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Original article

Earliest Zanclean age for the Colombacci and uppermost Di Tetto formations of the "latest Messinian" northern Apennines: New palaeoenvironmental data from the Maccarone section (Marche Province, Italy)

La Formation de Colombacci et le sommet de la Formation Di Tetto (« Messinien terminal » des Apennins septentrionaux) sont d'âge zancléen : Nouvelles données paléoenvironnementales sur la coupe de Maccarone (Marche, Italie)

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# Abstract

The occurrence of planktonic foraminifers in the latest Messinian deposits (uppermost Di Tetto Formation and Colombacci Formation) of the Marche Province (Apennine foredeep, Italy) has stimulated a debate since the 1970s. An earlier palynological study of the entire Maccarone section revealed a pronounced, and a sudden increasing frequency of saccate pollen grains which indicates more distal conditions, and thus a transgression. At first attributed to tectonic activity, this transgression is now interpreted as representing the Zanclean marine transgression after the discovery of *Ceratolithus acutus*, the calcareous nannofossil marker of the earliest Zanclean in the Mediterranean Sea. Evidence from marine dinoflagellate cysts and planktonic foraminifers supports this result. The Colombacci Formation and uppermost part of the Di Tetto Formation (i.e. the entire p–ev2 stratigraphic unit) belong to the earliest Zanclean. The so-called Lago Mare no longer has a regional chronostratigraphic sense, and should be understood as the invasion of Paratethyan organisms via surface waters owing to a connection at high sea-level between the Aegean Sea and the Eastern Paratethys (Dacic Basin). A new robust environmental reconstruction of the northern Apennine foredeep is proposed, which respectively considers the effects of tectonics and Mediterranean eustasy.

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# Résumé

La présence de foraminifères planctoniques dans les dépôts du Messinien terminal (sommet de la Formation Di Tetto et Formation à Colombacci) de l'avant-fosse apenninique (Italie, région adriatique) est sujette à discussion depuis les années 1970. L'étude palynologique de la coupe de Maccarone avait révélé une soudaine et forte augmentation des pollens à ballonnets traduisant un milieu plus distal dans sa moitié supérieure. Cette transgression, qui a d'abord été attribuée à l'activité tectonique, est ici établie comme étant la transgression marine du Zancléen après la découverte de *Ceratolithus acutus*, le marqueur chez les nannofossiles du Zancléen basal en Méditerranée. La présence conjointe de kystes de dinoflagellés marins et de foraminifères planctoniques appuie ce résultat. En conséquence, la Formation à Colombacci et la partie sommitale de la Formation Di Tetto, c'est-à-dire l'intégralité de l'unité stratigraphique p–ev2, relèvent du Zancléen basal. Les dépôts qui étaient attribués au

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Lago Mare n'ont plus de sens chronostratigraphique mais reflètent l'invasion d'organismes paratéthysiens à la suite d'échanges d'eaux de surface lors de connexions à haut niveau marin entre la mer Egée et le bassin Dacique (Paratéthys orientale). Une nouvelle reconstitution environnementale de l'avant-fosse apenninique septentrionale est proposée, qui prend solidement en compte les effets conjugués de l'activité tectonique et des variations du niveau marin méditerranéen.

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Keywords: Zanclean transgression; Calcareous nannofossils; Marine dinoflagellate cysts; Lago Mare

Mots clés : Transgression zancléenne ; Nannofossiles calcaires ; Kystes de dinoflagellés marins ; Lago Mare

# 1. Introduction

In the northern Apennines, the Messinian-Zanclean sedimentary succession overlying the evaporitic Gessoso-Solfifera Formation has been described as comprising of three clastic formations (Roveri et al., 1998), from the base to top:

- the Di Tetto Fm. consisting of clays and turbidites, including a volcanic ash dated at about 5.50 Ma (Odin et al., 1997); this formation is the lower unit of the post-evaporitic depositional sequence (Bassetti, 2000; Roveri et al., 2001); it has been assigned to the latest Messinian with respect to <sup>39</sup>Ar/<sup>40</sup>Ar dating of the volcanic ash, and is constrained by the astronomical age of the Miocene-Pliocene boundary at 5.33 Ma (Lourens et al., 1996, 2004);
- the Colombacci Fm. consists of alternating thin limestones and clays, containing remains from the Paratethys (ostracods: mostly of *Cyprideis*; molluscs), and assimilated into the socalled Lago Mare (Cita and Colombo, 1979; Orszag-Sperber, 2006); this is the upper unit of the post-evaporitic depositional sequence (Roveri et al., 2001), which is assigned to the latest Messinian in agreement with the classical understanding of the Lago Mare facies, and because of the Zanclean fossil content of the overlying clays; a geometrical unconformity separates this formation from the underlying one (Bassetti, 2000);
- the Argille Azzurre Fm. which constitutes the widespread early Zanclean facies, including the relevant planktonic foraminifers (Selli, 1973).

Recently, another subdivision was proposed on the basis of detailed sedimentological investigations (Roveri et al., 2001; Manzi et al., 2005; Roveri and Manzi, 2006):

- a post-evaporitic unit 1 (p–ev<sub>1</sub>) that overlies the Gessoso-Solfifera Fm., and comprises the ash layer and some turbidites; it has an estimated time-span of 5.60 to 5.40 Ma;
- a post-evaporitic unit 2 (p-ev<sub>2</sub>) i.e. separated from the underlying unit by a minor discontinuity; rich in turbiditic layers, it includes in its upper part the Colombacci limestones; it has an estimated time-span of 5.40 to 5.33 Ma, terminating where the Argille Azzure conformably overlies the Colombacci Fm.

