Cyclostratigraphy and astrochronology of the Tripoli diatomite formation (pre-evaporite Messinian, Sicily, Italy)

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ABSTRACT

The ongoing debate about the Messinian salinity crisis in the Mediterranean is fuelled in part by the lack of an adequate time control. The most accurate and, at the same time, detailed constraints are nowadays provided by the astronomical dating technique. Here we present an astronomical age model for the cyclically bedded Tripoli diatomite Formation on Sicily (pre-evaporite Messinian, Italy) based on an integrated stratigraphic study of three key-sections, Falconara, Gibliscemi and Capodarso. Characteristic sedimentary cycle patterns allow (i) the sections to be cyclostratigraphically correlated, the 'bed-to-bed' correlations being confirmed by high-resolution planktonic foraminiferal biostratigraphy, and (ii) the Tripoli cycles to be calibrated to the astronomical record. Despite minor misfits the correctness of the tuning is evident from the match between precession-obliquity interference in the astronomical target and its reflection in the sedimentary cycle record. The tuning provides absolute astronomical ages for all sedimentary cycles and planktonic foraminiferal events. The baes of the Tripoli is astronomically dated at 7.005 Ma, indicating that the onset of diatomite formation is diachronous in the Mediterranean since it started 300 000 years earlier on Sicily than on Gavdos, south of Crete. The top of the Tripoli, and thus the onset of the salinity crisis proper on Sicily, arrives at 5.98 Ma.

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Introduction

On Sicily, cyclically bedded diatomites of the Tripoli Formation stratigraphically underlie limestones and evaporites of the Gessoso-Solfifera Formation deposited during the Messinian salinity crisis in the Mediterranean. The age of the Tripoli (cf. Gautier *et al*., 1994; Butler *et al*., 1995; Clauzon *et al*., 1996; McClelland *et al*., 1996; Sprovieri *et al*., 1996a; Vai, 1997) and origin of the cyclic bedding remains highly controversial despite intensive study. Partly opposing scenarios explaining the cyclic diatomite formation include intensification of Atlantic inflow (due to glacio-eustatic sea-level lowering: Van der Zwaan and Gudjonsson, 1986), periodic upwellings (Gersonde, 1980; Thunell *et al*., 1984), surface water warming (Broquet *et al*., 1981), enhanced continental run-off (Meulenkamp *et al*., 1979), global sea-level rise in combination with enhanced upwelling (McKenzie *et al*., 1979) and pulsating tectonics (Pedley and Grasso, 1993).

Notwithstanding this, irrespective of the age of the Tripoli and the exact origin of the cyclic bedding, the substitution of sapropel cycles by Tripoli diatomite cycles points to an orbital control on the sedimentary cyclicity since sapropels are controlled astronomically (Hilgen *et al*., 1995; Sprovieri *et al*., 1996a). Here we further explore the astronomical link by investigating three classical Tripoli sections in detail, using an integrated cyclostratigraphic and planktonic foraminiferal biostratigraphic approach. In particular, we aim to ascertain the correlation potential of the sedimentary cyclicity and its capability of providing absolute ages for the Tripoli by tying characteristic sedimentary cycle patterns to astronomical target curves. Elaborating the astronomical link is expected to have far-reaching consequences for models proposed to explain the origin of the cyclic bedding in the Tripoli.

Setting and sections

We selected the Falconara, Gibliscemi and Capodarso sections because they occupied relatively distal basinal positions while tectonic deformation due to postdepositional thrusting in the direction of the African foreland is moderate compared with other Tripoli sections (see Fig. 1 for locations). The Falconara section was proposed as a potential Tortonian/Messinian boundary stratotype by Colalongo *et al.* (1979) and is located on southern Sicily, 3.5 km NW of Falconara castle between Licata and Gela. The Gibliscemi section is located 25 km east of Falconara and is known for its extraordinary succession of sapropel-bearing marls of the Licata Formation ('Argille di Licata') which underlie the Tripoli diatomites and have been employed to extend the astronomical timescale into the Middle Miocene (Hilgen *et al*., 1995). Capodarso represents the neostratotype section for the Messinian stage (Selli, 1960). The section is located on central Sicily along the NW flank of Monte Capodarso, 45 km north of Falconara (Fig. 1).

