



# Palaeobiology of Pliocene-Pleistocene shallow-water biocalcarenes (Northern Apennines, Italy) and their relationship with coeval sapropels

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**KEY WORDS** - Stratigraphy, Mollusca, Heterozoan carbonates, Mediterranean, Palaeoclimatology.

**ABSTRACT** - The interplay between carbonate and siliciclastic sediment production in shallow marine environments may result in the development of mixed depositional systems showing a cyclical arrangement of sedimentary facies. The palaeoenvironmental record associated with these cyclical facies changes is not always univocally correlated with eustatic oscillations, suggesting that other forcing processes have played an additional role. The Castell'Arquato Basin (CAB: Pliocene-Pleistocene, Northern Apennines, Italy) offers the opportunity to integrate the study of small and large-scale stratigraphic architectures with that of shell beds in shelf to deep-water successions. The analysis of diversity trends allows a first insight into the structure of CAB benthic communities associated with minor and major biocalcarenes. Biofacies types are identified through a multivariate analysis of a large quantitative database including shells of all molluscs, serpulids and brachiopods. The study shows that these bio-detrital deposits and their bracketing marine mudstones developed at inner-shelf settings and that taphonomic feedback played an important role in the stratigraphic distribution of biofacies. Benthic communities from shelly bottoms depend on the winnowing of fines by bottom currents, a factor that is not related to water depth in a simple manner. Heterogeneity of the seafloor is associated to high-diversity of communities of topset strata of major biocalcarenes. Communities living in siliciclastic bottoms depend on factors that are largely depth-dependant. The study confirms the correlation of major biocalcarene cycles with coeval deep-water sapropels, supporting the hypothesis of a more effective role of high-amplitude climatic changes driven by orbital forcing. This affects the source-to-sink dynamics of the whole basin and the biological structuring processes of shelfal depositional settings and related ecosystems.

## INTRODUCTION

Biodetrital macrofossil-rich beds resulting from the concentration of skeletal remains in coastal to outer shelf environments are widespread in the Cenozoic marine record (Kidwell et al., 1986; Abbott, 1998; Del Río et al., 2001; Hendy et al., 2006; Massari & D'Alessandro, 2012; Nalin et al., 2016; Dominici et al., 2020). The macrobenthic attributes of these deposits differ widely and appear to be characterised by highly variable and complex stratigraphic architectures (García-Ramos et al., 2019; Zecchin et al., 2019). Ultimately, these skeletal beds are the final stratal product of taphonomic filters intervening over sediment shed by the original carbonate factories (Hendy et al., 2006; Cherns et al., 2008; Kidwell, 2013; Brady, 2016; El Quot et al., 2017). The origin of bio-detrital stacked sequences is of great interest due to their many sedimentary, stratigraphic, palaeoclimatic and tectonic implications (Abbott, 1997; Avila et al., 2015; Scarponi et al., 2016; Tomašových et al., 2017). In this perspective, the Castell'Arquato Basin (CAB; Northern Apennines, Italy) offers an ideal venue for stratigraphic and palaeontological investigations, owing to its rich marine fossil record framed in a well-established chronostratigraphy (Rio et al., 1988; Roveri et al., 1998; Monegatti et al., 2001, 2002; Roveri & Taviani, 2003; Ceregato et al., 2007; Crippa et al., 2016, 2018). Distinctive skeletal-rich carbonate sedimentary beds are clustered at specific time intervals within the Pliocene-Pleistocene successions of

the Apennine-Maghrebian foreland basin system of the Mediterranean Basin (Pomar & Tropeano, 2001; Roveri and Taviani, 2003; Di Bella et al., 2005; Massari & Chiocci, 2006; Chiarella & Longhitano, 2012; Nalin et al., 2016; Dominici et al., 2020). Such macrofossil-rich, mollusc-dominated beds are best developed in the CAB, displaying a cyclical stacking pattern highlighted by the rhythmic alternation of biocalcarenes and mudstones. Previous palaeoecological analysis of biocalcarene-mudstone couplets suggests that their development is not primarily controlled by relative base-level changes (Cau et al., 2019). The rhythmic stacking pattern and stratigraphic distribution of Pliocene biocalcarene-mudstone cycles of Castell'Arquato and Caltanissetta Basins have a close genetic relationship with deep-water sapropel cycles, whose development is controlled by periodic changes in the Earth's orbital parameters. The carbonates bodies occur in fact as eccentricity-controlled clusters (over periods of 100-400 kyr) showing a time-correlation with sapropel clusters, starting from 3.1 Ma (Roveri & Taviani, 2003). To better understand which factors control deposition and to reconstruct palaeoenvironmental evolution in this important sector of the Mediterranean, the present study aims at integrating available knowledge of the macrobenthic content of the CAB biocalcarenes and associated mudstone units with a quantitative study of diversity trends and a multivariate ordination of abundance data, both studies based on a large mollusc-based dataset. We also discuss a precession-scale correlation between

CAB calcarenites and sapropels and provide a genetic model for the calcarenite-mudstone couplets related to oceanographic and climatic forcing.

### GEOLOGICAL SETTING AND BIOCALCARENITE SEDIMENTOLOGY

The Castell'Arquato Basin (CAB) is a Pliocene-Quaternary basin developed above the Northern Apennines

orogenic wedge (Roveri et al., 1998; Fig. 1); nearshore deposits prevail in the northwestern sector, while shelfal and bathyal deposits developed in the southeastern one. The basin fill records a large-scale composite depositional sequence (3<sup>rd</sup> order) bounded at its base by a late Messinian unconformity related to a major regional-scale tectonic pulse. This sequence can be split into four unconformity-bounded units (named, from the bottom upward, UM, LP, MP, UP) representing smaller-scale depositional sequences. The bounding surfaces of these units are dated respectively