One of the reference localities for this succession is the Maccarone section (close to Apiro:  $43^{\circ}24'20''$  N,  $0^{\circ}39'00''$  E, top of the section 430 m asl; Fig. 1), where the ash bed was

dated (Odin et al., 1997). At Moscosi, the Messinian gypsum underlying the Maccarone section is resedimented (Bassetti et al., 1994; Roveri et al., 1998, 2001; Bassetti, 2000; Manzi et al., 2005). The well-exposed section here (Fig. 2) has been the subject of several investigations, including those on foraminifers (Carloni et al., 1974a), and palynology (Bertini, 1992, 1994, 2002, 2006).

Results from these studies raised several inconsistencies:

- Relatively diverse if not abundant planktonic (and some benthic) foraminifers found discontinuously at about 60 m (and more continuously at about 20 m) below the Zanclean clays (Fig. 2; Carloni et al., 1974a). Moreover, a marine microfauna was found in several sections (sometimes associated with coccoliths) but systematically interpreted as reworked because of incompatibilities with the ostracod *Cyprideis* (Casati et al., 1976; Bassetti et al., 2003). Colalongo et al. (1976) admittedly expressed a more moderate viewpoint, and Carloni et al. (1974a) accepted the co-existence of this fauna with *Cyprideis*;
- Dinoflagellate cysts (including marine species such as *Impagidinium aculeatum*, *Lingulodinium machaerophorum*, *Spiniferites ramosus*) show a sudden improvement preservation, and increase in diversity 60 m below the Zanclean clays (Fig. 2; Bertini, 1992, 2006);



Fig. 1. Location map of the Maccarone section.

Fig. 1. Localisation géographique de la coupe de Maccarone.



Fig. 2. Lithology and traditional bio-chronostratigraphy of the Maccarone section with some micropaleontological data and pollen marker taxa. The updated chronostratigraphy proposed in the present work is shown in Fig. 3. Lithology after Bertini (2006), modified according to our observations: **a**, Volcanic ash; **b**, Turbiditic layer; **c**, Calcareous clay; **d**, Light clay; **e**, Grey clay; **f**, Black clay; **g**, Limestone. Bio- and chronostratigraphy is from Carloni et al. (1974a, 1974b), Bassetti et al. (1994), Odin et al. (1997), Roveri et al. (1998), Manzi et al. (2005), Bertini (2006), Roveri and Manzi (2006). Foraminiferal records are from Carloni et al. (1974a) with a discontinuous record of rare specimens from their sample 22A (i.e. at about the pev<sub>1</sub>b–pev<sub>2</sub> formation boundary), more continuous record of frequent specimens from their sample 42 (i.e. at the Di Tetto-Colombacci formation boundary), and continuous record of abundant specimens from their sample 49 (i.e. at the base of the Argille Azzurre Fm.). Dinoflagellate cysts are from Bertini (1992, 2006) who indicated a better preservation, and a slightly higher diversity in marine dinoflagellate cysts 40 m below the Colombacci Fm., and fully marine conditions (with the abrupt appearance of *Impagidinium patulum*) at the base of the Argille Azzurre Fm. Bertini (1992, 2006) also pointed out the early presence of Paratethyan dinoflagellate cysts (the so-called *Impagidinium* sp. 1) with respect to the Colombacci Fm. (somewhat 10 m below the first carbonate layer) in which they are frequent. Pollen records are from Bertini (1992): *Pinus, Cathaya, Cedrus, Tsuga, Abies*, and *Picea* have an amplified signal owing to their buoyancy (facilited by the presence of bladders) during aquatic transport; subdesertic elements: *Ziziphus, Croton*, Agavaceae, *Agave, Cordyline, Nolina, Prosopis, Lygeum, Calligonum*.

Fig. 2. Lithologie et bio-chronostratigraphie classique de la coupe de Maccarone complétée de quelques données micropaléontologiques et des taxons marqueurs dans la flore pollinique. La nouvelle chronostratigraphie déduite de ce travail est donnée dans la Fig. 3. Lithologie d'après Bertini (2006), modifiée selon nos observations : **a**, Cinérite ; **b**, Niveaux turbiditiques ; **c**, Argile calcaire ; **d**, Argile claire ; **e**, Argile grise ; **f**, Argile noire ; **g**, Calcaire. Bio- chronostratigraphie d'après Carloni et al. (1974a, 1974b), Bassetti et al. (1994), Odin et al. (1997), Roveri et al. (1998), Manzi et al. (2005), Bertini (2006), Roveri et Manzi (2006). Données sur les foraminifères d'après Carloni et al. (1974a), avec un enregistrement discontinu de rares spécimens à partir de leur échantillon 22A (à peu près la limite entre les formations pev<sub>1</sub>b–pev<sub>2</sub>), un enregistrement davantage continu de spécimens fréquents à partir de leur échantillon 42 (limite entre les formations Di Tetto et Colombacci), et un enregistrement continu de spécimens abondants à partir de leur échantillon 42 (limite entre les formation à Colombacci, et des conditions franchement marines (avec l'apparition soudaine d'*Impagidinium patulum*) à la base de la Formation des Argille Azzurre. De plus, Bertini (1992, 2006) souligne la présence de kystes de dinoflagellés paratéthysiens (sous l'appellation *Impagidinium* sp. 1) antérieurement à la Formation à Colombacci (10 m environ sous le premier lit carbonaté) dans laquelle ils sont fréquents. Données polliniques d'après Bertini (1992) : *Pinus, Cathaya, Cedrus, Tsuga, Abies* et *Picea* ont un signal amplifié dû à leur flottabilité facilité par leur(s) ballonnet(s) remplis d'air ; éléments subdésertiques : *Ziziphus, Croton*, Agavaceae, *Agave, Cordyline, Nolina, Prosopis, Lygeum, Calligonum*.