Integrated biostratigraphy and cyclostratigraphy

A quantitative biostratigraphic analysis of the planktonic foraminifera was carried out on section Falconara in order to pinpoint accurately the position of bio-events relative to the sedimentary cyclicity (Fig. 2). Planktonic foraminifera were routinely analysed in a qualitative way to check the position of events in sections Gibliscemi and Capodarso.

Monte Gibliscemi is the most suitable section to study the transition from the sapropel-bearing marls of the Licata Formation to the Tripoli diatomites. The Tortonian–Messinian boundary as evidenced by the First Regular Occurrence (FRO) of the *Globorotalia miotumida* group (*sensu* Sierro, 1985) is located just above the low-angle shearplane that marks a significant hiatus of 270 kyr in the upper part of the Licata Fm. (Hilgen *et al*., 1995; Krijgsman *et al*., 1995). Above the hiatus, 10 more sapropels are found up to the level where the first Tripoli diatomite bed is

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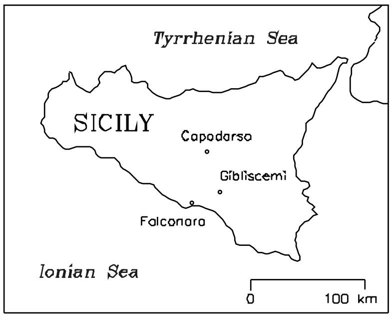

Fig. 1 Location map of the sections. For more details, see Colalongo *et al.* (1979) and Krijgsman *et al.* (1995).

observed. The basic sedimentary cycle of the Tripoli is tripartite and consists of a homogeneous greenish coloured marl followed by a reddish-brown laminite (sapropel) and capped by a white laminite (diatomite). Field observations reveal how the tripartite cycles of the Tripoli evolve from the bipartite sapropel cycles of the Licata Fm., which consist of homogeneous marl–sapropel alternations. Sapropels in the upper part of the Licata Fm. have a whitish diatomaceous top; this is replaced by diatomites in the Tripoli. At Gibliscemi, the tripartite cycles replace the bipartite sapropel cycles of the underlying Licata Formation over a short stratigraphic interval.

A detailed comparison with other Mediterranean sections (Krijgsman *et al.*, 1995, 1997) shows that despite some tectonic deformation no cycles are missing at Gibliscemi between the FRO of *G. miotumida* and the First Occurrence (FO) of *Globorotalia nicolae*, which occurs in the Tripoli cycle no. 9 (T9). The absence of deformation directly above the level of the *G. nicolae* FO implies that the succession is essentially continuous up to cycle T11. No attempt has

