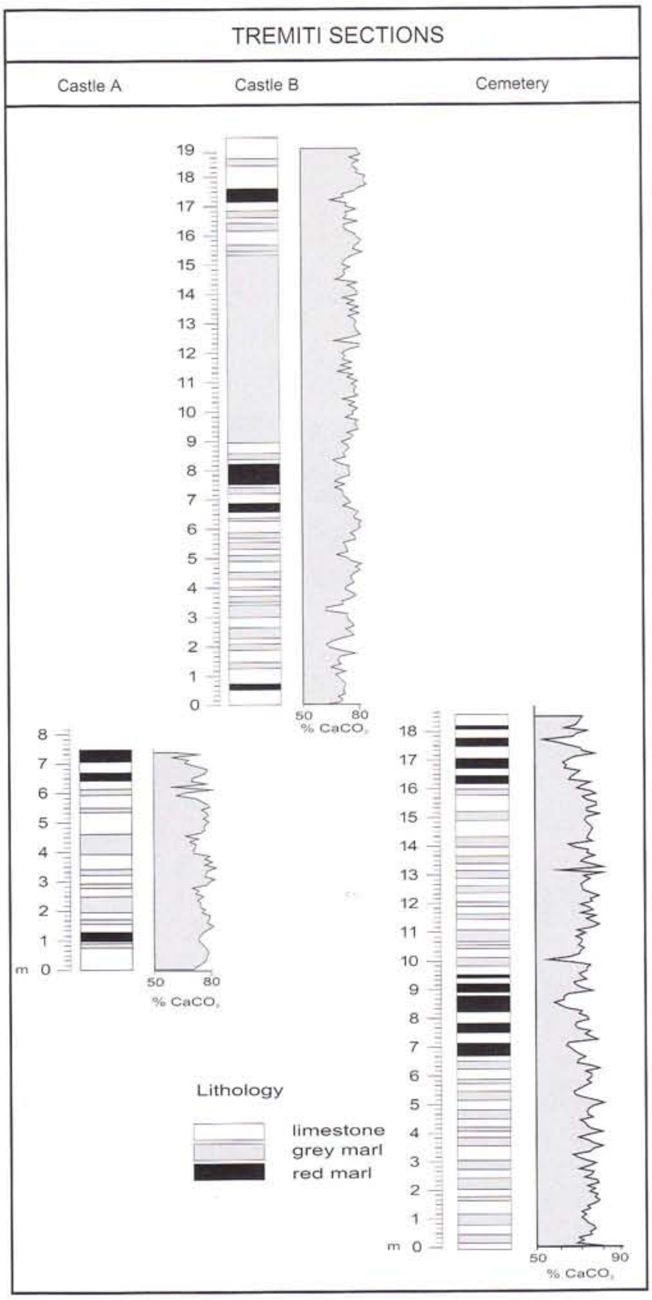


Fig. 2 (left) - Sampling trajectories of the Cemetery (a) and Castle (b) sections.

Fig. 3 (above) - Logs of lithology and $CaCO_3$ content of Cemetery and Castle sections.

consists of two subsections of 7.61 and 18.42 m thick, respectively (Fig. 3) separated by a shear plane (Fig. 4b). The lithologic cycles, well exposed in the subsection A (0 to 7.61 m) and in the lower part of the subsection B (0 to 9 m), consist of a quasi regular rhythmic alternation of indurated, whitish coloured, $CaCO_3$-rich marly limestones and grey coloured less indurated, $CaCO_3$-poor marly beds. In some stratigraphic portions of the section, red-coloured, $CaCO_3$-poor marls replace the grey coloured marls. Because of bad exposure, no lithologic cyclicity was observed in the overlying 5.84 m, although this occurs again in the uppermost 4 m of the section. In addition, a very distinct red layer between 17.2 and 17.6 m is recorded.

The marly limestones vary in thickness between 0.25 and 1 m and the red and grey coloured marls range in thickness from a few cm up to 1 m. Bioturbation is present throughout the section and molluscs referable to *Flabellipecten* and *Neopycnodonte* are sparsely present.

The carbonate content in the Cemetery and Castle sections shows high frequency fluctuations produced by higher carbonate content in the prominent carbonatic beds and lighter carbonate values in the grey-red marly layers (Fig. 3). Amplitude of the carbonate oscillations varies between 85% and 60%. Generally the mean value of carbonate content in the marly layers is 75% and rarely, 60%.

Material and methods

The planktonic foraminiferal analysis is based on 251 and 182 samples collected at a mean interval of 10-15 cm, from the Castle and Cemetery sections, respectively. Samples for foraminiferal analysis were first dehydrated in oven at 40 degrees, subsequently disaggregated in distilled water and washed with a 63 μm sieve. The dried residues were split with a microsplitter to obtain a fraction containing about 300 specimens. All the identifiable planktonic foraminifera were counted in the fraction >125 μm, picked out together with the not identifiable planktonic foraminifera, the benthic foraminifera, and the detritic fraction. Taxon abundance is expressed as percentage of the total fauna.

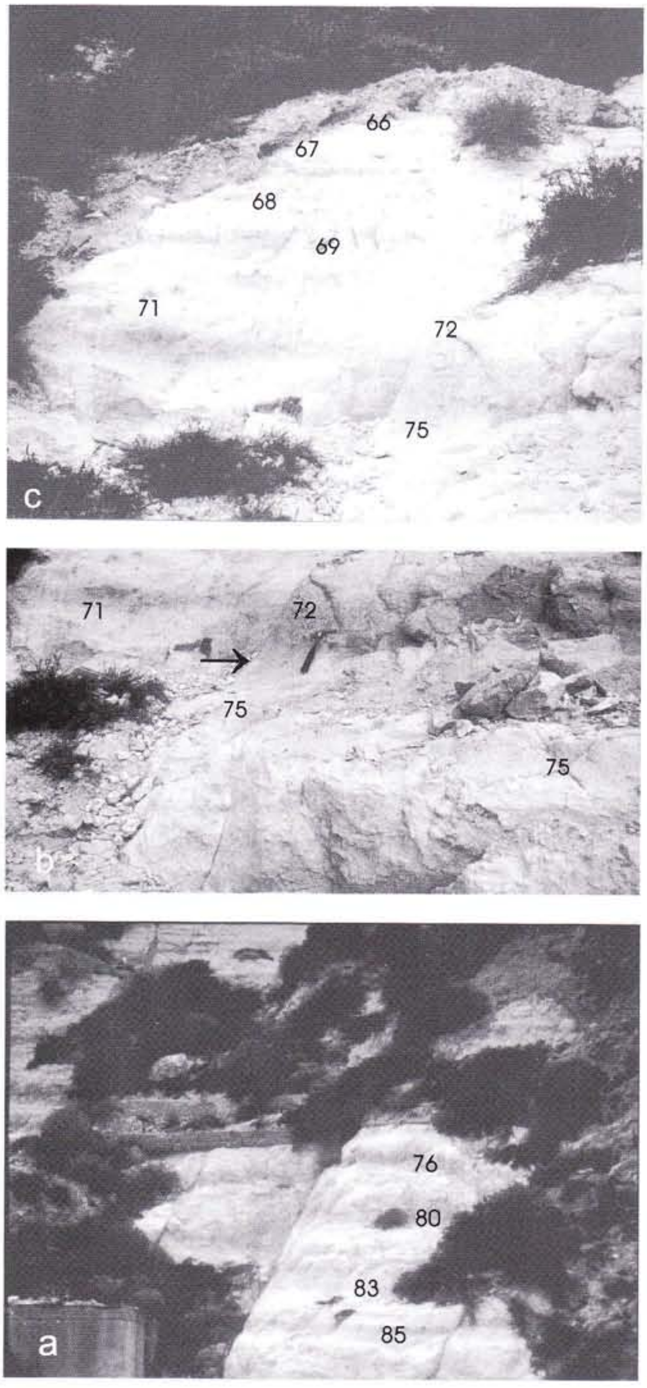


Fig. 4 - Selected sedimentary cycles from Castle section. a: subsection A; b-c: subsection B, the arrow shows the position of a shear plane.