- A rapid increase in abundance of *Pinus* pollen (from 30 to 75% on average) occurs also at about 60 m below the Zanclean clays, and 37 m below the first Colombacci limestone (Bertini, 1992, 1994, 2002, 2006), and the consequence of a tectonic event (Bertini, 2002, 2006) is discarded (Clauzon et al., 2005);
- Pollen of *Lygeum spartum*, a typical subdesertic plant (Brullo et al., 2002), was almost continuously recorded in association with other subdesertic elements (Agavaceae including *Agave*, *Nolina*, and *Cordyline* as well as *Croton*, *Prosopis*, and *Calligonum*) at such a high latitude along the lowermost 110 m of the section (sometimes up to 5%: Fig. 2; Bertini, 1992, 2006) in an humid palaeoclimatic context (Fauquette et al., 2006).

These discrepancies have prompted the present study. Highresolution sampling was performed on the lowermost Argille Azzurre, Colombacci, and uppermost Di Tetto formations at almost regular intervals (0.80–1 m) following deep excavations (45 samples versus 20 in the same interval by Bertini, 1992, 2002, 2006), and stopped when solifluction disturbed observation in the middle part of the Di Tetto Formation (Fig. 3).

Our investigations concern the nannoplankton (not previously documented in the section), dinoflagellate cysts, and planktonic foraminifers, focussing on an interval about 40 m thick including the uppermost part of the Di Tetto Fm., the entire Colombacci Fm. (i.e. the major part of the p–ev<sub>2</sub> unit), and the beginning of the Argille Azzurre Fm. (Fig. 3). Two modest geometrical unconformities have been reported,



Fig. 3. Revisited chronostratigraphy of the Maccarone section with the location of the studied samples and the recorded occurrences of the calcareous nannofossil stratigraphic markers *Ceratolithus acutus* and *Triquetrorhabdulus rugosus*. Lithology after Bertini (2006), and modified from our observations: **a**, Volcanic ash; **b**, Turbiditic layer; **c**, Calcareous clay; **d**, Light clay; **e**, Grey clay; **f**, Black clay; **g**, Limestone. Photographs: **A**, The entire Maccarone section (the vertical lines indicate sampled segments); **B**, The boundary between the Di Tetto and Colombacci formations; **C**, Upper provide the Maccarone section.

Fig. 3. Chronostratigraphie révisée de la coupe de Maccarone avec l'emplacement des échantillons étudiés et les enregistrements des nannofossiles calcaires marqueurs stratigraphiques *Ceratolithus acutus* et *Triquetrorhabdulus rugosus*. Lithologie d'après Bertini (2006), modifiée selon nos observations : **a**, Cinérite ; **b**, Niveaux turbiditiques ; **c**, Argile calcaire ; **d**, Argile claire ; **e**, Argile grise ; **f**, Argile noire ; **g**, Calcaire. Photographies : **A**, Ensemble de la coupe de Maccarone (les lignes verticales indiquent les segments échantillonnés) ; **B**, Limite entre les formations Di Tetto et Colombacci ; **C**, Partie supérieure de la coupe de Maccarone.

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respectively in the upper part of the Di Tetto Fm. (i.e. at the boundary between the  $p-ev_1$  and  $p-ev_2$  units (Roveri and Manzi, 2006), and at the boundary between the Di Tetto and Colombacci formations (Bassetti, 2000) (i.e. within the  $p-ev_2$  unit). They are related to the regional tectonic activity, that is well-recognized in marginal areas (Roveri et al., 1998, 2001) but not directly expressed in the Maccarone section itself.

## 2. Calcareous nannofossils

Calcareous nannofossils are generally abundant, except in the Colombacci Fm. (samples 20–35). Preservation is on the whole moderate, except in the Colombacci Fm., and the four lowermost samples of the studied section where it is poor, and in some samples where it is relatively good (Fig. 4). The assemblages are dominated by *Coccolithus pelagicus*, *Reticulofenestra pseudoumbilicus*, *Sphenolithus abies*, *S. moriformis*, *Triquetrorhabdulus rugosus*, and the small reticulofenestrids (Fig. 4). Of particular biostratigraphic significance are (1) *Triquetrorhabdulus rugosus* (nearly continuous occurrence from sample 1 to 25 and 34 to 42, and an isolated occurrence in sample 29), and (2) *Ceratolithus acutus* (nearly continuous occurrence from sample 5 to 15, isolated occurrences in samples 21 and 33, and a continuous record at the top of the section from sample 43) (Fig. 4).

The top of the calcareous nannofossil Zone NN11 is defined by the disappearance of *Discoaster quinqueramus* (Berggren et al., 1995a), the age of which was estimated at about 5.537 Ma



Fig. 4. Recorded occurrences of calcareous nannofossils in the present study. Key taxa are in bold face. For the reworked specimens, the size of the black rhombs relates to the amount of reworking.

Fig. 4. Distribution des nannofossiles calcaires trouvés dans notre étude. Les taxons marqueurs sont en caractères gras. Spécimens remaniés : la taille des symboles est en relation avec l'importance du remaniement.



Fig. 5. Comparison of Late Miocene and Early Pliocene bio- and chronostratigraphy in the Mediterranean Sea according to the "EEDEN Integrated Neogene Correlation Table" coordinated by Iaccarino, S. and Steininger, F.F. (unpublished) with the global time scale of Lourens et al. (2004).