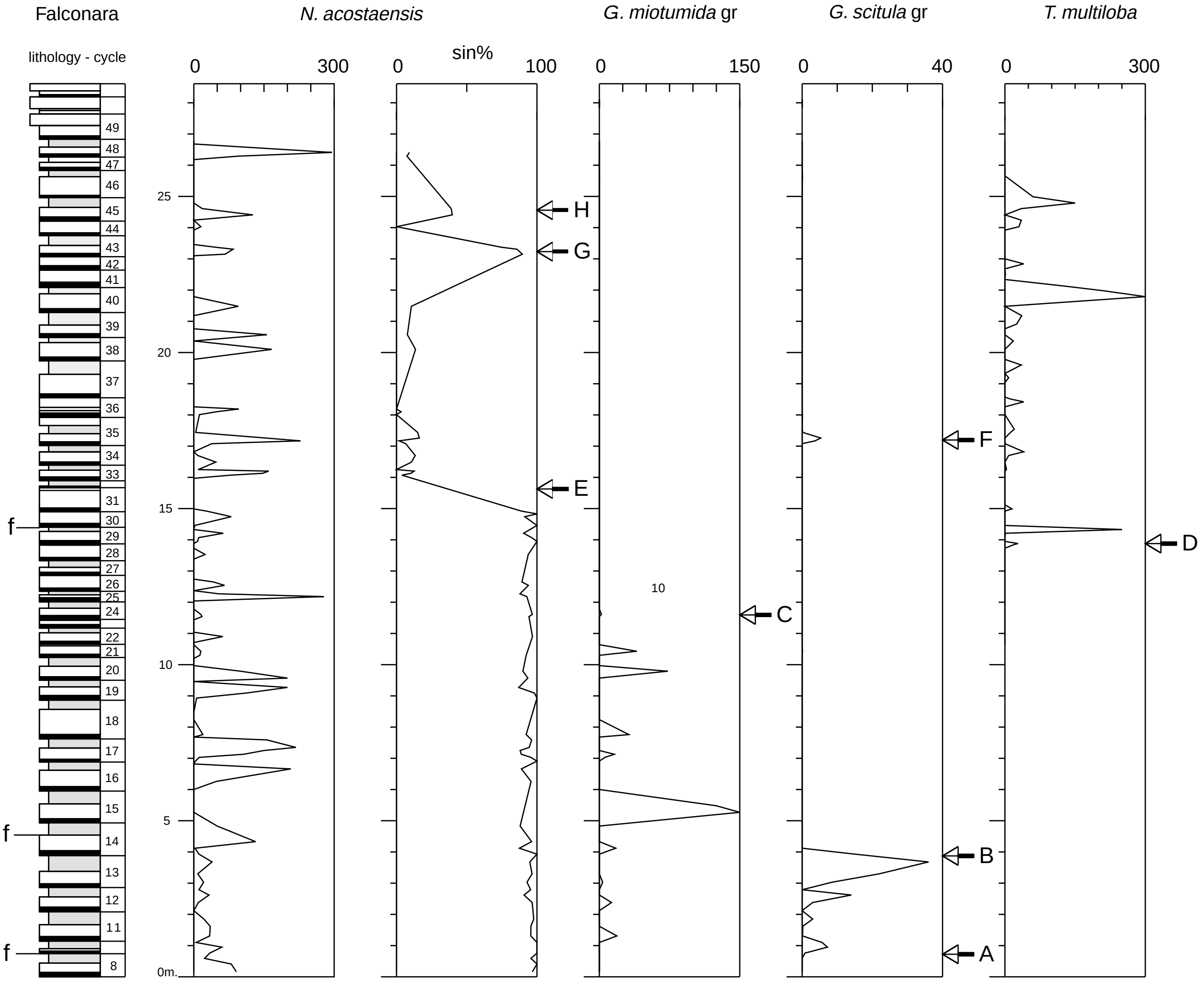

Fig. 2 Cyclostratigraphy and planktonic foraminiferal biostratigraphy of the Tripoli Fm. in the Falconara section, southern Sicily. Biostratigraphic data of marker species represent (average) number of specimens per field in a rectangular picking tray after surveying a standard number of fields (10 out of 45) containing between 300 and 400 foraminifera per field. Biostratigraphic events are indicated in stratigraphic order: (a) *G. nicolae* FO; (b) *G. nicolae* LO; (c) *G. miotumida* group LO; (d) *T. multiloba* FCO; (e) *N. acostaensis* S/D coiling change; (f) *G. scitula* influx; (g) *N. acostaensis* sinistral influx (up to 90%), and; (h) *N. acostaensis* sinistral influx (up to 40%). Tripoli diatomite cycle number refers to the total cycle number in the Tripoli Fm., including the older cycles in section Gibliscemi. Comparison with other Mediterranean sections and section Gibliscemi reveals that cycle T9 is missing at Falconara due to tectonic disturbance. Sapropels are often deformed as a consequence of shearplanes parallel to the bedding. Two shearplanes run (partly) oblique to the bedding eliminating cycles T14 and T29 on the eastern side of the sampled gully.

