

The Trave section (Monte dei Corvi, Ancona, Central Italy): an integrated paleontological study of the Messinian deposits

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ABSTRACT: The paleontologic data (calcareous nannofossils, foraminifers, ostracods, molluscs and pollen) of the Trave section (south of Ancona, central Italy) are presented in order to describe the fossil content of the pre-evaporitic and post-evaporitic units and evaluate the paleoenvironmental evolution of the sedimentary deposits from the Tortonian/Messinian boundary to the top of the Messinian.

Several calcareous plankton bio-horizons astronomically calibrated, temporally constrain the pre-evaporitic sequence between 7.44 Ma (FO of *Amaurolithus primus*) and 6.35 Ma (sinistral to dextral coiling change in *Neogloboquadrina acostaensis*). Resedimented evaporites mark the base of the post-evaporitic sub-unit p-ev₁ (5.6 Ma) which is overlain by the cyclic stacking pattern of p-ev₂ sub-unit. The MPI 3 zone of the Zanclean seals the section. The paleontological record of the post-evaporitic interval allows to verify that the p-ev₁/p-ev₂ boundary defined in terms of facies is well recognizable also in terms of bioevents; in fact, a Lago Mare low diversity assemblage first occurs a few meters below the boundary, while the first occurrence of *Loxocorniculina djafarovi*, continuously present all along the p-ev₂, is observed above it. A second change in the overall assemblage is recorded a few meters above the physical boundary, where the ostracod assemblage diversifies and Parathetyan dinocysts appear.

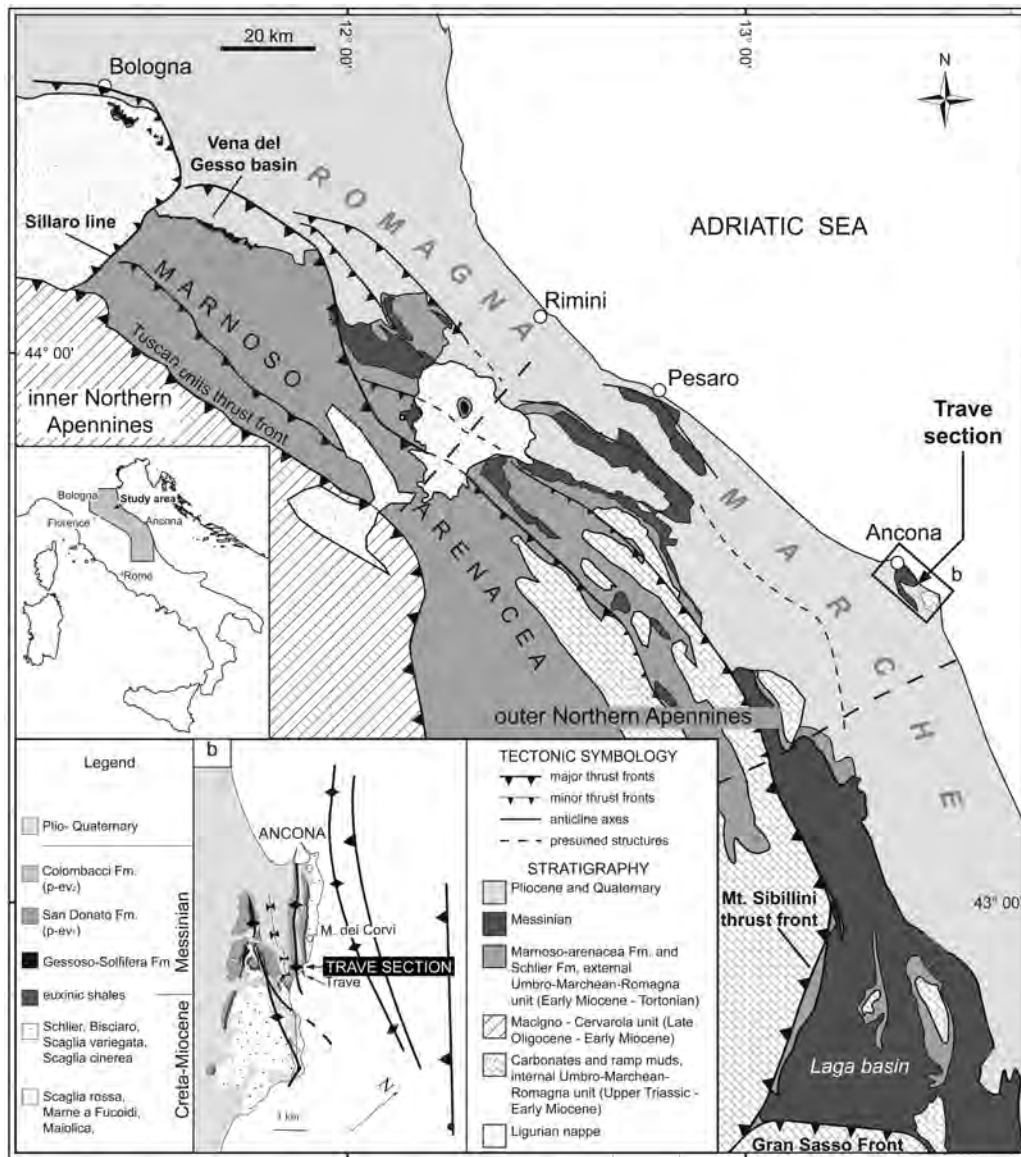
The open marine conditions during the late Tortonian gradually turned into the poor oxygenated water masses of the early Messinian (deposition of organic-rich layers) under a prevalent humid and warm climate. The presence, in the p-ev₁ sub-unit, of small-sized foraminifers, reworked calcareous plankton, and the absence of ostracods and normal marine foraminifer assemblages suggest a diluted marine environment due to strong runoff responsible for the deposition of a great amount of clastic sediments. Towards the top of the p-ev₁ and within the p-ev₂ the environment changes. The pollen record shows well evident wetter/drier fluctuations and the benthic foraminifers, ostracods, molluscs and dinocysts testify a decreasing water depth and alternating oligo- to mesohaline waters before the Pliocene deluge.

INTRODUCTION

The Messinian salinity crisis (MSC) in the Northern Apennines has been the object of a multidisciplinary review during the last 15 years (see Roveri et al. 2006 and reference therein). The three classical phases of the MSC, the pre-evaporitic (pre-ev), evaporitic (ev) and post-evaporitic (p-ev) are organized within a physical-stratigraphic framework, in order to reconstruct the evolution of this area during the upper Tortonian – lower Zanclean interval.

This research has resulted in a partial re-organization of the events of the MSC, from the bottom: a pre-evaporitic unit (up to 5.96 Ma, Krijgsman et al. 1999) characterized by rhythmic alternations of organic-rich shales evolving into sapropels; 2) an evaporitic unit (5.96 to 5.61 Ma) built up of primary gypsum only in marginal basins (Vena del Gesso basin) and of organic-rich and barren shales in deeper basins (Sapigno basin, Manzi et al. 2007), and 3) a post-evaporitic unit (5.61 to 5.33

Ma) separated from the underlying one by a regional unconformity marking an important phase of deformation of the Apennines. The base of the p-ev unit in the Northern Apennines is characterized by the occurrence of a complex of resedimented evaporites and includes the Di Tetto and Colombacci Fms. Two sub-units (p-ev₁ and p-ev₂ of Roveri et al. 2001), separated by minor unconformity can be recognized within this unit. The lower sub-unit occurs only in structural depressions and comprises a basal horizon made of resedimented evaporites overlain by siliciclastic deposits containing an ash layer dated 5.5 Ma (Odin et al. 1997). This sub-unit shows clear evidences of syn-tectonic deposition as suggested by rapid lateral thickness and facies changes. The upper sub-unit is characterized by sudden appearance of coarser-grained deposit testifying a drastic change in the fluvial drainage pattern. This sub-unit seals the intra-Messinian unconformity and is characterized by a clear cyclical stacking pattern (coarse grained fluvio-deltaic and fine grained basinal

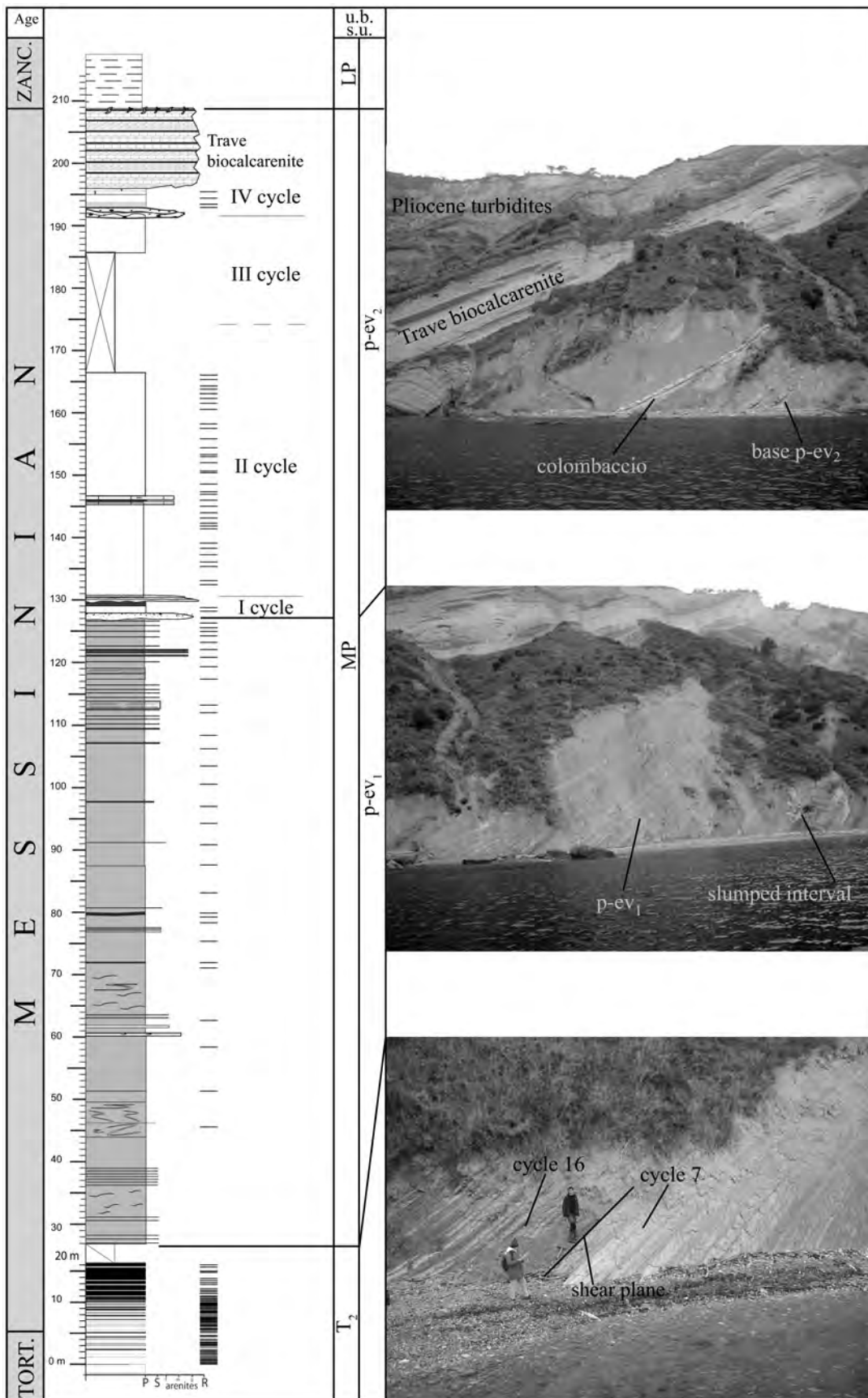


TEXT-FIGURE 1
Simplified geological map of the Conero area (after Roveri et al. 2005).

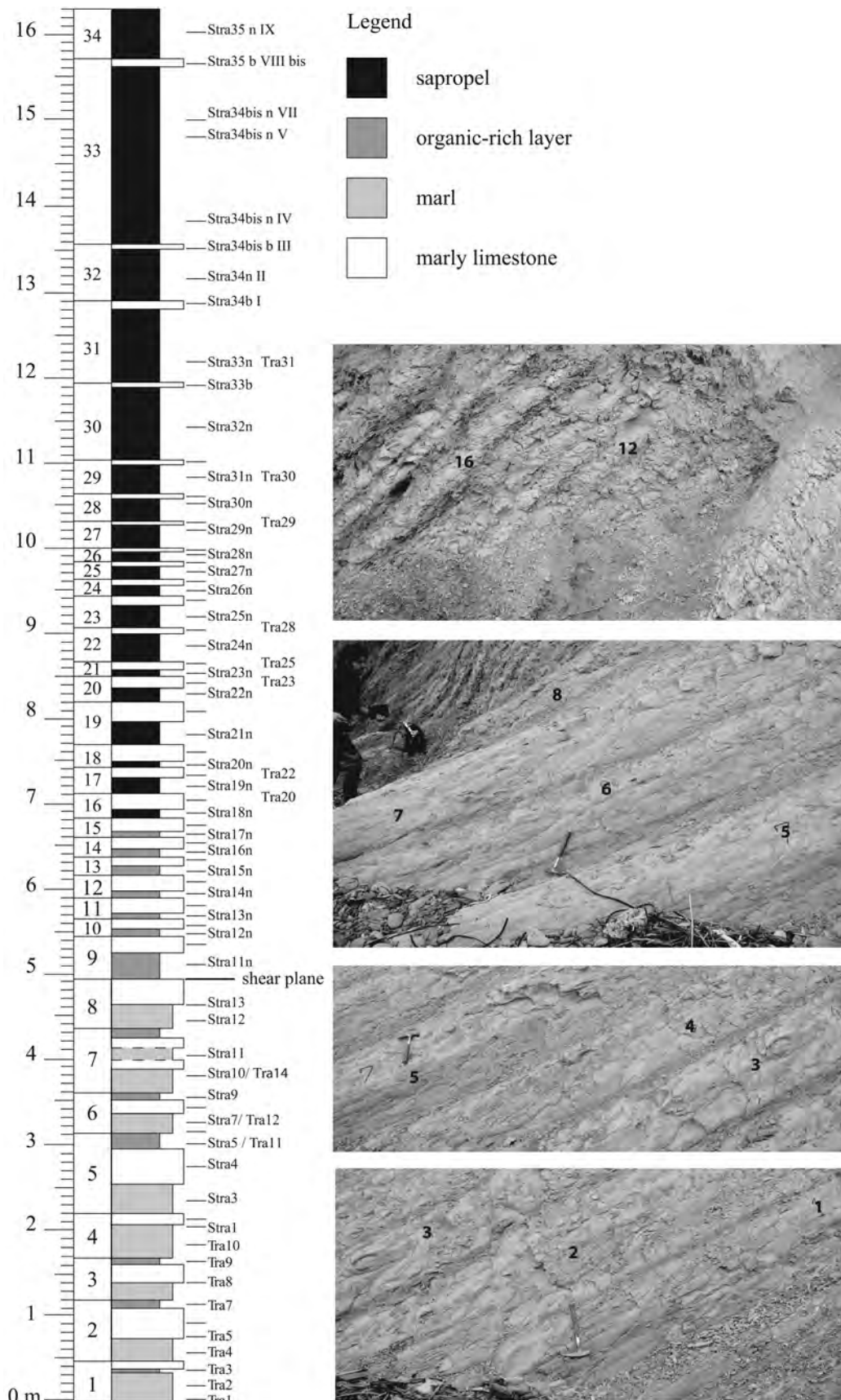
deposits) regularly alternated, suggesting a strong climatic control. Four to five precessionally controlled cycles are recognizable within this sub-unit throughout the whole basin, thus allowing to date its base at 5.42 Ma.

