



Late Messinian *Lago-Mare* ostracods and palaeoenvironments of the central and eastern Mediterranean Basin

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ABSTRACT - The ostracod assemblages with Paratethyan affinity from several late Messinian Lago-Mare deposits located in Italy and Crete (Greece) have been examined and the community analyses (number of species, Margalef and Shannon-Wiener indexes) and auto-synecological analyses have been performed on them. The results show that, generally, in the lower portion the post-evaporitic Messinian was characterised by unstable environments, which hosted poor ostracod communities characterised by low diversity, while in the upper portion the environmental conditions were more stable, allowing the subdivision of the environment hyperspace in several different niches and, thus, supporting high-diversity ostracod communities. Anyway, the correlation of the boundary between low- and high-diversity ostracod assemblages through the studied successions has shown to be heterochronous, probably because it is due both to local and regional factors. A more detailed palaeoenvironmental reconstruction across the late Messinian Lago-Mare successions showed that, while in the lower portion the palaeoenvironments are rather disomogeneous, even if investigated in nearby sections, in the upper part a general trend towards a deepening and freshening followed by a new salinity increase and depth decrease has been recognized. The palaeoenvironmental variability of the lower part probably was related to the superimposition of local factors on global climatic forcing, while in the upper part the high amplitude insolation peaks drove the palaeoenvironmental changes at a regional scale.

RIASSUNTO - [Ostracodi e ricostruzioni paleoambientali dell'intervallo Lago-Mare del tardo Messiniano nel Mediterraneo centrale e orientale] - Nel presente lavoro sono state analizzate le ostracofaune ad affinità paratetisiana provenienti da diverse successioni di Lago-Mare tardo-messiniane in Italia (successioni di wedge-top sul versante adriatico dell'Appennino settentrionale come Buttafuoco, Ca' Blindana, Montepetra, Perticara e Maccarone, successioni di avampaese sul versante Adriatico dell'Appennino settentrionale e centrale, come Trave e Maccarone) e a Creta (Grecia) (successioni di Ano Akria e Faneromeni nel Bacino di Iraklion) e su di esse sono state effettuate analisi di comunità (numero di specie, indici di Margalef e Shannon-Wiener) ed analisi auto/sinecologiche. I risultati mostrano come, in generale, la porzione inferiore dei depositi post-evaporitici fosse caratterizzata da ambienti instabili che ospitavano comunità di ostracodi discontinue e caratterizzate da bassa biodiversità, mentre nella porzione superiore le condizioni paleoambientali erano maggiormente stabili, permettendo la suddivisione dell'iperspazio ambientale in diverse nicchie ecologiche e supportando così associazioni ad alta biodiversità. Tuttavia, la correlazione del limite tra associazioni a bassa ed alta biodiversità nelle successioni analizzate ha mostrato come quest'ultimo sia eterocrono, probabilmente a causa di fattori locali. Una ricostruzione paleoambientale dettagliata, effettuata comparando il susseguirsi di diverse associazioni di ostracodi lungo le diverse successioni, ha mostrato che, mentre nelle porzioni inferiori il paleoambiente era piuttosto disomogeneo, nelle porzioni superiori, in prossimità del limite Messiniano-Zancleano, si nota un trend generalizzato verso l'approfondimento e l'addolcimento, seguito da un nuovo incremento della salinità e da condizioni di acque più basse. L'analisi della curva dell'insolazione Laskar 2004 per l'intervallo di tempo in esame ha evidenziato una minore ampiezza dei picchi di massimo e minimo nella porzione inferiore della curva ed un aumento dell'ampiezza dei picchi nella parte alta. È probabile, quindi, che la variabilità paleoambientale riscontrata nella parte bassa sia probabilmente legata alla sovrapposizione di fattori locali rispetto ai cambiamenti climatici globali, mentre, nella parte alta, le maggiori oscillazioni in ampiezza dei valori di insolazione guidarono i cambiamenti paleoambientali alla scala dell'intero bacino mediterraneo.

INTRODUCTION

After the deposition of the Lower Evaporites linked to the Messinian Salinity Crisis (MSC) (Hsü et al., 1973; Cita, 1973; Benson, 1975, 1976; Weijermars, 1988), verified in the Mediterranean area from 5.96 to 5.59 Ma (Krijgsman et al., 1999), the subsequent complete closure of the Atlantic/Mediterranean connections (Krijgsman et al., 1999; Blanc, 2006; Rouchy & Caruso, 2006) coupled with the onset of global humid climatic conditions (Griffin, 2002; Bertini, 2006) triggered the dilution of the hypersaline Mediterranean waters down to oligo-mesohaline conditions. This environmental and facies change was mentioned for the first time in the Mediterranean by Gignoux (1936), who called it "*Lac-Mer*" facies, translated by Ruggieri (1962) with the Italian

words "*mare-lago*" (afterwards changed in *Lago-Mare*). According to Ruggieri & Greco (1965), Ruggieri (1967), Benson (1986) and McCulloch & De Deckker (1989) after the MSC evaporitic phase the Mediterranean, isolated by the Atlantic Ocean, was transformed into a series of lagoons with reduced salinity. Cipollari et al. (1999 with refs.) and Gliozzi et al. (2002, 2007) revising the literature on the Mediterranean ostracod assemblages of the post-evaporitic Messinian showed that the *Lago-Mare* facies was widespread along the whole Mediterranean, from Spain to Cyprus. These ostracod assemblages were mainly characterised by Paratethyan species (Gliozzi et al., 2007) or endemic species derived from a Paratethyan stock (Bassetti et al., 2003), which entered the Mediterranean during the MSC diluted phase (Carbonnel, 1979). Recent papers (Clauzon et al., 2005;

Braga et al., 2006; Carnevale et al., 2006a, b; Popescu et al., 2007) suggest that during the post-evaporitic Messinian the Mediterranean area was affected by marine incursions from the Atlantic while, in their last paper, Carnevale et al. (2008) state that in this period the Mediterranean was a basin filled by marine water and the brackish *Lago-Mare* facies must be merely considered a marginal marine facies like deltas or coastal lagoons. On the contrary, recent detailed micropalaeontological studies on Italian and Crete (Greece) *Lago-Mare* successions (Gliozzi & Grossi, 2004; Grossi & Gennari, in press; Iaccarino et al., in press; Cosentino et al., 2006, 2007, unpublished data) did not reveal any marine influx in the Mediterranean, but only a variable brackish environment with salinities spanning from oligohaline to mesohaline. The marine fossil remains (calcareous nannofossils and foraminifers) recovered in those successions have been considered as reworked. The same conclusions were already reached by several other authors who studied different post-evaporitic Mediterranean successions in the Mediterranean area such as by Cita et al. (1978 with refs.) for the marine faunas recovered in the DSDP Leg.42, Site 376 located on the Florence Rise, W of Cyprus, Iaccarino et al. (1999) for the ODP Sites 974 (Tyrrhenian Basin) and 975 (South Balearic Basin), Bassetti et al. (2006) for the Nijar Basin (Spain), Rouchy et al. (2007) for the Chelif Basin (Algeria) and Trenkwalder et al. (2008) for the Northwestern Italy. The great scientific debate that is flourishing around the *Lago-Mare* facies shows that more data are needed to clarify the palaeogeography and the palaeohydrology of the Atlantic-Mediterranean-Paratethyan connections during the post-evaporitic Messinian.

The present paper (another tessera in the *Lago-Mare* puzzle), is based on the detailed sampling and micropalaeontological study of the ostracod assemblages of several Messinian post-evaporitic successions located in Italy and Crete and is focussed on the ostracod taxonomical composition, the diversity of the recognised assemblages and their palaeoenvironmental meaning. More in particular, the Italian successions are located in Adriatic wedge-top basins (Perticara, Buttafuoco, Montepetra, Ca' Blindana, and Maccarone), Adriatic foreland basins (Trave and Fonte dei Pulcini), and the Crete successions in the Hellenic forearc basin (Ano Akria and Faneromeni) (Fig. 1).

STRATIGRAPHIC FRAME

Although the MSC evaporitic deposits have been intensively studied since 1973 from a geodynamical, palaeohydrological and stratigraphical perspective by several authors (see Rouchy & Caruso, 2006 for a synthesis), less information deals with the stratigraphy of the post-evaporitic *Lago-Mare* sediments (see Orszag-Sperber, 2006 for a synthesis). They are considered within a unique stratigraphic unit by Butler et al. (1996, 1999), Krijgsman et al. (1999) and Rouchy & Caruso (2006), while Clauzon et al. (1996, 2005), Popescu et al. (2007), Roveri et al. (1998, 2001, 2005, 2006) and Roveri & Manzi (2006) recognized different depositional events within the *Lago-Mare* interval, which, in some cases, are translated in different stratigraphic units.

Clauzon et al. (1996, 2005) and Popescu et al. (2007) recognized up to three *Lago-Mare* events during which