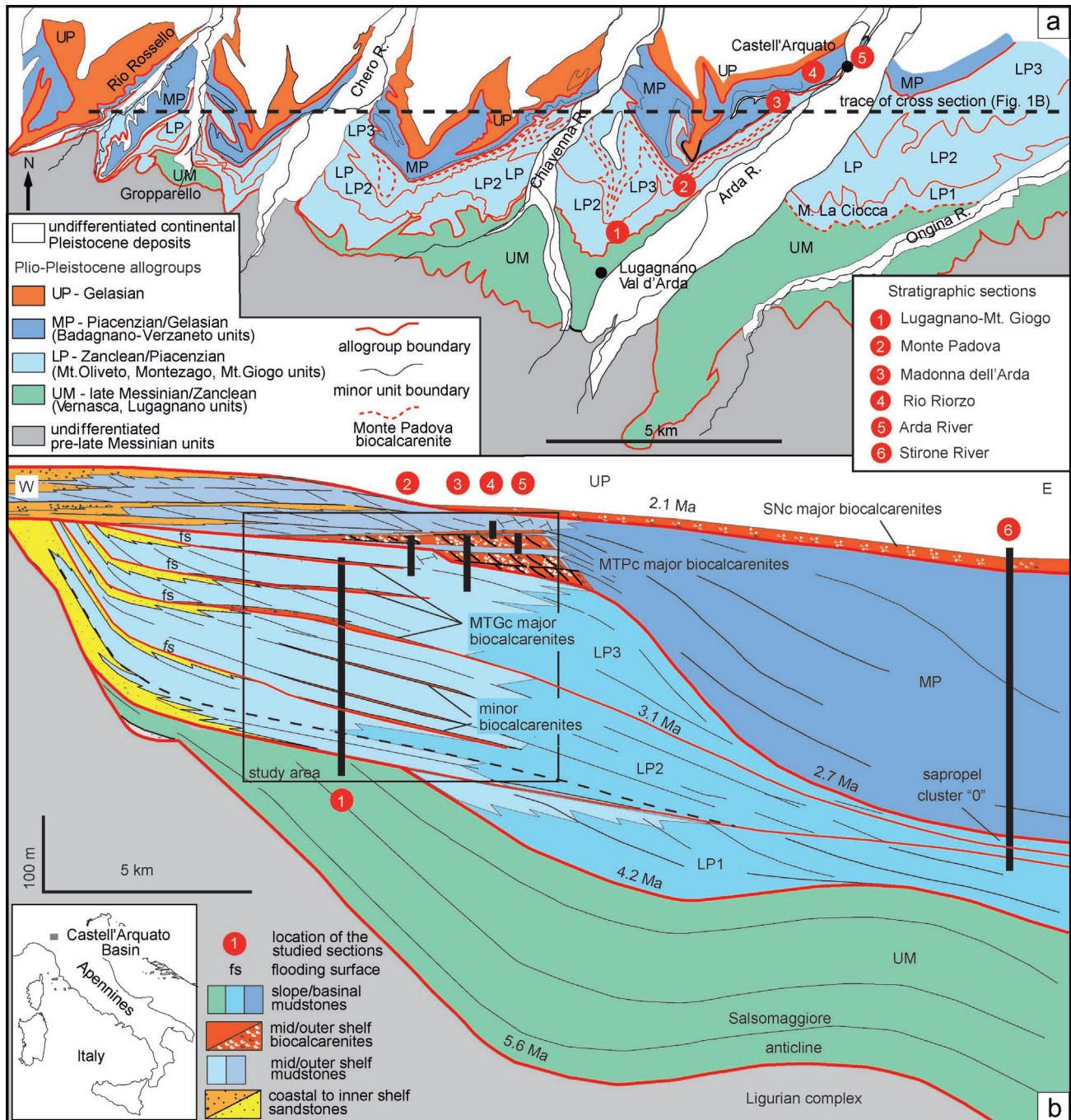


Fig. 1 - (color online) a) Simplified geological map of the Castell'Arquato Basin (CAB) and location of the studied stratigraphic sections (the Stirone section is located outside the area). The geological map shows the main allostratigraphic units identified within the Plio-Pleistocene succession outcropping in the CAB area. b) Stratigraphic architecture of the Pliocene-Pleistocene infill of the CAB, based on field and subsurface data. The model represents an idealised West-East transect from the basin margin towards its depocenter (Stirone River section; modified from Cau et al., 2019).

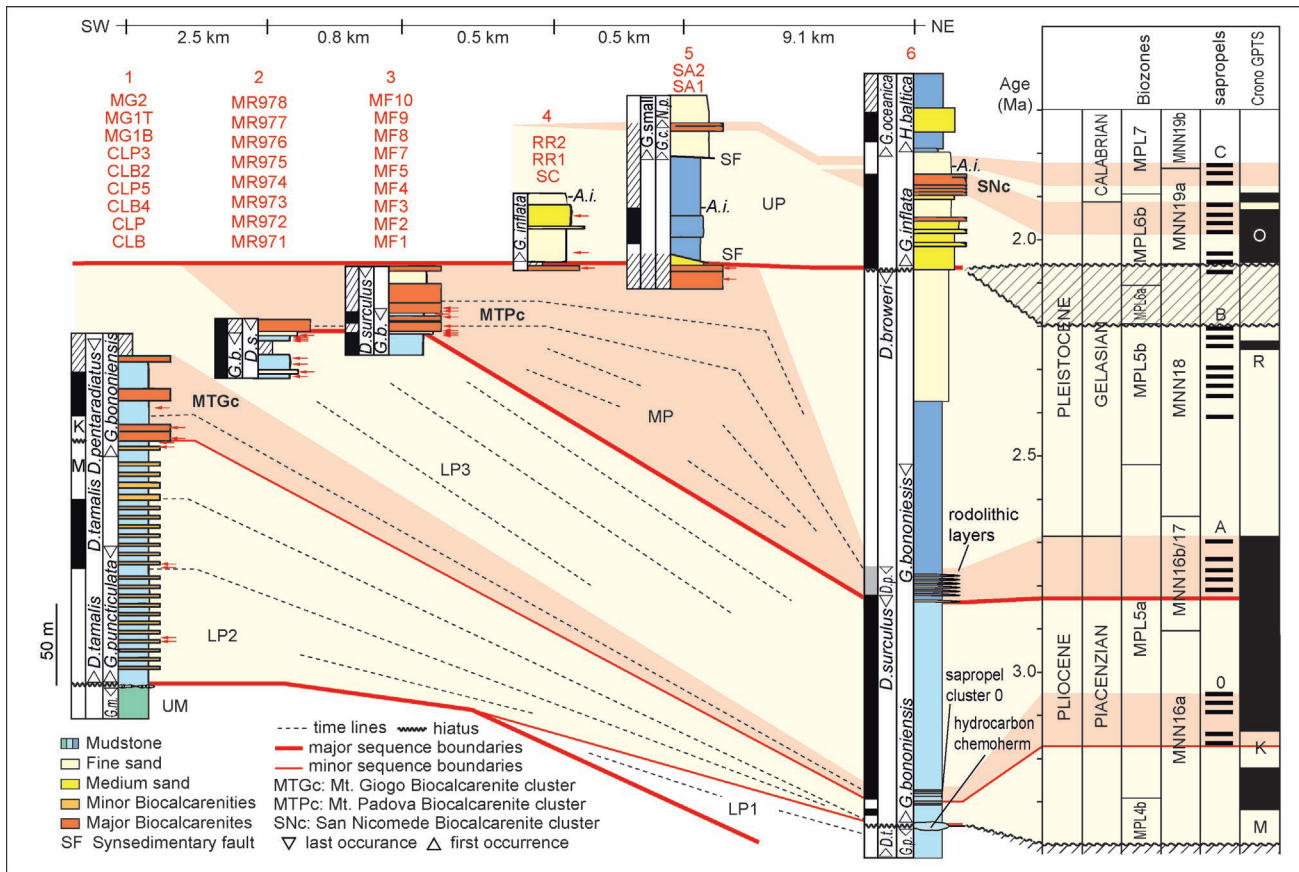


Fig. 2 - (color online) Stratigraphic logs, bulk sample position (red arrows) and correlation of studied sections within the Castell'Arquato Basin (CAB). Stratigraphic correlation is based on foraminifera and calcareous nannoplankton biozones and bioevents, magnetostratigraphic data, time distribution of sapropel clusters, marine isotope stages and astronomical parameters according to Lourens et al. (2004) and Laskar et al. (2004). Sections are (biostratigraphic and magnetostratigraphic data in parentheses): 1) Lugagnano-Monte Giogo (Rio et al., 1988; Roveri & Taviani, 2003); 2) Monte Falcone (Monegatti et al., 1997, 2002; Roveri & Taviani, 2003); 3) Madonna dell'Arda (Monegatti et al., 2001, 2002; Roveri & Taviani, 2003); 4) Rio Riorzo (Monegatti et al., 1997); 5) Arda (Dominici, 2001; Crippa et al., 2016; Monesi et al., 2016); 6) Stirone River (Capotondi, 1992; Mary et al., 1993; Channel et al., 1994; Iaccarino, 1996; Pervesler et al., 2011; Gunderson et al., 2012; Cau et al., 2015). Biostratigraphic events: G.small: *Gephyrocapsa* < 4  $\mu$ m; D.s.: *Discoaster surculus* Martini & Bramlette, 1963; D.p.: *Discoaster pentaladatus* Martini & Worsley (1970); D.t.: *Discoaster tamalis* Kamptner, 1967; G.m.: *Globorotalia margaritae* Bolli & Bermúdez, 1965; G.p.: *Globorotalia puncticulata* Hornibrook, 1981; G.b.: *Globorotalia bononiensis* Dondi, 1963; G.c.: *Globorotalia cariacensis* Rögl & Bolli, 1973; N.p.: *Neogloboquadrina pachyderma* (Ehrenberg, 1861); A.i.: *Arctica islandica* (Linnaeus, 1767); the other calcareous nanofossil or foraminiferal taxa are: *Discoaster brouweri* Tan, 1927; *Gephyrocapsa oceanica* Kamptner, 1943; *Globoconella inflata* (d'Orbigny, 1839); *Hyalinea balthica* (Schröter in Gmelin, 1791).

at ~ 5.6, 4.2, 2.7 and 2.1 Ma (Fig. 1; Roveri et al., 1998; Roveri & Taviani, 2003) and record important phases of thrust propagation. The LP depositional sequence is in turn subdivided in three smaller depositional sequences (LP1, LP2 and LP3; Figs 1 and 2). From bottom to top, LP2 minor biocalcarene lithosomes and their mudstone counterparts are 1-3 meter-thick, show tabular geometry and are formed by densely packed, minute, variably abraded and bioeroded shells in a coarse- to medium-grained sandy matrix (Fig. 3a). The biocalcarene fabric is chaotic; horizontal or imbricate valves (pectinids) are rarely observed, and the internal bedding is not usually recognisable. Best exposures of these deposits can be observed in the Lugagnano-Monte Giogo section along the southern margin of the CAB. In its central sector, biocalcarene bodies form three distinctive clusters separated by metric or pluridecamic mudstone intervals (Figs 1 and 2). The clusters are characterised by the stacking of individual sedimentary cycles formed by biocalcarene-mudstone couplets (Fig. 2). Major biocalcarenes are named, from

the bottom: Monte Giogo (MTGc; four couplets), Monte Padova (MTPc; five couplets), and San Nicomede (SNc; six couplets). According to the sequence-stratigraphic reconstruction proposed by Roveri et al. (1998) and Roveri & Taviani (2003), the lowermost cluster belongs to the transgressive systems tract (TST) of sequence LP3, whereas the middle and upper ones are assigned to the TSTs of sequences MP and UP. Major biocalcarenes are up to 10 m-thick, exceptionally up to 25 m in MTPc, and often show progradational geometries, with a typical topset-foreset-bottomset facies tripartition (Cau et al., 2019). The bottomset facies mainly consists of shell accumulations that in Monte Padova biocalcarenes show a preferential concave-down orientation in a coarse- to medium-grained sandy matrix (Fig. 3b). The foreset facies is characterised by weakly to well-cemented cliniform beds with concave-down disarticulated shells (Fig. 3c). The topset facies is represented by a poorly-cemented sandstone containing disarticulated skeletal remains without a preferential distribution (Fig. 3d). The bottom