The pre-ev phase is well documented in the marginal area of the Vena del Gesso basin in the western Romagna Apennines; here several studies (Krijgsman et al. 1997; Kouwenhoven et al. 1999) documented a synchronous evolution of bioevents towards stressed conditions preceding the deposition of the Lower Evaporites. More recently, Manzi et al. (2007) studied the same stratigraphic interval in a basinal setting (Fananello bore hole, Sapigno syncline, eastern Romagna Apennines); here, the pre-evaporitic sequence is followed by a barren interval, which appears to be the deep water counterpart of the Lower Evaporites, while the overlying resedimented evaporites mark the base of the p-ev phase (base of the MP unit, sub-unit-p-ev₁).

The p-ev₂ is characterized by the occurrence of the typical Lago Mare assemblages, including benthic foraminifers, ostracods, molluscs, dinocysts, and fish remains. These biota point to the presence of a widespread ipohaline water mass during the p-ev phase. In the post-evaporitic Sapigno section, Bassetti et al. (2003) and Grossi and Gennari (in press) described the presence of ostracod assemblages dominated, in the lower part, by *Cyprideis* and in the middle and upper part by *Amnicythere* spp. and *Loxocorniculina djafarovi*; the reconstructed paleoenvironment is characterized by oligohaline to mesohaline water of variable depth, even if Bassetti et al. (2003) suggest that the presence of *Cyprideis* could indicate hyperhaline condition. Similar ostracod assemblages are recorded in the western sector of Emilia Apennines by Iaccarino and Papani (1980). For what concerns the dinocysts, Bertini (2006) reported the occurrence of *Impagidinium* (?) sp.1, followed by *Galeacysta etrusca* and *Impagidinium* (?) sp. 2 in the p-ev₂ of the Maccarone section (Marche region), marking the local arrival of the Paratethyan

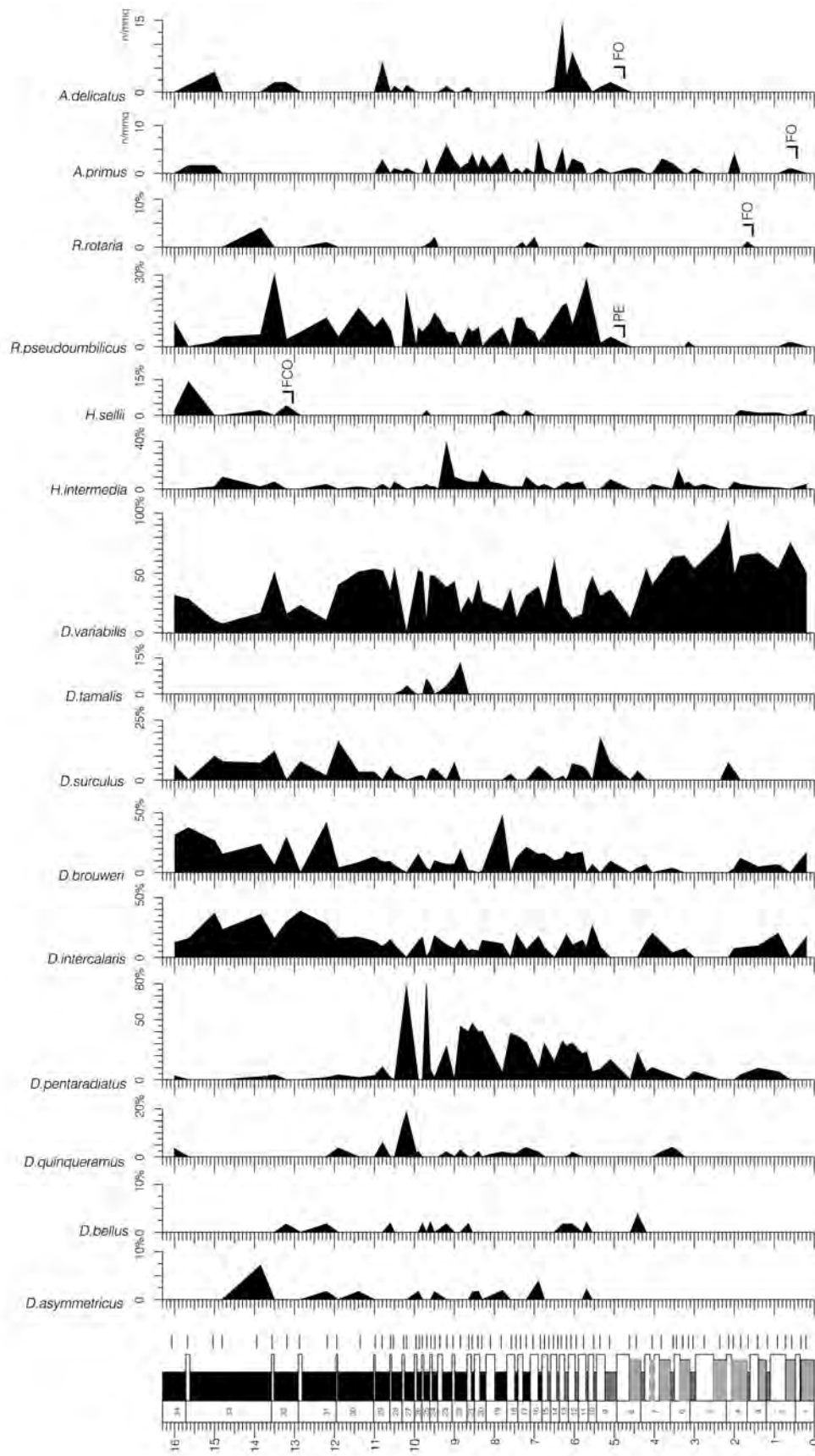


TEXT-FIGURE 2
Trave section: stratigraphic log after Roveri et al. 2005.

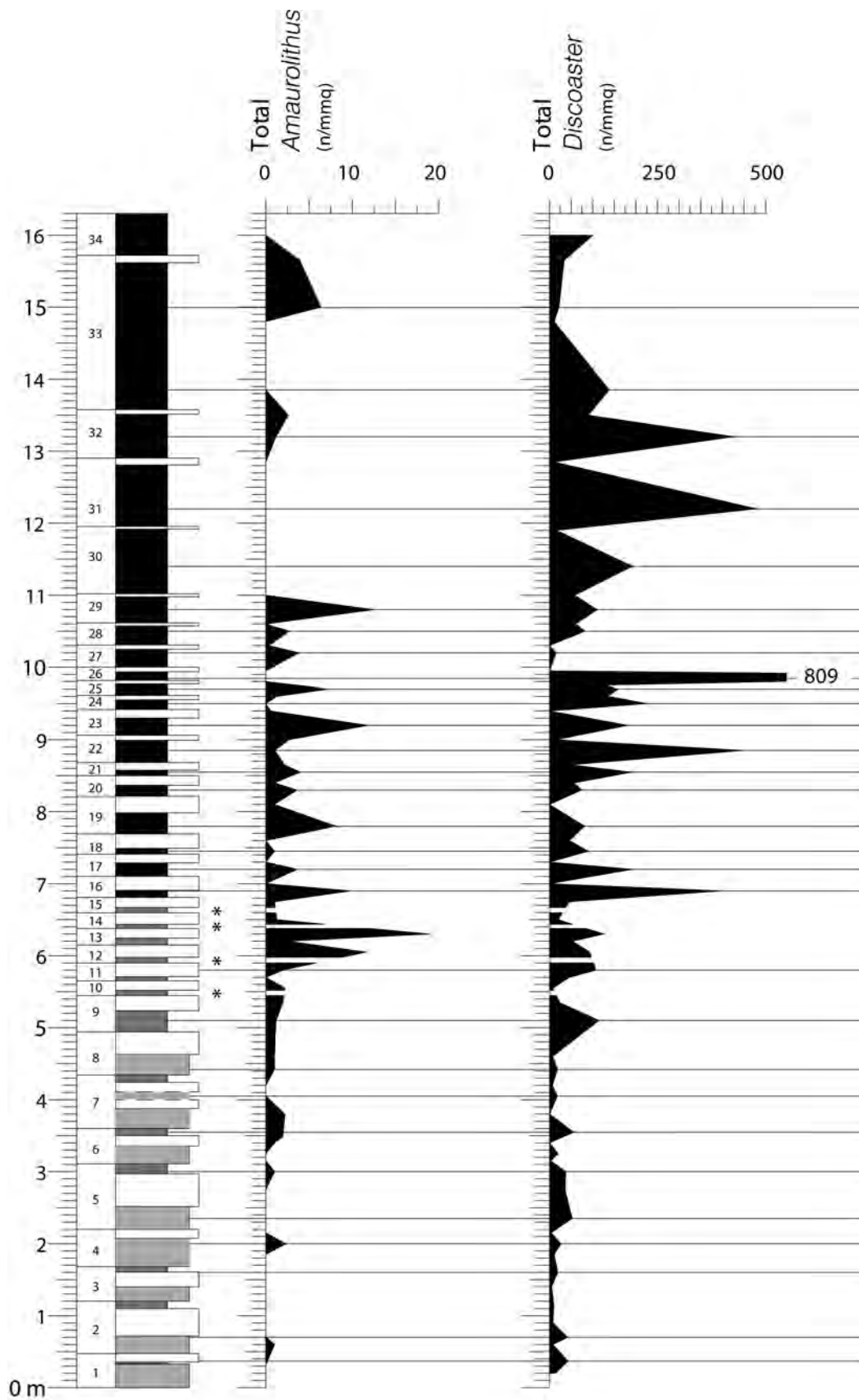


TEXT-FIGURE 3

Trave section: stratigraphic log of the pre-evaporitic interval. The samples taken from marly limestones are not numbered. Tra samples belong to an older sampling.



TEXT-FIGURE 4
Quantitative distribution pattern of selected calcareous nannofossils of the pre-evaporitic interval.



TEXT-FIGURE 5
 Frequencies of *Amaurolithus* and total “in situ” *Discoaster* in the pre-evaporitic interval, estimated as numbers related to a fixed area of the slide, converted to number/mm². Asterisks indicate samples not collected in the dark layers.

dinocyst contingent and in concomitance with a high abundance of *Pediastrum*, a hypohaline alga. In the same area (Cà Ciuccio section), Bellagamba (1978) documented the occurrence of abundant mollusc fauna belonging to the genera *Dreissena*, *Euxinocardium*, *Limnocardium*, *Plagiodacna*, *Pro-sodacna*, (*Hydrobia*), *Melanopsis* and *Melanoides*. From the same section Carnevale et al. (2006, 2008) recovered otoliths of eurihaline fishes (*Sciaenidae*, abundant) and stenohaline marine fishes (*Gobiids*, rare), which, according to the Authors, allow to claim that marine water was present in the Adriatic foredeep at least during uppermost p-ev phase.

The obvious predominance of hypohaline taxa within the p-ev deposits is coupled with the occurrence of eurihaline biota allowing speculation about water salinity and its origin. The Trave section, due to its morphotectonic position in the outer foredeep, should be a good potential to enlight the evolution of the pre-ev water mass into the p-ev phase with particular regards to the persistence of normal salinity water. The section was measured, sampled and studied through an integrated paleontological approach. Here we present the nannofossil, foraminifer, ostracod, mollusc and palynomorph data as a contribution for the paleoenvironmental characterization of the pre-evaporitic, lower (p-ev₁) and upper post-evaporitic (p-ev₂) Messinian units. The final goal of the paper is the reconstruction of the events characterizing the environmental history of the Messinian in this area.

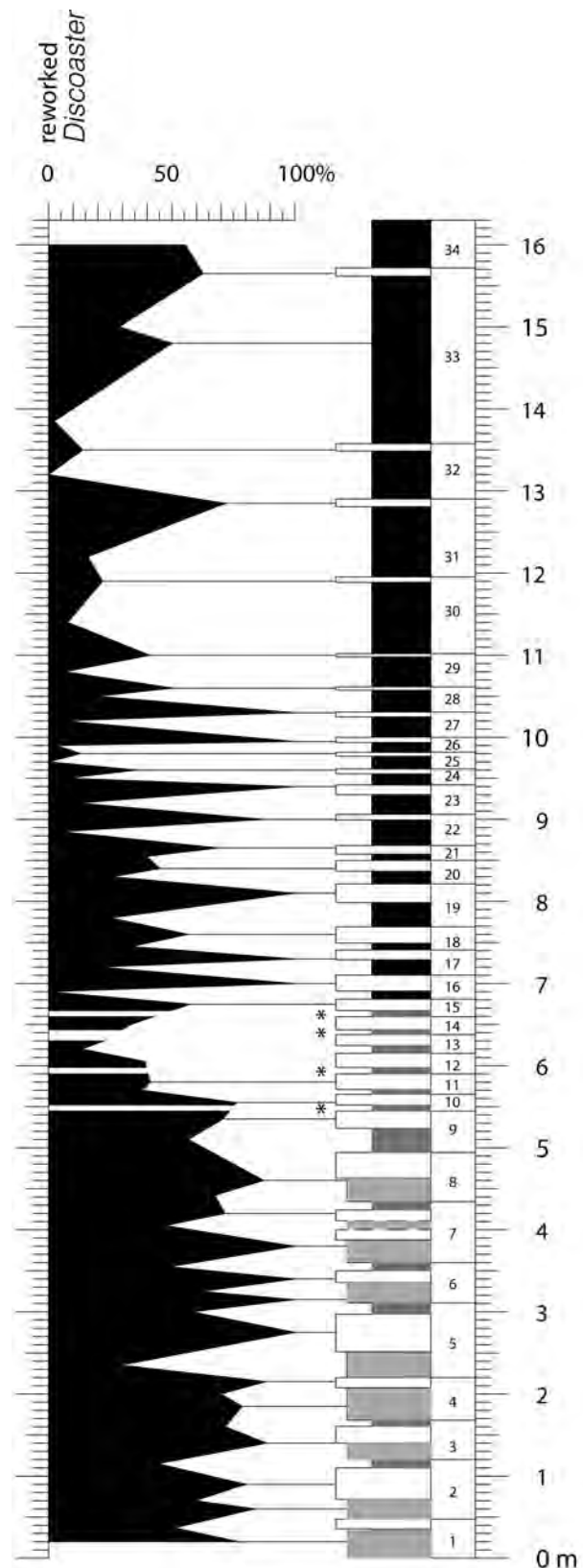
GEOLOGICAL SETTING AND LITHOSTRATIGRAPHY OF THE TRAVE SECTION

The study area (text-fig. 1) belongs to the central sector of the present-day foredeep basin and foreland ramp of the Outer Northern Apennine fold and thrust belt; the external element of the Apennine chain started to develop since Oligocene time propagating progressively toward ENE and involving the stratigraphic successions of three Mesozoic paleogeographic domains (Ligurian, Tuscan and Umbria-Marche-Adriatic) (Barchi et al. 2001).