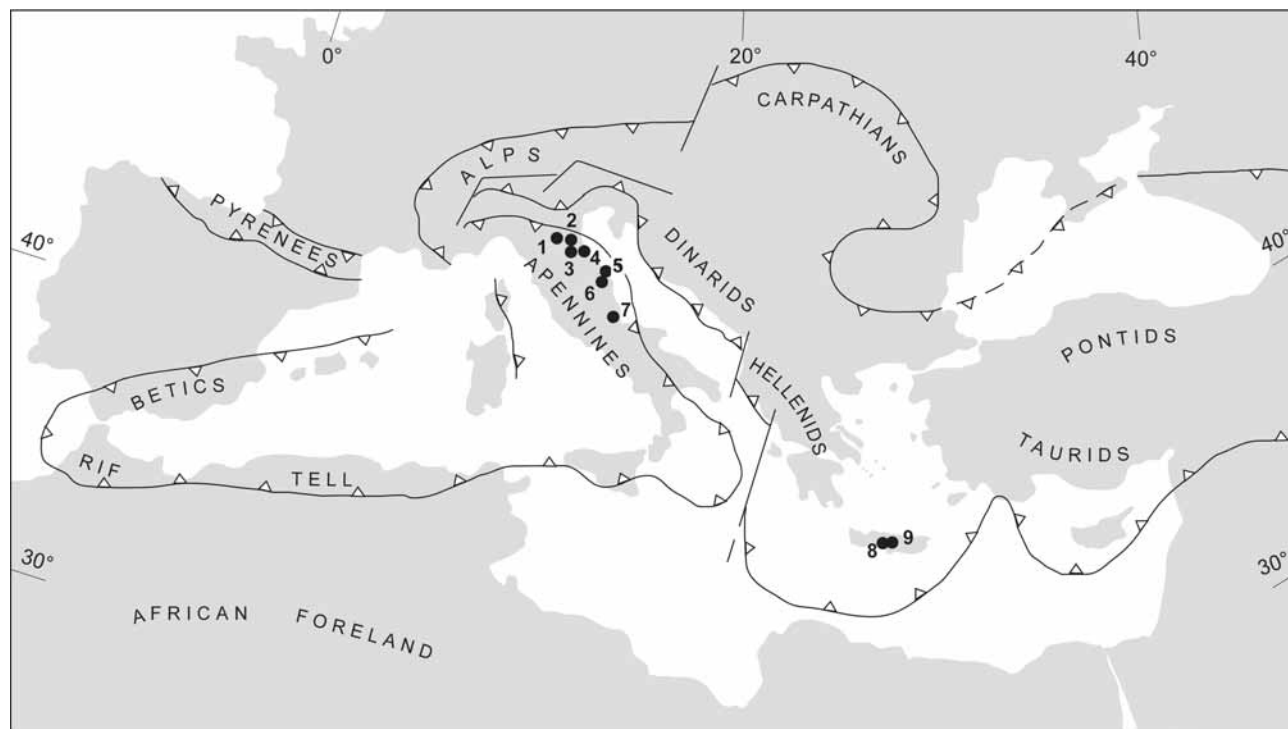


Fig. 1 - Tectonic sketch map of the Mediterranean area with the location of the studied successions. Legend: 1. Ca' Blindana borehole; 2. Montepetra borehole; 3. Buttafuoco section; 4. Perticara section; 5. Maccarone section; 6. Trave section; 7. Fonte dei Pulcini section; 8. Faneromeni section; 9. Ano Akria section.

exchanges between Mediterranean and Paratethys occurred, testified by dinocysts, molluscs and ostracods; according to these authors two of these episodes (LM1 and LM3) correspond to two sea-level highstands, during which the exchanges occurred in a marine palaeoenvironmental setting. The first *Lago-Mare* event occurred immediately after the end of the MSC evaporite deposition, while they considered the third early Zanclean in age. As stated in the introduction, in our opinion the data on marine incursions during the post-evaporitic Messinian are very feeble: the sporadic foraminifers collected in the *Lago-Mare* deposits are most probably reworked as well as the calcareous nannofossils, as demonstrated by the detailed quantitative analysis carried out by Cosentino et al. (unpublished data) for the *Lago-Mare* section of Fonte dei Pulcini.

Roveri et al. (1998, 2001, 2005, 2006) and Roveri & Manzi (2006) studying the stratigraphy of the Messinian post-evaporitic deposits of the Adriatic wedge-top and foreland basins, proposed a stratigraphic framework of the Mediterranean post-evaporitic Messinian as follows: above the Lower Evaporitic unit, cut at the top by a basin scale angular unconformity (lm), the post-evaporitic deposits are arranged into two post-evaporitic units ($p-ev_1$ and $p-ev_2$), separated by a regional unconformity (lm_1). According to these authors, the lower $p-ev_1$ unit is syntectonic in nature as indicated by the sedimentary facies and geometric characteristics and it only occurs in structural depressions. This unit is characterised by a basal complex of re-sedimented evaporites overlain by a monotonous succession of thin-bedded turbidites composed by laminated mudstones and siltstones containing minor sandstone bodies; only the upper part of the $p-ev_1$ unit shows cyclical lithological pattern. The unit includes an ash layer (dated about 5.5 Ma: Odin et al., 1997), a regional marker that allows correlations throughout the whole foredeep basin. The upper $p-ev_2$ unit, tabular and thickened in structural depressions, is characterised by a vertical repetition of sequences from coarse- to fine-grained sedimentary bodies, with a fining-upward pattern. Dark and rich organic layers, palaeosoils and, locally, up to three carbonate layers (“*colombaccio*”) are present. The base of the unit is represented by an erosional surface (the lm_1 unconformity). Within the $p-ev_2$ unit the authors recognize a high-frequency cyclical pattern forced by precessional orbital perturbations (Roveri et al., 1998). Four complete fining-upward depositional sequences have been identified, and the astrochronological calibration proposed by these authors shows that the $p-ev_2$ unit spans a short time interval of ~80-90 ka.

From a biostratigraphical point of view, Carbonnel (1979) defined the *Loxoconcha djafarovi* Zone, which included the whole post-evaporitic Messinian deposits with Paratethyan ostracod faunas; Bonaduce & Sgarrella (1999) and Iaccarino & Bossio (1999) recognize, for the same interval, two ostracod associations, named respectively “*Lago-Mare Biofacies 1*” and “*Lago-Mare Biofacies 2*” by the first authors and “*Cyprideis* assemblage” and “*L. djafarovi* assemblage” by the second authors. According to recent data (Iaccarino et al., in press; this paper), the micropalaeontological analyses of the Trave and Maccarone sections (Marche, central Italy)

showed that in the $p-ev_1$ sediments *L. djafarovi* is not present, while it occurs within the $p-ev_2$ deposits.

PALAEONTOLOGICAL ANALYSES

Wedge-top successions on the Adriatic side of the northern Apennines

The Buttafuoco and Ca' Blindana successions are located in the eastern sector of the Romagna Apennines, within the Giaggiolo-Cella syncline (Roveri et al., 2006) (Fig. 1).

The Buttafuoco section is 13 m thick (Fig. 2) and in the lower portion it includes about 9 m of silty sediments with millimetric sandy intercalations overlain by 0.5 m of black silts, rich in organic matter, and by 3.50 m of laminated blue-grey clays. At around 5.0 m a calcareous level (“*colombaccio*”) is recognized, correlated by Roveri et al. (2006) with the third and uppermost “*colombaccio*” of the Colombacci Fm. Thus, up to 9.50 m the Buttafuoco succession is referable to the upper portion of the Messinian $p-ev_2$, while the blue-grey clays are referable to the lowermost Zanclean (Roveri et al., 2006). Only five (BF 14-18) out of the eighteen samples analysed in the Messinian $p-ev_2$ portion of the succession were barren, including those collected from the dark layer; the others have given a well-preserved ostracod fauna, represented on the whole by the 21 species listed in Tab. 1. The community analysis performed through the number of species and the Margalef (richness) and Shannon-Wiener (diversity) indexes on all the analysed samples has shown that these species made different assemblages characterised by different biodiversities. The first two basal samples are characterised only by 3-4 species and by the lower values of the Shannon-Wiener (<1) and Margalef indexes (<0.4) while the remaining upsection samples are characterised by 12-14 species and higher values (Shannon-Wiener >1.5 and Margalef >0.5) (Fig. 2). From a palaeoenvironmental point of view, at the base (samples BF 1-2) ostracods are represented only by scarce *Cyprideis agrigentina*, *Tyrrhenocythere ruggierii*, *Loxoconcha mülleri*, and *L. eichwaldi*, pointing to a shallow and oligohaline waterbody. Upsection (samples BF 3-6) the ostracod associations become more diversified and referable to the “pointed candonids-Leptocytheridae assemblage” of Gliozzi & Grossi (in press), indicating a deeper and oligo-low mesohaline environment. In correspondence of the third “*colombaccio*” (samples BF 10-12) Leptocytheridae decrease while “pointed candonids” such as *Caspiocypris pontica*, *Pontoniella pontica*, *Zalanyiella venusta* and *Camptocypris* sp. 1 become dominant, pointing to a further deepening and salinity decrease (freshwater-oligohaline). Near the Messinian/Zanclean boundary (sample BF 13) *C. agrigentina* and *T. ruggierii* become again dominant, mirroring a shallower and more saline (oligohaline) waterbody. Samples BF 14-18 are barren of ostracods.

The Ca' Blindana borehole is represented by 60 m of laminated grey silts intercalated with thin arenaceous levels. At around 45 m and 14 m, two calcareous-marly levels have been detected, correlated by Roveri et al. (2006) respectively with the first and second

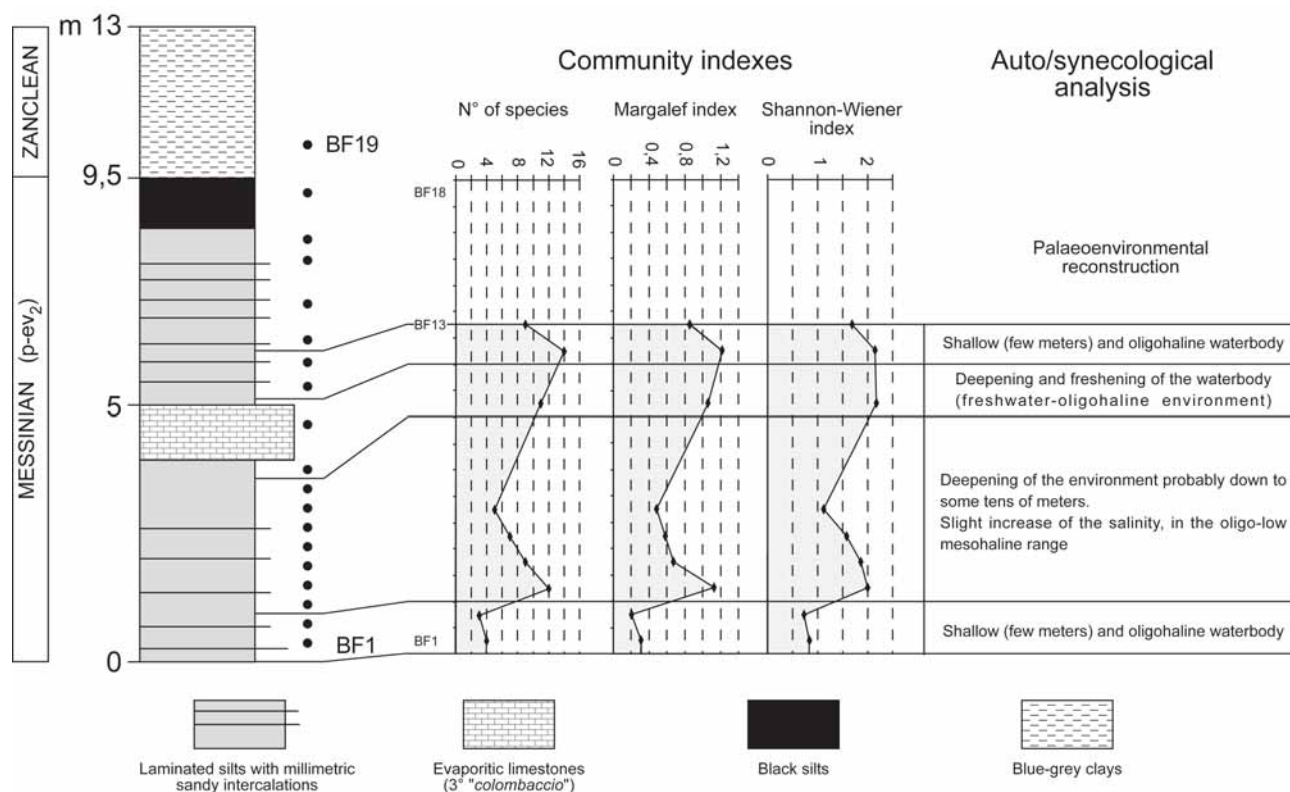


Fig. 2 - Stratigraphic log, community analysis indexes and palaeoenvironmental reconstruction of the Buttafuoco section.