Fig. 5. Bio- et chronostratigraphie du Miocène supérieur et du Pliocène inférieur de Méditerranée selon la charte établie par le Programme "EEDEN" coordonnée par Iaccarino et Steininger (inédit) comparée à la charte globale de Lourens et al. (2004).

by Backman and Raffi (1997), and precisely recalculated at 5.58 Ma by Lourens et al. (2004) (Fig. 5), although this species is very rare or even absent in the Mediterranean area (Rio et al., 1984). In the studied samples, only a few broken specimens of D. quinqueramus were observed, and are probably reworked. Ceratolithus acutus had a proposed range of 5.372-5.046 Ma in the equatorial Atlantic (Backman and Raffi, 1997) which was recalculated 5.35-5.04 Ma by Lourens et al. (2004) (Fig. 5). This datum precedes the disappearance of *Triquetrorhabdulus* rugosus (Berggren et al., 1995a, 1995b) placed at 5.28 Ma by Lourens et al. (2004). In the Mediterranean region, the first appearance of C. acutus was delayed until the beginning of the Pliocene (Cita and Gartner, 1973; Castradori, 1998) because of the isolation of the basin during the Messinian salinity crisis, the so-called "Non Distinctive Zone" of Iaccarino and Salvatorini (1982) (Fig. 5). Moreover, as in other Mediterranean and Atlantic sites (Backman and Raffi, 1997; Castradori, 1998), the two above-mentioned nannofossil events are not coincident: the extinction of T. rugosus is younger than the appearance of *C. acutus*. As a consequence, the presence of *C*. acutus in any Mediterranean sediment means that this deposit necessarily belongs to the earliest Zanclean (Fig. 5). At first sight, the studied interval from the Maccarone section, which records both Triquetrorhabdulus rugosus (samples 1-42), and Ceratolithus acutus (samples 5-45), belongs to the MNN12 Calcareous Nannofossil Zone of Rio et al. (1990) who emended the standard zonation of Martini (1971), that is, to the earliest Zanclean (Fig. 5).

Even we assume that highest occurrences of *T. rugosus* might represent reworking, the almost continuous presence of *C. acutus* throughout the investigated succession (except its base and some barren intervals) is referable to MNN12.

Also notable is the increased frequency of *Coccolithus pelagicus* towards the base of the study successions (samples

5–10). Siesser and Kaenel (1999) also reported an increased abundance of *C. pelagicus* (considered to be more related to cool surface waters, during the Pliocene; Bukry, 1981) in the Western Mediterranean area, within the lower part zone NN12. By contrast, the paracme of *Reticulofenestra pseudoumbilicus*, a bio-event reported in the lowermost zone MNN12 by such authors as Rio et al. (1990) and Di Stefano (1998) was not encountered in the studied section. This may be due to the reworking, which could have modified the original nannofloral composition. Alternatively, the basal Zanclean *R. pseudoumbilicus* paracme may have a limited applicability in the Mediterranean area (Van Couvering et al., 2000).

#### 3. Dinoflagellate cysts

More than 200 dinoflagellate cysts have been counted per sample, yielding a total of 45 taxa. The preservation of specimens is on the whole poor to moderate in the Di Tetto Fm. (samples 1–19) and moderate to good in the Colombacci Fm., and the lower part of the Argille Azzurre Fm. (samples 26–45).

Particular effort have been made to identify the brackish stenohaline Paratethyan species: Galeacysta etrusca, Impagidinium globosum, Millioudodinium bacculatum, Millioudodinium baltesii, Millioudodinium dektense, Millioudodinium pelagicum, Millioudodinium punctatum, Pontiadinium inequicornutum, Pontiadinium obesum, Pontiadinium pecsvaradense, Pyxidinopsis psilata, Romanodinium areolatum, Spiniferites balcanicus, Spiniferites bentorii subsp. budajenoensis, Spiniferites bentorii subsp. coniunctus, Spiniferites bentorii subsp. oblongus, Spiniferites bentorii subsp. pannonicus, Spiniferites cruciformis, Spiniferites galeaformis, Spiniferites inaequalis; Spiniferites maisensis, Spiniferites sagittarius, Spiniferites tihanyensis, Spiniferites validus, Spiniferites virgulaeformis. This was done by directly comparing the Maccarone specimens with topotypes of Paratethyan taxa as well as their corresponding original iconography and description. The following species are invalid, and a study is in progress with M.J. Head for their emendation: Impagidinium globosum Süto-Szentai, 1985, Millioudodinium baltesii Süto-Szentai, 1990, Millioudodinium dektense Süto-Szentai, 1990, Millioudodinium pelagicum Süto-Szentai, 1990, Millioudodinium punctatum Baltes, 1971, Spiniferites balcanicus Baltes, 1971, Spiniferites bentorii subsp. budajenoensis Süto-Szentai, 1986, Spiniferites bentorii subsp. coniunctus Süto-Szentai, 1988, Spiniferites bentorii subsp. oblongus Süto-Szentai, 1986, Spiniferites bentorii subsp. pannonicus Süto-Szentai, 1986, Spiniferites sagittarius Süto-Szentai, 1990, Spiniferites tihanyensis Süto-Szentai, 1988. One result of our taxonomic studies is that the Impagidinium sp. 2 of Corradini and Biffi (1988), also illustrated by Bertini (1992: Pl. 3, Fig. 9), is a morphotype of Spiniferites cruciformis (Wall et al., 1973): see Marret et al. (2004) and Mudie et al. (2004) for illustrative photographs. Corradini and Biffi (1988) suggested that Impagidinium sp. 1 may be equivalent to Millioudodinium (Leptodinium) bacculatum but did not consult the reference material of Baltes (1971). Our taxonomic investigations now indicate that Impagidinium sp. 1, as illustrated also by Bertini (1992: Pl. 3, Fig. 10) from the Maccarone section, is indeed *Millioudodinium bacculatum*, and not *Caspidinium rugosum* of Marret et al. (2004) (see also Sorrel et al., 2006) as claimed by Bertini (2006). Results are presented in a detailed dinoflagellate cyst occurrence diagram (Fig. 6a,b).