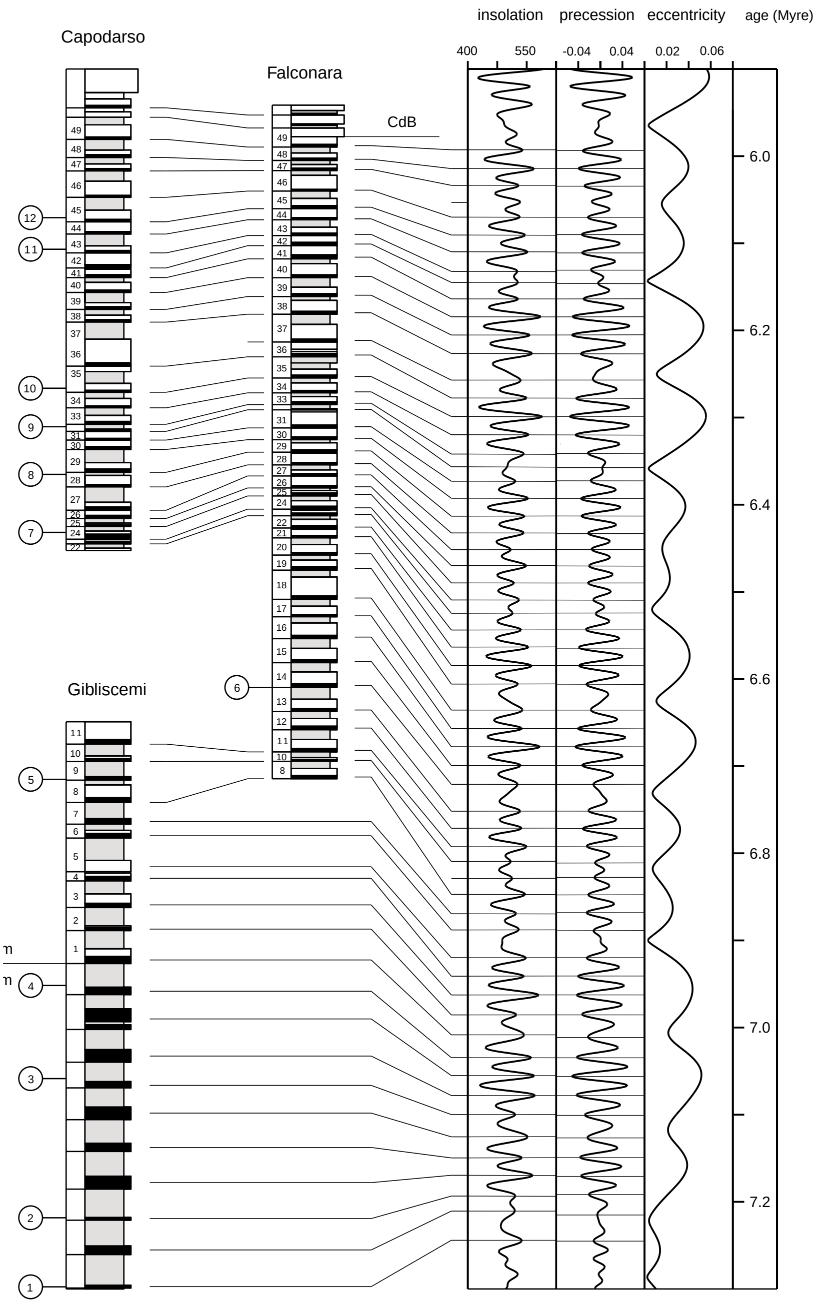

Fig. 3 Cyclostratigraphy and astronomical calibration of the Tripoli diatomite cycles in sections Gibliscemi, Falconara and Capodarso. Planktonic foraminiferal events have been numbered in stratigraphical order: (1) *G. miotumida* group FRO; (2) G. *miotumida* influx conical types; (3) dominantly left coiling *G. scitula* LO; (4) temporary disappearance *G. scitula* group; (5) *G. nicolae* FO; (6) *G. nicolae* LO; (7) *G. miotumida* group LO; (8) *T. multiloba* FCO; (9) *N. acostaensis* S/D coiling change; (10) *G. scitula* influx; (11) *N. acostaensis* sinistral influx (up to 90%), and; (12) *N. acostaensis* sinistral influx (up to 40%). The astronomical curves are based on the solution of Laskar (1990) and Laskar *et al.* (1993) with present-day values for tidal dissipation by the moon and dynamical ellipticity of the earth ($La90_{(1,1)}$).