Specie	Buttafuoco	Ca' Blindana	Montepetra	Perticara	Macarone	Trave	F. Pulcini	Faneromeni	Ano Akria
<i>Amniccythere</i> sp. 1		X		X					
<i>Amniccythere</i> sp. 2		X	X	X	X	X	X	X	X
<i>Amniccythere</i> sp. 3	X		X					X	X
<i>Amniccythere</i> sp. D (Miculan, in Bassetti et al., 2003)	X	X	X	X	X	X	X	X	X
<i>Amniccythere</i> <i>accularia</i> (Oleanu, 1989)				X		X	X		
<i>Amniccythere</i> <i>costata</i> (Oleanu, 1989)	X		X	X			X		X
<i>Amniccythere</i> <i>litica</i> (Livental in Agalarova et al., 1961)							X		
<i>Amniccythere</i> <i>multituberculata</i> (Livental, 1929)				X		X		X	
<i>Amniccythere</i> <i>palimpsesta</i> (Livental, 1929)	X	X	X	X	X	X	X		X
<i>Amniccythere</i> <i>propinqua</i> (Livental, 1929)	X	X	X	X	X	X	X	X	X
<i>Amniccythere</i> <i>subcaspia</i> (Livental in Agalarova et al., 1940)	X			X		X	X		
<i>Euxinocythere</i> (<i>Maeotocythere</i>) <i>praebaquana</i> (Livental in Agalarova et al., 1940)	X		X	X	X	X	X	X	X
<i>Euxinocythere</i> (<i>Maeotocythere</i>) <i>praebosqueti</i> (Suzin, 1956)						X	X		
<i>Euxinocythere</i> (?) sp.				X					
<i>Mediocythere</i> (<i>Sylvestra</i>) sp. B Ligios et al., 2008						X			
<i>Cyprideis</i> sp. 5	X	X	X	X		X	X		
<i>Cyprideis</i> <i>argentina</i> Decima, 1964	X	X	X		X	X		X	X
<i>Cyprideis</i> <i>anlavauensis</i> Carbonnel, 1979			X	X		X	X		
<i>Tyrhenocythere</i> <i>pontica</i> Livental in Agalarova et al., 1961	X	X			X	X	X	X	X
<i>Tyrhenocythere</i> <i>ruggieri</i> Devoto in Colacicchi et al., 1967	X	X	X		X	X	X	X	
<i>Tyrhenocythere</i> cf. <i>T. taurica</i> (Sinegub in Krstic, 1977)				X					
<i>Tyrhenocythere</i> sp.									X
<i>Loxocaula</i> <i>limata</i> (Schneider in Agalarova et al., 1940)				X	X	X	X	X	X
<i>Loxocaula</i> <i>eichwaldi</i> Livental, 1929	X	X	X	X	X	X	X	X	X
<i>Loxocaula</i> <i>kochi</i> Méhes, 1908	X		X			X			X
<i>Loxocaula</i> <i>mülleri</i> (Méhes, 1908)	X	X	X		X	X		X	X
<i>Loxocaula</i> <i>rhomboidalis</i> Pokorny, 1952	X	X				X			X
<i>Loxocomiculina</i> <i>djafarovi</i> (Schneider in Suzin, 1956)	X	X	X	X	X	X	X	X	X
<i>Cytherura</i> <i>pyramis</i> Schneider in Agalarova et al., 1940					X	X	X	X	
<i>Campocypris</i> sp. 1	X	X		X	X	X	X	X	X
<i>Campocypris</i> <i>alta</i> (Zalanyi, 1929)							X		
<i>Campocypris</i> <i>pontica</i> (Sokač, 1972)	X		X	X	X	X			X cf.
<i>Cypris</i> sp.	X	X	X		X	X	X	X	X
<i>Fabaeformiscandona</i> sp.		X			X			X	X
<i>Lineocypris</i> sp. 1				X			X		
<i>Pontoniella</i> <i>pontica</i> (Agalarova, 1961)	X		X	X	X	X	X cf.	X	X cf.
<i>Typhlocypris</i> sp.							X		
<i>Zalanyella</i> <i>venusta</i> (Zalanyi, 1929)	X		X	X	X	X	X	X	X

Tab. 1 - List of the ostracods collected in the studied late Messinian *Lago-Mare* successions.

“colombaccio” levels of the Colombacci Fm. and a palaeosol with roots and pedogenetic traces is evident at 34 m (Fig. 3). The Ca’ Blindana succession is referable to the Messinian p-ev₂. Ostracods recovered in the 61 analysed samples are scarce (several samples are barren), anyway interesting since they document a poorly recorded stratigraphical interval corresponding to the lower part of p-ev₂. On the whole, the ostracods are represented by the 16 species reported in Tab. 1 that, along the sediment-core, are arranged in oligospecific assemblages (maximum 7 species, but generally around 5). The assemblages are characterised by rather low Shannon-Wiener and Margalef indexes, which values are respectively <1.5 and <0.9 except for the uppermost sample that shows values of 1.64 and 0.98 (Fig. 3). In the lower portion of the sediment core, up to the sample CB 17, ostracods are scanty and characterised by the presence of dominant *C. agrigentina* accompanied by Loxoconchidae and *Tyrrhenocythere pontica*, mirroring a shallow and oligohaline environment. Upwards, the assemblages are slightly more diversified and their composition reflects the “Leptocytheridae assemblage” of Gliozzi & Grossi (in press), pointing to a slight deepening of the environment, which becomes mesohaline.

The Montepetra and Perticara successions are located in the eastern sector of the Romagna Apennines, east to the previous described successions, within the Sapigno syncline (Roveri et al., 2006) (Fig. 1).

The Montepetra succession is represented by a 114 m-thick sediment core, made of two lithological

complete fining-upward cycles characterised at the base by conglomerates and graded arenaceous levels and towards the top by massive or finely laminated silts. At 53 m a calcareous level is present, correlated by Roveri et al. (2006) with the uppermost third “colombaccio” of the Colombacci Fm., while at 51.5 m fifty centimeters of dark clays rich in organic matter start, overlain by blue-grey finely-laminated clays (Fig. 4). Roveri et al. (2006) and Grossi & Gennari (in press) referred the lower portion of the succession, up to 51 m, to the Messinian p-ev₂, while the blue-grey clays immediately above the dark level are referred to the lowermost Zanclean. On the whole, Grossi & Gennari (in press) recognized 19 species of ostracods (Tab. 1) in the 55 analysed samples. Generally, ostracods are well preserved and make up rather diversified assemblages, but differences in the number of species and in the Shannon-Wiener and Margalef indexes can be detected comparing the lower portion of the sediment core (from 114 to 83.50 m) with the upper portion: below there are no samples with more than 7 species and Shannon-Wiener and Margalef indexes are respectively <1.4 (except for the sample at 109.22 m) and <0.6, while in the upper portion assemblages are made by 7-11 species and the indexes are, respectively, >1.5 and >0.6 (Fig. 4). The uppermost samples (from 51.81 to 51.00 m), corresponding to the dark layer, are sterile. On the basis of the multivariate analysis, Grossi & Gennari (in press) made a detailed palaeoenvironmental reconstruction of the Montepetra succession, showing the alternance of high mesohaline assemblages made of *C. agrigentina*, few Loxoconchidae and benthic

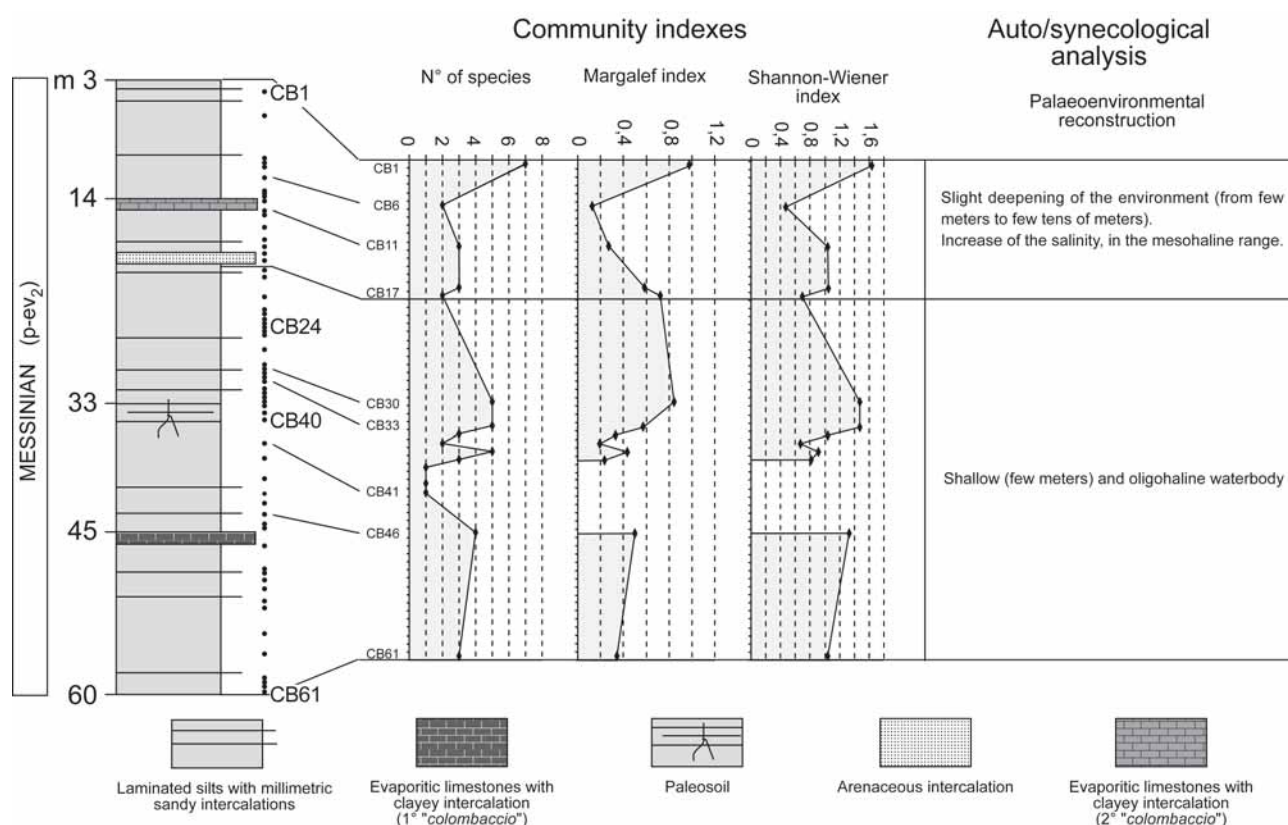


Fig. 3 - Stratigraphic log, community analysis indexes and palaeoenvironmental reconstruction of the Ca' Blindana sediment core.