The calcareous nannofossil analysis, is also based on 125 and 182 samples from the Castle and Cemetery sections, respectively. Smear slides were prepared from unprocessed sediments following standard techniques. To obtain the distribution patterns of selected calcareous nannofossil taxa, light microscope analysis was performed (transmitted light and crossed nicols) at about 1000 magnifications. Abundance data were collected using methodology described by Backman & Shackleton (1983), Rio et al. (1990) and extensively used in Mediterranean or extra-Mediterranean quantitative biostratigraphic studies of Neogene marine records (ODP sequences and land sections) (Backman & Raffi 1997; Di Stefano 1998; Fornaciari et al. 1996; Hilgen et al. 2000b; Raffi & Flores 1995; Raffi et al. 1995).

Carbonate content was determined by gasvolumetric methodology for both sections and was carried out on 251 (Castle section) and 182 (Cemetery section) samples.

In order to calibrate the cycles to the astronomical parameters, the methodologies proposed by Hilgen (1991a, 1991b) and Sprovieri (1992, 1993) were followed: the first author directly correlates the sedimentary cycles with one of the different numerical solutions of the insolation curve; the second uses the relative abundance fluctuations of *Globigerinoides* spp. to identify cycles. In the modern oceans *Globigerinoides* spp. lives in tropical and subtropical surface water masses and is considered to be a warm-water indicator (Bé & Tolderlund 1971; Cifelli & Smith 1974; Coulbourn et al. 1980).

Variations in their relative abundance essentially reflect variations in sea surface temperature (SST), the high relative abundance correlates with warmer periods.

By tuning of the lithologic cycles, the relative abundance fluctuations of *Globigerinoides* spp., and carbonate content to the astronomical curves, the age of the bioevents identified throughout the section were obtained. The quantitative data of carbonate content and *Globigerinoides* spp. were processed by spectral analysis using the SPAGEOS program (Bonanno et al. 1996). The spectral analysis and the filtering procedures are based on the standard approach of Jenkins & Watt (1968) and Weedon (1991) which makes it possible to highlight the harmonic structure of the obtained signal

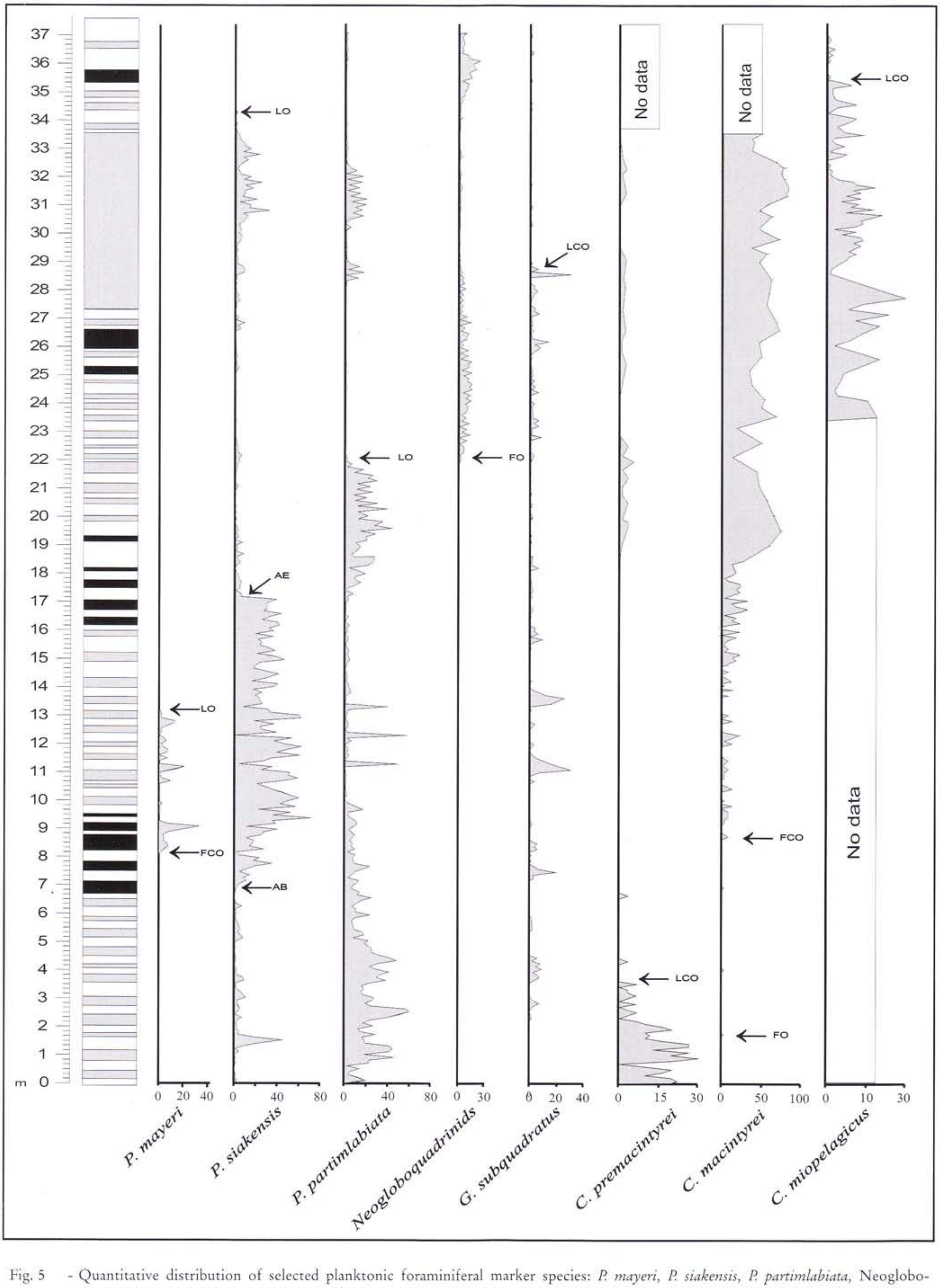


Fig. 5 - Quantitative distribution of selected planktonic foraminiferal marker species: *P. mayeri*, *P. siakensis*, *P. partimlabiata*, Neogloboquadrinids and *G. subquadratus* (as % of the total planktonic foraminiferal assemblage) and selected calcareous nannofossil marker species: *C. premacintyrei*, *C. macintyrei* and *C. miopelagicus* (as % of the total calcareous nannofossil assemblage).

and offers the opportunity to filter the original time series in selected frequency bands. These sophisticated filtering techniques were developed to identify in selected climate sensitive records ($CaCO_3$ and *Globigerinoides*), cyclic alternations correlatable with variations of the same order recognised in the insolation curve (Hilgen 1991a, 1991b; Lourens et al. 1996; Shackleton & Crowhurst 1997).