Fig. 7 displays the relative frequency of some marker taxa according to their ecological significance (marine euryhaline and stenohaline species, brackish stenohaline species). The reworked dinoflagellate cysts contain such taxa as *Achomosphaera alcicornu* (Eisenack, 1954), Davey and Williams, 1966, *Homotryblium oceanicum* (Eaton, 1976), Bujak et al., 1980, *Deflandrea* spp., *Spiniferites granulatus* (Davey, 1969b), Lentin and Williams, 1973), *Achomosphaera ramulifera* (Deflandre, 1937), and specimens that show an increased uptake of safranine stain. Their percentage is based on the total number of in situ plus reworked cysts (Fig. 7).

In contrast to Bertini (2006) we consider our quantitative study of dinoflagellate cysts (Fig. 7) to show an important environmental change in surface-water salinity. To characterize these environmental changes, taxa have been grouped according to their ecological significance (Fig. 7): (1) marine stenohaline dinoflagellate cysts indicated in bold characters on Fig. 6a, (2) marine euryhaline dinoflagellate cysts incorporating other marine taxa presented in Fig. 6a, (3) brackish stenohaline Paratethyan dinoflagellate cysts based on independent curves of marker taxa (*Spiniferites cruciformis, Galeacysta etrusca*, and *Pyxidiniopsis psilata*), and one curve for the other taxa listed in Fig. 6b, (4) the fresh-water alga *Pediastrum*. Reworked dinoflagellate cysts are also plotted on Fig. 7. A morphological study of *Galeacysta etrusca*, *Spiniferites balcanicus*, and *Romanodinium areolatum*, originating from different well-



Fig. 6. Recorded occurrences of dinoflagellate cysts in the present study: **a**, marine species; **b**, brackish Paratethyan species. Key taxa are in bold characters. Fig. 6. Distribution des kystes de dinoflagellés trouvés dans notre étude : **a**, espèces marines ; **b**, espèces saumâtres paratéthysiennes. Les taxons marqueurs sont en caractères gras.

Samples Preservation Galeacysta etrusca Spiniferites balcanicus	Romanodinium areolatum Spiniferites cruciformis Spiniferites inaequalis Pyxidinopsis psilata Impagidinium globosum Millioudodinium spp. Pontiadinium pecsvaradense Pontiadinium pecsvaradense Pontiadinium spp. Spiniferites bentorii budajenoensis Spiniferites bentorii budajenoensis Spiniferites bentorii pannonicus Spiniferites sentorii pannonicus Spiniferites sagittarius Spiniferites tihanyensis Spiniferites sigittarius Spiniferites sigittarius Spiniferites sigittarius Spiniferites segittarius Spiniferites segittarius Spiniferites sigittarius Spiniferites sigittarius Spiniferites sigittarius Spiniferites sigittarius Spiniferites sigittarius Spiniferites signasis Spiniferites signasis
45 44 44 42 41 40 39 38 37 38 37 36 36 37 36 37 36 37 37 37 37 37 37 37 37 37 37	on: O moderate to good ◆ moderate O poor to moderate □ poor

Fig. 6. (Continued).

dated Mediterranean and Paratethyan sections, suggests that these species probably represented different steps in evolution/ adaptation to environmental changes (probably in surfacewater salinity) of the same species (Popescu, unpublished). As a consequence, these taxa have been grouped within the *Galeacysta etrusca* curve (Fig. 7). It is also notable that the specimens identified in the present study as *Spiniferites cruciformis* and *Pyxidiniopsis psilata* display a range of morphologies just as they do in the Black Sea Holocene sediments (Wall et al., 1973). Our data from the entire Neogene of Paratethys show that the transition from oval to cruciform body, and the well- to poorly-expressed tabulation characterizes reduced surface-water salinity.

The lower and upper parts of the studied section (samples 1– 5 and 43–45, respectively) are dominated by the marine euryhaline (80%), and stenohaline (15%) dinoflagellate cysts documenting a typical marine environment (Fig. 7). The middle part of the studied section (samples 7–42) is characterized by prevalent brackish Paratethyan species, indicating a decrease in surface-water salinity.

The freshwater alga *Pediastrum* is frequent in the lower part of the studied section (samples 1–20) with an acme in samples 7 and 8 (in equal number to the dinoflagellate cysts), exactly where this event was also identified by Bertini (2006). It is noteworthy that the vertical distribution of *Pediastrum* is practically in phase with the greatest amounts of reworked dinoflagellate cysts (Fig. 7), and a palynofacies dominated by coaly microdebris and woody microfragments (samples 1 to 12), documenting an important arrival of freshwater probably because of an intensified river input (Poumot and Suc, 1994).

# 4. Planktonic foraminifers

This study only relates to the Colombacci Fm. and the lowermost Argille Azzurre Fm. On the whole, preservation is moderate to poor. Planktonic foraminifers are abundant and



Fig. 7. Distribution and relative frequency of dinoflagellate cyst markers in the present study, with location of the anoxic layer. Barren intervals are indicated by grey bands. Lithology: see Figs. 2 and 3.

Fig. 7. Distribution et fréquence relative des kystes de dinoflagellés marqueurs trouvés dans notre étude, avec l'emplacement du niveau anoxique. Les intervalles dépourvus de kystes de dinoflagellés sont indiqués par des bandes grises. Lithologie : voir Figs. 2 et 3.

diverse only in samples 41 (Colombacci Fm.), and 43–45 (Argille Azzurre Fm.). Reworked specimens are frequent. Results are given on Fig. 8, and are consistent with those published by Carloni et al. (1974a). However, planktonic foraminifers from sample 24 to 40 display a small size (found only within the <250  $\mu$ m fraction), a peculiarity also noticed by Colalongo et al. (1976) in the Colombacci Fm. of Cella, that indicates unfavourable environmental conditions. Ostracods are abundant in samples 38 to 42, as already pointed out by Carloni et al. (1974a) and Casati et al. (1976).