been made to extend the log further upwards because of the strong deformation observed higher in the succession. Moreover, the logged interval overlaps already with the much better exposed–and less deformed–Tripoli at Falconara, as evidenced by the mutually recorded *G. nicolae* FO (Fig. 3).

Our Falconara section starts with Tripoli cycle 8 and contains 41 cycles. Not all cycles, however, show the (ideal) tripartition because homogeneous marls/clays are lacking in a number of cycles (10). Another salient feature is the occasional alternation of thin (or absent) and thick beds. This holds both for the diatomites (cycles T22 to T30, and T38 to T40) as well as for the homogeneous marl/clay beds (cycles T20 to T24, T25 to T30, T37 to T40 and T42 to T46). The tripartite cycles are replaced by carbonate cycles of the Calcare di Base in the top part of the section. The Calcare represents the basal member of the Gessoso-Solfifera Formation (Decima and Wezel, 1973).

Only the upper part of the Tripoli is exposed at Capodarso although trenching uncovered an additional 6 cycles. Nevertheless, the same characteristics, i.e. 'tripartite' cycles occasionally lacking a homogeneous marl and alternating thin–thick patterns, are manifest. A comparison of the cycle patterns revealed one possible correlation between the Capodarso and Falconara sections (Fig. 4). This straightforward correlation is confirmed in detail by the planktonic foraminiferal biostratigraphy (Figs 2 and 3) and shows that section Capodarso contains Tripoli cycle T22–49. The cycles are thicker than in the Falconara section (average 64 cm compared with 59 cm at Capodarso). This difference is almost totally explained by increased thickness of the homogeneous marls at Capodarso.

In the recent literature, the cyclostratigraphic correlation potential of the Tripoli cycle patterns has not been recognized (Suc *et al.*, 1995) or fully employed (Sprovieri *et al.*, 1996b), and is even questioned or denied by some authors (Pedley and Grasso, 1993). Pedley and Grasso (1993) argue for a localized pulsating tectonic control of the cyclicity. According to these authors, each local basin is expected to have a cyclic signature (of its own) related closely but not necessarily identical to that of the adjacent basin. As a consequence of the local tectonic origin, the cyclic (their 'fourth-order') signals are likely to be nonsynchronous between basins. Contrary to our findings, Suc *et al.* (1995) state that lithological relationships are hard to establish between the Capodarso and Falconara sections.

The only studies that focus on cyclostratigraphic aspects of the Tripoli are by Sprovieri and coworkers (Sprovieri *et al.*, 1996a, b). Independently following the same line of reasoning outlined in Hilgen *et al.* (1995), they suggest that the Tripoli cycles are controlled by the astronomical precession cycle. They do not employ the characteristic cycle patterns themselves but concentrate instead on the number of cycles between successive biostratigraphic events, which is found to be the same in a number of Tripoli sections. Our cyclostratigraphic correlations also make it likely that the diatomite cycles are controlled astronomically.

Astronomical tuning

Sapropel patterns in the 'Argille di Licata' support a strong astronomical control (Hilgen *et al.*, 1995). The patterns, in combination with the results of multidisciplinary proxy studies (Nijenhuis *et al.*, 1996; Schenau *et al.*, 1999; see also Sprovieri *et al.*, 1996a), indicate that Miocene sapropels had the same origin as their younger Plio-Pleistocene counterparts, namely dominantly precession-controlled 'dry–wet' oscillations in (circum-)Mediterranean climate. As a consequence, sapropels have been used to extend the astronomical timescale into the Miocene by matching them to the astronomical record (Hilgen *et al.*, 1995).