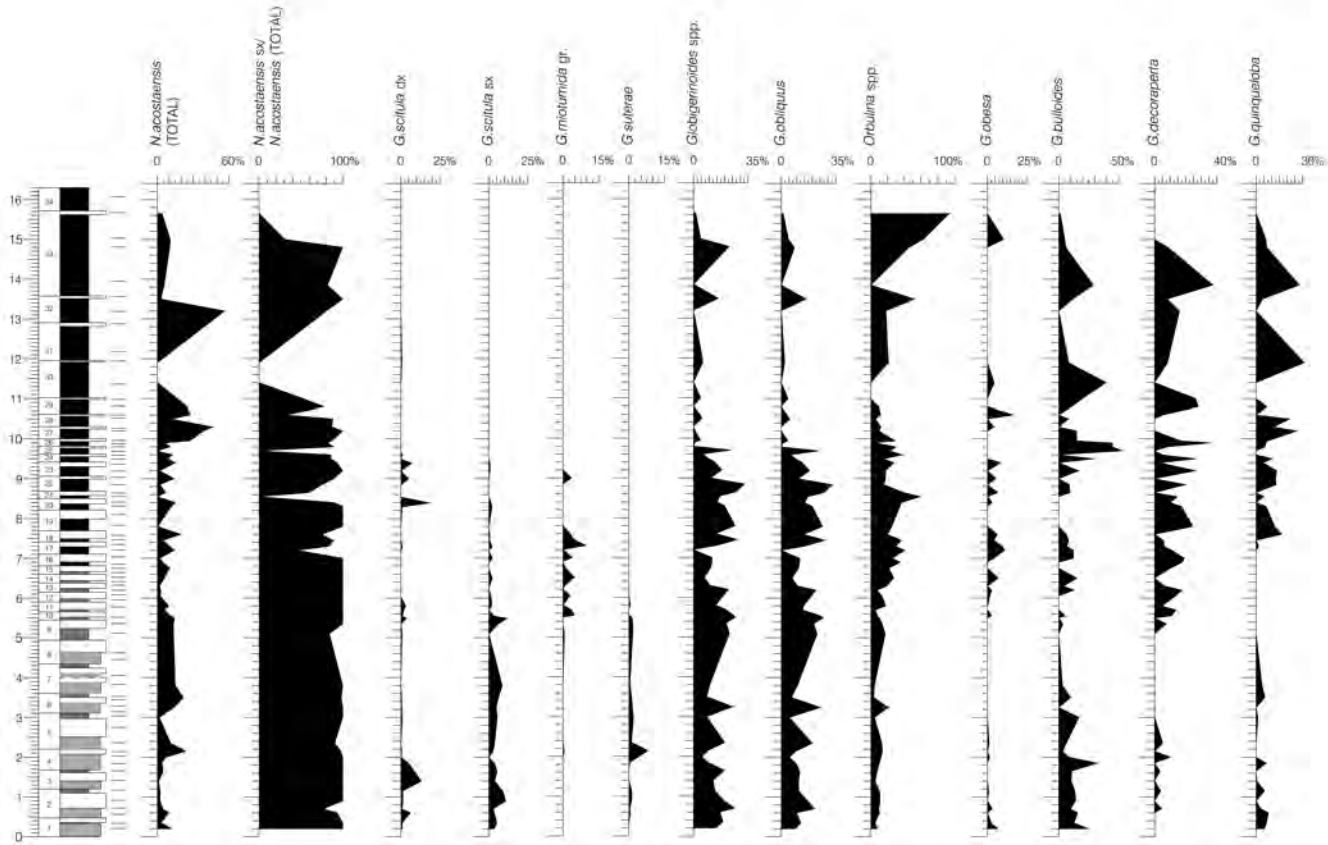
In the last years, several physical and stratigraphic studies have been carried out in the Adriatic foreland with the aim to point out the history of the Northern Apennines during the Messinian time (see Roveri et al. 2005 and references therein).

The Tortonian-Messinian succession crops out along the sea-cliff between Monte dei Corvi and Mezzavalle, south of Ancona (text-fig. 1) not too far from the Tortonian Global Stratotype Section and Point (GSSP; Hilgen et al. 2005); these deposits are part of a southwest dipping monocline disrupted by reverse faults and minor folds which represents the southern flank of a large-scale anticline whose axis lies offshore, at a short distance from the coastline. This important structure is strongly eroded at sea (Roveri et al. 2005) and unconformably sealed by Upper Pleistocene deposits; its southern flank is overridden by the ramp anticline of the M. Conero thrust sheet, at whose core Mesozoic basinal carbonates crop out (Maiolica Fm.). According to Roveri et al. (2001, 2005), the Messinian sedimentary sequence, in this area, is represented by the pre-evaporitic deposits and post-evaporitic sub-units p-ev₁ and p-ev₂.

The Trave section, 210m thick, starts from the base of Monte dei Corvi sea cliff (text-fig. 2) and comprises from the bottom (Roveri et al. 2005): 1) 4.9m of grey/light bioturbated marls and indurated marly-limestones organized in 8 lithological cy-



TEXT-FIGURE 6
Percentages of reworked *Discoaster* in the pre-evaporitic interval. The wide fluctuations clearly indicates that the maximum percentage of reworked *Discoaster* (up to 100%) concentrates in the limestone layers or in the grey marls. Asterisks indicate that samples were not collected in the dark layers.



TEXT-FIGURE 7
Quantitative distribution pattern of selected planktonic foraminifers in the pre-evaporitic interval.

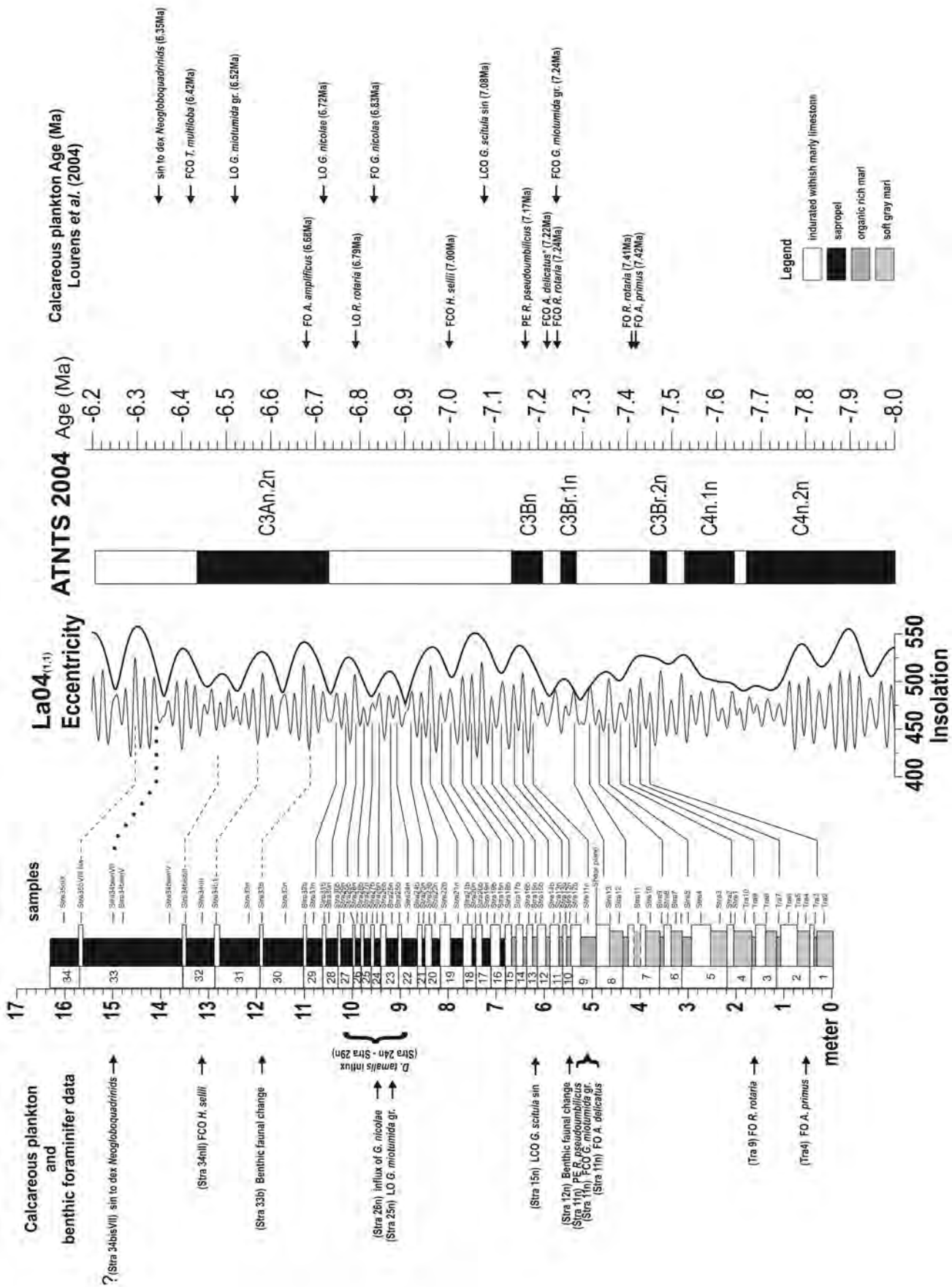
cles; 2) 11.30m of organic-rich marls (less distinct in the first 1.8m) and indurated marly limestones carbonates organized in 26 lithological cycles; between cycles 8 and 9, a shear plane is present, above which the cyclicity pattern changes into homogeneous marly limestone-sapropel alternations (text-fig. 3); the brownish layer at the top of the pre-evaporitic interval could be a volcanic ash layer but bad preservation hampered any analysis; 3) about 20m of laminated microcrystalline gypsum (re-sedimented), covered by a recent slide, which marks the base of the p-ev₁ unit; 4) 100m of p-ev₁ consisting of laminated grey silty marls containing at its basal part a thick, chaotic marly horizon; 5) 75m of p-ev₂ characterized by the sudden appearance of thin, coarse-grained sandstone bodies (the lowermost of which marks the base of the p-ev₂) rhythmically alternated with thick laminated mudstone bodies containing a locally abundant, macrofauna. Three main cycles are recognizable in the p-ev₂, formed by dkm-thick, sharp-based sandstone-mudstone couplets; a fourth cycle is suggested to be present in the covered interval (Roveri et al. 2005). Two laminated, micritic limestones ('colombacci'), up to 1m thick are intercalated in the mudstone body of the second and fourth cycle (text-fig. 2). The Messinian succession contains at its top a bioalcalarenitic horizon (well known as 'Trave') abruptly overlain by lower Pliocene massive mudstones whose planktonic foraminifer assemblages document an Early Pliocene age (MPI3) (Roveri et al. 2005).

BIOSTRATIGRAPHY

Calcareous nannofossils

The samples (81) for the calcareous nannofossil analyses were prepared following the standard methodology of "smear slide". Quantitative analyses were carried out with a light microscope at 1250× magnification. The distribution pattern of selected taxa (text-fig. 4) has been reconstructed counting a maximum of 100 specimens within the genera *Discoaster*, *Helicosphaera* and *Reticulofenestra* (>3µm). The frequencies of *Amaurolithus* and total *Discoaster* were estimated as numbers related to a fixed area of the slide, converted to number/mm² (text-fig. 5). Distribution curves are provided only for the biostratigraphically useful species. The quantitative distribution pattern of other nannofossils and the paleoecological implication are not given in the present paper as a more detailed paper on this topic is currently in progress.

The calcareous nannofossil assemblages are abundant along the whole pre-evaporitic succession; the degree of preservation is generally poor in the lowermost part (up to 5.5m) and gets better in the intermediate and upper intervals: the general conditions are anyway sharply better in the grey/black layers. Reticulofenestrids (*Reticulofenestra* and *Dictyococcites* genus) are dominant in the nannofossil assemblages, followed by



TEXT-FIGURE 8

Tuning of the basic small-scale sedimentary cycles of the pre-evaporitic interval. The limestone layers of the uppermost part of the section are tentatively correlated with 100 ky eccentricity maxima. The dextral/sinistral coiling change of *N. acostaiensis* is tentatively located in sample Stra 34bisnVII. The small arrow indicates the level of drastic decrease of the benthic foraminifer assemblage (Stra 11n).

TABLE 1

Position of the recognized calcareous nannofossil events in the pre- evaporitic succession of the Trave section, inferred astrochronological age and comparison with other Mediterranean sections.

Calcareous nannofossil events	Lourens et al., 2004	Trave section (present paper)		Pissouri M. section (Morigi et al., 2007)	Metochia section (Raffi et al., 2003)	Faneromeni section (Negri & Villa 2000)	M. del Casino section (Negri et al., 1999)
	Age (ma)	Age astronomically derived (Ma)	sample/cycle	Age astronomically derived (Ma)/Chron	Age astronomically derived (Ma)/Chron	Age astronomically derived (Ma)/Chron	Age astronomically derived (Ma)/Chron
6 <i>H. sellii</i> FCO	7.00	6.5	Stra 34n/32	6.526 / C3An.2n	6.478 (FO)	7.049-7.053 / C3Ar	6.964-6.968 / C3Ar
5 <i>D. tamalis</i> INFLUX		6.917-6.789	Stra 24n/22-29n/27				
4 <i>A. delicatus</i> FO	7.22	7.18	Stra 11n/9	7.197 / C3Bn	7.134 / C3Bn	7.249-7.250 / C3Br.1r	7.218-7.226
3 <i>R. pseudoumbilicus</i> PE	7.17	7.18	Stra 11n/9		7.170 / C3Br.1r		
2 <i>R. rotaria</i> FO	7.41	7.40	Tra 9/3	7.435 / C3Br.2r	7.4 / C3Br.2r	7.419-7.423 / C3Br.2r	7.398-7.405 / C3Br.2r
1 <i>A. primus</i> FO	7.42	7.44	Tra 4/2	7.449 / C3Br.2r	7.423 / C4Br.2r	7.429-7.432 / C3Br.2r	7.440-7.446 / C3Br.2r

Coccolithus pelagicus, *Helicosphaera carteri* and *Sphenolithus abies*.

The intermediate portion of the section, characterized by the best degree of preservation, also shows a higher diversification in the nannofloras, with higher relevant abundance of *Geminolithella rotula*, *Pontosphaera* spp., *Syracosphaera* spp., *Scyphosphaera* spp. and *Umbilicosphaera* spp., which are normally subordinate in the nannofossil assemblages.

The cyclic lithological pattern of the pre- evaporitic succession is well evidenced by the strongly fluctuating abundance curve of the total “in situ” *Discoaster* which dominates the dark layers (text-fig. 5). The genus *Amaurolithus* shows a similar behaviour, especially in the intermediate part of the section. The calcareous levels always yield high percentages of reworked *Discoaster* (calculated as percentages within the total “in situ” + reworked *Discoaster*), mainly represented by *D. deflandrei*, and in some cases autochthonous specimens were not recorded (text-fig. 6). The six-rayed *D. variabilis* and the five-rayed *D. pentaradiatus* showing a vicariant distribution, are the most abundant within the discoasterids assemblages. *D. variabilis* together with *D. brouweri*, *D. intercalaris* and *D. surculus*, dominate the upper part. Low percentages and scattered distribution patterns are shown by the five-rayed *D. asymmetricus*, *D. bellus* and *D. quinquerramus* (also including *D. berggreni* specimens). The latter, used as zonal marker in standard oceanic schemes, is not abundant in the studied section and cannot be used for biostratigraphic correlation in the Mediterranean region. In any case, we agree with previous authors (Mazzei 1985; Cipollari and Cosentino 1995) that state that typical specimens of this species are present in the Mediterranean area (Plate 1). The quantitative analysis of the discoasterids pointed out a sharp horizon, in the intermediate part of the section, where *Discoaster tamalis*, an Early-Middle Pliocene species, is clearly present. The presence of *D. tamalis* in the Messinian sediments of the Mediterranean region, already documented by previous authors (e.g. Negri et al. 1999), is here estimated quantitatively, for the first time.

The occurrence of *Helicosphaera sellii*, typical of the Early Pliocene-Early Pleistocene time interval, in Miocene sediments of the Mediterranean region has been widely debated in previous studies (e.g. Raffi et al. 2003; Morigi et al. 2007). Typical *H. sellii* specimens (Plate 1) intermittently occur in the lowermost and intermediate part of the Trave section, becoming more common in the uppermost portion.

The quantitative analysis among the Reticulofenestrids group (*Reticulofenestra* >3µm, according to Raffi et al. 2003) pointed out the almost total absence of *Reticulofenestra pseudo-*

umbilicus in the lower part of the section and the rare and scattered presence of *R. rotaria*, firstly used as marker in the Mediterranean Messinian sediments by Theodoridis (1984).