# 5. Discussion

Many consistent lines of evidence reveal the evolution of aquatic and continental environmental conditions in the area of Maccarone, which can be extended to the entire Adriatic foredeep, and Po Basin by integrating the available information.

Marine Zanclean Mediterranean waters entered this region before the arrival of the planktonic foraminifers *Sphaeroidinellopsis* and then *Globorotalia margaritae*, the marker species of zones MPI1 and 2, respectively, which belong to the early Zanclean (Cita and Gartner, 1973). This is attested by (1) the first appearance of *Ceratolithus acutus*, the nannofossil marker for the base of the Pliocene in the Mediterranean which cannot be explained by reworking (Fig. 3), (2) the almost regular occurrence of non-reworked planktonic foraminifers (Fig. 8), and (3) marine dinoflagellate cysts (Figs. 6 and 7). The early arrival of Zanclean foraminifers might be detected through the record in the uppermost Di Tetto Fm. of the benthic species *Uvigerina rutila* (Carloni et al., 1974a: sample 22A), which being a marker for the Zanclean (Iaccarino, 1967; Cita and Gartner, 1973), likewise cannot be suspected of reworking. Additional evidence of the normal marine condition of the Colombacci Fm. was recently provided by Carnevale et al. (2006a) who studied otoliths of euryhaline marine fish from the Ca'Ciuccio section close to Montecalvo in Foglia. These authors proposed that the marine refilling of the Mediterranean preceded the Miocene-Pliocene boundary.

The marine incursion operated in two pronounced steps:

• the first one occurred in the upper Di Tetto Fm. (starting before sample 1 and lasting through sample 15) based on (1) the abundance of marine euryhaline dinoflagellate cysts (*Impagidinium aculeatum*, *Nematosphaeropsis labyrinthus*, *N*. cf. *lemniscata Spiniferites ramosus*, *S. bulloideus*, *Lingulodinium machaerophorum*, *Operculodinium centrocarpum*, *Pentapharsodinium dalei*) accompanied by marine stenohaline taxa (*Impagidinium patulum*, *I. strialatum*, *Spiniferites bentorii*, *S. mirabilis*, *S. hyperacanthus*,



Fig. 8. Recorded occurrences of planktonic foraminifers in the studied samples of the Colombacci and Argille Azzurre fms. Fig. 8. Distribution des foraminifères planctoniques dans les échantillons étudiés des formations à Colombacci et des Argille Azzurre.

S. membranaceus, S. cf. falcipedius, Achomosphaera, andalousiensis) (Fig. 7), and (2) the coeval diversity in calcareous nannofossils including the appearance of *Ceratolithus acutus* (Figs. 3 and 4);

• the second step occurred in the Colombacci Fm., and intensified in the Argille Azzurre Fm. (samples 23–45); it is marked (1) by strongly anoxic conditions (about 80% of a yellow and fleecy amorphous organic matter in the palynofacies of samples 23–26 corresponding to black and grey clays) probably caused by a contrasted water stratification (Poumot and Suc, 1994) (Fig. 7), (2) marine euryhaline dinoflagellate cysts which increase again in parallel to the marine stenohaline species (Fig. 7), (3) diversity of calcareous nannofossils more manifest from sample 33 (Fig. 4), (4) increasing diversity in planktonic foraminifers, these displaying a normal size from sample 41(Fig. 8).

Between these two steps, influx of marine water continued as evidenced by dinoflagellate cysts, in sample 20 for example (Fig. 7), and more continuously by calcareous nannofossils (Fig. 4). The process is characteristic of an influx of marine waters overflowing a sill (the Otrante Sill in this case), surface waters entering first the isolated basin with dinoflagellates and coccoliths, followed by deeper waters with more abundant foraminifers. Among the latter, the planktonic marker species entered the Apennine foredeep when salinity reached a sufficiently elevated level for their persistent presence. At the beginning of the transgression, the euryhaline dinoflagellate cysts are more abundant than the steohaline ones, as explained by their great capacity to adapt within a large salinity and temperature range (Marret and Zonnerveld, 2003).

The dinoflagellate cyst record shows that the so-called Lago Mare event (corresponding to the Colombacci Fm.: Cita and Colombo, 1979; Bassetti et al., 2003; Orszag-Sperber, 2006) is sandwiched within the marine transgression here referred to the earliest Zanclean (Figs. 3 and 7). Accordingly, the classical interpretation of a Lago Mare event as resulting from the draining of Paratethyan brackish waters into an almost desiccated Mediterranean Basin (Hsü et al., 1973; Cita et al., 1978: Fig. 12, p. 1018) is fully disproved as already demonstrated by Clauzon et al. (2005) on the basis of such evidence as the coeval inflow of Mediterranean marine waters into the Eastern Paratethys. Actually, two Lago Mare events happened in the Mediterranean Sea as a result of cross exchanges with the Eastern Paratethys at high sea-level, the first event just before the Mediterranean desiccation, and the second event caused by the reflooding of the Mediterranean Sea during the earliest Zanclean (Clauzon et al., 2005). The Lago Mare

event recorded at Maccarone is that of the earliest Zanclean. It documents the existence of high sea-level connections with the Eastern Paratethys allowing inflow to the Mediterranean of reduced salinity surface waters originating from the Paratethys, transporting stenohaline dinoflagellates, and larvae of ostracods and molluscs. As also coroborated by fish remains, the Lago Mare events occurred when the Mediterranean Sea was full of water: see Carnevale et al. (2006b) for the first Lago Mare event, and Carnevale et al. (2006a) for the Zanclean one. As a consequence, the systematic dismissal of marine elements as reworked within the Lago Mare events (in accordance with the conventional assumption that it is impossible to record ecologically mixed fossil assemblages), must be abandoned. The records of foraminifers and calcareous nannofossils within the Colombacci deposits, such as at Cella (Colalongo et al., 1976), Gualdo (Casati et al. (1976), and Monticino (Rio and Negri, 1988) regain their full significance. The small size of planktonic foraminifers testify to the unfavourable quality of waters. The significance of the ostracod species in the region has been clarified by Bassetti et al. (2003) who demonstrated their weak relationship with the contemporaneous Paratethyan species. These results pointed out the risk to define the Lago Mare events on the basis of the ostracods only, and reinforced the ecological significance of such events.