Biostratigraphic data

Calcareous Plankton

The planktonic foraminiferal record from the S. Nicola composite section includes 14 bioevents, which are widely used for intra-Mediterranean correlations (Foresi et al. 1998; Giannelli & Salvatorini 1975; Hilgen et al. 2000b; Iaccarino 1985; Iaccarino et al. 2001; Iaccarino & Salvatorini 1982). The stratigraphic position and the abundance pattern of selected biostratigraphic events, which represent important control points for an accurate correlation with the other sequences, are reported in Fig. 5 and Fig. 6.

The calcareous nannofossil assemblage is also well preserved and abundant. Only the *Discoaster* genus shows a high recristallization. Six bioevents which are used for intra-Mediterranean correlation (Fornaciari et al. 1996; Hilgen et al. 2000b) were recorded in the composite section and plotted in Fig. 5 and Fig. 6. For more detail about the abundance patterns of the different taxa see Foresi et al. (2002).

Cyclostratigraphy

According to Hilgen (1991a) the sapropels are correlated to precession minima/summer insolation maxima in the Northern hemisphere and small-scale and large-scale sapropel clusters to 100.000 and 400.000 years eccentricity maxima, while alternating thin-thick sapropels reflect precession-obliquity interference (Lourens et al. 1996; Hilgen et al. 2000b). We tuned the red and grey marly layers to precession minima/summer insolation maxima. Consequently, they correspond to the sapropels in the Mediterranean (Hilgen et al. 2000a). In addition, high values of *Globigerinoides* spp. in the red/grey marly beds, confirm the phase relation (*Globigerinoides* maxima/precession minima) used for our tuning (Sprovieri 1992, 1993; Sprovieri M. et al. 1999).

The abundance curves of selected taxa (*Globigerinoides subquadratus*, *Paragloborotalia siakensis* and *Paragloborotalia partimlabiata*) in the Tremiti sections were used to correlate the studied sedimentary records with the M. Gibliscemi section, astronomically calibrated by Hilgen et al. (2000b). The strong similarity of the abundance patterns allowed us to consider the Acme End (AE) of *P. siakensis*, the Last Occurrence (LO) of *P. partimlabiata* and the Last Common Occurrence (LCO) of *G. subquadratus* recognised in both sections as synchronous events (Fig. 7). These bioevents were used as tie points to calibrate astronomically the Tremiti sedimentary sequence.

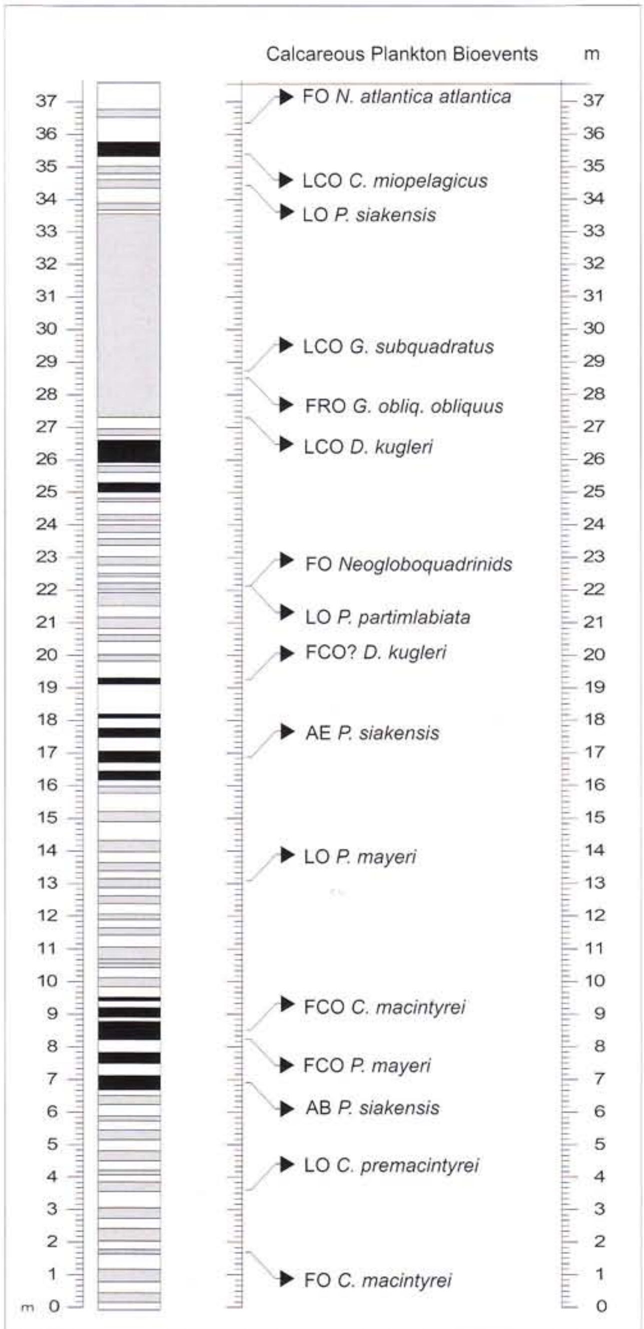


Fig. 6 - Integrated biostratigraphy of S. Nicola composite section and relative position of selected calcareous plankton bioevents.

In particular, the AE of *P. siakensis*, corresponding to the strong decrease of *P. mayeri* in the M. Gibliscemi section, calibrated at 12.006 Ma in cycle -87 (Hilgen et al. 2000b), the LO of *P. partimlabiata*, corresponding to the abrupt decrease of *P. partimlabiata*, calibrated at 11.799 Ma in cycle -80 (Hilgen et al. 2000b), and the