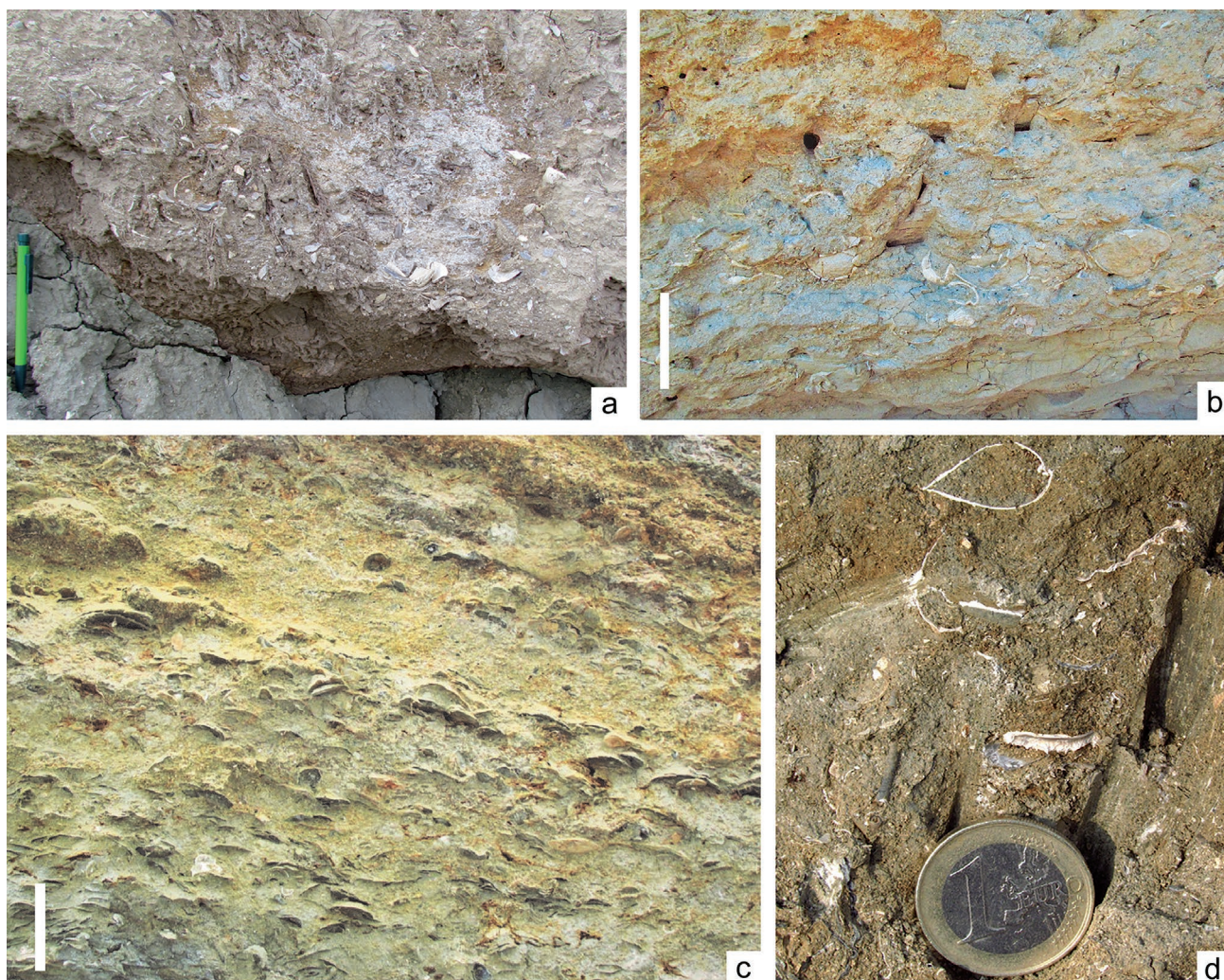


Fig. 3 - (color online) Detail of shell-beds. a) Densely-packed shells in a minor biocalcareneite (LP2; pen for scale = 14 cm). b) Bottomset shell-bed (Monte Giogo biocalcareneite; scale bar = 10 cm). c) Foreset complex shell-bed showing dense packing of concave-down scallop shells (Monte Padova biocalcareneite, MTPc; scale bar = 10 cm). d) Topset shell bed in a poorly-cemented sandstone, characterised by articulated and disarticulated bivalve shells without a preferential orientation (Monte Giogo biocalcareneite, MTGc; coin for scale = 2.2 cm).

and topset deposits enclose rich macrofauna, with abundant epifaunal suspension-feeders and herbivores. The foreset facies is characterised by an oligotypic macrofauna, organised in poorly preserved horizons of mainly imbricate pectinid and ostreid valves, associated with abundant trace fossils (*Ophiomorpha* and *Thalassinoides*).

#### *Palaeobathymetric trends*

At the basin scale, the palaeobathymetric curve shows an overall shallowing-upward trend, due to the long-term tectonically-driven basin evolution (Cau et al., 2019). No significant bathymetric changes were appreciated in sequence LP2, whereas in sequence LP3 the deepest samples were from the basal units and two out of three of the shallowest samples from the top units, possibly indicating a shallowing upward trend. Biocalcareneites of sequence MP record a more complex pattern, with an overall deepening-upward trend in the basal part, followed by a shallowing-upward trend in the upper part. Finally, in sequence UP, sandstone samples indicate shallow-water settings. Regarding the individual biocalcareneite-mudstone couplets of both minor and major bodies, available

palaeobathymetric estimates suggest that deeper water conditions were attained during the deposition of bioclastic lithosomes (Fig. 4). This scenario supports the conclusion that biocalcareneite clusters form the transgressive systems tracts of three depositional sequences (Roveri et al., 1998; Roveri & Taviani, 2003). The amplitude of such inferred palaeobathymetric oscillations envisaged at the scale of individual biocalcareneite-mudstone couplets appears very small (< 15 m; Cau et al., 2019). These results cannot be explained by the consecutive landward and seaward shifts of depositional settings driven by sea-level fluctuations alone. Additional forcing factors need to be considered to account for the observed facies and palaeoecological changes.

#### METHODS

The studied sections are Lugagnano-Monte Giogo, Monte Falcone, Madonna dell'Arda, Rio Riorzo and Arda River, from the West to the East (Fig. 2). The samples used in our study are taken from Cau et al. (2019), with

the inclusion of a sample (MF5) collected in the Madonna dell'Arda section. Bulk samples range from 0.5-1.0 liters for sandstones and calcarenites, to 25-32 liters for mudstones (Cau et al., 2019). The new quantitative exploration of these macrofaunal collections, mainly consisting of molluscs, allows to improve the analysis regarding the more proximal portions of the biocalcarenic bodies. Diversity statistics applied to individual collections include: 1) number of species-level taxa, or species richness (S), and 2) Simpson index ( $\lambda$ ), ranging from 1 (all taxa are equally present) to 0 (one taxon completely dominates the community). Species-rich palaeocommunities are expected to be associated with low dominance, evidence of stable environmental conditions during shell bed formation. Multivariate ordination was obtained by Detrended Correspondence Analysis (DCA), an indirect ordination method based on similarity coefficient computed on percent-transformed abundance data and after reduction of an arch effect. This is commonly used to detect ecological gradients (Patzkowsky & Holland, 2012; and references therein). To reduce the complexity of the data, we arbitrarily excluded those taxa that appear in less than six samples, statistically not significant for the result of the multivariate study. All quantitative analyses were carried out with the PAST statistics software (Hammer et al., 2001). Previous palaeobathymetric interpretation of the biocalcarenic-mudstone couplets were based on a weighted average of the bathymetry of extant species found on CAB samples (Cau et al., 2019). Here we investigate the significance of the distribution of samples and characterising species in the ordination space to better frame the relative importance of depth-dependent, marine ecological factors. Following previous similar studies (Scarponi & Kowalewski, 2004; Dominici et al., 2008) we aim at testing to what degree the main axis of the DCA ordination (DC1) reflects bathymetry, with deeper- and shallower-water species ordered at the two extremes of the ordination. This is done by estimating present-day water depth preferences of extant species retrieved in CAB samples from the Italian Mollusc Census database by ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development; [http://www.santateresa.enea.it/wwwste/banchedati/bd\\_ambmar.html](http://www.santateresa.enea.it/wwwste/banchedati/bd_ambmar.html)). These estimates provide insights on long-term palaeobathymetric trends and are a link to reconstruct bathymetric change within individual biocalcarenic-mudstone couplets. Palaeobathymetry controls to a large degree the distribution of species and samples along the ordination space (Patzkowsky & Holland, 2012), while other factors are considered when interpreting distribution along the second axis (Scarponi & Kowalewski, 2004; Scarponi et al., 2014). Independent evidence used to infer palaeoenvironmental control includes the distribution of the main lithologies associated with the palaeontological quantitative dataset (Dominici et al., 2008), subdivided here into sandstone, mudstone, calcarenite and further subdivisions of these three basic types (Cau et al., 2019).