Ceratholiths are here mainly represented by *Amaurolithus primus* and *A. delicatus*; in particular *A. primus* is intermittently present in the lower part of the section and become rather abundant in the intermediate and uppermost part, *A. delicatus* becomes significantly present in the nannoflora from cycle 9 upwards. Both species reach high concentration values preferably in the dark layers. Different morphotypes of *A. primus*, from the most primitive up to the most evolved, have been recognized, as well as intergraded forms between *A. primus* and *A. delicatus* (Plate 1). Furthermore, specimens have been referred to the *Triquetrorhabdulus-Amaurolithus* intergraded forms (*sensu* Negri et al. 1999) and to the *Triquetrorhabdulus-Nicklithus* transitional forms (*sensu* Raffi et al. 1998; 2003). No typical *Amaurolithus amplificus* (*Nicklithus amplificus* in Raffi et al. 2003) was recorded along the section.

Several biohorizons, astronomically calibrated in the Mediterranean (Lourens et al. 2004), have been detected in the pre- evaporitic interval and listed in Table 1. The age for each bio-event has been compared with the age assigned to the same (or similar) horizon in other Mediterranean sections by previous authors.

The First Occurrence (FO) of *A. primus* (at 7.42 Ma), whose biostratigraphic value is well established both in Mediterranean and oceans, is recorded in the lowermost part of the section in cycle 2 (Tra 4 at 0.6 meters). The FO of *R. rotaria* dated at 7.41 Ma, occurs at the top of cycle 3 (Tra 9 at 1.6 meters). The biostratigraphic usefulness of this species has been widely discussed (Flores et al. 1992; Negri et al. 1999; Hilgen et al. 2000a, b; Negri and Villa 2000; Raffi et al. 2003; Krijgsman et al. 2004). However, although the age obtained for the FO of the species is in good agreement with the calibration obtained elsewhere in the Mediterranean, in our opinion and according to previous authors (e.g. Raffi et al. 2003) *R. rotaria* is not considered a reliable marker. A conspicuous interval of absence of *R. pseudoumbilicus* was pointed out in the late Miocene of both oceans (Backman and Raffi 1997, and reference therein) and Mediterranean (Raffi et al. 2003). The end of this paracme interval (PE), dated at 7.17 Ma, occurs in sample Stra 11n at the base of cycle 9 (at 5.1 meters) as the *A. delicatus* FO whose age is dated at 7.22 Ma in Morocco (Lourens et al. 2004). The distribution of *D. tamalis* between cycles 21 and 27 (Stra 24n and Stra 29n) is here called *D. tamalis* “influx” (Table 1). Although the presence of this species in Upper Miocene Mediterranean successions has previously been reported, no indication has been given for the age of this event. The last nannofossil event

recognized at the top of the section, is the FCO of *H. sellii* occurring at 13.2 meters (cycle 32, Stra 34nII). The age here obtained for this event (6.5 Ma) is comparable to the age inferred at Pissouri Motorway section by Morigi et al. (2007), but differs from that reported by Lourens et al. (2004) as FCO of *H. cf. sellii* at 7.00 Ma in the eastern Mediterranean. These discrepancies point out a low degree of reliability for this event (Table 1). From a biostratigraphic point of view the interval almost entirely falls within the subzone MNN11a of Raffi et al. (2003), confined by the FO of *A. primus* and by the FO of *Nicklithus amplificus*.

Planktonic foraminifers

Quantitative analysis of the planktonic foraminifers has been focused on the 16.5 meters of the pre-evaporitic interval represented by 81 samples. The quantitative distribution pattern of selected planktonic foraminifer categories having biostratigraphic significance has been plotted. The patterns are based on the counting of 200-250 specimens from splits >125µm. The planktonic foraminifers are abundant and well preserved in all the studied samples. In particular, they show a better preservation in the sapropel layers from cycle 10 upwards.

Globigerinoides obliquus is particularly abundant in the lower-middle part of the section up to 10 meters. From cycle 27 up to the top section this species occurs more irregularly. *Orbulina universa* shows a long-term increasing pattern even if in the upper part of the record it occasionally reaches high abundance values (text-fig. 7). *Globoturbotalita decoraperta* and *Globigerina bulloides* show a similar long-term trend and are continuously present from the upper part of cycle 9 to the top section. *Globorotalia suteri* occurs from the base up to cycle 9. *Globotalia menardii* 5 (dextral form) is poorly represented along the section but shows a peak in cycle 10 (Stra 12n). The first specimens of *G. miotumida* gr. are recorded in cycle 5, but only from cycle 9 (Stra 11n) up to cycle 23 (Stra 25n) this taxon is commonly and regularly present (FCO). Upwards the taxon occurs only sporadically and does not enter in the counting procedure. The FCO of *Turbotalita multiloba* has not been recorded possibly due to the low sampling rate in this part of the section. Left coiled *Globorotalia scitula* shows a progressive decrease in abundance from the base up to its Last Common Occurrence (LCO) recorded in cycle 13 (Stra 15n). By contrast dextrally coiled *G. scitula* only occurs in some samples with high abundance values. *Turbotalita quinqueloba* shows a long-term abundance increase mainly from cycle 19 upwards. The influx of *G. nicolae* in sample Stra 26n (cycle 24) is interpreted as its FO. *Neogloboquadrina acostaensis* is common only occasionally along the whole section showing mainly left coiling direction. The sinistral to dextral coiling change of neogloboquadrinids is tentatively placed at 15m (cycle 33 – sample Stra 34 bis n VII) where the sinistrally coiled specimens show an abrupt drop.

From a biostratigraphic point of view, cycles 1 to 8 are late Tortonian in age and fall within the upper part of planktonic foraminifer Subzone MMi12b (Iaccarino et al. 2007) whose base is defined by the FO of *G. suteri* astronomically dated at 7.81 Ma (Sprovieri et al. 1999). Cycles 9 to 34 are Messinian in age and belong to Biozone MMi13 (Iaccarino et al. 2007). More precisely cycles 9-23 are referable to MMi 13a Subzone whose base is identified by the FCO of *G. miotumida* gr. This event is well recognizable in all the Mediterranean and extra-Mediterranean sections (Hilgen et al. 2000b) and virtually coincides with the GSSP of the Messinian (Hilgen et al. 2000a) dated astro-

TABLE 2

Inferred biochronology of selected calcareous plankton events and benthic foraminifer assemblage changes

	Planktonic	Lourens et al. 2004	Trave Section	
		Age (Ma)	Age astronomically derived (Ma)	sample/cycle
i	S/D <i>N. acostaensis</i>	6.35		? Stra 34bisn VII/33
h	FCO <i>T. multiloba</i>	6.42		not found
g	LO <i>G. miotumida</i>	6.52	6.88	Stra 25n/22
f	LO <i>G. nicolae</i>	6.72		not found
e	FO <i>G. nicolae</i>	6.83	6.84	Stra 26n/24
d	LCO <i>G. scitula</i> sx	7.08	7.09	Stra 15n/13
c	FCO <i>G. miotumida</i>	7.24	7.18	Stra 11n/9

	Benthic	Kouwenhoven et al. 1999 (Ma)	Age astronomically derived (Ma)	sample/cycle
		b	increasing abundance of stress-tolerant species	6.8/6.7
a	drastic deep benthic foraminifer decrease	7.16	7.16	Stra 12n/10

nomically at 7.251 Ma. Cycles 24 to 34 are assigned to MMi13b Subzone whose base is identified by the FO of *G. nicolae* (Table 2).

CYCLOSTRATIGRAPHY AND ASTRONOMICAL TUNING

The pre-evaporitic interval shows distinct cycles numbered 1–34 from bottom to top. The cycles are not distributed evenly throughout the succession but reveal distinct patterns. The expression of the sedimentary cyclicity changes throughout the section. The basic small-scale cycle from 1 to 8 is a triplet consisting of softer grey marls, white limestones and organic-rich layers at the top. According to the tuning adopted for the astronomical calibration of lower Tortonian Monte dei Corvi section (Conero area, close to Ancona) by Hilgen et al. (2003), the organic-rich layers to the top of the carbonate were correlated with precession minima. The basic sedimentary cycle from 9 to 34 is a couplet consisting of indurated whitish marly limestone and laminated brownish to black colored organic-rich bed (used as lower limit of the cycle, text-fig. 8) is similar to that recognized in the well-known and tuned M. del Casino section cropping out in the Romagna area (Krijgsman et al. 1997). The brown sediments, here referred to as ‘sapropels’, are more distinct between cycle 16 (at 6.8 meters) and the top. The marly limestone layers are thicker in the lower part while the sapropel thickness increases in the upper part of the section. The tie-points considered to calibrate the pre-evaporitic interval is based on the drastic decrease of the benthic assemblage (astronomically dated at 7.16 Ma by Kouwenhoven et al. 1999) which postdates the T/M boundary (Kouwenhoven et al. 1999, 2006), on the FO of *A. primus* (astronomically dated at 7.42 Ma by Lourens et al. 2004) and on the distinct cyclic bedding with well-developed sapropels. For the tuning, we used the numerical solution LA04(1,1) of Laskar et al. (2004) calculated for the summer season (June–July) at 65°N as insolation forcing for the studied record. The phase relation adopted is based on the correlation of sapropel layers with precession minima/summer insolation maxima in the Northern hemisphere (Hilgen 1991) and small-scale and large-scale sapropel clusters to 100 and 400 kyr

TABLE 3
Floristic list

<i>Taxodium/Glyptostrobus</i> type	Oleaceae	Asteraceae Cichorioideae
<i>Sciadopitys</i>	<i>Fraxinus</i>	Brassicaceae
<i>Sequoia</i> type	<i>Phillyrea</i>	Cyperaceae
<i>Pinus</i>	<i>Olea</i>	Dipsacaceae
<i>Picea</i>	<i>Tilia</i>	<i>Knautia</i>
<i>Abies</i>	<i>Rhus</i>	Ericaceae
<i>Cedrus</i>	<i>Ilex</i>	<i>Geranium</i>
<i>Tsuga</i>	<i>Buxus</i>	Poaceae
Pinaceae sacc. indeternined	Celastraceae	<i>Lygeum</i>
<i>Cathaya</i>	<i>Hippophae</i>	Lamiaceae
Cupressaceae	<i>Microtropis fallax</i>	<i>Phlomis</i>
Inaperturated	Coriariaceae	Fabaceae
<i>Ephedra</i>	<i>Eucommia</i>	Menispermaceae
Betulaceae	Euphorbiaceae	<i>Plantago</i>
<i>Betula</i>	<i>Euphorbia</i>	<i>Limonium</i>
<i>Corylus</i>	<i>Myrica</i>	Polygonaceae
<i>Carpinus</i>	Myrtaceae	<i>Polygonum</i>
<i>Ostrya</i>	<i>Nyssa</i>	<i>Rumex</i>
<i>Alnus</i>	Arecaceae	Ranunculaceae
<i>Quercus</i>	Rhamnaceae	Rosaceae
<i>Quercus ilex</i> type	<i>Rhoiptelea</i>	<i>Neurada</i>
<i>Fagus</i>	<i>Symplocos</i>	<i>Sanguisorba</i>
<i>Castanea</i>	<i>Hedera</i>	<i>Galium</i>
Ulmaceae	<i>Platanus</i>	Apiaceae
<i>Ulmus</i>	Rubiaceae p.p.	Urticaceae
<i>Zelkova</i>	<i>Salix</i>	Cannabaceae
<i>Celtis</i>	Sapotaceae	<i>Tricolporopollenites sibiricum</i>
<i>Acer</i>	<i>Eleagnus</i>	Convolvulaceae
Juglandaceae	Icacinaceae	<i>Myriophyllum</i>
<i>Carya</i>	Loranthaceae	<i>Sparganium</i>
<i>Pterocarya</i>	Borraginaceae	Pteridophyta
<i>Engelhardia</i>	Caryophyllaceae	<i>Pediastrum</i>
<i>Juglans</i>	Cistaceae	<i>Botryococcus</i>
Hamamelidaceae	<i>Helianthemum</i>	Tasmanaceae
<i>Distylium</i>	Chenopodiaceae	<i>Concentricystes</i>
<i>Parrotia</i>	Asteraceae Asteroideae	Dinocysts
<i>Liquidambar</i>	<i>Artemisia</i>	Other Algae
	<i>Centaurea</i>	

eccentricity maxima, while alternating thin-thick sapropels reflect precession-obliquity interference (Lourens et al. 1996; Hilgen et al. 2000 a, b). The tuning is probably accurate to the level of the individual precession/insolation cycle from the base up to cycle 29. Moreover, the occurrence from the base section up to cycle 9 of alternating thin-thick hemipelagic grey marls and indurated whitish carbonate layers clearly reflecting the precession-obliquity interference, strengthen the validity of the tuning in the lower part of the section (text-fig. 8). In the uppermost part of the section the lack of good biostratigraphic constraints and the inaccuracy of the cyclic pattern prevent correct tuning.

The astronomically derived age for the base of the pre-evaporitic interval of the Trave section is 7.45 Ma, while the age of *A. primus* results to be 7.44 Ma. The *G. miotumida* FCO as well as the FO of *D. delicatus* and the PE of *R. pseudoumbilicus* whose ages are respectively calibrated at 7.24 Ma, 7.22 Ma, 7.18 Ma, fall in cycle 9 (Stra 11n). The astronomically derived ages of the LCO of *G. scitula* sinistral and LO of *G. miotumida* are younger than those of Lourens et al. (2004) possibly due to more severe environmental conditions in the studied area. The drastic decrease of benthic foraminifer assemblage dated at 7.167 Ma occurs in cycle 10 (Stra 12n). The ages of *R. pseudoumbilicus* PE (at 7.18 Ma) and of *R. rotaria* FO (at 7.40 Ma) well approximate those reported in Lourens et al.

(2004) (Table 1). It follows that the base of the Messinian which approximates the FCO of *G. miotumida* gr. is not recorded: at least 4 cycles are missing between cycle 8 and 9.

The *D. tamalis* “influx” is constrained between 6.917 and 6.789 Ma. The age of the top of the pre-evaporitic interval is not astronomically detectable, but the drop of sinistral neogloboquadrinids could correspond to the sinistral/dextral coiling change calibrated at 6.35 Ma, suggesting a hiatus of about 750 Kyr between the top of the pre-evaporitic interval and the base of p-ev1.

PALEOENVIRONMENTAL DATA: PRE-EVAPORITIC INTERVAL

Benthic foraminifers

The benthic foraminifers of 81 samples were analyzed with the aim to reconstruct paleoenvironmental trends and events preceding the Messinian salinity crisis (MSC). Samples come from hemipelagic marly clays and/or sapropels and prominent indurated carbonate layers. The percentages of benthic foraminifers were estimated by counting 100 to 300 specimens from the 125µm fraction. The relative abundances of some selected taxa were plotted in order to define changes in the assemblages along the pre-evaporitic succession (text-fig. 9) and these data were compared with those from the Monte del Casino section

published by Kouwenhoven et al. (1999) in the Vena del Gesso basin. The relative frequencies show four major faunal assemblages changing, through time, from open marine to stressed environment.