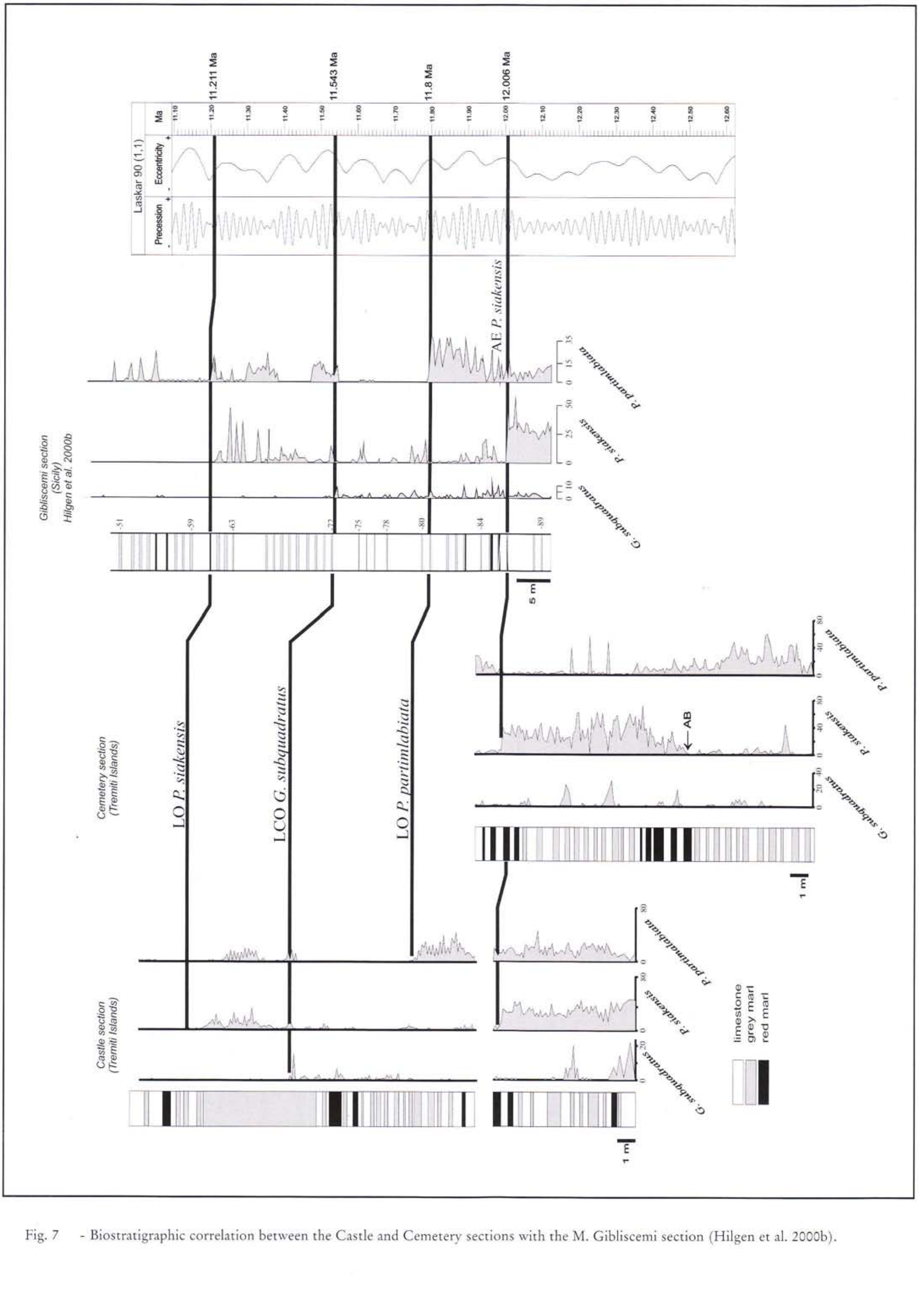


Fig. 7 - Biostratigraphic correlation between the Castle and Cemetery sections with the M. Gibliscemi section (Hilgen et al. 2000b).

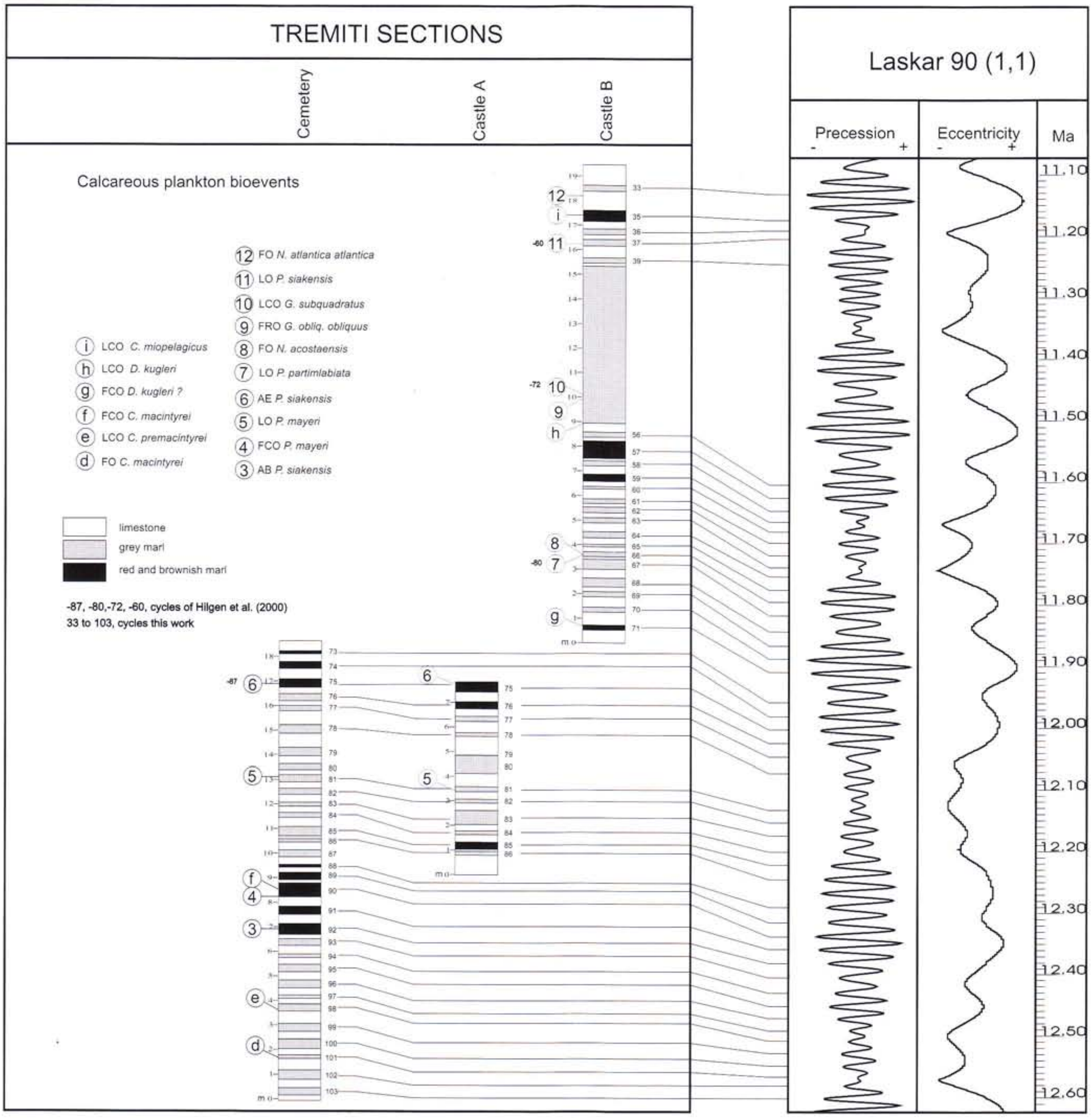


Fig. 8 - Integrated stratigraphic correlation of the Cemetery and Castle sections within the astronomically tuned integrated stratigraphic framework.

LCO of *G. subquadratus* with an age of 10.539 Ma in cycles -72 (Hilgen et al. 2000b) were used as the starting point for tuning our sedimentary cycles at the Tremiti Islands (Fig. 7).

Fifty-two sedimentary cycles were recognised in the S. Nicola composite section (Fig. 8) and are informally and progressively numbered from the top, starting from cycle 33, to the base of the section (Tab. 1). Informal cycles 1 to 32 are recorded in the Case Pelacani section located in the southern part of Sicily and astronomically calibrated by Caruso et al. (2002).