The relationship between sapropels and Tripoli diatomites observed in the field cannot be explained other than by the supposition that the diatomites are astronomically controlled also and, hence, that they can be used for astronomical tuning. The observed relationships further indicate that the (sapropelitic base of the) laminites correspond to precession minima and summer insolation maxima, and that homogeneous marls correspond to precession maxima and insolation minima. The–additional–effect of obliquity on insolation results in interference patterns that correspond to thin (or absent)/thick alternations in the sedimentary cycles. Such interference patterns preferably develop at times of eccentricity minima when the precession amplitude is reduced. For our purpose, we employed the astronomical solution of Laskar (1990) and Laskar *et al.* (1993) with present-day values for tidal dissipation by the moon and dynamical ellipticity of the earth ($La90_{(1,1)}$). This solution yielded an excellent fit with sedimentary cycle patterns in the Mediterranean Plio-Pleistocene (Lourens *et al.*, 1996) and has subsequently been used to establish a late Miocene astronomical timescale for the interval from 6.7 to 12.2 Ma (Hilgen *et al.*, 1995; unpubl. data).

We used the positions of the first and last occurrences of *Globorotalia nicolae* as a starting point for our tuning exercise. These events are recorded in Tripoli cycle T9 and T14 and have previously been dated astronomically at 6.829 and 6.72 Ma (respectively) in sections located on Crete and in northern Italy (Hilgen *et al.*, 1995; Krijgsman *et al.*, 1997). Using these ages, all diatomite cycles were tuned to the $La90_{(1,1)}$ precession and summer insolation time series (Fig. 3).

Almost all cyclostratigraphic details show an excellent fit with the astronomical curves. In particular, thin/thick alternations in the homogeneous marls/clays mirror precession–obliquity interference patterns in insolation minima whereas thin/thick alternations in diatomites reflect interference patterns in insolation maxima. The alternating thin (or absent)/thick patterns in cycles T20 to T30 correspond to the prolonged interval of interference in the insolation target centred around the 400-kyr eccentricity minimum at 6.5 Ma. Cycles T30–31, T36, and T41–42 that lack a homogeneous marl, correspond to low-amplitude insolation minima largely related to 100-kyr eccentricity minima, whereas cycle T44 again reflects precession–obliquity interference. Finally, the extraordinarily thick cycles T18 and T37 correspond to asymmetric precession cycles having a longer than average periodicity of ~ 30 kyr.

There are only a few exceptions. The insolation time series predicts that cycle T46 rather than T44 lacks a homogeneous marl, and fails to explain the thinner homogeneous of cycle T38 and the absence of a homogeneous marl/clay bed in cycle T21. The extraordinary thickness of the diatomite of cycle T46 indicates that this cycle may well represent a double cycle in which a homogeneous marl and a sapropel are not developed. A small inaccuracy in the astronomical solution is the most likely explanation for the cycle T21 and T38 misfits because the (shifts in) interference patterns can be extremely sensitive to small changes in the astronomical solution. However, despite these (minor) misfits, we assume that the astronomical tuning of the Tripoli diatomite cycles is essentially correct. Ongoing research directed at improving the accuracy of the astronomical solution may result in minor modifications but will not seriously affect the tuning and, hence, the astronomical ages of the Tripoli formation.

Our astronomical calibration provides absolute ages for all sedimentary cycles and planktonic foraminiferal events (Tables 1, 2). Astronomical ages for the Tripoli base and top arrive at 7.008 and 5.98 Myr. The base of the diatomites in section Gibliscemi is 300,000-years older than the base of the diatomite succession on Gavdos (dated at 6.696 Myr; cycle M94 in Hilgen *et al.*, 1995; Krijgsman *et al.*, 1995), indicating that the onset of diatomite formation is diachronous in the Mediterranean. The Tripoli top dated at 5.98 Ma marks the onset of the main evaporite phase of the salinity crisis on Sicily. The synchroneity of this event on a Mediterranean scale is the subject of a separate paper (Krijgsman *et al.*, 1999).