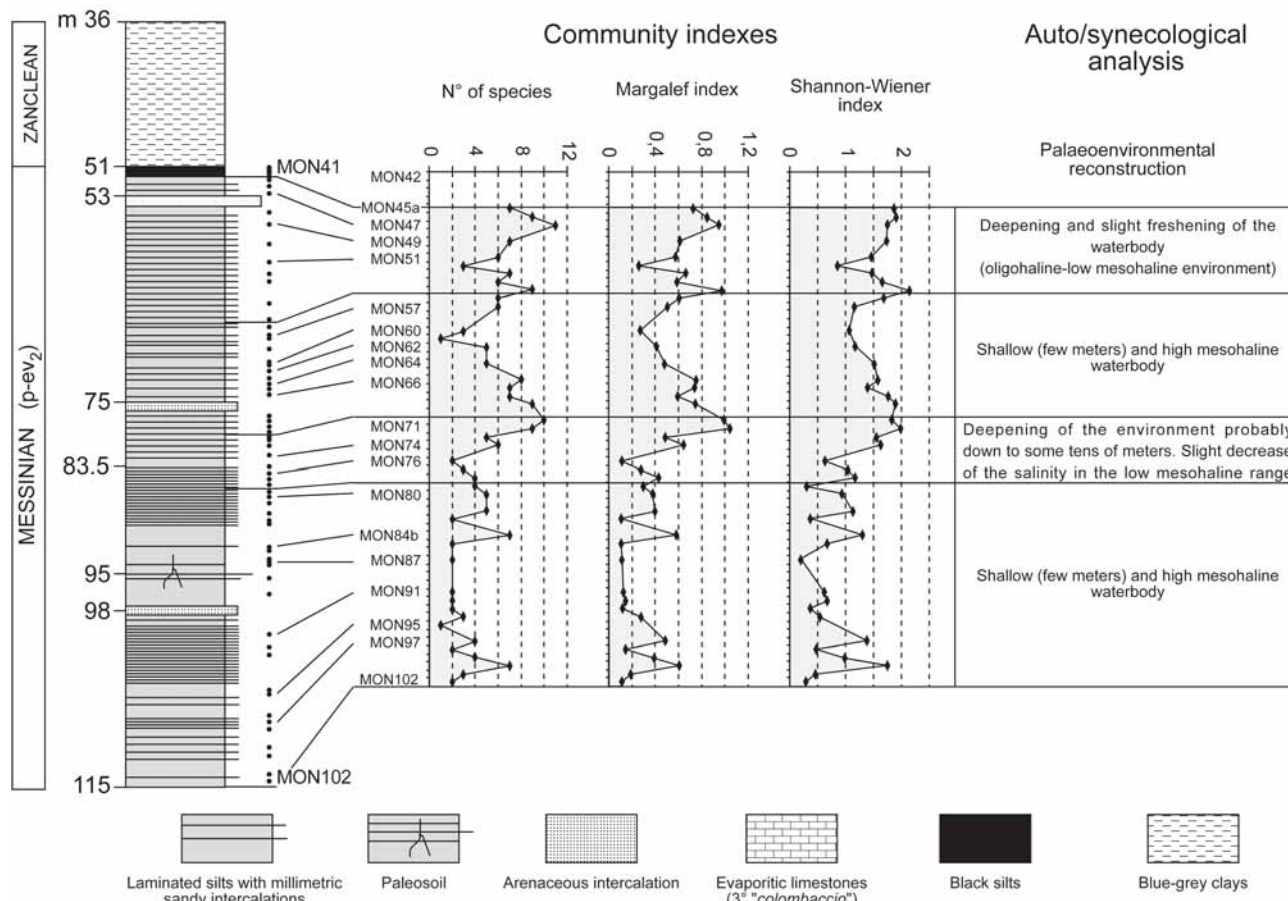


Fig. 4 - Stratigraphic log, community analysis indexes and palaeoenvironmental reconstruction of the Montepetra sediment core.

foraminifers such as *Ammonia tepida* and *Elphidium* spp. with two episodes of deepening and freshening ["Leptocytheridae assemblage" *sensu* Gliozzi & Grossi (in press) in samples MON 79-71 and "pointed candonids-Leptocytheridae assemblage" *sensu* Gliozzi & Grossi (in press) in samples MON 56-45a], down to the oligo- low mesohaline range in the upper portion of the succession, including the third "colombaccio" level (Fig. 4).

Perticara is a short (19.5 m-thick) section made, from the base up to about 15 m, by grey-greenish finely laminated clays with thin silty intercalations (Fig. 5). These clays are overlain by 2 m of dark clays rich in organic matter and, at around 17 m, by blue-grey clays. Along the succession, between 7.5 and 9 m, a 90 cm-thick calcareous level is recognizable, correlated by Gliozzi & Grossi (2004) to the uppermost third "colombaccio" of the Colombacci Fm. Thus, the grey-greenish clays of the lower portion can be ascribed to the Messinian p-ev₂ interval, while the blue-grey clays are referable to the early Zanclean. Gliozzi & Grossi (2004) recognized the presence of 22 ostracod species (Tab. 1) in 31 out of 35 analysed samples. Apart from few samples in which the ostracods are scarce, and the uppermost samples, corresponding to the dark layer, which are barren, the ostracod assemblages are characterised by high diversity, as shown by the number of species per samples (generally comprised between 9

and 18), and by the high values of the Shannon-Wiener (generally >1.5) and Margalef (generally >1) indexes (Fig. 5). Gliozzi & Grossi (2004), basing their detailed palaeoenvironmental reconstruction on the multivariate analysis results, recognized two low mesohaline episodes, the first in the lower portion below the third "colombaccio", characterised by the "Leptocytheridae assemblage" (*sensu* Gliozzi & Grossi, in press) and the second above it, characterised by the transition between the "pointed candonids-Leptocytheridae" and "Leptocytheridae assemblages" (*sensu* Gliozzi & Grossi, in press), divided by a deep and freshwater-oligohaline episode, represented by the "pointed candonids assemblage" (*sensu* Gliozzi & Grossi, in press) in correspondence of the "colombaccio" layer.

Maccarone is a well exposed, 230 m-thick section located in the outer Umbro-Marche Apennine sector, within the Cagnore-S. Urbano syncline (Fig. 1) (Odin et al., 1997; Bertini, 2006; Roveri et al., in press, with refs). In the lower 197.5 m, it is mainly silty clayey in composition, with millimetre to centimetre arenaceous laminations, more frequent in the lower portion. A disconformity is evident at 121 m, correlatable with the regional unconformity that divides the p-ev₁ from the p-ev₂ sedimentary succession. In the upper portion of the Maccarone pelitic section, three calcareous levels are evident at 178, 188 and 195 m, referable respectively,

to the first, second and third “colombaccio” of the Colombacci Fm. Between the first and second “colombaccio” one more decimetric calcareous layer is recognizable at 186.5 m. At 197.50 m the silty clays are overlain by blue-grey clays referable to the early Zanclean (Fig. 6). The portion of succession comprised between the p-ev₁/p-ev₂ unconformity and the Messinian/Zanclean boundary can be ascribed to the Messinian p-ev₂ succession. In this portion, 155 samples have been analysed, spaced every 50 cm, and they gave a rather well-preserved ostracod fauna even if discontinuous; ostracods (*Cyprideis* instars) are present in the sample immediately above the unconformity and in very few samples upsection, while they become abundant from about 175 m. On the whole 19 species have been recognized (Tab. 1). Except for the lower portion of the examined p-ev₂ interval, in which the number of species is low (4-5) and the Margalef indexes are <1, the remaining upsection samples are richer in species (8-13) and display higher Margalef indexes (generally >1, up to 1.47) except for the uppermost samples, which show, again, low values around 0.7. The Shannon-Wiener indexes are rather high (from 1.5 to 2) along the p-ev₂ succession, except for the lower and uppermost samples in which it is <1.4 (Fig. 6). The auto/synecological analyses carried out on these samples show a gradual change from a shallow-oligohaline environment dominated by *C. agrigentina*, *Loxoconchidae*, *T. ruggierii* and *T. pontica* (up to sample MC 367) to a slightly deeper and oligo-low mesohaline waterbody, indicated by the “pointed candonids-Leptocytheridae assemblage” (*sensu* Gliozzi & Grossi, in press), in correspondence of the samples MC 371-378, and, finally,

towards a rather deep and freshwater-oligohaline environment characterised by the “pointed candonids assemblage” (*sensu* Gliozzi & Grossi, in press) in the sample interval MC 382-397a, which includes the third “colombaccio” level (Fig. 6).