The most drastic change is recorded in the lower part of the section, at sample Stra 12n (cycle 10), in correspondence of the disappearance of *Cibicides wuellerstorfi*, *C. italicus*, *Siphonina reticulata*, and somewhat later, *C. bradyi* which are indicative of relatively deep, open marine, oxic environment with normal salinity (Lutze 1977; Van der Zwaan 1982; Lutze and Thiel 1989; Verhallen 1991; Sjoerdsma and Van der Zwaan 1992; Kaiho 1994). This drop is well correlatable with that observed in Monte del Casino section (Kouwenhoven et al. 1999). From sample Stra 21b (cycle 18) to sample Stra 26b (cycle 23) the above mentioned "oxyphilic species" (Kouwenhoven et al., 1999) are gradually replaced by a transitional assemblage mainly characterized by *Bolivina scalprata miocenica*, *Uvigerina rutila*, *U. peregrina* (Van der Zwaan 1982) and *Melonis affinis* which suggest varying degrees of oxygen and salinity at the seafloor. In particular, *U. peregrina* is considered to proliferate under raised organic flux and/or a decreased oxygen content and perhaps increased salinity (Van der Zwaan 1982; Lutze and Coulbourn 1984; Verhallen 1991; Sjoerdsma and Van der Zwaan 1992; Loubère 1994, 1996). A third minor change is recorded from sample Stra 29b (cycle 26) to sample Stra 33b (cycle 30) where the species diversity further decreases and the assemblage is mainly represented by *Cibicidoides kullenbergi*, *C. pseudoungerianus*, *Hanzawaia boueana*, *Bulimina subulata* and *Bolivina dilatata*.

From sample Stra 33b (cycle 30) up to sample Stra 34 bis n VII (cycle 34), *B. dilatata*, *B. subulata* are the most common species and show a regular increase in abundance (*B. subulata*). These assemblage dominating taxa, are considered to have opportunistic behaviour and tolerance to dysoxia, but also to high bottom water salinity (*B. dilatata*, Van der Zwaan 1982; Verhallen 1991; Jorissen et al. 1992; Kaiho 1994; Loubère 1996, 1997; *B. subulata*, Verhallen 1991; Van der Zwaan 1982; Kaiho 1994). Onwards the samples are barren. The same trend is observed in Monte del Casino and Metochia sections by Kouwenhoven et al. (2003) after 6.8/6.7 Ma who concluded that the benthic assemblage shows evidence of a step-wise isolation of the Mediterranean deep water mass and, at a later stage, to increasing salinity (Table 2).

Molluscs

Macrofossils are uncommon in the pre-evaporitic succession but do occur at some levels, especially those associated with dysaerobic marls. They include fish remains (skeletons, scales, decalcified otoliths) and molluscs both holoplanktonics (undetermined thecosomatous pteropods) and benthics. The latter comprehend bivalves (*Propeamussium duodecimlamellatum*, Lucinidae sp., *Cardiomya* cf. *costellata*, etc.) and gastropods (*Aporrhais* sp., *Nassarius* ex gr. *semistriatus*) pointing out a relatively deep muddy depositional setting (outer shelf/upper slope). This fauna correlates well with pre-evaporitic deposits cropping out in Cyprus (Merle et al. 2002) and Romagna and Piedmont, Italy (Taviani 2005 and unpublished data).

Pollen and dinocysts

The 68 pollen taxa (Table 3) from the pre-evaporitic succession are shown in the summary pollen diagram of text-fig. 10 where groups have been traced on the basis of known, present-day ecology of correlative taxa. Concentration curves of palyno-

TABLE 4

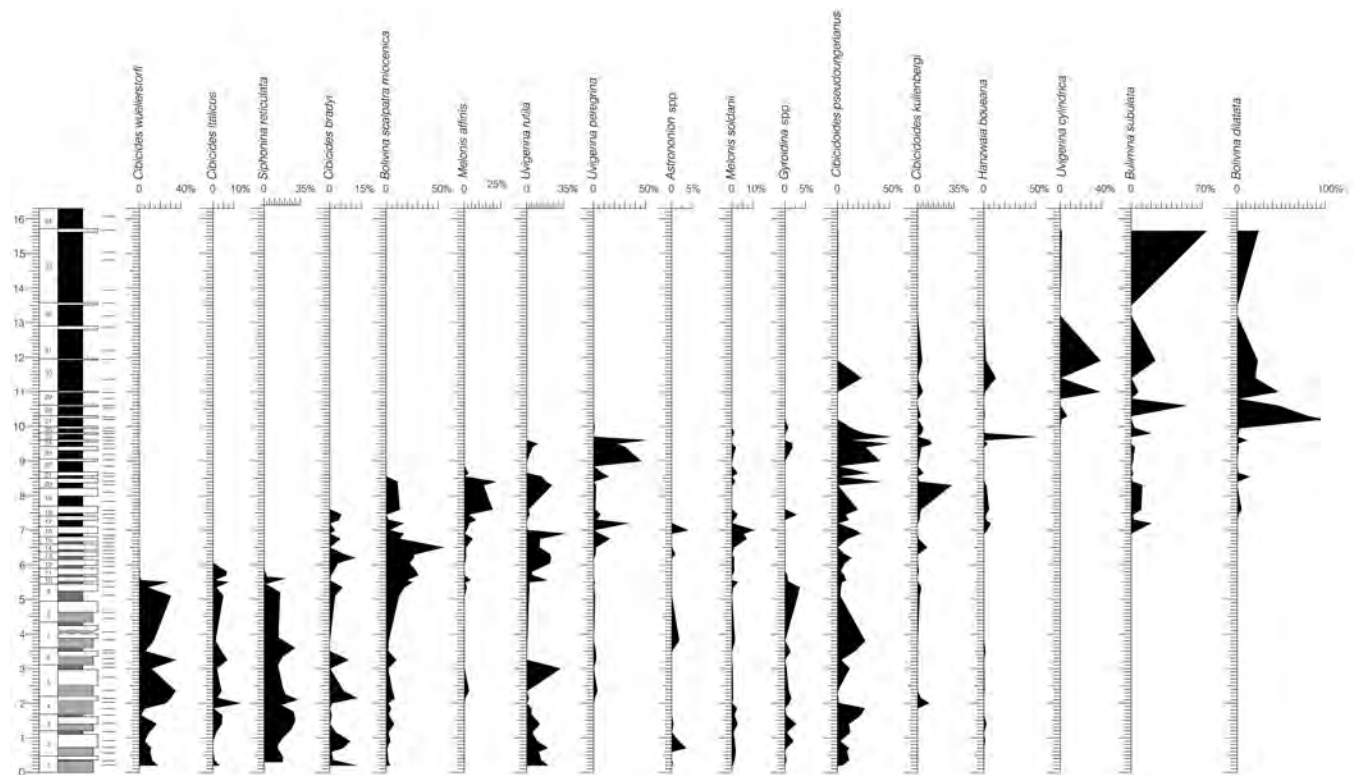
Oxygen and carbon isotopic values of *Ammonia beccarii*

Taxon	Sample/unit	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
<i>Ammonia beccarii</i> sx	TRA 60 (p-ev1)	-3,53	-1,20
<i>Ammonia beccarii</i> dx	TRA 60 (p-ev1)	-2,68	-1,54
<i>Ammonia beccarii</i> sx	TRA 68 (p-ev2)	-2,90	-1,58
<i>Ammonia beccarii</i> dx	TRA 68 (p-ev2)	-3,75	-1,55

morphs are on the right of text-fig. 10. Palynomorph preservation is quite good. Samples from the lower cycles (1-6) have low concentration in both pollen (327 grains/gr to 13456 grains/gr) and dinocysts (336 to 1757 cysts/gr); the latter generally reach higher values than pollen with the exception of Tra 11 in the organic-rich layer of cycle 5. Between cycles 7 and 20, samples are barren (Tra 17 and Tra 20) or with low concentration values, always less than 700 palynomorphs/gr (Tra 16, 22). Samples from the upper cycles are characterized by the highest concentrations in palynomorphs; however, pollen concentration (up to 340298 grains/gr) is always higher than dinocyst concentration (up to 3815 cysts/gr), at the opposite of lower cycles. As a whole, the organic-rich layers of the lower cycles show higher values in the concentration of dinocysts whereas the sapropels of upper cycles (plus Tra 11) are richer in pollen. In marls and carbonates, concentration is lower than in organic-rich layers; however, in the former dinocysts concentration is higher than that of pollen.

Pollen assemblages, especially in the lower cycles, are largely dominated by Pinaceae bisaccate, the most abundant of which is *Pinus*. Meso to microthermic conifera are also present and sometimes have significant occurrences such as in Tra 5 and Tra 25. Subtropical to warm temperate arboreal taxa reach the highest percentage values in the upper cycles where herbs remain very poorly represented (never over 10%) as in the lower cycles. The high percentage values of *Pinus* can be explained by the analysis of its taphonomic features. In fact, *Pinus* pollen is readily transported for long distances and often over-represented in marine settings. At Trave, its dominance and the large occurrence among dinoflagellate assemblages of *Nematosphaeropsis labyrinthus*, *Impagidinium* spp., *Spiniferites* spp. suggest open marine settings for the deposition of the lower cycles. Here, specifically, the large occurrence of *N. labyrinthus*, an oceanic eutrophic species, and the subordinate presence of the oceanic and oligotrophic taxa such as *Impagidinium patulum* suggest a nutrient supply. On the contrary in the upper cycles *N. labyrinthus* is strongly reduced (Tra 23 and Tra 31), *I. patulum* is virtually absent and *Spiniferites* spp. is scattered. In the middle cycles, the paucity of both pollen and dinocysts may be explained by the occurrence of oxidized conditions. From cycle 20 the progressive increase in both total pollen concentration and percentage values of subtropical to warm temperate taxa as well as the decrease in dinocyst concentrations and dinocyst vs pollen ratio (text-fig. 11) testify an environmental change. The latter may be explained by two main factors, - a regressive trend which enhanced terrestrial input and more severe anoxic conditions which gave rise to more distinct sapropel formation but also to worse preservation of palynomorphs.

At Trave the distribution and composition of marine palynomorph assemblages are in good agreement with those described for the Sicilian coeval sections which suggest prevalent thalassocratic conditions during the Terravecchia deposition



TEXT-FIGURE 9
Quantitative distribution pattern of selected benthic foraminifers of the pre-evaporitic interval.

followed by a shallowing trend along with slightly higher sea-surface temperatures during the Tripoli (Suc et al. 1995; Londeix et al. 2007). Terrestrial assemblages are dominated by humid subtropical to warm temperate taxa whereas in Sicily they are mainly represented by herbaceous taxa (including subdesertic ones) typical of dry open environments, according to the presence of a latitudinal north-south gradient (e.g. Bertini 2006, Fauquette et al. 2006).

PALEOENVIRONMENTAL DATA: POST-EVAPORITIC INTERVAL

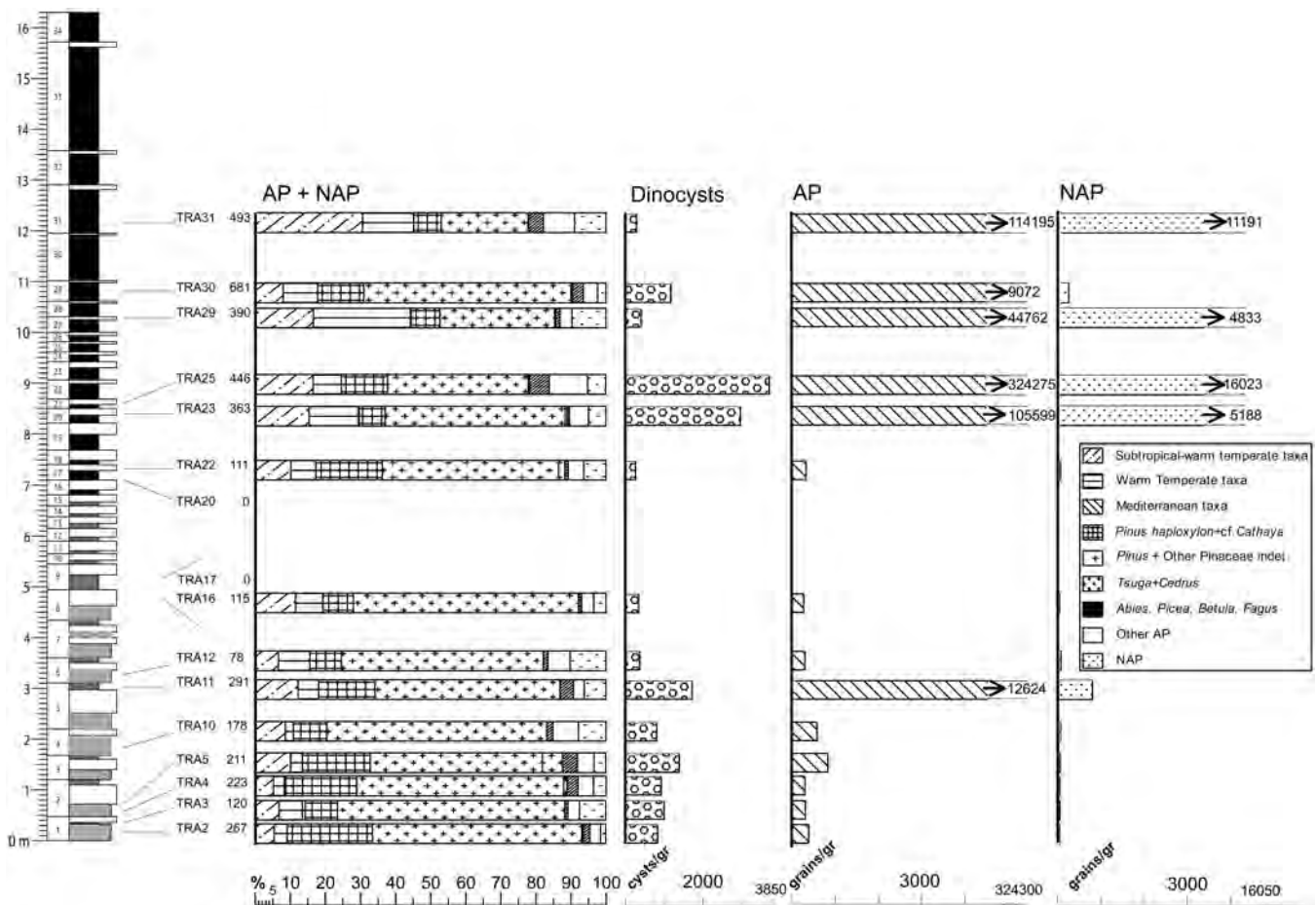
Foraminifers and calcareous nannofossils

The preservation and the abundance of the foraminifers from p-ev₁ and p-ev₂ units allowed only a qualitative analysis. In the p-ev₁ unit from the base up to 122m, the planktonic foraminifers are generally scarce and taxa show different degrees of preservation (preventing a precise taxonomic recognition) and ages (text-fig. 12). A few are of Langhian age (*Praeorbulina* spp.), while others of Serravallian age (*Paragloborotalia partimlabiata*, *P. siakensis*, *Neogloquadrina atlantica praeatlantica* and *Globigerinoides subquadratus*) and Tortonian age (*Globorotalia saheliana*). It is worth mentioning that *Dentogloboquadrina altispira*, *Globoquadrina dehiscens*, *Globorotalia* gr. *menardii* taxa are still present in the Zanclean stage but whose stratigraphic distribution is unknown in the Mediterranean basin during the late Messinian. Additional taxa of long biostratigraphic range are present (e.g. *T. quinqueloba*, *G. decoraperta*, *O. universa*, *Globigerinoides trilobus*). Finally, many samples from p-ev₁ unit contain specimens of *Globorotalia puncticulata* whose presence is due to contamination. Benthic foraminifers are rare to very rare and interpreted as re-

worked until 122m, where there is an assemblage made up of abundant *Ammonia tepida* and rare *Elphidium* sp. (*A. tepida* assemblage). Therefore, the p-ev₁ unit can be considered devoid of autochthonous foraminifers until 122m.

Calcareous nannofossil assemblages in the p-ev₁ unit are common but badly preserved. They consist of long-ranging species (*Coccolithus pelagicus*, *Helicosphaera carteri*, *Pontosphaera* spp., *Sphenolithus abies*), subordinate Cretaceous forms, Eocene up to Early Miocene species (*Coccolithus eopelagicus*, *Criboecentrum reticulatum*, *Cyclicargolithus abisectus*, *C. floridanus*, *Dictyococcites bisectus*, *Discoaster deflandrei*, *Helicosphaera compacta*, *H. euphratis*, *H. oblique*, *H. recta*, *Reticulofenestra umbilica*, *Zygrhablithus bijugatus*), and Early-Middle Miocene species (*Calcidiscus premacintyreii*, *Helicosphaera walbersdorfensis*, *Sphenolithus heteromorphus*). Typical Messinian forms have not been recorded in this interval.