## RESULTS

The dataset used in diversity statistics includes 271 benthic invertebrate taxa belonging to 199 genera,

dominantly molluscs (gastropods: species richness  $S = 167$ ; bivalves:  $S = 97$ ; scaphopods:  $S = 5$ ), with one annelid and one brachiopod (Supplementary Material, Tab. 1: *Acanthocardia* gr. *echinata* includes *A. echinata* [Linnaeus, 1758] and *A. spinosa* [Lightfoot, 1786]; *Aequipecten* gr. *opercularis* includes *A. opercularis* [Linnaeus, 1758] and *A. scabrella* [Lamarck, 1819]; *Euspira* spp. includes *E. helicina* [Brocchi, 1814], *E. catena* [da Costa, 1778], *E. pulchella* [Risso, 1826] and *E. macilenta* [Philippi, 1844]). The average proportion of the excluded taxa for DCA in each sample is 0.12%. The final matrix on which the latter is based is formed by 31 samples and 91 species-level taxa (Supplementary Data, including the original matrix formed by 271 taxa). Diversity trends in the studied successions are compared to published palaeobathymetric trends (Fig. 4).

### *Species diversity of shell beds*

Minor biocalcarenites of unit LP2 show a significantly higher species richness compared to mudstones (e.g., CLB4,  $S = 102$ , versus CLP5,  $S = 19$ ; Fig. 4). In unit LP3, the major MTG biocalcarenic shows a higher richness (MG1B and MG1T,  $S = 67$  and  $88$ , respectively) compared to the mudstone interval (MG2,  $S = 49$ ). In the mud-sandy interval between the MTG and MTP biocalcarenites, a gradual upward decrease in the number of taxa is recorded (from MR971,  $S = 71$ , to MF3,  $S = 15$ ). Within the MTP biocalcarenic cluster, richness is higher in bottomset (MF9,  $S = 97$ ) and topset facies (MF7,  $S = 100$ ; and SC,  $S = 105$ ; see Cau et al., 2019 for facies), and strongly reduced in foreset and mudstone deposits (MF5 and MF10,  $S = 6$  and  $8$ , respectively; MF8,  $S = 36$ ).

Values of the Simpson Index ( $\lambda$ ) show a pattern generally consistent with the richness curve. In some cases  $S$  and  $\lambda$  show opposite trends (see CLP, MG1T, MF4, MF5, MF9 and RR2 in Fig. 4). The low dominance of the two generalist taxa *Saccella commutata* (Philippi, 1844) and *Ditrupa arietina* (O.F. Müller, 1776) in assemblage CLP determines a relative high  $\lambda$ , similar to that of the biocalcarenic sample. In the MTG1 biocalcarenic, MG1T records a highest number of taxa, but a lowest value of diversity with respect to MG1B. This condition is due to high abundance *Anomia ephippium* (Linnaeus, 1758), an eurybathic epifaunal bivalve that favours hard or coarse-skeletal substrates (*A. ephippium* = 24.08%). In unit LP3, species richness and Simpson's  $\lambda$  show an upward consistent trend which culminates in correspondence of sample MF3. In MF3 samples the low diversity values are due to high dominance of *Anomia ephippium* and *Aequipecten* gr. *opercularis* (52.3% and 24.9% respectively). Also in MTF biocalcarenic samples the low diversity values are due to the high dominance of *A. ephippium*, in foreset (MF5 and MF10,  $\lambda = 0.372$  and  $\lambda = 0.111$ ; *A. ephippium* > 75%) and in bottomset facies (MF4 and MF9 samples;  $\lambda = 0.215$  and  $\lambda = 0.694$ ; *A. ephippium* > 60%) (Fig. 4 and Supplementary Data). The mudstone assemblages that show a low diversity values (CLP5 and MG2,  $\lambda = 0.548$  and  $\lambda = 0.454$ ) are characterised by the high dominance of *Corbula gibba* (Olivi, 1792) or *Ditrupa arietina* (> 50 %) (Fig. 4 and Supplementary Data).

### *Detrended Correspondence Analysis*

The Detrended Correspondence Analysis (DCA) results show that biocalcarenites collections, in particular

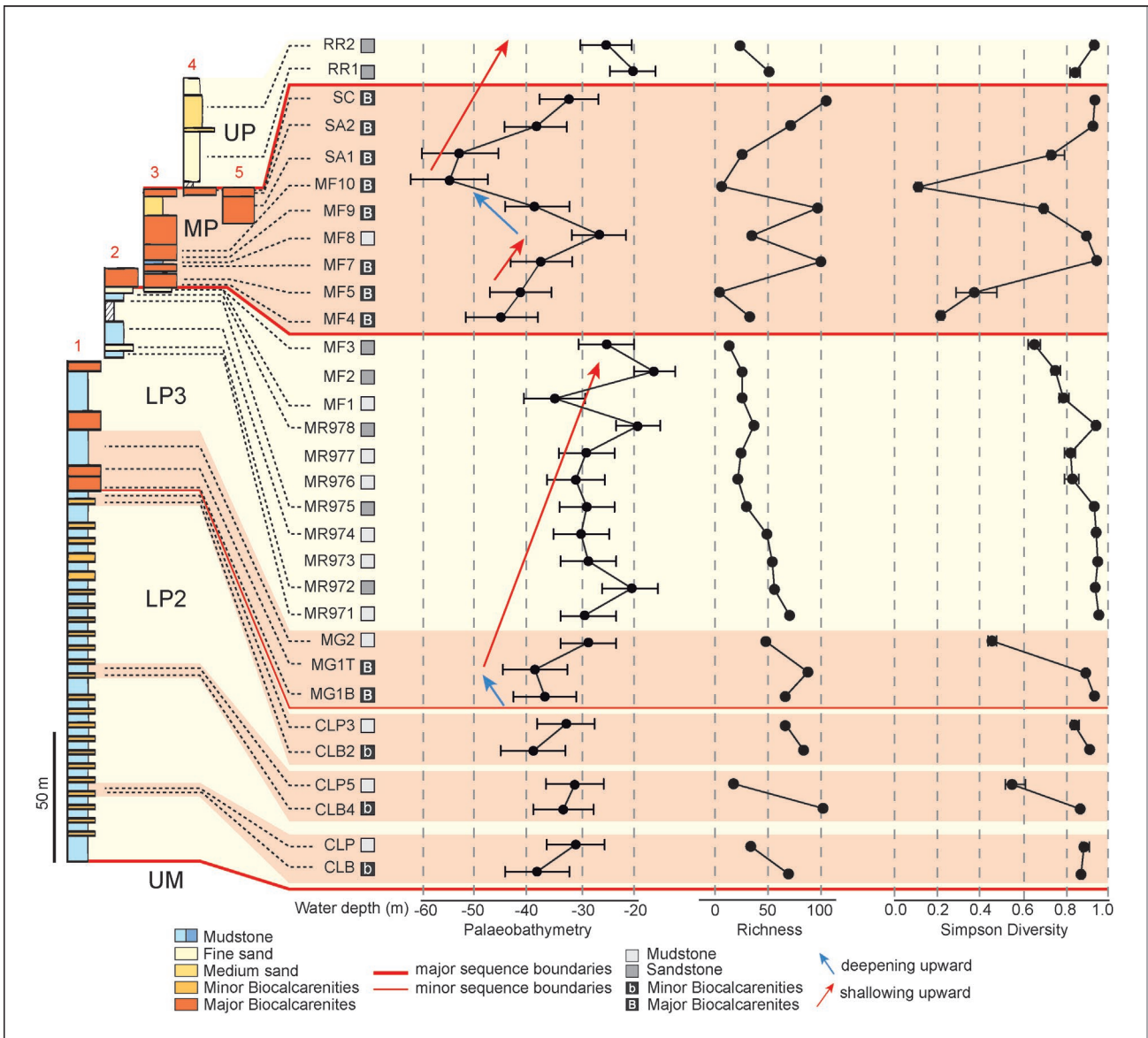


Fig. 4 - (color online) Synthetic lithostratigraphy of the studied succession, with sample position, facies types, plot of inferred palaeobathymetry, taxonomic richness, and Simpson Index for the studied samples.