Foreland successions on the Adriatic side of the northern and central Apennines

The Trave section, more than 230 m thick, is located on the Conero promontory and pertains to the foreland domain of the northern Apennines (Fig. 1). Iaccarino et al. (in press) studied the Messinian post-evaporitic portion of this section, from about 27 to 209 m, which includes the p-ev₁ interval from 27 to 127 m and the p-ev₂ interval from 127 to 195 m, characterised by coarse sediments alternated with clayey-silty intervals. At around 145 and 195 m two calcareous level, correlated respectively with the first and third “colombaccio” of the Colombacci Fm., are present and from 196 to 209 m a thick calcarenitic level crops out, referred in literature as the “trave” (Iaccarino et al., in press) (Fig. 7). Ostracods from the Trave successions are rather rich and referable to 27 species (Tab. 1). Except for the lowermost portion of the studied succession (up to 127 m, corresponding to the p-ev₁ interval), in which Shannon-Wiener and Margalef indexes are rather low (respectively <1.2 and 1), in the remaining p-ev₂ portion of the section, number of species, Shannon-Wiener and Margalef indexes are rather high, respectively from 6 to 14, around or >1.5 and >1. More in particular, the highest values of the community indexes are recognizable in the p-ev₂ portion below the first “colombaccio” (from 127 to 137 m) and in the upper portion, from 148 to 195 m (Fig. 7).

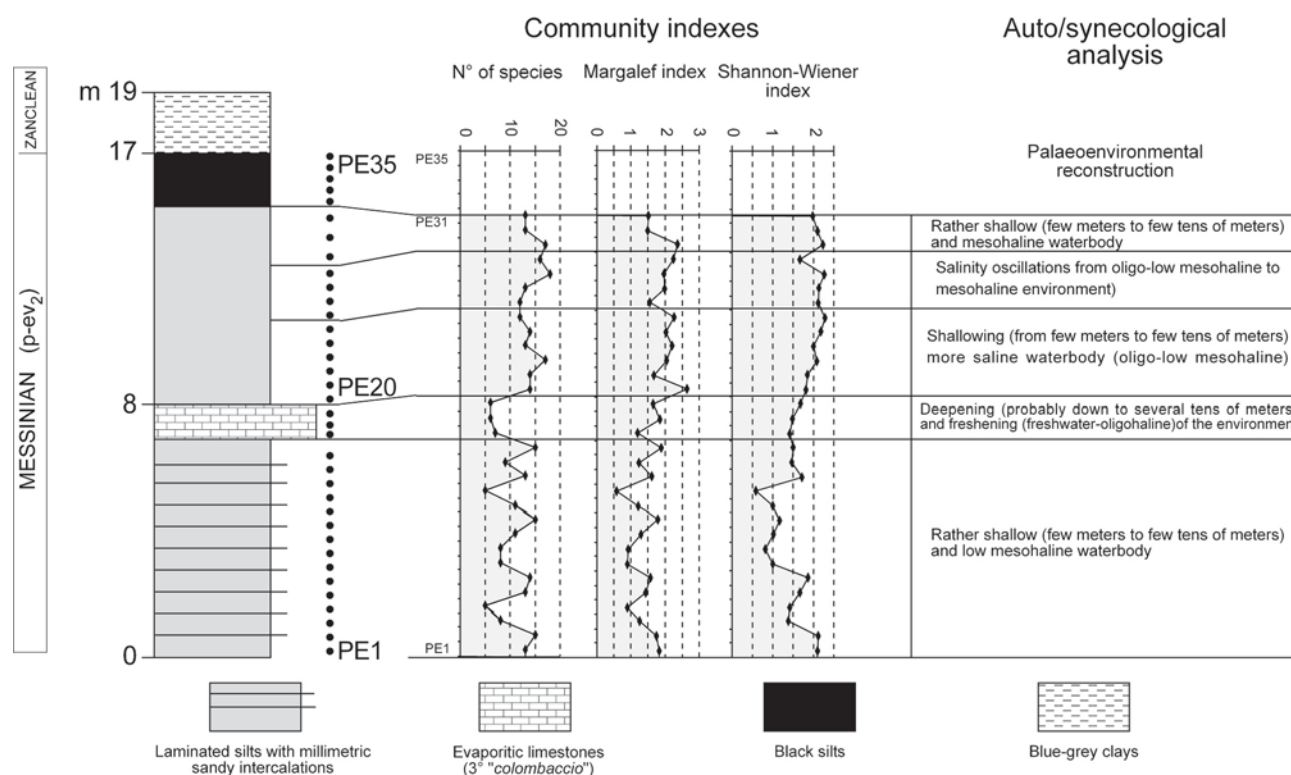


Fig. 5 - Stratigraphic log, community analysis indexes and palaeoenvironmental reconstruction of the Perticara section.

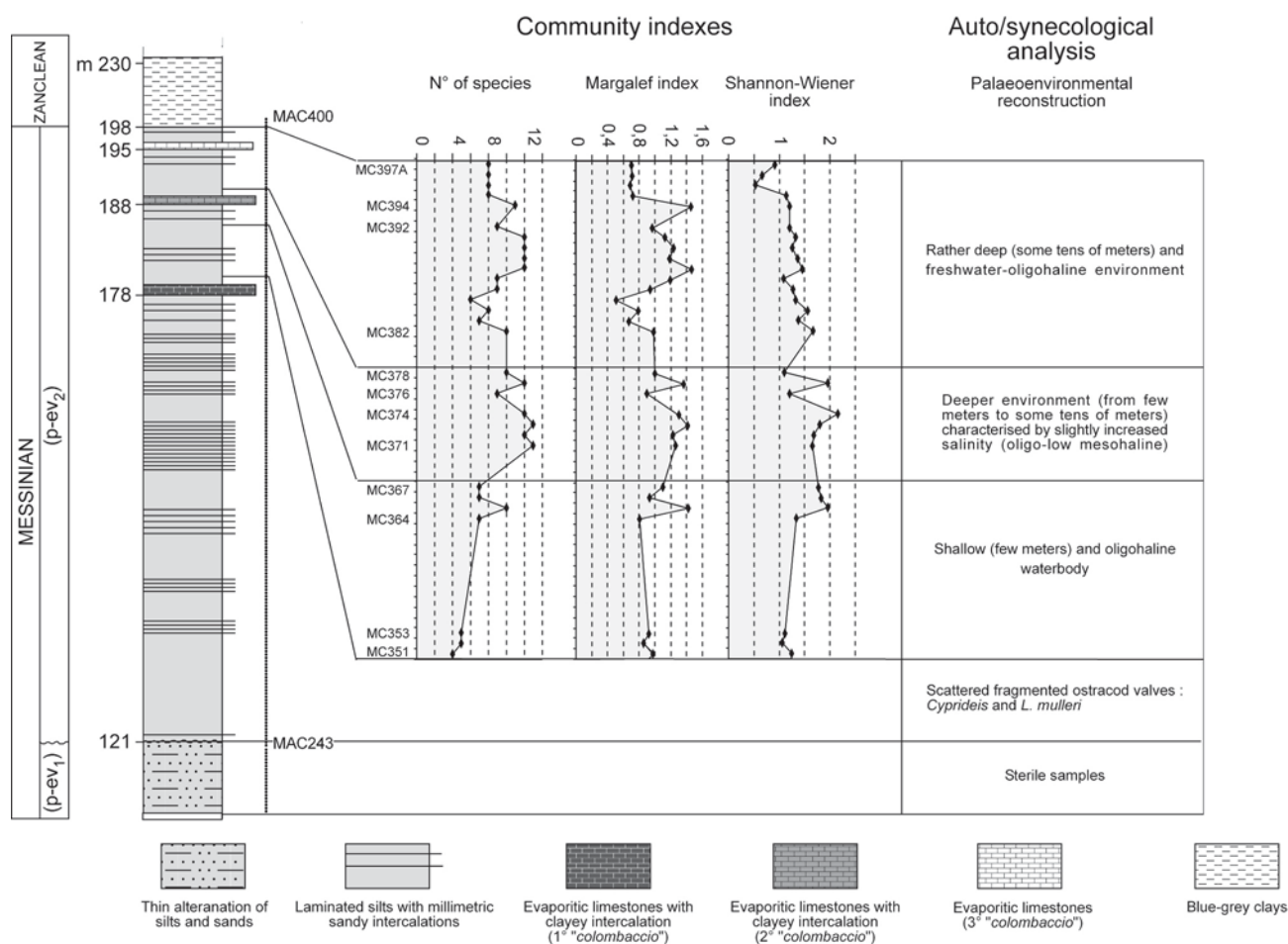


Fig. 6 - Stratigraphic log, community analysis indexes and palaeoenvironmental reconstruction of the Maccarone section.

Iaccarino et al. (in press) showed that the lower portion of the succession deposited in a shallow-water environment which became progressively more saline (from oligo- to meso-haline) as pointed out by the initial ostracod assemblages made by *C. agrigentina*, Loxoconchidae and *T. ruggierii*, followed by associations in which *T. ruggierii* disappears and *C. agrigentina* and *Loxocorniculina djafarovi* are dominant; upsection, they recognize a progressive deepening and slight freshening of the environment, with the “pointed candonids-Leptocytheridae assemblage” (*sensu* Gliozzi & Grossi, in press), followed, up to the “trave” biocalcarene, by a long rather shallow and freshwater-oligohaline episode testified by the dominance of “pointed candonids” accompanied by *Tyrrhenocythere* spp. (Fig. 7).

The Fonte dei Pulcini composite section (Fonte dei Pulcini A and Fonte dei Pulcini B) is located in Abruzzo and pertains to the outer central Apennine foreland domain (Cipollari et al., 2003; Cosentino et al., 2005, unpublished data) (Fig. 1). The Fonte dei Pulcini A section is made by a 53 m-thick succession made of a cyclic alternance of brown-reddish, dark grey and light grey clays, sampled every 50 cm for a total amount of 107 samples (Fig. 8). The whole succession has been referred to the Messinian p-ev₂ interval (Cosentino et al., 2005) and does not include

the Messinian/Zanclean boundary, which crops out few meters above in the neighbouring section Fonte dei Pulcini B (Cipollari et al., 2003). The ostracod fauna collected at Fonte dei Pulcini (Cipollari et al., 2003; Gliozzi & Grossi, 2004; Cosentino et al., unpublished data) is, on the whole, referable to 25 species (Tab. 1). The community indexes show a rather sharp change between the lower and upper portion of the succession. In the lower one, up to 14.0 m, the ostracod assemblages are scanty, generally with less than 10 species among which *L. djafarovi*, *L. eichwaldi*, *C. anlavauxensis* and *C. alta* are dominant. Both Margalef and Shannon-Wiener indexes are generally below 1.5. In the upper portion, on the contrary, ostracod assemblages are well diversified, with a high number of species (up to 23), Margalef indexes generally comprised between 1.66 and 4 and Shannon indexes always >2, reaching 2.7 (Fig. 8). Gliozzi & Grossi (in press) and Cosentino et al. (unpublished data) provided a detailed palaeoenvironmental reconstruction of the Fonte dei Pulcini A succession, by means of the multivariate analysis. At the base, up to sample FP 30 it starts with a shallow and mesohaline environment testified by the presence of *C. anlavauxensis* and Loxoconchidae, which evolves, up to sample FP 25, towards a slightly deeper and low mesohaline environment as recorded by