In the p-ev₂ unit between the two coarse-grained beds, the foraminifer diversity increases due to the presence of rare individuals of *Criboelphidium* sp., *Haynesina germanica*, *Ammonia baculites* sp. and *Neoconorbina* sp. This assemblage is typical of an infralittoral and estuarine environment characterized by shallow and brackish water conditions (Almogi-Labin et al. 1995, Alve and Murray 1994). These taxa gradually disappear just above the second coarse-grained bed within the p-ev₂ unit where fresh water ostracods and reworked foraminifers are dominant. The same benthic foraminifer assemblage characterizing the p-ev₁/p-ev₂ transition reappears at 193m, just below the "Trave biocalcarenite" at the top of the section; here they represent a little percentage of the benthic assemblage. Isotopic



TEXT-FIGURE 10

Palynological diagrams of the pre-evaporitic interval. From the left, summary pollen diagram, concentration curves of dinocysts, arboreal (AP) and non arboreal plants (NAP).

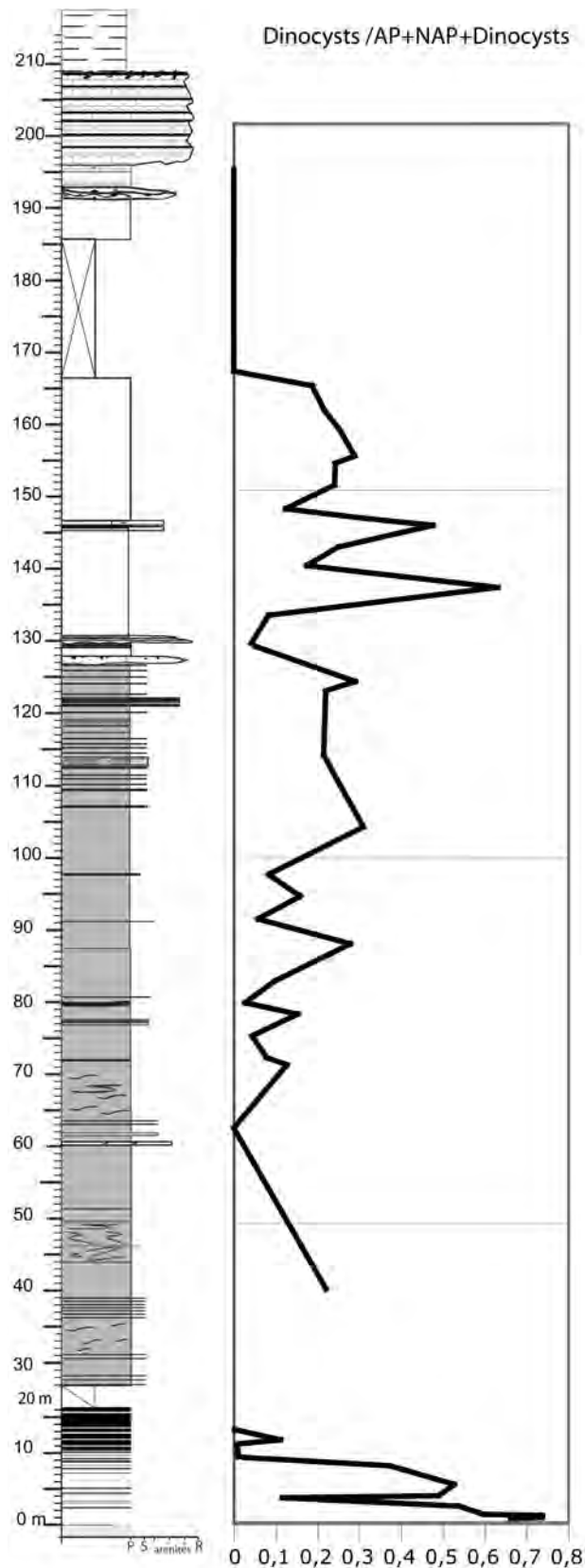
analysis on *A. tepida* shells from samples Tra 60 (top of p-ev₁) and Tra 68 (base of p-ev₂) suggests the presence of a prevalently hypohaline water body (Table 4) at the transition of the two units. These data are in good agreement with those obtained from the “colombacci limestone” in the Adriatic foredeep (Bassetti et al. 2004). The microscope analysis did not reveal the presence of calcite overgrowth or traces of diagenesis on the shell of the specimens which might have explained the low values of the carbon isotopes (M. Sprovieri, personal communication).

Ostracods

The ostracods of 42 samples from p-ev unit were analysed. Each sample was disgregated in a 5% H₂O₂ solution, washed using a 0.63 mm sieve and then dried. No less than 300 valves for sample were handpicked under a stereomicroscope. Each species frequency was normalised to 10 g of dried sieved sample and the relative abundance in percentage was calculated for each taxon. The ostracods are mainly present in p-ev₂ unit, where 27 species referable to 14 genera occur: *Amnicythere* sp. D Miculan, *Amnicythere* sp. 2 Gliozzi and Grossi, *A. accicularia* (Olteanu), *A. multituberculata* (Livental), *A. palimpsesta* (Livental), *A. propinqua* (= *A. cymbula*) (Livental), *A. sub-*

caspia (Livental in Agalarova et al.), *Euxinocythere* (*Maeotocythere*) *praebaquana* (Livental), *E. (Maeotocythere) praebosqueti* (Suzin), *Mediocytherideis* (*Sylvestra*) sp., *Cyprideis agrigentina* Decima, *C. anlavauxensis* Carbonnel, *Cyprideis* sp. 5 Gliozzi and Grossi, *Tyrrhenocythere pontica* (Livental) *T. ruggierii* Devoto, *Loxocauda limata* (Schneider), *L. eichwaldi* Livental, *L. kochi* (Méhes), *L. mülleri* (Méhes), *L. rhombovalis* Pokorný, *Loxocorniculina djafarovi* (Schneider), *Cytherura pyrama* Schneider, *Camptocypris* sp. 1 Gliozzi and Grossi, *CaspioCypris pontica* (Sokac), *Cypria* sp., *Pontiella* sp., *Zalanyiella venusta* (Zalanyi).

Seven of these genera (*Amnicythere*, *Euxinocythere*, *CaspioCypris*, *Cytherura*, *Loxoconchissa*, *Loxocorniculina*, *Pontiella*, *Zalanyiella*) are widespread during Miocene in the Paratethyan domain and migrated into the Mediterranean area only during the latest Messinian Lago Mare event (Carbonnel 1979); Bonaduce and Sgarrella 1999; Gliozzi 1999; Gliozzi et al. 2002; Gliozzi and Grossi in press and references therein). Six genera (*Loxoconcha*, *Cypria*, *Cyprideis*, *Loxocauda*, *Mediocytherideis* (*Sylvestra*) and *Tyrrhenocythere*) are widespread in the Neogene/Quaternary of both the Paratethyan and Mediterranean domains: *Loxoconcha* and *Tyrrhenocythere* are represented only by Paratethyan species which migrated into the



TEXT-FIGURE 11
Dinocyst vs pollen ratio of the pre- and post- evaporitic interval. AP: arboreal plants, NAP: non arboreal plants.

Mediterranean exclusively during the latest Messinian event, *Cyprideis* and *Mediocytherideis* (*Sylvestra*) are represented by Mediterranean species (Carbonnel 1979; Bonaduce and Sgarrella 1999; Gliozzi 1999; Gliozzi et al. 2002; Gliozzi and Grossi in press and references therein).

Paleoecological data on the Trave species are few. Some of them, concerning living species, can be derived from the zoological literature (Gofman 1966; Yassini and Ghahreman 1976; Boomer et al. 1996), while for the extinct taxa, Gliozzi and Grossi (2004, in press) provided a possible synecological characterization of the Lago Mare assemblages. Leptocytheridae are characteristic of shallow (down to 100m depth) and oligo-mesohaline waters (optimum 12.5-13.5‰).

At a generic level, the “pointed candonids” (*Camptocypria*, *Pontoniella* and *Zalanyiella*) are characteristic of shallow to deep water (down to a few hundred meters) and fresh-oligohaline conditions (Gofman 1966; Gliozzi and Grossi 2004), *Cyprideis* is strongly euhaline and characteristic of very shallow water (optimum < 10m) (Neale, 1988 and references therein), *Tyrrhenocythere* is characteristic of shallow water (down to about 30m) and oligo-mesohaline conditions (optimum 12.5-13.5‰) (Bronsthein 1947; Gofman 1966; Naydina 1970; Schornikov 1974; Yassini and Ghahreman 1976; Boomer et al. 1996).

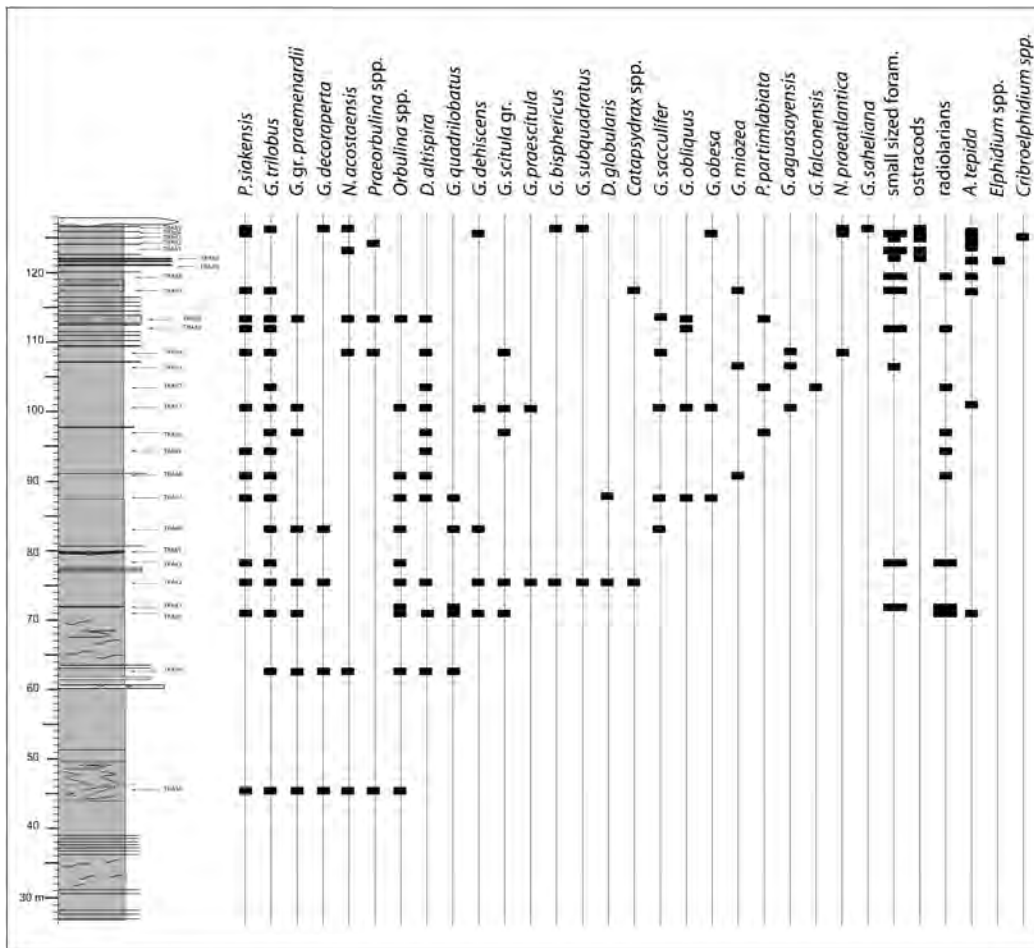
Community structure analysis (CSA) has been performed on the ostracod assemblages collected at the Trave section. Three assemblage structure indexes were calculated for each sample using the software package PAST (PAleontological STatistics, ver. 1.52) (Hammer et al. 2001): Richness index, Shannon index (S.I.) and Equitability index (Dodd and Stanton 1990). Looking at the results, the samples generally show medium-high richness coupled with rather high values of Shannon index, particularly in the upper part of the section (text-fig. 13). These parameters affect rather stable environments, which lead to the establishment of several mature ostracod communities. Nonetheless, it is possible to recognize some changes among the ostracod communities, affecting environmental variations.

The following assemblage clusters were recognized in the post-evaporitic deposits:

Interval A (27-122m, Tra 1-Tra 59): interval barren of ostracods

Interval B (122-127m, Tra 60-Tra 65): ostracod assemblages are dominated by *Cyprideis agrigentina* and *Tyrrhenocythere ruggierii* (generally with >1000/10g normalized valves) and in a subordinated way by *Loxoconcha milleri* (>100). Richness and Shannon indexes are rather low (S.I. <1.2, text-fig. 13). These communities suggest that the environment was characterized by shallow and oligohaline waters.

Interval C (127-133m, Tra 68-Tra 36): a decrease in *C. agrigentina* and the entry of *Loxocorniculina djafarovi* with similar frequency values with respect to *C. agrigentina*, are recorded within this interval. Ostracod communities are rather even, with an increasing presence in leptocytherids; *T. ruggierii* is present only at the base of the interval (Tra 68); Candoninae are scarce. Diversity index increases, with S.I. between 1.35 and 1.9 (text-fig. 13). The ostracod assemblage records a salinity increase (mesohaline).



TEXT-FIGURE 12

Distribution chart of selected planktonic foraminifers in p-ev₁ sub-unit.

Interval D (135-144m, Stra 37-Stra 43): *L. djafarovi* dominates the assemblage, leptocytherid frequencies are stable while the abundance of some Candoninae species increases. *C. agrigentina* exit and *L. mülleri* becomes scarce. Diversity index is rather variable: some samples have rather high S.I. values (1.7-1.8), others have low S.I. values (< 1.0); Equitability index is also variable, but is generally < 0.6 (text-fig. 13). The increase of Candonidae testifies deeper waters, while the still high frequency of Leptocytheridae suggests a light decrease in salinity, perhaps be in the low mesohaline range.

Interval E (145-147m, Tra 78-Tra 81): this interval, corresponding to the basal “colombaccio” limestone, is barren of ostracods.