Our age model deviates significantly from other models for the Tripoli diatomites (Gautier *et al.*, 1993; McClelland *et al.*, 1996; Sprovieri *et al.*, 1996a, b; Vai, 1997). These models, however, all lack the tight constraints provided by the detailed cyclostratigraphy used in the present study. Sprovieri *et al.* (1996a, b) do not take sedimentary cycle patterns into account in their astronomical age model and they employ climate proxy records of Atlantic DSDP site 552 to cover the interval marked by the Messinian evaporites in the Mediterranean. This site, however, is less suitable for astronomical tuning because it lacks the multiple holes necessary to overcome serious problems encountered at core breaks (see Ruddiman *et al.*, 1986).

Finally, the astronomical link has far-reaching implications for models trying to explain Tripoli diatomite formation. For instance, glacio-eustatic sealevel variations are not involved primarily because glacial cyclicity was dominantly obliquity-controlled during the Messinian (Hodell *et al.*, 1994) whereas the Tripoli diatomite cycles are dominantly precession-controlled (see also Sierro *et al.*, 1999). The dominance of precession in controlling the cyclicity rather points to a regional climate-for-

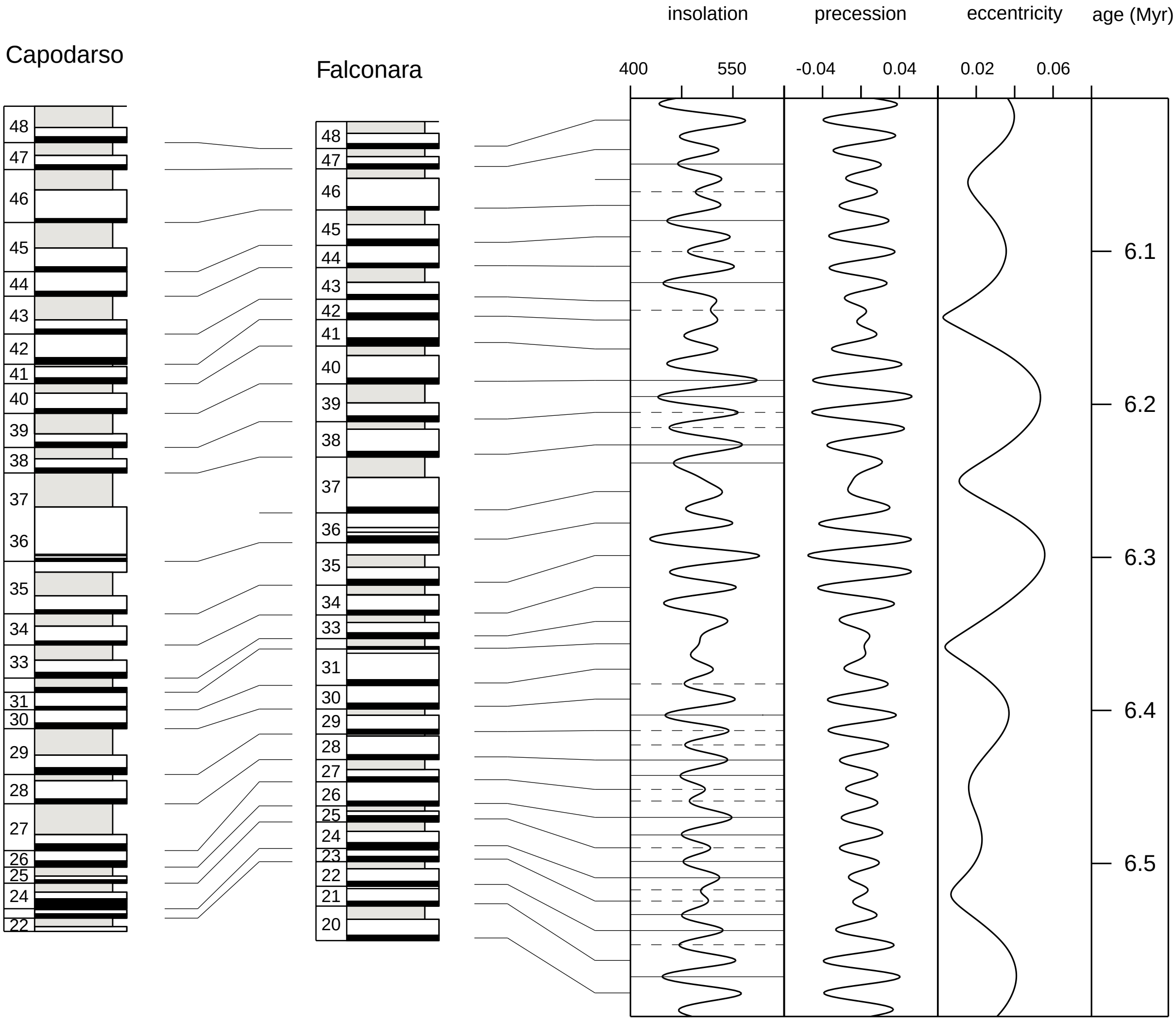

Fig. 4 Astronomical tuning for cycle T20 to T48 of the Tripoli Fm. in the Falconara and Capodarso sections showing details of the tuning of alternating thin–thick beds of diatomites and marls in successive cycles to precession–obliquity interference patterns in the astronomical target. Solid horizontal lines crossing the insolation curve mark diatomite and marl beds of increased thickness, dashed lines mark beds of reduced thickness. For further explanation see text.

Table 1 Astronomical ages for sapropel mid-points of the Tripoli diatomite cycles without time lag between insolation maxima and sapropels mid-points as employed in earlier studies

Cycle	Age	Cycle	Age	Cycle	Age	Cycle	Age	Cycle	Age