The older 11 cycles (103-93) recorded in the lowest part of the S. Nicola section, contain the First Occurrence (FO) of *Calcidiscus macintyrei* (cycle 101) and the LCO of *C. premacintyrei* (cycle 98). Their astronomical ages are 12.57 and 12.51 Ma, respectively (Tab. 2). This interval is dominated by grey layers intercalated to white carbonate beds. We compared the larger-order lithologic cycle patterns, present at the base of the section spanning 200 ky, with the astronomic eccentricity curve (Laskar et al. 1993). The lowest part of this interval, where carbonate beds are more prominent and thicker than the uppermost cycles (97-93), is clearly controlled by 100 ky eccentricity minima while the uppermost quasi-regular alternation of cycles reflects the increase in amplitude of the precession index (Fig. 8).

Above this interval we recognised a first cluster of five red layers, from cycle 92 to cycle 88, correlated to high frequency fluctuations in the precession index (Fig. 8). The First Common Occurrence (FCO) of *P. mayeri* and the FCO of *C. macintyrei* are recorded in the red marly layer of cycle 90 (Tab. 2, Fig. 8). The Acme Base (AB) of *P. siakensis* recorded in the red marly layer of cycle 91, has an astronomical age of 12.38 Ma (Tab. 2, Fig. 8).

Cycles 87 to 77 are characterised by three cycles (87-85) controlled by eccentricity maxima, and by eight cycles (84-77) clearly controlled by a long period of eccentricity minima well recognisable both in Cemetery and Castle A sections (Fig. 8). In this interval (cycles 87-77) the white prominent carbonate beds are progressively thicker upwards (Fig. 8). In the grey marly layer of cycle 81 (Fig. 8) the LO of *P. mayeri* is recorded, at the astronomical age of 12.14 Ma (Tab. 2).

Upward another cluster of five red layers (cycle 76-71) and one extra-cycle in the thick white carbonate bed of cycle 73 are recorded (Fig. 8). This cluster fits excellently with the high amplitude fluctuations of the precession curve between 12.03 Ma and 11.91 Ma. In this interval, in the red marly beds of cycle 75 the AE of *P. siakensis* is recorded at the astronomical age of 12.00 Ma (Fig. 8 , Tab. 2).

Section	Grey/Red layer	Age (ka)	Section	Grey/Red layer	Age (ka)
Castle	Cycle 33	11.137	Castle/Cemetery	Cycle 78	12.079
Castle	Cycle 35	11.180	Castle/Cemetery	Cycle 79	12.100
Castle	Cycle 36	11.197	Castle/Cemetery	Cycle 80	12.120
Castle	Cycle 37	11.211	Castle/Cemetery	Cycle 81	12.139
Castle	Cycle 39	11.252	Castle/Cemetery	Cycle 82	12.158
Castle	Cycle 56	11.608	Castle/Cemetery	Cycle 83	12.179
Castle	Cycle 57	11.630	Castle/Cemetery	Cycle 84	12.204
Castle	Cycle 58	11.651	Castle/Cemetery	Cycle 85	12.227
Castle	Cycle 59	11.669	Castle/Cemetery	Cycle 86	12.249
Castle	Cycle 60	11.685	Cemetery	Cycle 87	12.271
Castle	Cycle 61	11.704	Cemetery	Cycle 88	12.294
Castle	Cycle 62	11.725	Cemetery	Cycle 89	12.318
Castle	Cycle 63	11.743	Cemetery	Cycle 90	12.341
Castle	Cycle 64	11.759	Cemetery	Cycle 91	12.363
Castle	Cycle 65	11.779	Cemetery	Cycle 92	12.385
Castle	Cycle 66	11.800	Cemetery	Cycle 93	12.409
Castle	Cycle 67	11.822	Cemetery	Cycle 94	12.434
Castle	Cycle 68	11.848	Cemetery	Cycle 95	12.455
Castle	Cycle 69	11.871	Cemetery	Cycle 96	12.476
Castle	Cycle 70	11.893	Cemetery	Cycle 97	12.495
Castle	Cycle 71	11.914	Cemetery	Cycle 98	12.512
Cemetery	Cycle 73	11.963	Cemetery	Cycle 99	12.532
Cemetery	Cycle 74	11.985	Cemetery	Cycle 100	12.553
Cemetery	Cycle 75	12.006	Cemetery	Cycle 101	12.571
Castle/Cemetery	Cycle 76	12.029	Cemetery	Cycle 102	12.585
Castle/Cemetery	Cycle 77	12.053	Cemetery	Cycle 103	12.605

Tab. 1 - Stratigraphic position and astronomical ages of the sedimentary cycles.

Cycles 72 to 56 are characterised by a regular alternation of couplets of grey marly beds, sometimes replaced in the uppermost part by red marly ones, and white marly limestones. Cycles 72 to 65 fit excellently with the high-amplitude fluctuations of the precession curve between 11.94 Ma and 11.78 Ma (Fig. 8, 4). From cycle 64 to cycle 56, the decreases in thickness of the cycles, has been interpreted as a change in the sedimentation rate (Fig. 8). In addition, the red marl of cycles 57 is very thick. The LO of *P. partimlabiata* and the FO of Neogloboquadrinids are recorded in the grey marly layer of cycle 66, (Fig. 8, 4, and Tab. 2). Their age is 11.8 Ma (Tab. 2).

Cycles from 55 to 40 were identified using the *Globigerinoides* and carbonate content fluctuations, because the sedimentary cycles were not recognisable, due to bad exposure. The carbonate fluctuation pattern is very similar to that occurring in the underlying segment (Fig. 3, 9). The LCO of *G. subquadratus* occurs in cycle 53, and the LO of *P. siakensis* is in the grey marly layer of cycle 37, at the astronomical ages of 11.54 and 11.21 Ma, respectively (Tab. 2).

In the uppermost cycles (39-33), the fluctuations of analytical and filtered *Globigerinoides* curves suggest the presence of two extra-cycles, one in cycle 38 and one in cycle 35 (Fig. 8).

Tuning of climate sensitive proxy records

The periodic fluctuations recorded in the faunal (*Globigerinoides*) and carbonate content were processed by spectral analysis. The Fourier Transformation Function was applied to the autocorrelation function (Jenkins & Watts 1968) of an equally spaced sequence of data in the original record, for which a constant sediment accumulation rate is supposed. Results of spectral methodologies combined with the lithological patterns, showed that the classic Milankovitch periodicity can be represented through the modulation forcing of the studied sedimentary record (Shackleton & Crowhurst 1997).

The spectrum interpretation is firstly based on the elementary cycles (precessional forced) recognised in the section (Fig. 9). The detailed study of the cycle thickness throughout the different subsections (Fig. 8), provided an average thickness of 60-70 cm for the cycles of the Cemetery section and of 35-50 cm for the Castle section (Fig. 8). As a consequence, cycles 91, 92 (Cemetery section) and cycles 63, 64 (Castle section), effectively represent the elementary cycles (Fig. 8). Secondly, the interpretation of the power spectral analysis of the *Globigerinoides* and $CaCO_3$ content was realised assuming two different sedimentation rates calculated for the Cemetery and Castle sections (57 cm/21ky and 48 cm/21ky, respectively) and using two tie points previously astronomically calibrated by Hilgen et al. (2000b) at 12.539 (LCO of *G. subquadratus* in -72 cycle) and 11.799 (abrupt decrease of *P. partimlabiata*, in -80 cycle) Ma, respectively. These two biostratigraphic events were recognised in the middle part of the S. Nicola composite section at 28.89 m in cycle 53 and at 22.17 m in cycle