the bottomset and the foreset facies, have the highest scores along both axis 1 and 2. In particular, collections MF4, MF5 and MF10, those with lower  $\lambda$  (Fig. 4), show higher DC1 scores (Fig. 5), whereas the lowest scores are associated with mudstone collections MR971, MR972, MR976 and MG2. Among dominant species, high DC1 scores are associated with *Anomia ephippium*, *Pecten flabelliformis* (Brocchi, 1814) and *Aequipeecten* gr. *operularis*, mostly from imbricated shell-beds indicative of high energy unidirectional currents. Hydrodynamic stress and winnowing are a possible forcing that favours the development of coarse-grained substrates in offshore settings. The same factor supports the opposite scenario: low hydrodynamic stress promotes deposition of fine-grained sediments. Also the taxa distribution in the multivariate space corroborates this interpretation: the highest DC1 scores correspond to taxa that thrive in sandy, coarse or hard bottoms, while the taxa typical of muddy or mixed substrates show low or intermediate

values. The central scores of the DC1 axis is associated with gastropod species of genus *Bittium*, particularly abundant in biocalcarenesite samples, in association with other small herbivores such as *Alvania* and *Tricolia* in biocalcarenesites of the Arda section (samples SA1 and SA2; Fig. 5). The presence of this epifaunal grazers suggests the development of a vegetal cover.

DC2 scores (24.6% of the variation in the data; Fig 5), although often difficult to interpret (Scarponi et al., 2014), provide here additional information on the ecological structure of the original benthic communities. DC2 distribution of taxa and samples is correlated with changes in the substrate, high scores mainly corresponding to collections from biocalcarenesite samples, in particular from the topset facies (SA2, SC, MF7), in association with taxa such as *Glycymeris glycymeris* (da Costa, 1778), *Clausinella punctigera* (Dautzenberg & H. Fischer, 1906), and *Thylacodes arenarius* (Linnaeus, 1758). These macrobenthic assemblages are mainly characterised by

epifaunal taxa associated with coarse sandy or skeletal substrates. In particular, the high scores along the DC2 axis are related with small-sized grazing gastropods (*Bittium*, *Alvania*, *Pusillina*) that suggest the presence of a vegetal cover. Conversely, taxa and samples with low DC2 scores are primarily linked with soft mixed-siliciclastic substrates, particularly mudstone, where infaunal suspension feeders thrive. Infaunal bivalves, such as *Venus nux* Gmelin, 1791 and *Corbula gibba*, are in fact generally more abundant in mudstones than in coarse-grained substrates. These data suggest that score along DC2 is inversely proportional to sedimentation rate, high rates of fine-grained sedimentation and high water turbidity corresponding to low scores and low rates of sedimentation, with development of shelly hard substrata within the photic zone, with high scores (Figs 5 and 6).

## DISCUSSION

### Palaeoecology of biocalcarenes

Previous palaeobathymetric results based on preferred water depth range of extant species indicate that CAB shell beds formed at water depths ranging about 20-60 m (Cau et al., 2019). These trends appear in good agreement with the reconstruction of the sequence stratigraphic architecture of the CAB proposed by Roveri et al. (1998) and support previous qualitative estimates of Monegatti et al. (1997, 2001, 2002). The present study shows that score along main axis DC1 does not correlate with water depth (Figs 5 and 6), contrary to expectations based on previous applications of the method (Patzkowski & Holland, 2012), tested several times through independent controls on absolute depths (Scarponi & Kowalewski, 2004; Dominici et al., 2008; Scarponi et al., 2014). We propose that the distribution of CAB taxa and samples along DC1 axis is a function

of water energy, with relatively deeper environments swept by bottom currents forming physical analogues of shallow water, wave-swept shoreface environments. Characterising taxa of biocalcarenes document in fact a faunal assemblage developed on coarse-grained skeletal substrates in conditions of variable hydrodynamic stress. As in previous multivariate cluster analysis (Cau et al., 2019), the present analysis does not discriminate between topset, foreset or bottomset biofacies, nor between major and minor biocalcarenetic bodies. Biocalcarenes are associated with opportunistic epifaunal bivalves of genera *Aequipecten*, *Pecten* and *Anomia* (Fig. 5). Their known ecological preferences are consistent with the above interpretation. The ubiquitous byssally-attached pectinid *Aequipecten opercularis*, often in association with the free-living *Pecten maximus* (Linnaeus, 1758) and other scallops, presently inhabits inner-to-middle shelf sandy to shell-gravel bottoms, attracted by substrate heterogeneity of vegetated substrates (Kamenos et al., 2004). The gradual formation of a shelly bottom favours the larval settlement of the byssally attached bivalve *Anomia ephippium* (Bromley, 1999; Studencka, 2018) as an example of a biotically-driven sequential faunal change (taphonomic feedback; Kidwell & Jablonski, 1983). This xenomorphic eurybathic sessile, known to exploit shelfal hard substrates (Poirier et al., 2010), is variable in CAB samples, with occasional high dominance. Other characterising taxa of the calcarenite recurring macrobenthos, such as *Calyptrea chinensis* (Linnaeus, 1758), *Thylacoides arenarius*, *Limaria loscombi* (G.B. Sowerby I, 1823), *Ostrea* sp., *Barbatia candida* (Helbling, 1779), *Limopsis minuta* (Philippi, 1836), *Clausinella punctigera* (Dautzenberg & H. Fischer, 1906) and *Astarte sulcata* (da Costa, 1778) are also shell-gravel dwellers. High abundance of the serpulid *Ditrupa arietina*, an extant taxon with a known distribution largely independent from sediment texture, suggests conditions of sedimentary

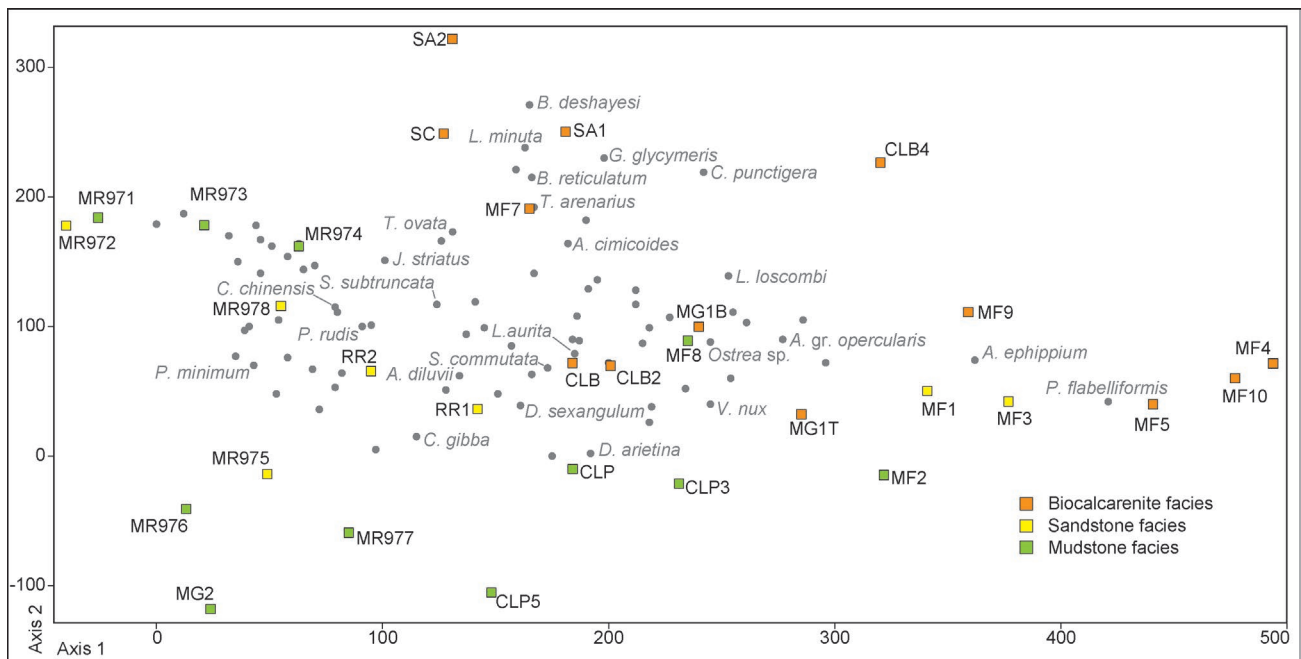


Fig. 5 - (color online) Detrended correspondence analysis ordination of species and samples. DCA axis one eigenvalue 0.517; axis two eigenvalue 0.246.