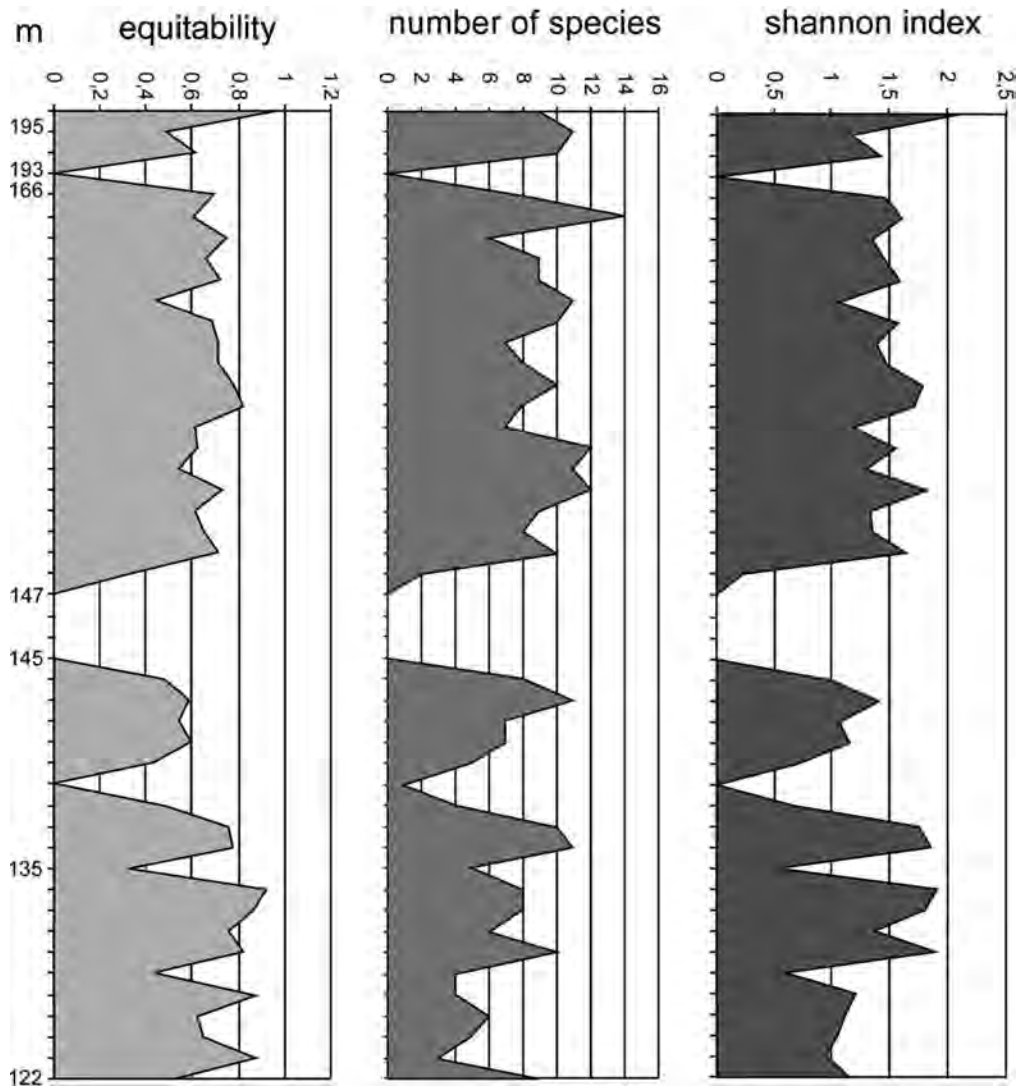
Interval F (147-166.5m, Stra 45-Stra 58): *T. ruggierii* reappears, with a higher frequency in the lower part of the interval; *L. djafarovi* shares the assemblage dominance with *Caspiocypris pontica*, and also all the other Candonidae species are well represented (in particular, *Cypria* sp. is very abundant); *Euxinocythere (Maeotocythere) praeabaquana* is common; *L. mülleri* is absent. Community index is rather high, with S.I. values between 1.3 and 1.9 and the Equitability index generally between 0.6 and 0.8 (text-fig. 13). There are no significant variations in depth with respect to the previous interval, and so it is possible to suggest rather deep conditions, coupled with a

slight salinity decrease (overall in the first part of the interval) due to the high frequencies of Candonidae. In particular, sample Stra 48 is characterized by increasing abundance of *T. ruggierii* and by very high abundance of Candoninae, testifying a further deepening pulse. Interval F is followed by about 27m of covered succession. Above it, Interval G was identified.

Interval G (193-195.5m, Stra 59-Stra 61): this interval immediately precedes the uppermost “colombaccio”. *L. djafarovi* is still present but not as the dominant species; Leptocytheridae are less diversified (*Amnicythere accicularia*, *A. palimpsesta* and *A. subcaspia* are absent). *Tyrrhenocythere pontica* is present, *Caspiocypris pontica* and *Cypria* sp. decrease their frequency. Sample Stra 61, collected in correspondence of the last “colombaccio” limestone, is characterized by lower frequencies than Stra 59 and Stra 60. S.I. still shows high values, and diversity is high as well too (about 10 species). The trend observed in Interval E continues in this interval, in which these assemblages testify deep and oligohaline waters.

Molluscs

Molluscs represent the only macrofaunal group detected in the Trave section and have been recorded by various authors (Capellini 1879; Gillet 1968; Ionna 2000; Esu 2007). Although unevenly distributed, they occur only in the upper p-ev₂ sub-unit.



TEXT-FIGURE 13

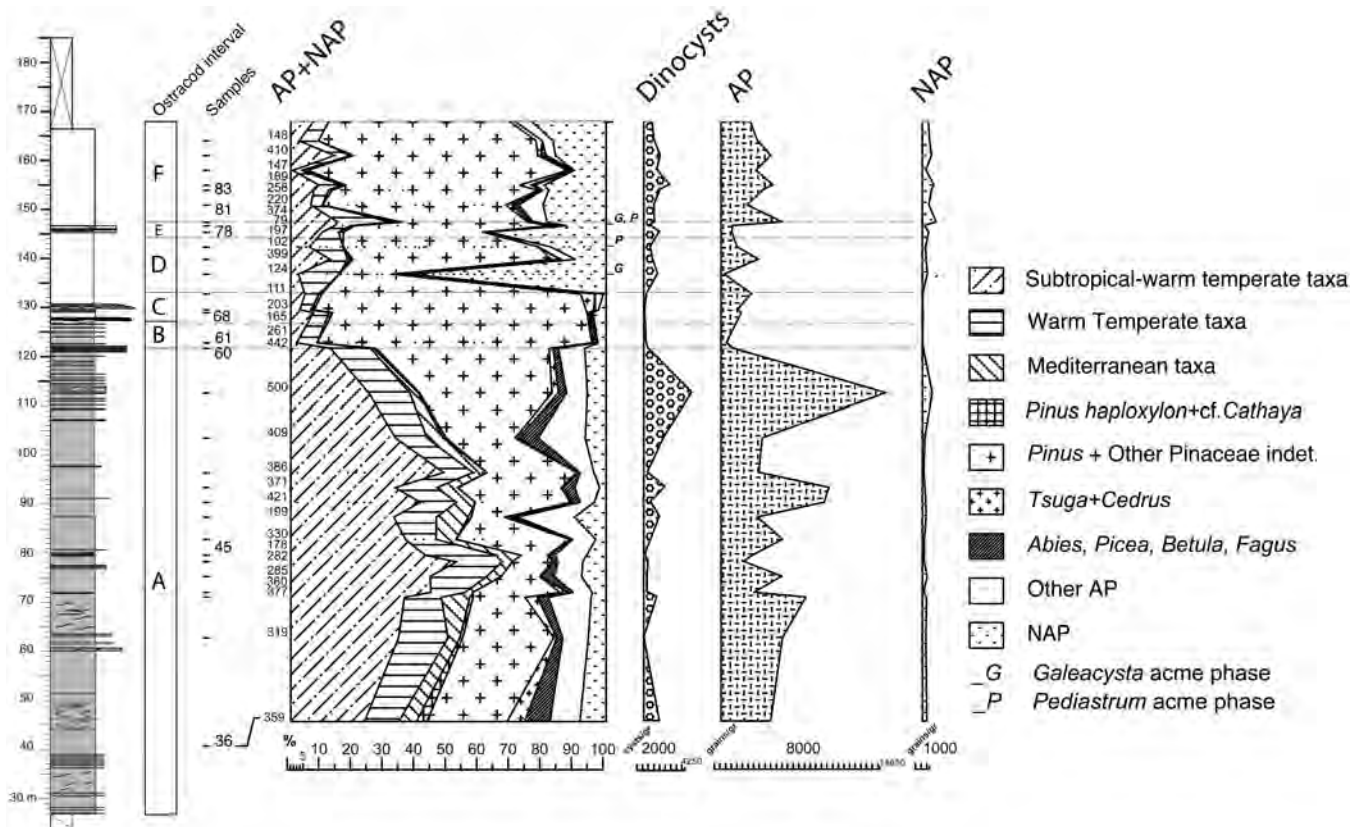
Equitability, number of species, and Shannon index parameters for the ostracod assemblage in the p-ev₁ and p-ev₂ sub-units.

Mudstones from 127 to 166m contain many macrofossiliferous horizons. The assemblages are dominated by bivalves, mainly diverse Lymnocardinae (*Euxinocardium subodessae*, *Limnocardium otiophorum*, *Pontalmyra* cf. *incerta chiae*, *Pseudocatillus* sp., *Plagiodacna* sp. among the others; Esu, 2007 and this paper), *Dreissena* ex gr. *rostriformis*, and occasional gastropods (hydrobiaceans, *Melanopsis narzolina* and *Melanoides* sp.). Bivalves are often disarticulated and parallel to the stratification suggesting reworking by currents. Lymnocardinae also occur in sandy units in the upper part of the p-ev₂ sub-unit. Abundant mollusc debris, showing imbrication and stratal isorientation, contribute to the conglomerates and coarse sandstones of the Trave horizon at the p-ev₂ top. Overall the p-ev₂ fauna is of Pontian affinity (Gillet 1968; Esu 2004, 2007) and suggests hypo- to mesohaline conditions. Fossils from the “Trave horizon” are chalky and highly fragmented but clearly dominated by Lymnocardinae and subordinate gastropods (hydrobiaceans and *Melanopsis*) suggesting the same environmental conditions as in the p-ev₂ sub-unit.

Pollen and dinocysts

The 99 pollen taxa from p-ev₁ and p-ev₂ sediments have been grouped in the summary diagram of text-fig. 14 largely on the basis of known, present-day ecology of correlative taxa. On the right of the diagram, concentration curves of arboreal, non arboreal and dinocysts are depicted.

In p-ev₁, pollen grains are generally in higher concentration (up to 15478 grains/gr) and better preserved than in p-ev₂ sediments. Pollen concentration largely fluctuates; it suffers a drastic decrease in both samples Tra 60 and Tra 61; in the overlying p-ev₂ samples, concentration increases but never reaches significant values being always less than 6636 grains/gr (maximum value in Tra 81). Dinocyst concentrations show a similar trend with values between 83 and 4241 cysts/gr in p-ev₁ and 66 and 2284 cysts/gr in p-ev₂; concentration shows repeated fluctuations, the higher value is reached in sample 56 (as well as the pollen) the lower values in samples 39 (barren) and 45. The dinocyst vs pollen ratio is always below 0.5 (text-fig. 11).



TEXT-FIGURE 14

Palynological diagrams of the p-ev₁ and p-ev₂ sub-units. From the left, ostracod interval, summary pollen diagram, concentration curves of dinocysts, arboreal (AP) and non arboreal plants (NAP).

The p-ev₁ terrestrial flora is dominated by pollen of subtropical-warm temperate trees prevalently *Engelhardia* with subordinate *Taxodium*, *Quercus*, *Myrica*, Sapotaceae, *Carya*, *Pterocarya*, *Carpinus*. Mediterranean taxa are also well expressed by the occurrence of *Olea* and *Quercus ilex-coccifera* type. Coniferous taxa are dominated by *Pinus* which however, is generally subordinate to the total pollen assemblages, at least up to sample Tra 52 where, on the contrary, it shows a progressive increase up to its acme phase in sample Tra 61, the topmost pollen record in the p-ev₁ deposits. This event is coincident with the major concentration decrease in both pollen and dinocyst values. *Abies*, *Picea*, *Cedrus*, *Tsuga* and *Cathaya* are also present, sometimes in significant quantities, as at the base of p-ev₁. Herbaceous taxa are generally subordinate being always below 10%; they prevalently include cosmopolitan taxa such as Asteraceae, Poaceae and Chenopodiaceae. Dinocysts from p-ev₁ consist principally of marine taxa, sometimes very well preserved.

In p-ev₂, pollen assemblages show an overall change with respect to p-ev₁ expressed by three main features: 1) generally higher percentage values of *Pinus* or herbs, 2) strong reduction of subtropical-warm temperate taxa and 3) quite well evident fluctuations in the percentage curve of the main vegetal groups.

Dinocysts assemblages show a major change in their composition marked by the arrival to dominance of the so-called Lago Mare taxa (*Galeacysta etrusca*, *Impagidinium* sp.1-3, Corradini and Biffi 1988) in correspondence of Tra 75. Such taxa

are well expressed and fluctuate up to Tra 87. *Pediastrum*, a chlorococcalean algae, is also present from Tra 76 with a maximum value in Tra 77. In the p-ev₂ deposits, the dinocyst vs pollen ratio shows two main peaks (text-fig. 11) correlating with the dominance of Lago Mare dinocysts (see *Galeacysta* acme phases in text-fig. 14).

On the whole, pollen assemblages detected in the p-ev₁ and p-ev₂, delineate the vegetation and climatic conditions in the terrestrial environments attesting to prevailing subtropical to warm temperate climate. Humid conditions, indicated by high frequencies of *Engelhardia*, are common throughout the p-ev₁ portion where it is hard to recognize cyclical patterns. On the contrary cyclical fluctuations, marked by the successive peaks in herbs, especially Asteraceae accompanied by Chenopodiaceae and Poaceae, are well expressed in the p-ev₂ deposits. The absence of *Lygeum* (with the exception of sparse grains) deserves mention as this species marks the p-ev₁ strata at Maccarone, just above the cineritic layer dated at 5.5 Ma (Bertini 2006). In the Trave section this important key-horizon is not present; this is probably related to the relative marginal setting with respect to the main foredeep and/or due to the occurrence of slides at the base of the p-ev₁ unit where the ash layer is commonly found (see also Roveri et al. 2005). Consequently this stratigraphic portion is completely lacking.

Dinocysts, though not specifically analyzed in this work, contribute significantly to the reconstruction of the aquatic environment changes and indicate the start of favorable conditions for

the development of the classical Lago Mare dinocyst facies in the upper portion of p-ev₂. Such a change in aquatic environments is also testified by the concomitant increase in abundance of *Pediastrum*. At present this taxon is common in lakes or slow-moving rivers and streams and is also known from coastal brackish waters of the Baltic Sea where salinities are below ca 5 or 10 psu. At Trave, the presence of *Pediastrum*, possibly marks freshwater events close to the occurrence of Lago Mare dinocyst assemblages in the uppermost Messinian; the same has been recorded at both Maccarone (Bertini 2006) and Eraclea Minoa (Londeix et al. 2007).

CONCLUSIONS

The sedimentary sequence of the Trave section encompasses the upper Tortonian to Lower Zanclean interval. The pre-evaporitic sequence is characterized by the accumulation of rhythmically interbedded marls, marly limestones and organic-rich deposits.

In terms of biostratigraphy the pre-evaporitic interval is referable to the Subzones MMi 12b-MMi 13b of Iaccarino et al. (2007) and to the subzone MNN11a of Raffi et al. (2003). In terms of cyclostratigraphic calibration the pre-evaporitic sequence is constrained between 7.45 Ma and about 6.30 Ma. Several foraminifer and nannofossil biohorizons were detected at the Tortonian/Messinian boundary and astrochronologically dated. The T/M boundary, dated at 7.251 Ma, is not recorded in the section. In fact the FCO of *G. miotumida* gr. which closely approximates the boundary, falls above the shear plane, in cycle 9 as the *R. pseudoumbilicus* PE whose age is calibrated at 7.18 Ma (Lourens et al. 2004), and only one cycle below the drastic decrease of the benthic foraminifer assemblage (exit of *C. wuellerstorfi*, *C. italicus*, *S. reticulata*, *C. bradyi*) calibrated at 7.16 Ma (Kouwenhoven et al. 1999) (Table 2). These biochronological evidences confirm the presence of a hiatus estimated at 80 Ky between cycles 8 and 9.