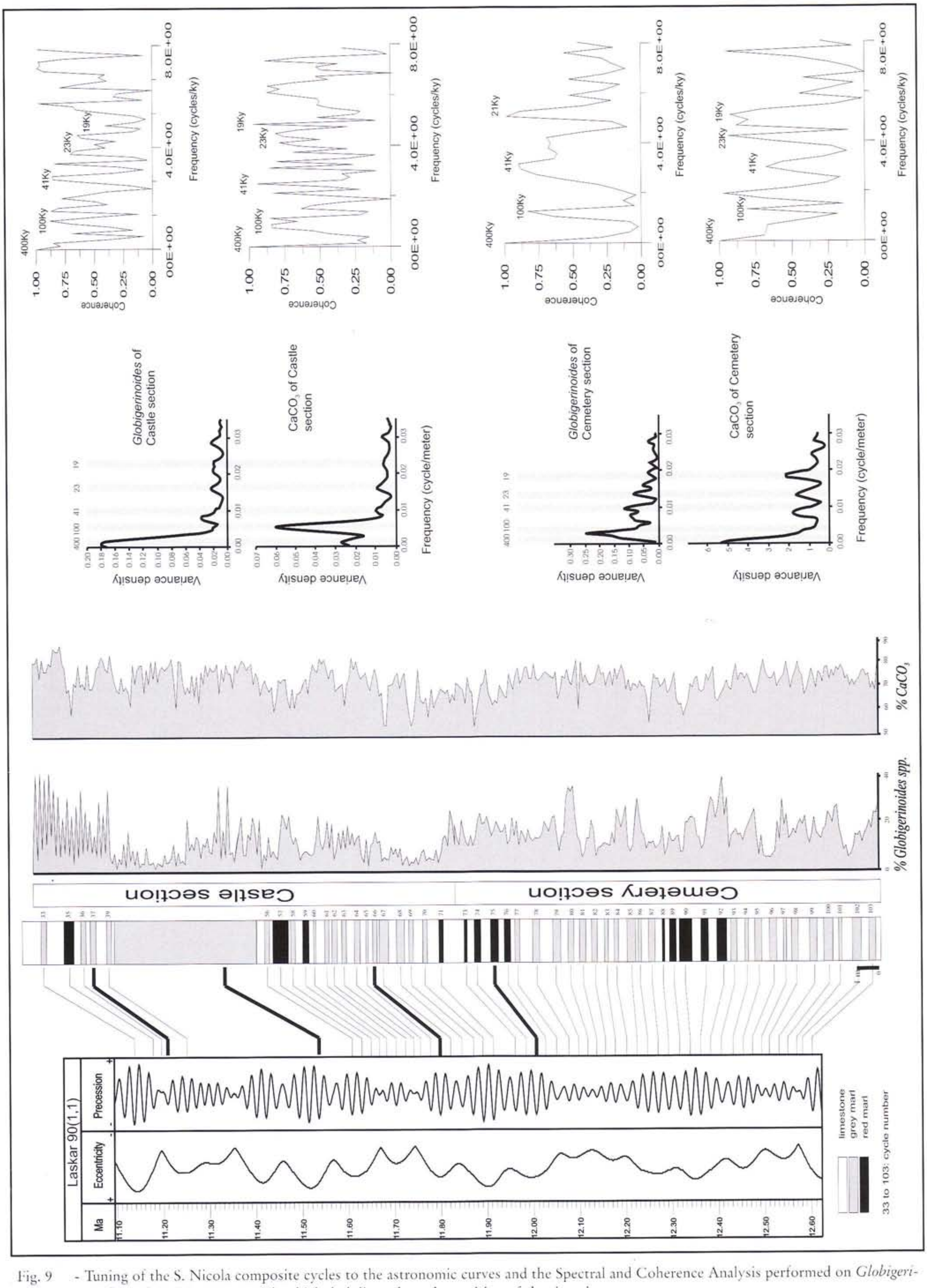


Fig. 9 - Tuning of the S. Nicola composite cycles to the astronomic curves and the Spectral and Coherence Analysis performed on *Globigerinoides* and $CaCO_3$ content. The thick dark lines show the position of the tie points.

Species	Event	Cycle	Position(m)	Age	Section
Planktonic foraminifera:					
Neogloboquadrina atlantica atlantica	FO	34	36,39	11,16	Castle
Paragloborotalia siakensis	LO	37	34,49	11,21	Castle
Globigerinoides subquadratus	LCO	53	28,89	11,54	Castle
Globigerinoides obliquus obliquus	FRO	53	28,69	11,54	Castle
Neogloboquadrina atlantica preatlantica	FO	66	22,17	11,80	Castle
Neogloboquadrina acostaensis	FO	66	22,17	11,80	Castle
Paragloborotalia partimlabiata	LO	66	22,17	11,80	Castle
Catapsydrax parvulus	FCO	66	22,17	11,80	Castle
Paragloborotalia siakensis	AE	75	17,2	12,00	Castle/Cemetery
G. decoraperta gr.	FCO	81	13,1	12,14	Castle/Cemetery
Paragloborotalia mayeri	LO	81	13,1	12,14	Castle/Cemetery
Paragloborotalia mayeri	FCO	90	8,1	12,34	Cemetery
Paragloborotalia siakensis	AB	92	6,9	12,38	Cemetery
Calcareous nannofossils:					
Coccolithus miopelagicus	LCO	35	35,29	11,18	Castle
Discoaster kugleri	LCO	56	27,29	11,60	Castle
Discoaster kugleri	FCO?	71	19,20	11,90	Castle
Calcidiscus macintyrei	FCO	90	8,2	12,34	Cemetery
Calcidiscus premacintyrei	LCO	98	3,6	12,51	Cemetery
Calcidiscus macintyrei	FO	101	1,7	12,57	Cemetery

Tab. 2 - Stratigraphic position and astronomical ages of the calcareous plankton events.

66, respectively (Tab. 1, 2).

The frequency mode recorded in the spectra of *Globigerinoides* and $CaCO_3$ proxy records of the S. Nicola composite section (Fig. 9), shows very similar features. High variance density occurs at 2.27 and 1.56 cycles/meter (Fig. 9). The values correspond to 0.64 and 0.44 m, respectively. These values have been recorded both in the *Globigerinoides* and in the $CaCO_3$ spectra. According to the sedimentation rate they are interpreted as corresponding to the precessional cycle range (23