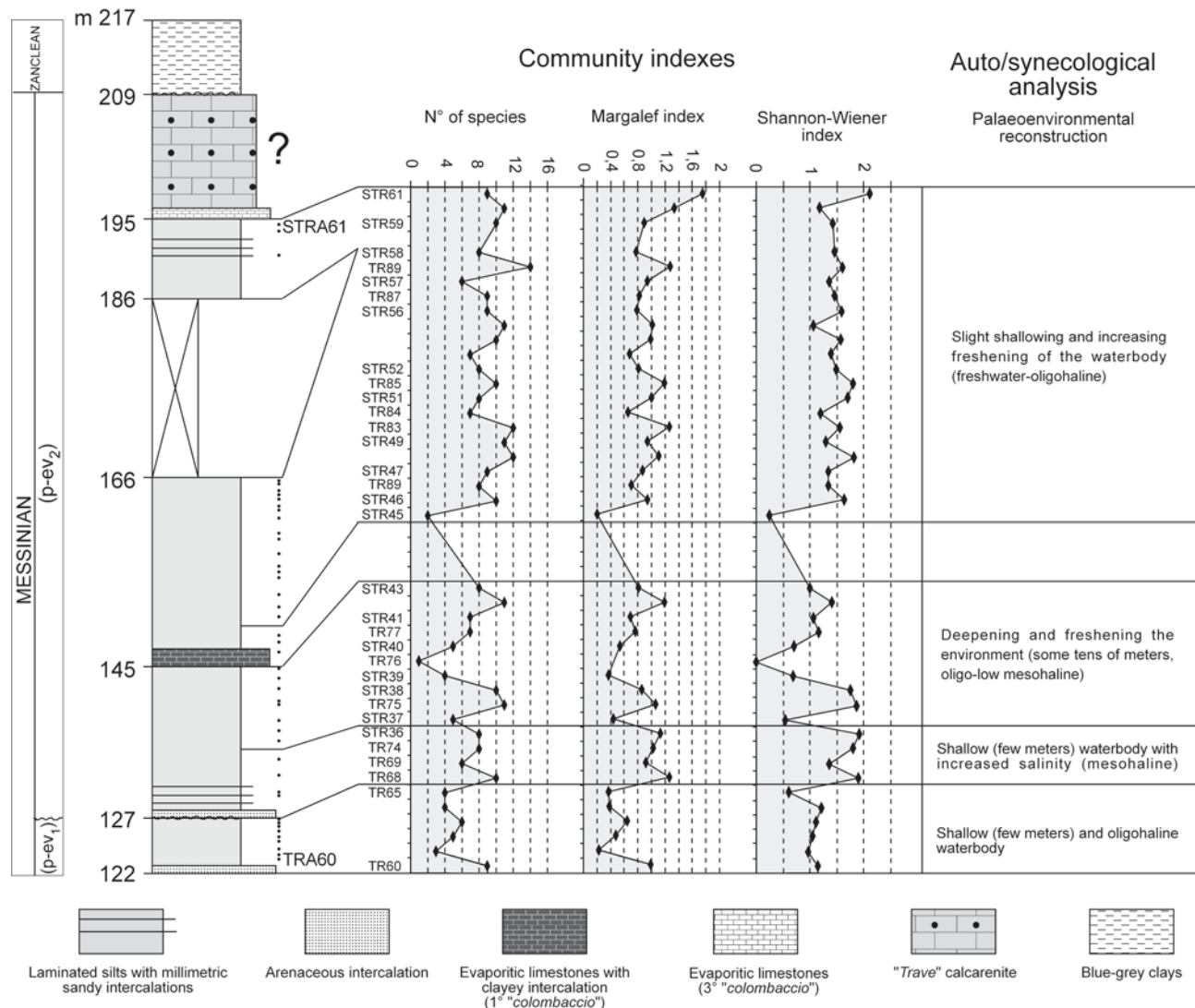


Fig. 7 - Stratigraphic log, community analysis indexes and palaeoenvironmental reconstruction of the Trave section.

the “Leptocytheridae assemblage” (*sensu* Gliozzi & Grossi, in press). Upsection, in samples FP 22-18 the occurrence of *T. ruggierii* and *T. pontica* testifies salinity decrease in the oligohaline range. Integrating the data on ostracod assemblages from Fonte dei Pulcini A and B sections, from sample FP 15 to sample MAJ 4 a progressive slightly deepening and salinity increase is recorded, from “pointed candonids-Leptocytheridae” to “Leptocytheridae assemblages” (*sensu* Gliozzi & Grossi, in press) (Fig. 8).

Crete Hellenic forearc basin

The studied sections of Ano Akria and Faneromeni are located in the Iraklion Basin (central Crete), in the Messarà plain (Fig. 1).

The Ano Akria section is a composite section with a total thickness of 52 m, made of clayey-silty deposits intercalated to thick channellized conglomerates and arenaceous levels. The section includes the Messinian/Zanclean boundary, signed by an unconformity (Cosentino et al., 2007) (Fig. 9). Eighty-six samples have been

analysed, which gave 22 ostracod species (Tab. 1). Ostracods collected at Ano Akria are generally badly preserved, often decalcified and deformed. Several samples are sterile but those which bear ostracods gave rather diversified ostracod assemblages, characterised by several species (up to ten), particularly in the lower more brackish portion of the succession. Here, Shannon-Wiener and Margalef indexes are >1.5. In the upper oligohaline portion, on the contrary, diversity decreases: number of species does not exceed 5 species/sample and Shannon-Wiener and Margalef indexes are low, respectively <1.3 and <1 (Fig. 9). The succession started to sediment in a rather deep and oligohaline basin (samples AA 17-19) as testified by the dominance of the pointed candonids, accompanied by very few Leptocytheridae, and then gradually turns to a shallower and more saline (oligo- to mesohaline) environment, richer in Loxoconchidae, Leptocytheridae and accompanying *C. agrigentina*. Only in the uppermost part (samples AA 78-85), the environment turns again to a deeper and freshwater-oligohaline environment, testified

by the “pointed candonids assemblage” (*sensu* Gliozzi & Grossi, in press) (Fig. 9).

A similar framework is recognizable in the Faneromeni succession, a 13 m-thick section, made of a similar intercalation of clayey silts and conglomerate levels. Also in this section, the uppermost Zanclean sediments are divided by the Messinian succession by an unconformity (Cosentino et al., 2007) (Fig. 10). The ostracod assemblages are, on the whole, made by 19 species (Tab. 1). In the lower portion, up to sample FA 17, diversity is very low, as testified by the number of species per sample comprised between 1 and 4. In the upper portion of the section, on the contrary, the number of species per sample increases from 8 to 15. Anyway, except for samples FA 18 and FA 19, which show high Shannon-Wiener and Margalef indexes (respectively >1.6 and >1.4), the indexes are rather low (Fig. 10). The palaeoenvironmental changes recorded at Faneromeni matches well those recognized in the upper portion of the Ano Akria section: from a shallow and mesohaline environment, dominated by *Loxoconchidae* and *C. agrigentina*, the waterbody became deeper and less saline (oligo-low mesohaline), characterised by the “pointed candonids-Leptocytheridae” assemblage (*sensu* Gliozzi

& Grossi, in press). At Faneromeni, probably a younger portion of Messinian succession is preserved below the Messinian/Zanclean unconformity, since a new change in the environment is recorded, not recognizable at Ano Akria: the environment turns again towards shallower and mesohaline conditions as testified by the occurrence of *Loxoconchidae* and *C. agrigentina* (Fig. 10).

DISCUSSION

Several Messinian post-evaporitic successions in the Mediterranean area have been analysed in a micropalaeontological and palaeoenvironmental perspective, and the community analyses have been performed on them: Perticara, Buttafuoco, Montepetra, Cà Blindana and Maccarone (Adriatic wedge-top basins), Trave and Fonte dei Pulcini (Adriatic foreland basins), Ano Akria and Faneromeni (Crete Island, Hellenic forearc basin). On the whole, these successions intercept the upper portion of the Messinian post-evaporitic deposits, included by Roveri et al. (2005) in the p-ev₂ unit, except for the base of the Trave succession that, according to