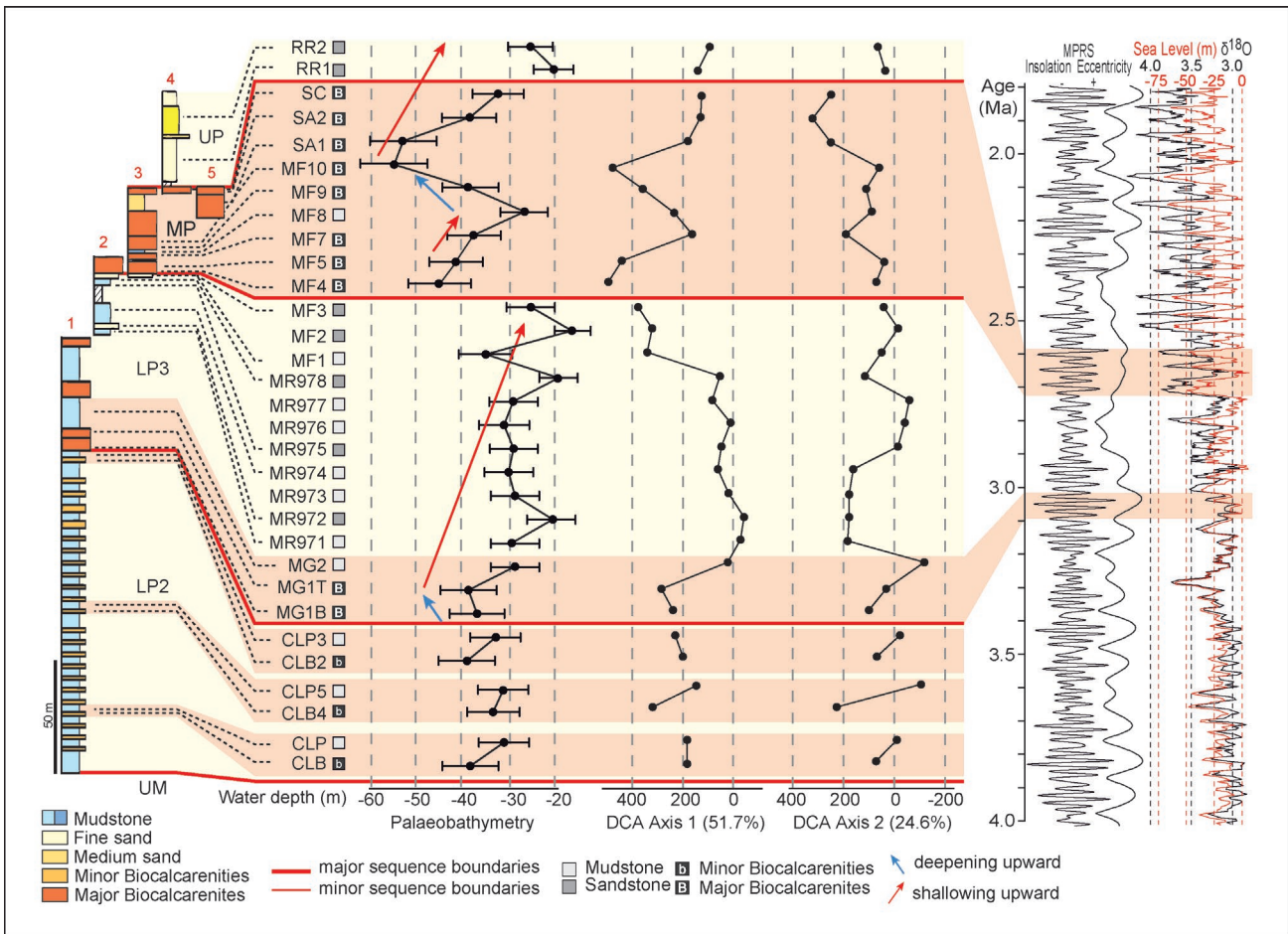


Fig. 6 - (color online) Comparison between absolute palaeobathymetric inferences of Cau et al. (2019) and DCA scores along axis one (DC1) and two (DC2) of the ordination (see also Figs 4 and 5). Stratigraphic correlation of CAB sections is based on bio-magnetostratigraphic data and astronomical parameters (see caption of Fig. 2).

instability (Cosentino & Giacobbe, 2006). *Timoclea ovata*, a filter feeder displaying high abundance in inner to middle shelf sandy and shell-gravel substrata, may also indicate the influence of bottom currents (Kamenos et al., 2004). Herbivore/deposit-feeding gastropods such as *Bittium reticulatum* (da Costa, 1778), *B. deshaysi* (Cerulli Irelli, 1912), *Jujubinus striatus* (Linnaeus, 1758) and several species of rissoids suggest an algal cover in the photic zone. The occasional presence of species characteristic of low energy muddy substrates commonly reported in shelf settings, like *Corbula gibba*, *Venus nux* and *Dentalium sexangulum* (Gmelin, 1791), may indicate sedimentological reworking from older deposits. Among the calcarenite assemblages, those associated with the foreset facies are characterised by the highest dominance of *A. ephippium* and the lowest species richness. These ecological traits suggest environments of the inner shelf with coarse-grained sediments subject to the most intense background currents (Maughan, 2001).

The results of the present DCA are consistent with other palaeobiological studies of mollusc abundance distributions. Macrobenthic assemblages associated with shelly bottoms are commonly offset in ordination multivariate analyses of large dataset, separated from depth gradients typical of siliciclastic bottoms (e.g., Dominici & Kowalke, 2007; Dominici et al., 2019).

Available evidence suggests that CAB biocalcarenes formed as a heterogeneous coarse-grained sandy skeletal bottom, covered with a thin algal film at inner or middle shelf depths. Occasional exhumation and mixing of taxa typical of muddy sediments, intercalated between episodes of formation of the coarse shelly layers, contributed to the high diversity of CAB shell beds. Biocalcarenes rich with scallops, oysters and other large epifaunal taxa are typical of Piacenzian and Gelasian transgressive episodes recorded in Mediterranean successions of other Italian basins (Zecchin et al., 2003, 2006; Nalin et al., 2016; Dominici et al., 2020).

#### Palaeoecology of mudstones

The mudstone and sandy-mudstone deposits are characterised by a poor skeletal content and assemblages dominated by filter-feeders or detritivores. Infaunal taxa typical of soft muddy bottoms from offshore to middle shelf depths, such as *Amusium cristatum* (Bronn, 1828), *Limopsis aurita* (Brocchi, 1814), *Phaxas adriaticus* (Coen, 1933), *Abra nitida* (O.F. Müller, 1776) and *Anadara diluvii* (Lamarck, 1805) are common. The ubiquitous presence of *Ditrupa arietina* is indicative of high sedimentation and turbidity (Cosentino & Giacobbe, 2006; Hartley, 2014). A similar consideration also applies to *Saccella commutata*, a eurybathic infaunal bivalve taxa that tolerates the stress



related to the increase of sedimentation rates (Gianolla et al., 2010). *Corbula gibba* shows a variable abundance, attaining at times high dominance (samples CLP5, MG2). This is a well-studied opportunistic infaunal bivalve showing peaks of abundance in shelf settings characterised by periodical oversilting (Di Geronimo et al., 1987; Hrs-Brenko, 2006; Maselli et al., 2014; Scarponi et al., 2014) or by hypoxia (Benvenuti & Dominici, 1992; Dominici, 2001; Fuksi et al., 2018). Based upon the ecology of the above species, CAB mudstones document shelf bottoms subject to much higher fine-grained sedimentation rates and less frequent or less efficient winnowing events with respect to biocalcarenites. This interpretation is further supported by the concomitant decreased importance of *Anomia ephippium*. High abundance of the opportunistic *C. gibba* characterises occasional high mud inputs. The mudstone macrofaunal association recurs in the Pliocene and Pleistocene of CAB (Dominici, 2001; Crippa et al., 2018) and other Mediterranean basins (D'Alessandro et al., 2003; Scarponi et al., 2014; Dominici et al., 2018), at intervals with similar palaeoenvironmental meaning.