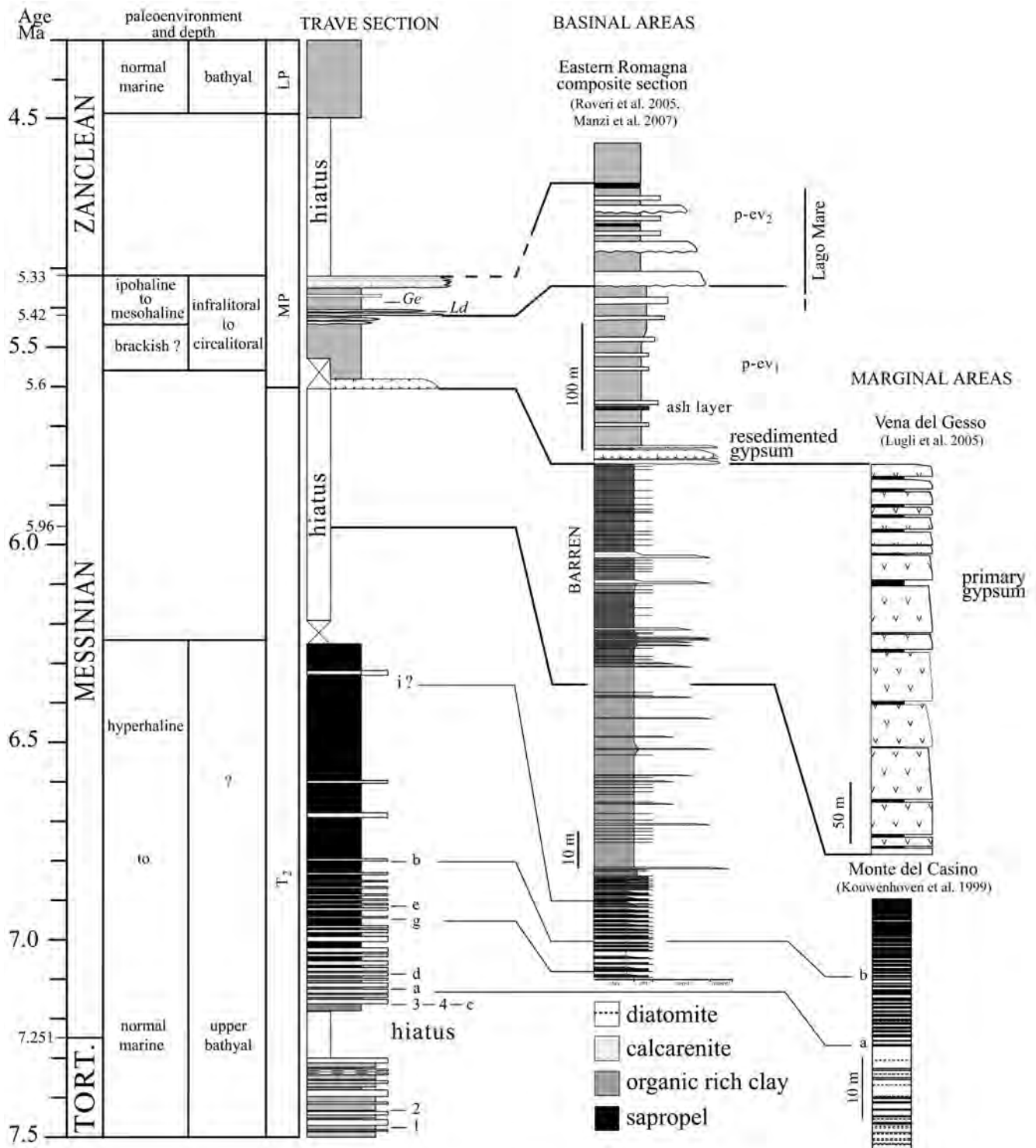
The pre-evaporitic sequence is overlain by the post-evaporitic siliciclastic p-ev₁ and p-ev₂ sub-units. The base of the p-ev₁ and p-ev₂ are marked respectively by resedimented evaporites and by a coarse-grained sandstone body (Roveri et al. 2005). The p-ev₁/p-ev₂ boundary formerly defined physically (Roveri et al. 1998) is well recognizable also in terms of bioevents: a low diversity Lago Mare assemblage first occurs a few meters below it, while *L. djafarovi* first occurs and is continuously present all along the p-ev₂ above the boundary. A second change in the overall assemblage is recorded a few meters above the physical boundary, where ostracod assemblage diversifies and Parathetyan dinocysts appear.

The Messinian deposits are topped by the “Trave biocalcarenite” which is abruptly overlain by massive mudstones of Early Pliocene age (planktonic foraminifer Zone MP13). Three hiatuses have been recognized along the Trave sequence: the lowest one between Tortonian and Messinian spanning 80 Kyr and the middle one between the top of the pre-evaporitic and post-evaporitic interval spanning about 750 Kyr. The upper hiatus is documented at the top of the Trave calcarenite straddling about 1.5 Ma of Early Pliocene.

In regards to the paleoenvironmental evolution, changes in faunal and floral composition are not recorded in the uppermost part of the Tortonian, even if horizons richer in organic matter are interbedded in the sedimentary succession. Fauna and flora point out open marine conditions. The evolution of the MSC

proceeded gradually, under a prevalent warm and humid climate as testified by pollen assemblages characterized by subtropical to warm-temperate taxa. From cycle 16 onwards the grey organic-rich layers are substituted by very distinct (black) laminated sapropels. However, a major shift towards more restricted environments started during the deposition of cycle 10 in correspondence of the exit of the species (*C. wuellerstorfi*, *C. italicus*, *S. reticulata*) representing normal marine conditions (at 7.16 Ma). In the latest levels (from cycle 30 upwards) the benthic assemblage (*B. subulata*, *B. dilatata*) clearly indicates increasing dysoxia as a consequence of the salinity increase and a drastic decrease of deep-water ventilation. As there is no evidence of increased surface productivity it is likely that the absence of deep-water outflow played an important role. Due to the constriction of the Atlantic gateway, the residence time of deep waters increased and the deep water mass became increasingly saline (at times too saline to allow benthic life) (Kouwenhoven et al. 2003). The increasing sedimentation of organic-rich deposits and poorly diversified fossil assemblages in deep basins is in agreement with the increasing isolation of the Mediterranean basin which led to complete anoxia (Manzi et al. 2007) (text-fig. 15). The integrated paleontological data obtained from the study of the post-evaporitic sequence indicate, for the p-ev₁ and p-ev₂, an abrupt change from iperhaline to hypohaline conditions in the hydrologic regime.

A brackish environment, characterized by strong terrigenous input, too deep to allow viability of euhaline benthic foraminifers and too mesohaline for the calcareous plankton is suggested for the p-ev₁. In fact, p-ev₁ deposits are characterized by foraminifer assemblages consisting of rare planktonic taxa of different ages and abundant very small-sized specimens not clearly autochthonous, by reworked calcareous nannofossils, and by the absence of ostracods except for the uppermost part (122–127m). The pollen data suggest a prevalently humid climate. On the base of the interdisciplinary data, the p-ev₁ sub-unit is suggested to be deposited in a marine basin strongly diluted by intense run-off. It is just in the uppermost part of p-ev₁ that typical Lago Mare biofacies, strongly imprinted by diverse *Lymnocardinae* assemblages, poorly diversified ostracod assemblage (interval B) and euhaline, shallow water benthic foraminifers occurs. All these evidences indicate oligohaline and shallower water conditions. Shallow water depth could explain the delayed entry in the basin of the Lago Mare dinocysts during interval D. The major fresh water influx occurring at the top of p-ev₁/ base of the p-ev₂ is comparable with the paleoenvironmental change characterizing the onset of the deposition of the Arenazzolo Fm in Sicily (Bonaduce and Sgarrella 1999). The paleontologic data from the p-ev₂ sub-unit indicate alternating infralitoral and fresh water input as well fluctuation of salinity (meso-hypohaline range), depth (ten to hundreds meters) and climate condition. Wetter/drier fluctuations are well expressed by the peaks in the relative abundance curve of herbs and arboreal pollen (text-fig. 14). The ostracods and the dinocysts which represent the best paleontologic signal for the paleoenvironmental reconstruction of the post-evaporitic phase suggest the following reconstruction: from 127m to 133m the ostracod assemblage records a salinity increase (mesohaline) for the disappearance of *Tyrrhenocythere ruggierii*, the scarcity of *Candonidae* and the increasing presence of *Leptocytheridae*. From 135m to 144m, the increasing presence of *Candonidae* and the appearance of Lago Mare dinocysts indicate deeper waters, while the still high frequency of *Leptocytheridae* suggests a slight decrease in salinity in the low mesohaline range. The deposition of the “colombaccio”



TEXT-FIGURE 15

Paleoenvironmental evolution of the Trave section and comparison with the Fanantello and Vena del Gesso stratigraphy; a to i and 1 to 4 and a to i are referred to the foraminifer and nannofossil events listed in Tables 1 and 2; *Ld*: FO of *Loxocorniculina djafari*; *Ge*: FO of *Galeacysta etrusca*.

(corresponding to interval E, barren of ostracods) could indicate poorly oxygenated bottom water due to increased continental water input (acme of *Pediastrum*), thus corresponding to the maximum flooding surface as suggested by Bassetti et al. (2004). Ostracods, from 147m to 166.5m, record rather deep conditions, coupled with a slight salinity decrease due to abundant Candonidae and Lago Mare dinocysts. This trend continues from 193m to 195.5m (immediately below the uppermost “colombaccio”) in which deep and oligohaline waters are testified by the presence of “pointed” candonids and scarce leptocytherids. Therefore, the paleontologic data from the p-ev₂ sub-unit indicate alternating hypo and mesohaline environmental conditions as a consequence of cyclic fresh water input in an inherited marine environment, in response to climatic variations. Cyclic stacking pattern is a constant characteristic of the p-ev₂ sub-unit in the Northern Apennines and is thought to be related to precessional cyclicity (Roveri et al. 2006). No obvious marine influxes from the Atlantic Ocean were detected/discovered, even if small sized planktonic foraminifers at the base of p-ev₁ may indicate a residual marine water body. The only fossils observed within the “Trave biocalcarenite” are the occurrence of *Melanopsis* and hydrobiacean gastropods, that could indicate the presence of the same environmental conditions as in the underlying p-ev₂. The recognition of the MPI3 Zone in the overlying Pliocene marls, representing the first normal marine sediments after the MSC, should imply a non-deposition surface at the top of the “Trave biocalcarenite”, as already suggested by Roveri et al. (2005).

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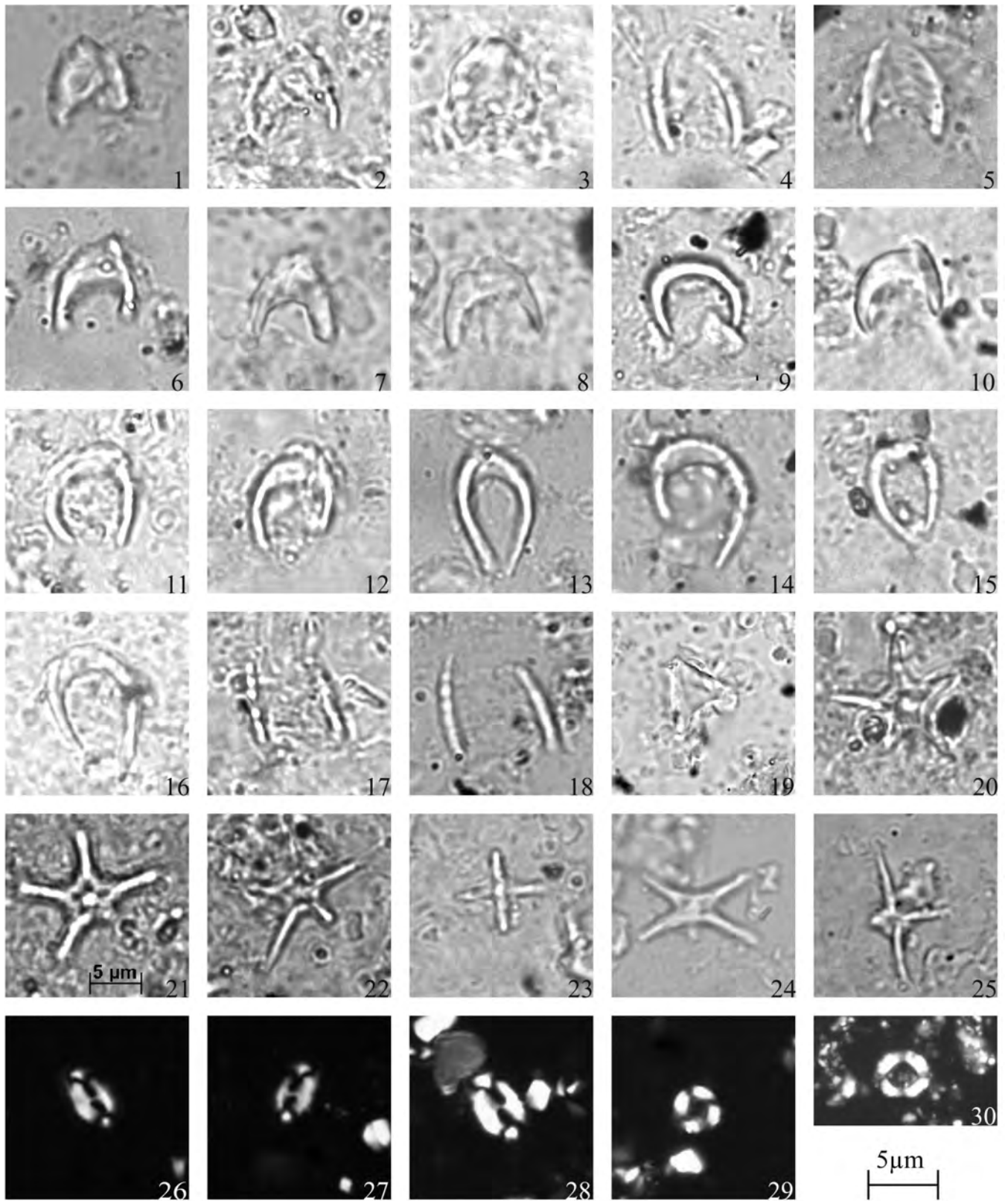
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PLATE 1

Photographs of selected calcareous nannofossils.

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| 1–5 <i>Amaurolithus primus</i> (Bukry and Percival), primitive morphotypes (1. Sample Stra 24b; 2. Sample Stra 18n; 3. Sample Stra 30n; 4. Sample Stra 25n; 5. Sample Stra 21n). | 19 <i>Triquetrorhabdulus-Nicklithus</i> transitional form (<i>sensu</i> Raffi et al., 1998) (Sample Stra 35bVIIIbis). |
| 6–8 <i>Amaurolithus primus</i> (Bukry and Percival) (6. Sample Stra 25n; 7. Sample Stra 22n; 8. Sample Stra 23n). | 20 <i>Discoaster berggrenii</i> Bukry (Sample Stra 19n). |
| 9–12 <i>Amaurolithus primus-Amaurolithus delicatus</i> intergrade (9. Sample Stra 31n; 10. Sample Stra 31n; 11. Sample Stra 18n; 8. Sample Stra 27n). | 21–22 <i>Discoaster quinqueramus</i> Gartner (21. Sample Stra 18n; 21. Sample Stra 19n). |
| 13–16 <i>Amaurolithus delicatus</i> Gartner and Bukry (13. Sample Stra 25n; 14. Sample Stra 31n; 15. Sample Stra 34bisVIIIn; 16. Sample Stra 34bisVIIIn). | 23–25 <i>Discoaster tamalis</i> Kamptner (23. Sample Stra 27n; 24. Sample Stra 24n; 25. Sample Stra 27n). |
| 17–18 <i>Triquetrorhabdulus-Amaurolithus</i> intergrade (17. Sample Stra 19n; 18. Sample Stra 25n). | 26–28 <i>Helicosphaera sellii</i> Bukry and Bramlette (Sample Stra 35bVIIIbrown). |
| | 29–30 <i>Reticulofenestra rotaria</i> Theodoridis (29. Sample Stra 35bVIIIbrown; 30. Sample Stra 24n). |



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