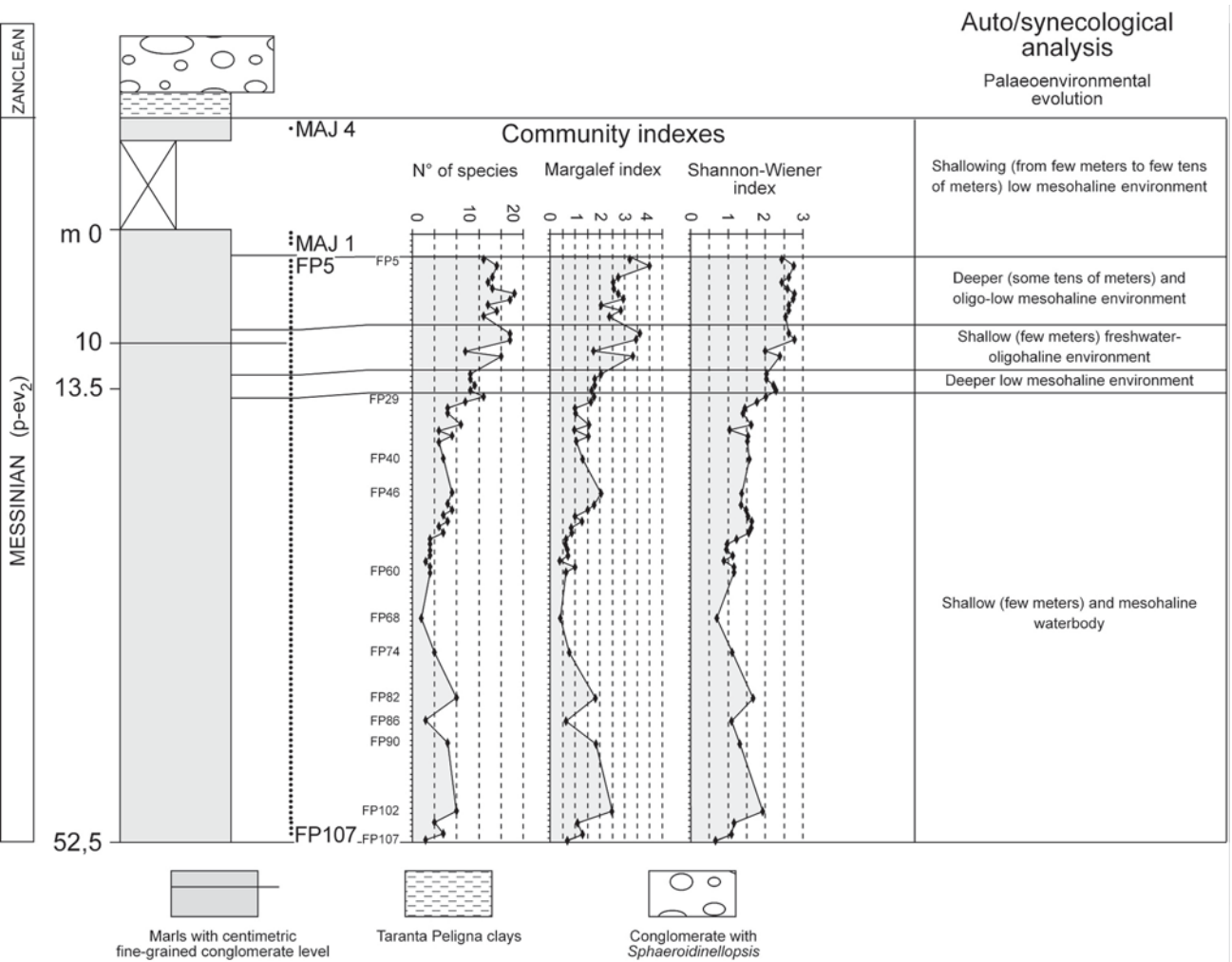


Fig. 8 - Stratigraphic log, community analysis indexes and palaeoenvironmental reconstruction of the Fonte dei Pulcini composite section.

Iaccarino et al. (in press) is correlatable to the upper portion of the p-ev₁ *sensu* Roveri et al. (2005) and for the lower portion of the Maccarone succession.

The “community analysis” methodology studies the structural characteristics of the community, which are strictly driven by the environment. In particular, the

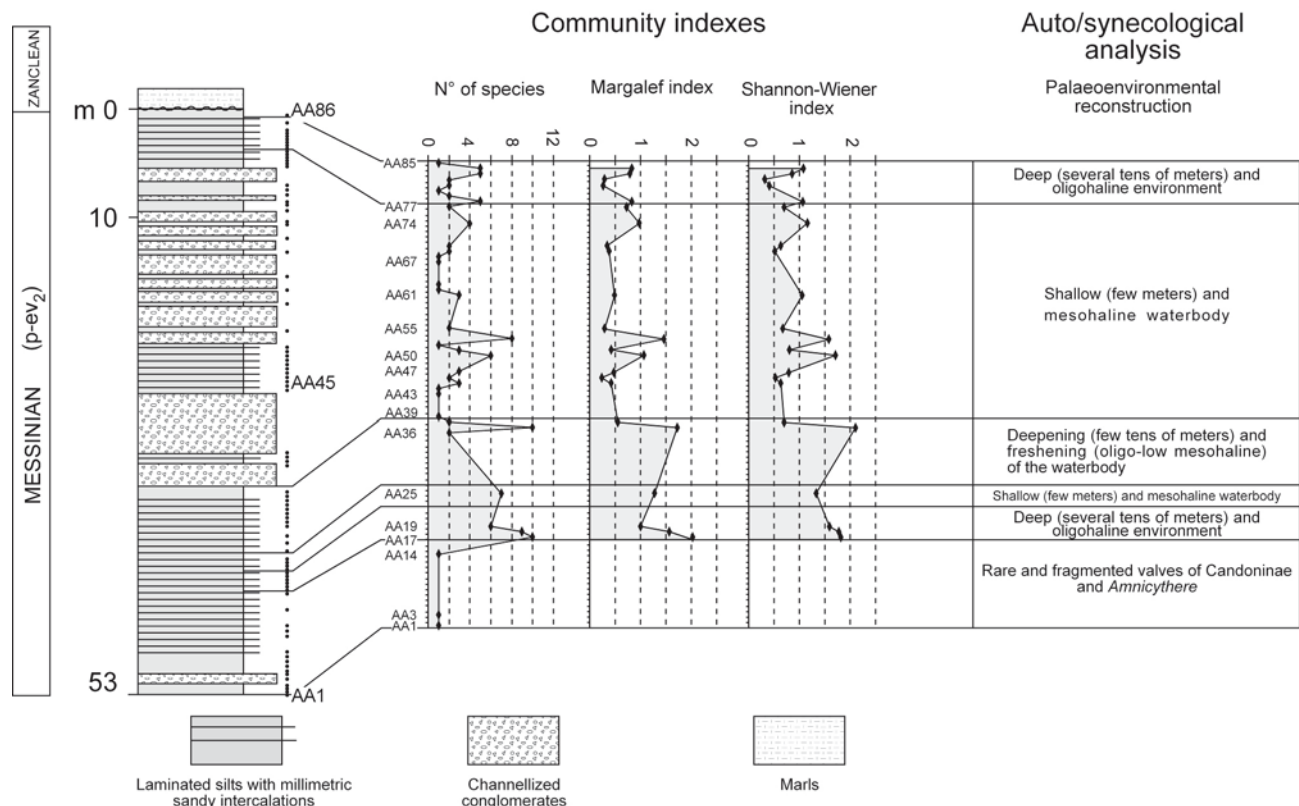


Fig. 9 - Stratigraphic log, community analysis indexes and palaeoenvironmental reconstruction of the Ano Akria section.

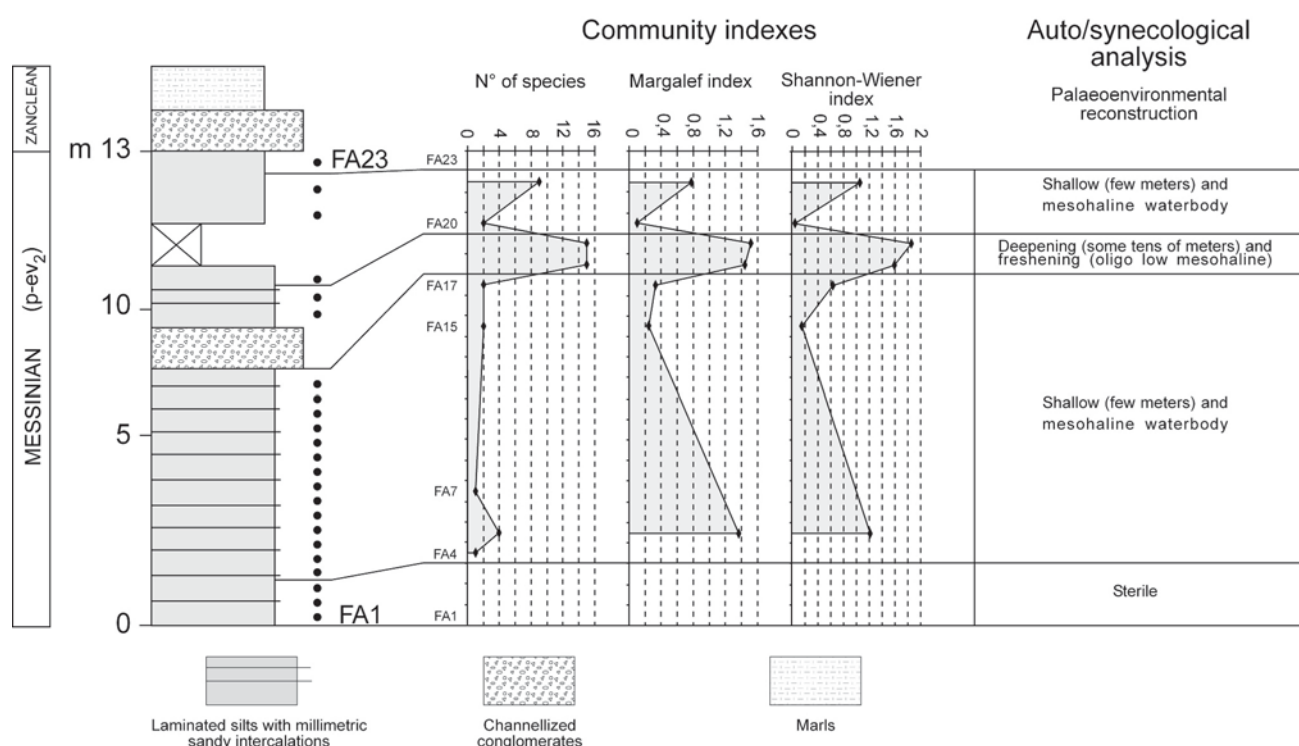


Fig. 10 - Stratigraphic log, community analysis indexes and palaeoenvironmental reconstruction of the Faneromeni section.

“diversity approach” used in this paper, utilizing the richness (number of species) and Margalef index (directly connected with the number of niches of the environmental hyperspace and its resource breadth) and the Shannon-Wiener index (which in some way gives indications on the environmental stability; Dodd & Stanton, 1990), makes it possible to reconstruct the palaeoenvironmental evolution of an area along time, without the need to know the palaeoecological characterization of each species of the community. This is particularly useful in those cases, as the late Messinian *Lago-Mare* communities, in which the assemblages are mainly made of extinct species or, even, genera, and very few data are available about the autecology of each taxon (Gliozzi & Grossi, in press). Generally speaking, the more the communities are diversified, that means high number of species and high values of the Margalef and Shannon-Wiener indexes, the more the environment is stable, because it has had the time to subdivide in a great number of ecological niches (Dodd & Stanton, 1990).

If the community analysis is flanked by an auto/synecological approach, the information about the palaeoenvironmental changes become more detailed and, eventually, it is possible to link the palaeoenvironmental changes to the forces that caused them. From this point of view, the data discussed in the previous paragraph lead to recognize seven different types of ostracod assemblages, each one characteristic of a different palaeoenvironment (Tab. 2).

