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, Giblisicemi 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 bases 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; Clauzun et al., 1996; McClelland et al., 1996; Sprovieri et al., 1996a; Vai, 1997) and origin of the cyclic bed remains highly controversial despite intensive study. Partially opposing scenarios explaining the cyclic diatomite formation include intensification of Atlantic inflow (due to glacio-eustatic sea-level lowering: Van der Zwaan and Gudjonsen, 1986), periodic upwellings (Gersende, 1980; Thunell et al., 1984), surface water warming (Broquet et al., 1985), 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 cycle 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, Giblisicemi 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 Giblisicemi 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 neostate formation 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 Giblisicemi and Capodarso. Monte Giblisicemi 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 Sierr, 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
observed. The basic sedimentary cycle of the Tripoli is tripartite and consists of a homogeneous greenish coloured marl followed by a reddish-brown laminitate (sapropel) and capped by a white laminitate (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 Gibilsemci, the tripartite cycles replace the bipartite sapropel cycles of the underlying Licata Fm. 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 Gibilsemci 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

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

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**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. multioba 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 Gibilsemi. Comparison with other Mediterranean sections and section Gibilsemi 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.
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. nicolaе* 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 tripartition 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 biorstratigraphy (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 (Sprøvieri 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

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. scutula* LO; (4) temporary disappearance *G. scutula* group; (5) *G. nicolaе* FO; (6) *G. nicolaе* LO; (7) *G. miotumida* group LO; (8) *T. multiloba* FCO; (9) *N. acostaensis* S/D coiling change; (10) *G. scutula* 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)).

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.

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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) laminates correspond to precession minima and summer insolation maxima, and that homoge- neous 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 (La901,1). 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 nicolai 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 La901,1 precession and summer insolation time series (Fig. 3).

Almost all cyclostratigraphic details show a remarkably good 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 Giblisem 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 synchronicity 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 Siervo 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

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<td>6.205</td>
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<td>6.792</td>
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<td>6.563</td>
<td>T31</td>
<td>6.373</td>
<td>T41</td>
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cing mechanism similar to that proposed for sапропел formation. The observation that thin-thick alternations in diatomites follows a progression-obliquity interference patterns in insolations maxima suggests that deposition of Triopoli diatomites is related causally to sапропел 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 (Sierr et al., 1999). Such a mechanism is consistent with the observed relationship between sapropels and diatomites in the field.

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

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