#### Genetic model for biocalcarenite-mudstone couplets

The present palaeoecological analysis of CAB biocalcarenites is consistent with their complex internal architecture, resulting from a polyphasic development in inner to outer shelf settings (Cau et al., 2019). The rich macrobenthic concentrations of biocalcarenites result from the repeated action of currents generated by intense storms, extreme fluvial flood events or geostrophic currents. The common occurrence of planar to high-angle cross-laminations and imbricated pectinid pavements supports this interpretation. Foreset biofacies are represented by oligotypic assemblages that suggest an ecosystem stressed by persistent hydrodynamic disturbance. This regime is responsible for the winnowing of the fine grained component of the sediment. The upper component of each calcarenite-mudstone couplet develops instead at times of reduction of winnowing on top of a biodetrital bottom at inner or middle shelf depths, following the collapse of the biocalcarenite epibenthic community. The CAB mudstone biofacies represents a wider spectrum of environments, ranging from relatively stable to highly stressed settings due to high mud input. The initial phase of the following couplet is characterised by a mixed assemblage composed of sand-and mud-dwellers. This condition is recorded in minor biocalcarenites and bottom facies of the major biocalcarenite deposits (samples CLB, MG1B and MF9). As bottom energy starts to increase again, the benthic ecosystem evolves to a low diversity community adapted to a coarse-sandy matrix. Winnowing and the long residence time of shells on the seafloor leads to their abrasion, in association with clinostratified deposits of the forest facies that move basinward by the action of unidirectional currents. The flat-bedded deposits recovered in topset facies and in minor biocalcarenite bodies, show a higher fossil diversity respect to other facies, suggesting a lower hydrodynamic disturbance, oligotrophic and well-oxygenated bottom conditions, with a rich epifaunal component that includes herbivores. The gradual return to conditions of fine-grained siliciclastic sedimentation causes the collapse of the biocalcarenite fauna and leads to a sparse association of infaunal taxa

that are tolerant to periodic environmental stressors, like high rates of fine-grained sedimentation or hypoxia.

#### CAB and additional Mediterranean Pliocene and Pleistocene sapropels

Chronostratigraphic constraints show that Mediterranean Pliocene and Pleistocene biocalcarenitic bodies occur in clusters coeval to sapropel clusters "0", "A", "B" and "C" (in the sense of Lourens et al., 1996; see Roveri & Taviani, 2003). Mediterranean Neogene sapropels are deep-water sediments rich in organic matter, characterised by thin lamination, absence of bioturbation and macrofossils and high decrease of benthic foraminiferal diversity (Rohling et al., 2015). These features suggest that sapropel formed under conditions of persistent sea-floor anoxia which inhibited the macrobiological activity. Several sapropels are preceded by a short interval containing microfaunas indicative of severe bottom-water oxygen depletion, that sometimes return within, or can persist into the sapropel (Jorissen, 1999; Abu-Zied et al., 2008; Schmiedl et al., 2010; Rohling et al., 2015). In the CAB, sapropels have been recognised in the Campore (Ceregato et al., 2007) and Stirone River sections (Cau et al., 2015), identified as sapropel cluster 0 (Roveri & Taviani, 2003; Cau et al., 2019). In proximity of these horizons, macrobenthic low-diversity assemblages are characterised by indicators of oxygen-depleted environments (e.g., *Mysella bidentata* [Montagu, 1803] in the Campore section; Ceregato et al., 2007) or by the dominance of the pectinid *Deletopecten vitreus* (Gmelin, 1791), also suggesting a hypoxic environment (Ceregato et al., 2007; Cau et al., 2015). Palaeoecology of shell beds rich with *Bittium*, *Alvania* and other small herbivores, immediately preceding sapropels at Campore (samples 4-5 in Ceregato et al., 2007), suggests a possible direct correlation with the coeval Monte Giogo biocalcarenite, these thin layers forming its deep-water expression. The study of micro- and nanofossil assemblages associated with Mediterranean sapropelitic sequences in Sicily and Calabria (Sgarella et al., 2012), thus offers another excellent palaeoecological record for a comparison with the present shallow water macrobenthic dataset. In Piacenzian-Gelasian sapropel clusters "0" and "A", marl levels interposed to sapropels are characterised by dominance of species of food-limited and well-oxygenated settings, such as *Cibicides pachyderma* (Rzehak, 1886), *C. wuellerstorfi* (Schwager, 1866), *Anomalinoidea helacinus* (Costa, 1857), *Planulina ariminensis* d'Orbigny, 1826, *Siphonina reticulata* (Czjžek, 1848) and deep-water miliolids (Sgarella et al., 2012; Cau et al., 2015). On the other hand, the sapropels are dominated by hypoxia-tolerant species typical of eutrophic environments. Generally, assemblages in different sapropel layers show marginal changes and appear dominated by *Bulimina aculeata* d'Orbigny, 1826, *B. striata* d'Orbigny in Guérin-Méneville, 1832, *B. inflata* Seguenza, 1862, *Uvigerina peregrina* Cushman, 1923, and *Bolivina dilatata* Reuss, 1850 (Sgarella et al., 2012; Cau et al., 2015). Among planktic foraminifera, very high percentages of *Globorotalia bononiensis* Dondi, 1962 or *Neogloboquadrina acostaensis* (Blow, 1959) in correspondence of sapropel layers (Sprovieri et al., 2006; Cau et al., 2015) support an eutrophic environment with water stratification (Sgarella et al., 2012).

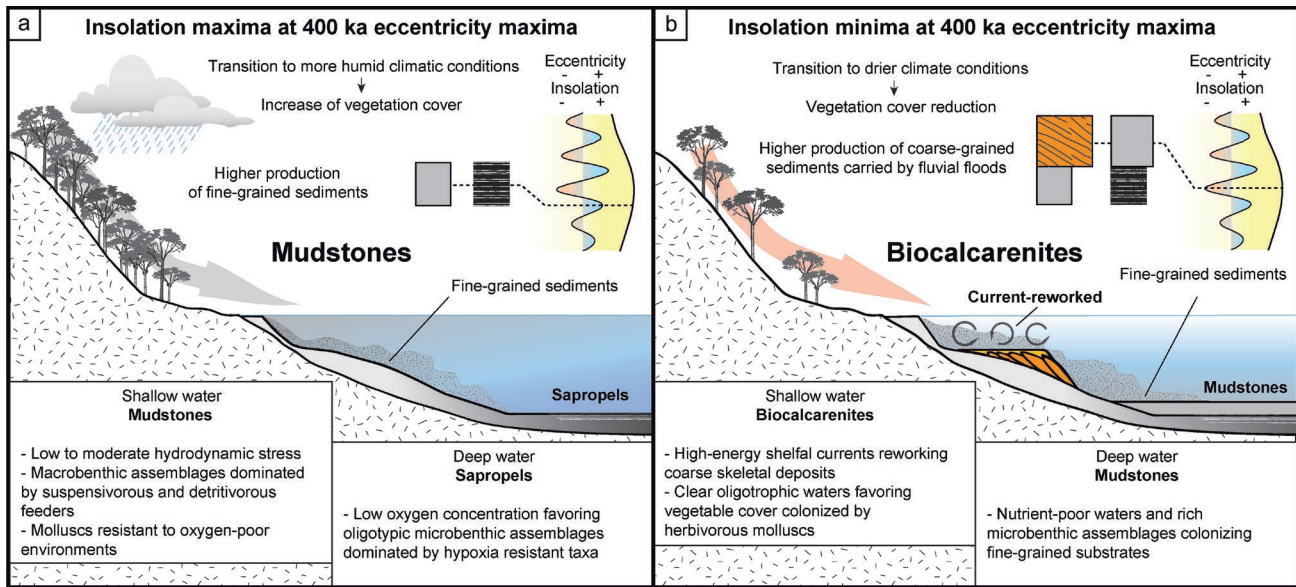


Fig. 7 - (color online) Schematic model for biocalcarenite and sapropel deposition. a) Mudstones in shelfal settings and sapropels (or organic rich layers) in deeper settings were deposited during warm-wet phases at insolation maxima. b) Biocalcarenite (major or minor cycles) in shelfal settings and mudstones in deep-water settings were deposited during cold-arid phases at insolation minima.