The community analyses performed on each *Lago-Mare* succession show that the upper portion of the post-evaporitic Messinian (p-ev₂) is generally characterised by unstable palaeoenvironments, in which ecological parameters such as salinity and depth repeatedly change preventing the setting of mature and diversified communities. Particularly in the lower portion of the examined post-evaporitic successions, the assemblages are made by very few species (3-4, max. 7) and Shannon-Wiener indexes are often far lower than 1.5. Anyway, going upwards in the successions, a trend towards increased palaeoenvironmental stability and assemblage diversity is observable in many studied successions: the number of species is generally greater than 7 (up to 23) and the Shannon-Wiener index is always >1.5, often near 2 and, in the case of the Fonte dei Pulcini section, >2.5. This is often linked to the bloom of the “pointed candonids-Leptocytheridae assemblage” or to the “Leptocytheridae assemblage”, both representing rather diversified communities that point to rather deep and oligo- low mesohaline to mesohaline environments. The setting of such environments could be driven both by local and regional forces and, for this, the boundary between low- and high-diversity ostracod assemblages is heterochronous and cannot be used as a biostratigraphic tool (Fig. 11).

Coupling the community analysis results with the palaeoenvironmental analysis made using the auto/synecological approach, and using the lithostratigraphic correlations proposed by Roveri et al. (2006) and

OSTRACOD ASSEMBLAGE	TAXONOMIC COMPOSITION	PALAEOENVIRONMENT	REFERENCES
“pointed candonids” assemblage	“Pointed candonids” (Camptocypris, Caspiocypris, Lineocypris, Pontoniella, Zalanyiella) sometimes accompanied by scarce Leptocytheridae or Loxoconchidae.	Freshwater/oligohaline deep waterbodies (from some tens of meters to not more than 100 m of depth)	Gliozzi & Grossi (in press)
“pointed candonids”-Leptocytheridae assemblage	Candoninae and Leptocytheridae are rather diversified, particularly the Leptocytheridae contingent, which can include, up to 10 different species. Accompanying species can include a few Loxoconchidae, <i>Cytherura pyrama</i> and <i>Loxocauda limata</i> .	Oligo/low mesohaline, rather deep waterbodies, (from few meters to not more than 100 m of depth)	Gliozzi & Grossi (in press)
Leptocytheridae assemblage	Rich contingent of Leptocytheridae (up to 11 species), accompanied by few Loxoconchidae.	Oligo-low mesohaline or mesohaline, rather shallow waterbodies (from few meters to not more than 50 m of depth)	Gliozzi & Grossi (in press)
<i>Tyrrhenocythere</i> assemblage	Dominant <i>Tyrrhenocythere</i> species, which are accompanied by subordinated <i>Cyprideis</i> , Loxoconchidae and Leptocytheridae.	Freshwater/oligohaline shallow waterbodies (from few meters to not more than 30 m of depth)	Gliozzi & Grossi (in press)
<i>Cyprideis</i> - Loxoconchidae- <i>Tyrrhenocythere</i> assemblage	The presence of <i>Tyrrhenocythere</i> , together with <i>Cyprideis</i> and Loxoconchidae species is relevant, sometimes accompanied by <i>Cypria</i> and Candoninae.	Oligohaline shallow waterbodies (few meters of depth, probably not more than 10-15 m)	This paper
<i>Cyprideis</i> - Loxoconchidae assemblage	Dominated either by <i>Cyprideis</i> or by Loxoconchidae species, sometimes with subordinated few Leptocytheridae.	Mesohaline, shallow waterbodies (few meters of depths, probably not more than 10-15 m)	This paper
<i>Cyprideis</i> - <i>Ammonia</i> assemblage	Dominated by <i>Cyprideis agrigentina</i> and <i>Ammonia tepida</i> , sometimes accompanied by <i>Elphidium</i> .	High mesohaline to hyperhaline shallow (few meters, probably not more than 10-15 m) waterbodies, depending to the accompanying species.	Grossi & Gennari (in press)

Tab. 2 - Taxonomic composition and palaeoenvironmental meaning of *Lago-Mare* ostracod assemblage, derived from the auto/synecological analyses.



Cosentino et al. (2005) it is possible to depict, more in detail, the palaeoenvironmental evolution of the *Lago-Mare* succession. In particular, the two main ecological parameters, depth and salinity, will be considered.

In the lower part of the analysed post-evaporitic Messinian, corresponding to the uppermost part of the p-ev₁ and the lower portion of the p-ev₂ (*sensu* Roveri et al., 2006), the studied successions (Ca' Blindana, Montepetra, Maccarone, Trave, and Fonte dei Pulcini) suggest rather homogeneous depths, corresponding to very shallow (few meters) waterbodies except at Trave where in the upper portion of this interval, more or less in correspondence with the first “*colombaccio*” a sensible deepening is recorded down to some tens of meters. These similar conditions could be linked to the regressive trend, which characterised the upper part of the p-ev₁ subunit, suggested by Roveri et al. (2006), resulting in the setting of shallow waterbodies. On the contrary, the salinity variations suggest local influences. In fact, it is possible to recognize the setting of an oligo- low meso-haline environment at Ca' Blindana, while in the nearby Montepetra succession a brackish high mesohaline palaeoenvironment is detected. At Trave, located eastwards, the salinities are intermediate, oligo-mesohaline to mesohaline, while at Maccarone, the p-ev₁ and the lower p-ev₂ sediments are sterile, pointing to an unfavourable environment, at least for the benthic communities. More southwards, at Fonte dei Pulcini a mesohaline environment is recorded. Going upwards in the *Lago-Mare* succession, the sediments that in the Romagna-Marche area are comprised between the first and second “*colombaccio*” (Fig. 11) seem recording more local depth variations: a progressive slight deepening of the environment, from few meters at the base of this interval to few tens of meters in the upper part at Ca' Blindana and Montepetra, a slight shallowing of the waterbody at Trave, while at Fonte dei Pulcini the environment remained shallow and at Maccarone the ostracod assemblages are so scanty to prevent any palaeodepth interpretation. Concerning salinities, oligo- low meso-haline waterbodies are detected at Ca' Blindana and Maccarone, a more oligohaline environment at Trave and still a high mesohaline environment at Montepetra. Thus, also in this case, local factors affected the *Lago-Mare* environment. A more homogeneous *Lago-Mare* waterbody is recognized in the interval between the second and third “*colombaccio*”, in the Romagna-Marche sections where the waterbodies show a progressive deepening and more saline (mesohaline) (from high mesohaline to low mesohaline at Montepetra) conditions, except for Trave and Maccarone sections in which oligohaline waters are dominant and the waterbody depths are similar to those of the previous interval. A mesohaline environment is recognizable also in the lower portion of the Fonte dei Pulcini section where the waterbody shows alternate variations of depth from deeper conditions (some tens of meters) to few meters and again to deeper conditions. Mesohaline and shallow waterbodies are recorded in the Crete successions of Ano Akria and Faneromeni. These portions are probably correlatable to the *Lago-Mare* interval comprised between the second and third “*colombaccio*” (Fig. 11). In correspondence of

the third “*colombaccio*”, few meters below the Messinian/Zanclean boundary, in the Romagna-Marche successions a remarkable salinity reduction and deepening is testified: at Buttafuoco, Perticara, Maccarone, and Trave freshwater-oligohaline waters are recorded, while at Montepetra the same oligo-low mesohaline conditions continues from below. At Fonte dei Pulcini the same salinity decrease, coupled with deeper conditions is observable in correspondence of the rich in carbonate levels correlated by Cosentino et al. (2005) to the third “*colombaccio*”. Even at Crete, both the Faneromeni and Ano Akria successions record upsection a less saline and deeper pulse. Finally, in the uppermost part of the *Lago-Mare* studied successions, below the Messinian/Zanclean boundary and below the sterile dark layer, when present, a general increase of the salinity and shallower depths are recorded (Buttafuoco, Perticara, Fonte dei Pulcini, Faneromeni), while at Montepetra and Maccarone the freshwater-oligohaline rather deep environment seems to persist till the end of the Messinian.

In conclusion, while in the lower part of the upper post-evaporitic Messinian, rather variable environments are recorded through the central and eastern Mediterranean, due to local factors, in the uppermost part a palaeoenvironmental homogeneity is recognizable at a regional scale, probably driven by global climatic changes. Cosentino et al. (unpublished data), tuning the magnetic susceptibility curve recorded at Fonte dei Pulcini A with the Laskar 2004 curve (Laskar et al., 2004), showed that the section is included in the time-interval comprised from 5.396 to 5.336 Ma. This tuning is useful to chronologically constrain also the other studied successions that, following the correlation scheme proposed in Fig. 11, could correspond, more or less, to the same period (except for the p-ev₂ portion of the Maccarone section, which probably exceed 5.4 Ma). In this way it is possible to use the Laskar 2004 curve (Fig. 12) to investigate the short period climatic variations in

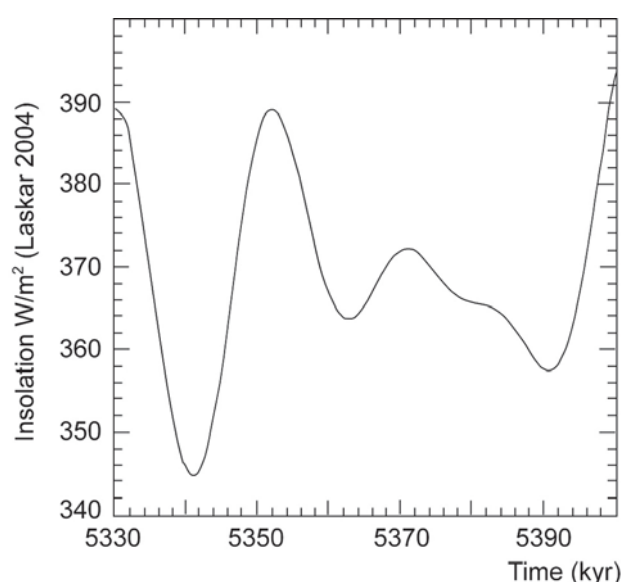


Fig. 12 - Laskar 2004 summer (June+July/2) insolation curve (43° N) for the interval 3.330-3.340 Ma.

the latest Messinian. After the insolation maximum registered around 5.4 Ma, the insolation curve shows two low amplitude peaks up to 5.36 Ma, which could mirror weak global climatic effects (Hilgen et al., 2000), and only after, until the Messinian/Zanclean boundary at 5.33 Ma, the curve shows again high amplitude oscillations. So, during the sedimentation of the lower portion of the studied successions, the weak global climatic changes were probably masked by variable local conditions occurred in the different small Mediterranean *Lago-Mare* basins while, in the upper part, the stronger climatic oscillations superimposed, driving the palaeo-environmental evolution of the central and eastern Mediterranean area at a regional scale.

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