In the middle part of the Maccarone section, the relative frequency of Pinus pollen rapidly (within just a 5.5 m thick interval) increases from 33 to 78% in parallel with a moderate increase in the other saccate pollen grains (Cathaya, Cedrus, Tsuga, Abies, and Picea: Fig. 2; Bertini, 2002, 2006). Pinus in particular but also other saccate pollen grains are known to be over-represented in distal aquatic sediments because they are more buoyant during water and air transport (Heusser, 1988; Beaudouin et al., 2007). Such a shift has been correctly understood as reflecting a transgressive trend resulting in an increasing distance of the locality from shore (Bertini, 2002). However, this event was attributed to tectonic activity in the northern Apennines (Bertini, 2006), and associated with the regional unconformity separating p-ev2 from p-ev1 units (Bertini, 2002). This break appears too abrupt to be explained by a tectonic event, especially when considering the unlikelihood of a transgressive trend occurring in an area undergoing compression (the Maccarone subaquatic sediments of the Colombacci Fm. have been uplifted to 380 m asl). It is much more plausible to explain a rapid retreat of the shoreline by the sudden marine Zanclean transgression, as documented herein.

The lower part of the studied section (samples 1–17) is characterized both by large numbers of reworked dinoflagellate cysts, a palynofacies rich in coaly microparticles and woody microfragments, and presence of abundance of *Pediastrum*. The intense river input could relate to the tectonic phase to which interstratified marginal deltaic conglomerates belong consistently (Roveri et al., 2001; Manzi et al., 2005). This tectonic phase was still active when the Zanclean marine flooding occurred, as recorded at the base of unit p–ev2. At the end of deposition of the Colombacci Fm., a decrease in tectonic activity might have caused a rise in sea level at the beginning of the Argille Azzurre deposition, thereby allowing the late arrival of the planktonic foraminifer markers of the early Zanclean.

The two step scenario of the Messinian salinity crisis as conceived by Clauzon et al. (1996) is based on the following basic observations: all around the Mediterranean Basin, the Messinian marginal evaporites are cut by an impressive erosional surface itself overlain by early Zanclean Gilberttype fan deltas (Clauzon et al., 1996, 2005, in progress). These features prove that two successive drops in sea-level occurred: the first was a minor one that caused the deposition of the marginal evaporites; then, a severe drawdown resulted in the cutting of deep fluvial canyons joining the central basin evaporites in the almost desiccated abyssal plains (Lofi et al., 2005). Signs of these two steps are detected in the Maccarone area: the resedimented evaporites from marginal areas document the first sea-level drop; and the unexpected presence (with significant percentages) of subdesertic plants at such a high latitude during the time-span 5.50-5.40 Ma (Fig. 2) at a time when the scenario of Clauzon et al. (1996, 2005) places the almost complete desiccation of the Mediterranean Sea. Today, Lygeum spartum (the most abundant subdesertic element recorded at Maccarone) does exceed a latitude of 40°30' N in the Italian Peninsula (Brullo et al., 2002). Bertini (2006) invokes a drier climatic episode to explain this northward expansion of subdesertic elements, a hypothesis fully contradicted by (1) the regional floral context denoting humid warmtemperate conditions (abundance of Taxodiaceae, Engelhardia, Quercus, etc.; Bertini, 1992) as also supported by palaeoclimatic quantification (Fauquette et al., 2006), (2) the absence of any drier phase at that time in North Africa where, on the contrary, a wetter episode is documented (Griffin, 2002; Fauquette et al., 2006). It is more plausible to accept that subdesertic plants moved northward because the southern Italian Peninsula had become uninhabitable during the paroxysmic phase of desiccation: indeed, a subdesertic plant, adapted to very xeric conditions, thrives when it receives a large quantity of water but is alone having survived a very dry climate.

Two of the debated scenarios of the Messinian salinity crisis have considered the question of the Adriatic and Po region where shallow-water primary evaporites are still in place on the margin but were resedimented later within the Apennine foredeep which never desiccated (Roveri et al., 1998, 2001; Bassetti, 2000):

• it was proposed by Manzi et al. (2005) and Roveri and Manzi (2006) to enlarge the Adriatic foredeep model to the whole Mediterranean Basin, postulating that "a large part of the evaporites lying on the Mediterranean floor could have a clastic origin" (Manzi et al., 2005: p. 899). This implies that the Mediterranean Sea never dried out, a proposal that fully contradicts the nature, and thickness of the Mediterranean central basins evaporites inferred from seismic profiles (Savoye and Piper, 1991; Gorini et al., 2005; Sage et al., 2005; Bertoni and Cartwright, 2006), and the presence of deep fluvial (i.e. subaerial) canyons separated by a well-expressed erosional surface on the interfluves (Chumakov,

1973; Clauzon, 1973, 1978; Savoye and Piper, 1991; Gorini et al., 2005; Lofi et al., 2005; Bertoni and Cartwright, 2006);

• Clauzon et al. (1997, 2005) suggested that the Adriatic and Po region persisted as a perched lake (because they display a continuous subaquatic sedimentation during the time-interval of the Mediterranean desiccation), isolated from the desiccated Mediterranean Sea as a result of the combined effects of the Otrante Sill, and the positive hydrologic budget of the region surrounded by uplifting massifs. A significant part of the Dacic Basin experienced a similar evolution (Clauzon et al., 2005) when both the Mediterranean Sea and Black Sea simultaneously desiccated (Gillet, 2004). The Marmara Sea probably persisted too as a perched isolated lake based on the palaeogeography published by Çağatay et al. (2006), and our own recent field observations.