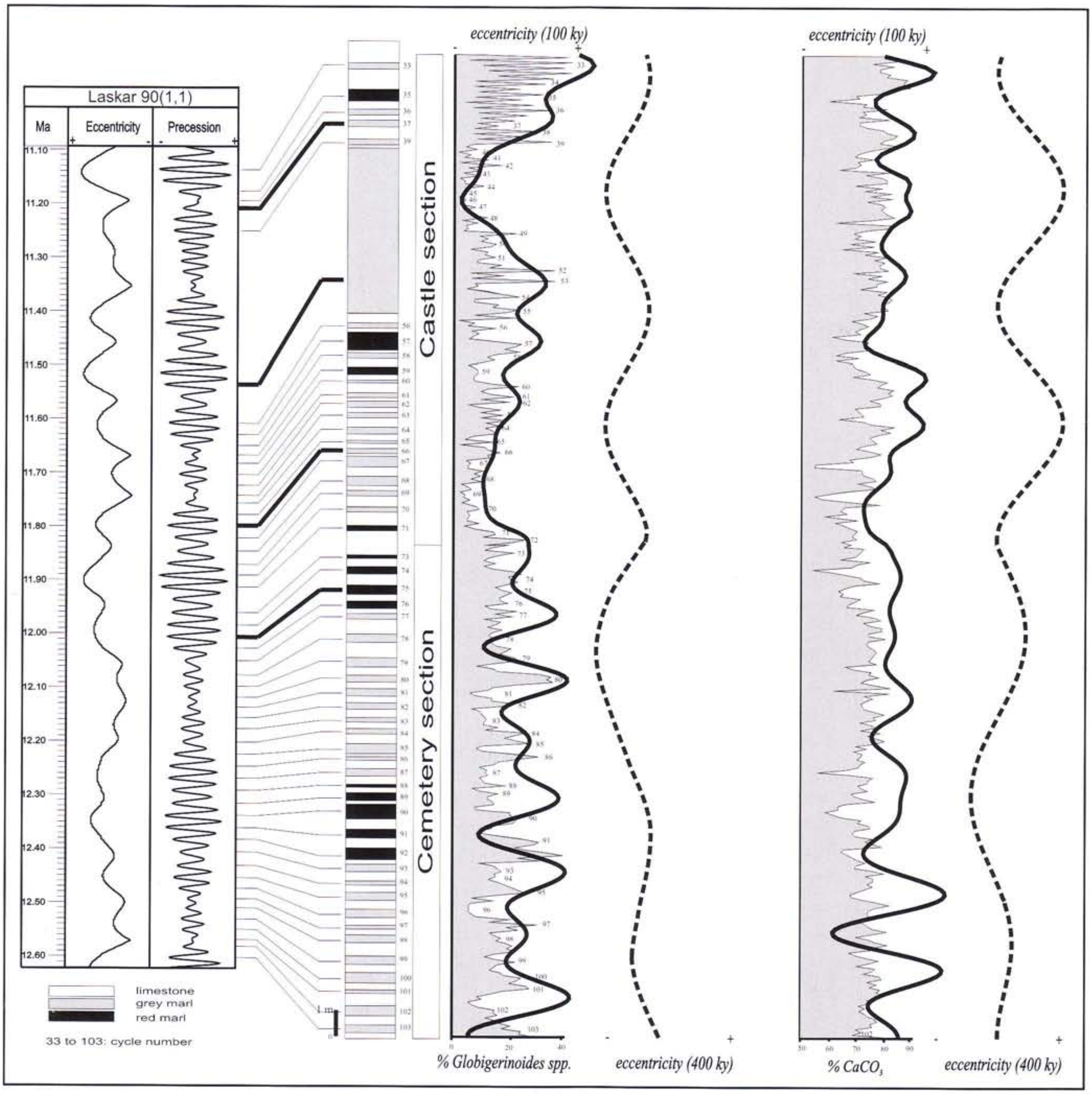


Fig. 10 - Comparison between the original data of *Globigerinoides* and $CaCO_3$ content with the same proxies filtered in the 400 ky (dashed line) and 100 ky (heavy line) eccentricity bands.

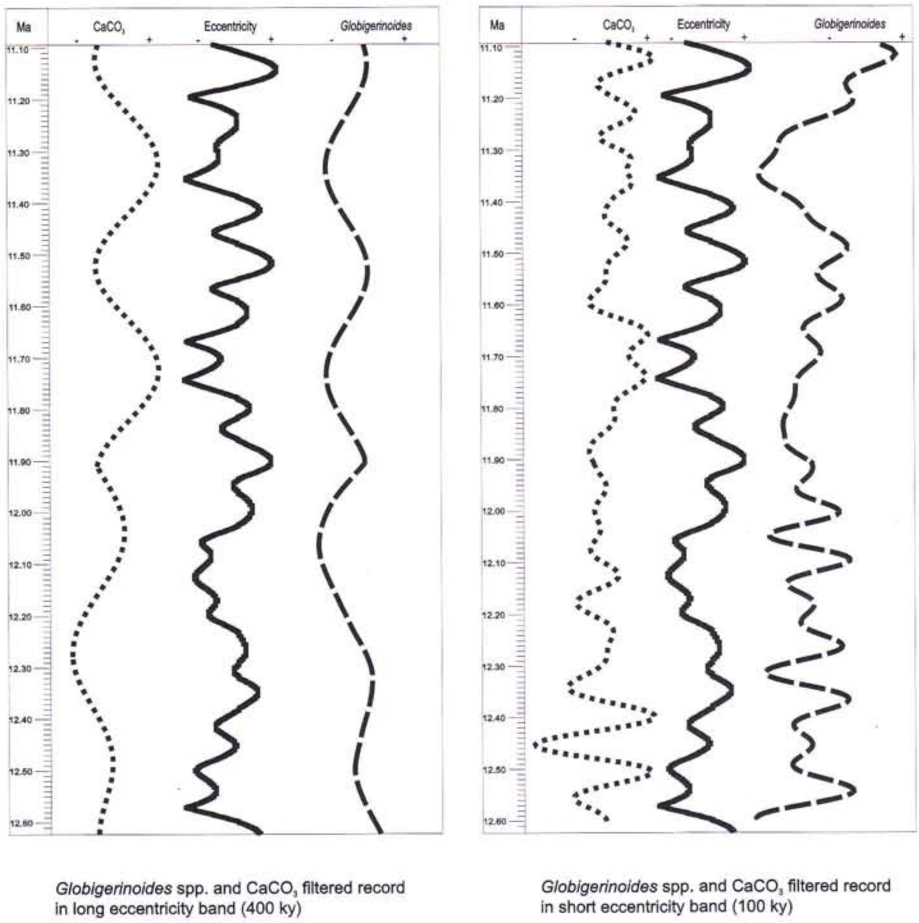


Fig. 11 - Comparison between the *Globigerinoides* and $CaCO_3$ content filtered data in the 400 ky and 100 ky eccentricity bands with the astronomic curve of eccentricity.

to 19 ky). These data were confirmed by the thickness of the lithologic elementary cycle recorded in the composite section (Fig. 9). The other main peaks, with high variance density at 9.38, 5.47 and 7.81 cycles/meter, were interpreted as corresponding to obliquity and eccentricity (100 and 400 ky) periodicity, respectively (Fig. 9).

Different band pass filters were applied to extract selected long and short-eccentricity frequency from the original faunal and geochemical time series. Each filtered signal was compared with the same harmonic component recognised in the astronomical curve of Laskar et al. (1993) and with the sedimentary cycles, producing a first order calibration of the studied sequence (Fig. 10). This procedure provides the reliability of the successive calibration cycle to cycle and the precessional cycles recognised in the filtered climate sensitive records. For more details see Sprovieri M. et al. (2002).

According to Shackleton & Crowhurst (1997) the most appropriate method for evaluating the reliability of our tuning is the complex demodulation process or other means like band-pass filtering. These procedures could be a useful tool for calibrating sedimentary sequences characterised by high variance concentrated in the precession frequency band (Shackleton et al. 1995; Shackleton & Crowhurst 1997; Sprovieri M. et al. 2002). In this work we used the band-pass filtering procedure.

To prove the correctness of the sequence of the filtered precessional signals, the *Globigerinoides* and carbonate values were subsequently filtered in the eccentricity frequency band (100-400 kyr) and compared with the amplitude of the astronomic eccentricity (Laskar et al. 1993).