T10	6.810	T20	6.585	T30	6.393	T40	6.184		
T9	6.829	T19	6.606	T29	6.413	T39	6.205	T49	5.993
T8	6.847	T18	6.635	T28	6.432	T38	6.226	T48	6.015
T7	6.869	T17	6.657	T27	6.452	T37	6.257	T47	6.034
T6	6.887	T16	6.678	T26	6.470	T36	6.278	T46	6.070
T5	6.920	T15	6.699	T25	6.490	T35	6.299	T45	6.091
T4	6.941	T14	6.721	T24	6.509	T34	6.320	T44	6.110
T3	6.963	T13	6.752	T23	6.524	T33	6.342	T43	6.132
T2	6.985	T12	6.771	T22	6.544	T32	*	T42	6.145
T1	7.008	T11	6.792	T21	6.563	T31	6.373	T41	6.164

Table 2 Ages of planktonic foraminiferal events in section Falconara based on the astronomical ages of the sapropel midpoints in combination with linear interpolation of sedimentation rate

Species	Event	Age (Myr)
N. acostaensis	sin. influx (40%)	6.087
N. acostaensis	sin. influx (90%)	6.126
G. scitula	influx (dex)	6.295
N. acostaensis	S/D coiling change	6.337
T. multiloba	FCO	6.415
G. miotumida gr.	LO	6.506
G. nicolae	LO	6.722

cing mechanism similar to that proposed for sapropels. The observation that thin/thick alternations in diatomite beds follow precession–obliquity interference patterns in insolation maxima suggests that deposition of Tripoli diatomites is related causally to sapropel formation. A possible scenario includes nutrient storage at times of sapropel formation followed by nutrient release when the density stratification of the water column becomes (seasonally) interrupted (Sierro *et al.*, 1999). Such a mechanism is consistent with the observed relationship between sapropels and diatomites in the field.

The observation that laminite formation may persist through a precession-controlled sedimentary cycle has important consequences for deciphering the palaeoclimatic and palaeoceanographic significance of laminites and diatomites. Such reconstructions, however, are far beyond the scope of the present paper which aimed at the cyclostratigraphic correlation potential and the astronomical dating of the Tripoli diatomite Formation on Sicily.

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