Combining the former data from Bertini (1992, 1994, 2002, 2006), especially those concerning the lower part of the Maccarone section, together with our new data focussing on the upper part of the section with a higher sampling resolution (including dinoflagellate cysts, calcareous nannofossils, and planktonic foraminifers) as well as data recently published on the area (micropaleontological and geochemical information by Bassetti et al., 2003, 2004, respectively, and fish records from Carnevale et al., 2006a), it is possible to reconstruct a reliable environmental evolution of the Apennine foredeep in the late Messinian through early Zanclean. This evolution, which is fully consistent with the geodynamic reconstruction depicted by Roveri et al. (1998, 2001), is summarized in Fig. 9, and may be described as follows. Two main geodynamic events significantly influenced the environments during a period of relatively stable warm and wet climate (Fauquette et al., 2006):

- a powerful tectonic activity continuously affected the region during the Mediterranean Sea desiccation at a time when the Adriatic–Po basin was a perched lake surrounded by uplifting landmasses. This is clearly evidenced by geological observations (Roveri et al., 1998, 2001; Bassetti, 2000), and is supported by strong signs of an intense run-off in the palynological residues (abundant reworked palynomorphs, coaly and woody microparticles, presence of *Concentricystes*, abundance of *Pediastrum*). The continuity of this intense tectonic activity during a relatively long interval explains the absence of any unconformity in the foredeep as reported for the Maccarone section. During the earlier part of this phase, subdesertic plants spread northwards. This should be understood as an epiphenomenon caused by the desiccation of the Mediterranean (Fauquette et al., 2006);
- a marine transgression conceals the effects of tectonism within the sedimentary record because of its suddenness and considerable amplitude. This is undoubtedly the Zanclean transgression as revealed by the coccolith marker *Ceratolithus acutus*. In the Maccarone area, the effects of run-off are henceforth less well expressed probably because the deltaic zones and shoreline were pushed back inland. As another consequence of this event, turbiditic layers progressively disappeared from the foredeep. Tectonic activity probably



Fig. 9. Proposed environmental evolution of the Apennine foredeep area in the late Messinian and early Zanclean.

Fig. 9. Évolution environnementale de la région de l'avant-fosse des Apennins à la fin du Messinien et au début du Zancléen.

continued but it was less obvious in the sedimentary record. The Zanclean transgression re-established relationships with the Eastern Paratethys through a gateway going from northern Greece up to the Dacic Basin via the Macedonian and Bulgarian basins (Clauzon et al., 2005). This connection allowed brackish surface waters originating from the eastern Paratethys to reach the Adriatic-Po region with their cortege of immigrant living organisms. Evidence for the invasion of Paratethyan dinoflagellates ceases in the second metre of the Argille Azzurre Fm. presumably because of the tectonic closure of the North Aegean-Dacic Basin gateway. In the earliest Zanclean (i.e. the youngest Di Tetto and the entire Colombacci deposits), salinity was probably low in the Apennine foredeep, favouring the immigrant dinoflagellates while creating unfavourable conditions for the alreadyarrived planktonic foraminifers. The water column rapidly stratified, and led to anoxic deposits (black layers rich in amorphous organic matter: possibly representing sapropels). The alternation between calcareous beds ("colombacci"), and clays might be understood as resulting from variations in salinity as foreseen by Bassetti et al. (2004). The somewhat ambiguous environmental conditions reported for the Colombacci Fm. by geochemists (Casati et al., 1976; Molenaar and De Feyter, 1985; Bassetti et al., 2004) probably originate in the difficulty for waters of various quality to mix. Such waters would have included locallysourced former freshwater enriched by a continuous intense run-off, normal marine Mediterranean waters entering the basin, and surface Paratethyan brackish waters.

A final consequence of these results is the necessary revision of the regional stratigraphy, chronostratigraphy, and geological mapping caused by moving the p–ev2 unit into the Zanclean Stage.

#### 6. Conclusion

We emphasize the importance of the Maccarone section, part of which was revisited in our investigations. Our study demonstrates the value of multiple approaches, and exposes the danger of systematically rejecting data simply because it contradicts classical assumptions. Two meaningful advances characterize this work:

- a closing of the debate initiated in Bologna in 1967 at the 4th Congress of the Regional Committee on Mediterranean Neogene Stratigraphy about whether the Colombacci Formation is Messinian or Pliocene in age. It unequivocally belongs to the earliest Pliocene, as does the underlying uppermost part of the Di Tetto Fm. (i.e. the entire p–ev2 stratigraphic unit);
- the lowering in the regional stratigraphy of the Zanclean transgression. This allows, after integrating all available data, a new reconstruction of terrestrial and aquatic environments that is fully compatible with the regional geodynamic picture (Roveri and Manzi, 2006), recent advances in regional palaeoenvironmental studies (Bassetti et al., 2004; Carnevale et al., 2006a), and the Lago Mare scenario formulated by Clauzon et al. (2005). The invasion of Paratethyan species is clearly the consequence of the Zanclean high sea-level that connected the Mediterranean to the Eastern Paratethys.

The failings of the Lago Mare as chronostratigraphic unit are manifest. Within the Apennine foredeep, an area under strong geodynamic control, the respective effects of local tectonics and Mediterranean eustasy have been clarified. Because of the suddenness and amplitude of the Zanclean transgression, it is the Mediterranean eustatic signature that prevails in the sedimentary and palaeobiological records.

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