The results of this procedure carried out on the *Globigerinoides* and $CaCO_3$ records are shown in Fig. 11. A good match visually exists between the amplitude modulation of the *Globigerinoides* and $CaCO_3$ data filtered in the short and long-eccentricity bands with the same harmonic components than the orbital eccentricity. This visual match is confirmed by coherence analysis between the two proxy and the astronomic data (Fig. 9), which show high coherence values for the eccentricity and precession frequency bands.

At the level of the 400 ky, it seems likely that the tuning is correct over the whole interval, because the amplitude of the signal as demodulated, appears to rise every 400 ky, and clearly confirms the well know phase relation carbonate content minima/eccentricity maxima, and eccentricity maxima/*Globigerinoides* maxima (Fig. 11). At level of 100 ky (component of the eccentricity) there is a slight mismatch between the upper and lower part of the section, suggesting that a small change in the sedimentation rate occurs (Fig. 11).

The filtering of *Globigerinoides* and carbonate content in the precession frequency bands and the correlation with the precession curve produce a most complete calibration of our proxy (Fig. 12).

Correlation cycle by cycle to the insolation curve of Laskar et al. (1993) allowed us to attribute an astronomic age to all cycles and consequently to the identified calcareous plankton bioevents (Tab. 1, 2).

Conclusions

The sedimentary cyclicity combined with the spectral analysis and the filtering procedures carried out on the S. Nicola composite section, allowed the recognition of the astronomical precession periodicity. We could also confirm that the *Globigerinoides* abundance is ultimately controlled by Earth's orbital cycles (Sprovieri 1992, 1993), as well as the sedimentary cycles (Hilgen et al. 1997).

The astronomical calibration of the identified cycles provides absolute ages for all the calcareous plankton bioevents (planktonic foraminifera and nannofossils). They are well comparable with the astrochronological data recently published for the Mediterranean region in coeval sediments (Hilgen et al. 2000b).

In particular, an age of 11.21 Ma and 11.80 Ma for the LO of *P. siakensis* (= *P. mayeri* of Hilgen et al. 2000b) and the FO of *N. acostaensis*, respectively were obtained. These ages are in agreement with the age 11.205 ± 0.004 Ma and 11.781 ± 0.002 Ma given by Hilgen et al. (2000b) in M. Gibliscemi section, for the LO of *P. mayeri* and the FO of *N. acostaensis*. The obtained astronomical ages are younger and older, respectively than those obtained by Turco et al. (2002) at Ceara Rise (Leg 154, Site 926A, Equatorial Atlantic Ocean). Therefore the LO of *P. siakensis* and the FO of *N. acostaenis* are diachronous and cannot be considered

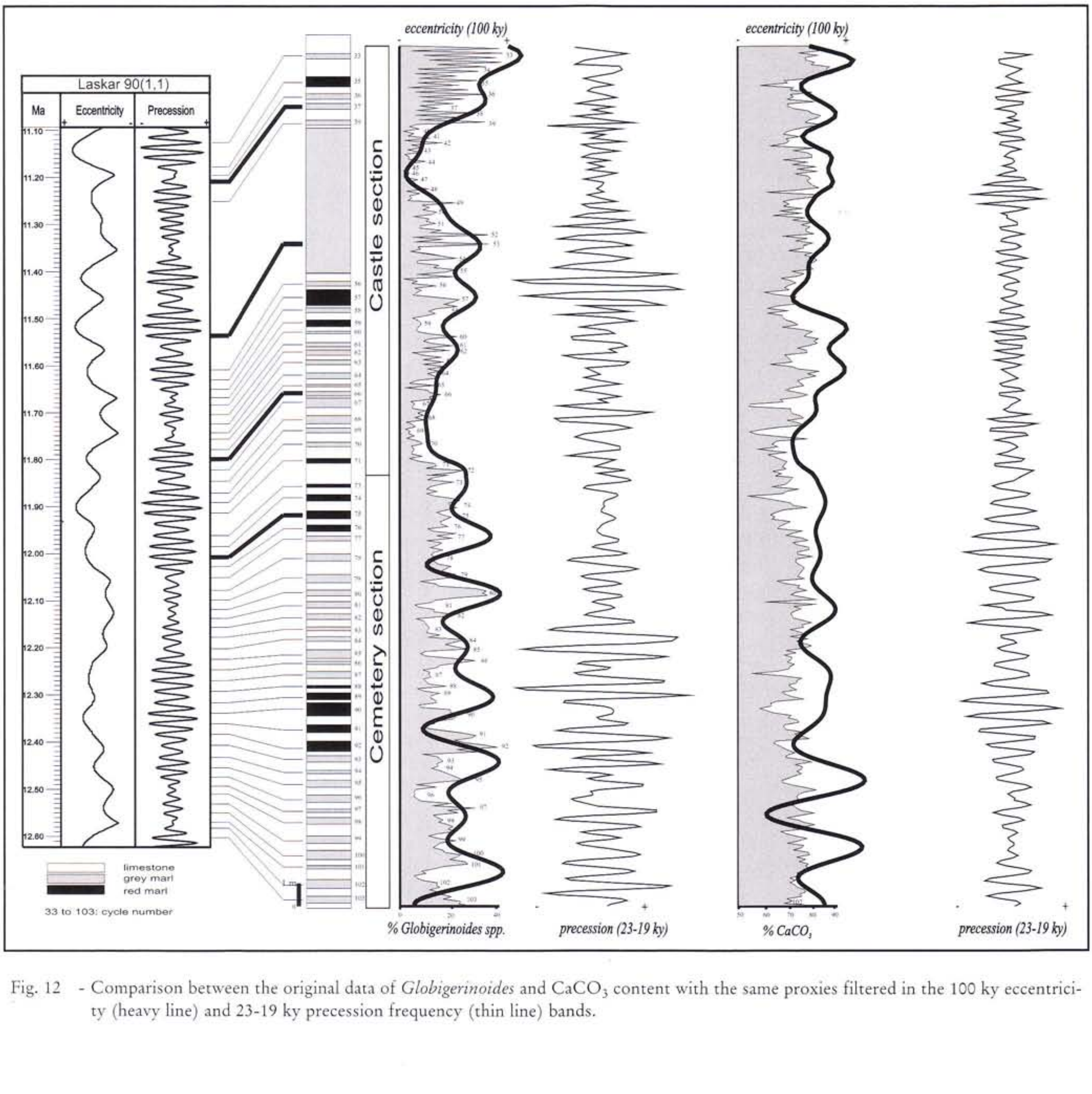


Fig. 12 - Comparison between the original data of *Globigerinoides* and $CaCO_3$ content with the same proxies filtered in the 100 ky eccentricity (heavy line) and 23-19 ky precession frequency (thin line) bands.

potential bioevents for recognising the Tortonian/Serravallian boundary (Foresi et al. 1998; Hilgen et al. 2000b; Iaccarino et al. 2001).

An age of 11.54 Ma for the LCO of *G. subquadratus* was obtained. This astronomic age, results similar to that (11.53 Ma) obtained by Turco et al. (in press) at Ceara Rise (Leg 154, Site 926A, Equatorial Atlantic Ocean). This astronomic age, makes the LCO of *G. subquadratus*, a potential candidate to define the Serravallian/Tortonian boundary (Lirer et al. 2001; Turco et al. in press).

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