Sapropels are more common in the eastern Mediterranean (East of the Strait of Sicily) than in the western Mediterranean, where they are also known as Organic Rich Layers (Cramp & O'Sullivan, 1999; Rohling et al., 2015). Eastern and western Mediterranean sapropels are well correlated (Cramp & O'Sullivan, 1999) and record the development of reduced bottom water oxygenation (Rohling, 1994; Cramp & O'Sullivan, 1999; Negri et al., 2009a, b) at precessional minima (Hilgen, 1991, 1993, 1995; Lourens et al., 1996, 2001), in response to enhanced monsoon-fueled river discharge along the North African margin (Rohling et al., 2002, 2004, 2015; Grelaud et al., 2012). These conditions are enhanced during Neogene eccentricity maxima (100–400 kyr frequency), as testified by formation of more developed sapropel clusters well-tuned to the astronomical curves (Lourens et al., 1996). The precession minimum is characterised in the northern hemisphere by higher summer insolation and reduced winter insolation, increasing the seasonal contrast and enhancing summer monsoon intensity (Rohling et al., 2015; and references therein). Intensification of northern hemisphere precipitations is considered a key source for extra freshwater delivery into the basin during sapropel times. This condition has resulted in stronger stratification of the water column and reduced deep ventilation with consequent oxygen depletion (Nijenhuis & De Lange, 2000). An enhanced nutrients input from erosion and greater insolation has determined high primary phytoplankton productivity (Capozzi et al., 2006; Negri et al., 2009a, b). It is also believed that low oxygenation can be related to intense and persistent microbial activity in response to the high availability of organic matter (Rio et al., 1997).

#### *An astro-climate model for biocalcarenites and sapropels formation*

Detailed data on oxygen isotope records provide an exhaustive palaeoclimatic reconstruction of the Pliocene-

Pleistocene interval (Lisiecki & Raymo, 2005). At global scale the Zanclean and Piacenzian stages are recognised as two relatively warm-climate periods, with several relatively warmer peaks, including the Mid-Piacenzian Warm Period (MPWP, 3.29–2.97 Ma; Dowsett et al., 2011). During the transition to the Pleistocene, the global climate underwent a passage to substantially colder conditions. In the northern hemisphere the onset of the glaciation stage is dated at around 3.6 Ma, ending at 2.4 Ma and intensifying at around 2.7 Ma (De Schepper et al., 2014). Slow tectonic forcing, such as the closing of ocean gateways or of the Tibetan Plateau building, has been suggested as the possible cause of this initial glaciation stage (Mudelsee & Raymo, 2005), other hypotheses including the establishment of modern ocean circulation and a decrease at global scale in atmospheric carbon dioxide (De Schepper et al., 2014; and references therein). Mediterranean biocalcarenite and sapropel clusters jointly appear in the same discrete time intervals, starting from c. 3.1 Ma (Roveri & Taviani, 2003). A possible model for biocalcarenite formation involves modification in the source-to-sink system, linking astronomic, climatic and marine ecosystem forcing in accordance with the most accredited genetic model for sapropel cycles (Fig. 7). At global and regional scale, astro-climatic changes and relative rainfall and vegetation changes in source areas are factors controlling sediment production, storage and output in a basin over short time scales ( $10^0 - 10^5$  years), whereas at the scale of an entire source-to-sink system, the evolution of catchment areas is considered the most important factor (Sømme et al., 2009).

Several authors have assumed the influence of a dry vs wet rhythm as an important sedimentation modulation factor, and the orbitally-driven climatic changes have been considered as the dominant forcing function for several Pliocene-Pleistocene carbonate-terrigenous successions of the Mediterranean area (Butler & Lickorish, 1997; Catalano et al., 1998; Roveri & Taviani, 2003; Massari

& Chiocci, 2006; Capozzi et al., 2006; Massari & D'Alessandro, 2012; Nalin et al., 2016; Dominici et al., 2020). In particular, the precession cycle controls the seasonal insolation contrast, but its impact depends on the degree of eccentricity of the orbit: at low-eccentricity the precession cycle has no impact, while at eccentricity maxima the precession has the maximum impact (Rohling, 2001). This condition has been clearly documented for deep marine sapropel sequences (Rohling et al., 2015). We suggest that this astronomical modulation can be also applied to shelfal settings, and particularly to the biocalcarenite-mudstone cyclicity.

Sapropels and biocalcarenites clusters occur in discrete time intervals and each of them corresponds to 400 ka eccentricity maxima (Roveri & Taviani, 2003). Mineralogical and temperature-interpretation data confirm that the mudstone dominated hemicycles of sapropel cycles are characterised by reduced riverine input and enhanced windblown sediment supply (Marino et al., 2009; Rohling et al., 2015). The biological and sedimentological aspects of the CAB biocalcarenite deposits appear better related to phases of sediment starvation occurring at insolation minima. On the shelf, phases characterised by the discontinuous activation of powerful bottom-currents, reworking coarse and skeletal sediments (winnowing), followed by low-energy conditions with higher silting and water turbidity, are the most evident sedimentologic and palaeontologic signals. The high diversity observed at the top of the major bodies (topset facies) and in minor cycles suggests lower hydrodynamic disturbance, oligotrophic and well-oxygenated bottom conditions and vegetated mats favoured by relative water clarity. During biocalcarenite formation, the fine grained sediments input enabled the formation of muddy environments and the related benthic fauna in deeper-water settings (Fig. 7). Conversely, wetter periods are characterised by mud deposition in shallow-water and sapropel deposition in deeper-water. We suggest that in the shallow-waters of the CAB, a phase of higher and more continuous fluvial discharge mainly carrying fine grained sediments favoured formation of offshore muddy environments and the related benthic fauna. The presence in some cases of low-diversity assemblages suggests the development of eutrophic and poor-oxygenated conditions (Fig. 7).

In the northern hemisphere, the cyclical change of palaeovegetation has allowed to recognise a climatic evolution from hot-humid interglacial stages to dry-cold glacial ones during the Pliocene-Pleistocene (Massari & D'Alessandro, 2012; and references therein). The analysis of carpological and pollen assemblages of northern Italian successions are in good agreement with the results obtained from isotopic data and suggests that temperature decrease is one of the causes of the disappearance from the plant fossil record of several species, in particular at the Zanclean/Piacenzian and Piacenzian/Gelasian transitions (Bertini, 2001; Fauquette & Bertini, 2008; Martinetto et al., 2018). The Gelasian carpological floras cannot be distinguished from those of the latest Piacenzian, due to the lack of data in the crucial time interval between 2.8 and 2.5 Ma. An affinity with Calabrian floras has been suggested (Martinetto et al., 2018).

The present model could be tested through a specific study of the palaeoflora along sapropel-biocalcarenite

intervals. In source area the vegetation cover is a key factor for soil erosion and relative sediment formation (Corenblit et al., 2007; Nunes et al., 2008, 2009; and references therein). Based on the framework deduced in the Mediterranean area, where climate changes and the relative responses of vegetation and soil erosion have been reconstructed (Corenblit et al., 2007; Nunes et al., 2009; and references therein), we suggest that during 100/400 ka eccentricity maxima, at the precession minima (insolation maxima), a thicker vegetation cover resulted in reduced soil erosion and in lowered sediment input to the basin with respect to the precession maxima (insolation minima) condition. This corresponds to times of the biocalcarenite formation. In agreement with currently available models (Corenblit et al., 2007), we suggest that at sapropel times the thicker vegetation cover enabled a higher input of mud. At insolation minima, instead, a relatively minor vegetation cover favoured greater soil erosion soil, causing the production and transport of coarser-grained sediments in the basin through episodes of catastrophic floods (see Mutti et al., 1996). Fluvial floods in arid regions cause stronger soil erosion and in temperate climates river incision mainly occurs during the arid seasons (Molnar et al., 2006), due to episodic storms (Renschler et al., 1999; Romero-Díaz et al., 1999; Renschler & Harbor, 2002; Nunes et al., 2008, 2009). The largest rainfall events do not necessarily produce in fact the maximum soil erosion (Romero-Díaz et al., 1999; González et al., 2004) and the erosive power of rainfall events is negligible when soils are well covered with vegetation (Marques et al., 2007). Numerous geomorphic observations from temperate regions suggest that rivers incise valleys and carry a higher amounts of coarse debris only during the largest, and hence rarest, floods (Molnar et al., 2006). Higher energy winnowing events further reduced the fine-terrigenous component of the coarse bioclastic seafloor.

## CONCLUSIONS

The present study on the diversity and palaeoecology of macrobenthic data collected in the biocalcarenitic successions of the Castell'Arquato Basin confirms known palaeobathymetric trends recognised at different time scales. Multivariate ordination analysis expands our knowledge of controlling factors, suggesting that bottom currents played an important role, merging with the signal dictated by depth-dependant factors. Eustatic variation, although contributing to the development of the observed cycles, does not seem to be the main forcing for the origin of the biocalcarenite-mudstone couplets, nor for the single biocalcarenitic architecture. The biocalcarenite assemblages and those of the mudstones show opposite palaeoecological significance, the first indicating low sedimentation rates and sediment winnowing, favouring biotically-driven taphonomic feedback through the gradual accumulation of skeletal remains, the second driven by higher sediment input and times of siltation of the seafloor. High energy hydrodynamic regime activated by bottom currents, oligotrophic and sediment-starved conditions in the basin suggest a genetic linkage between biocalcarenite formation at shelf depths and sapropel formation in deeper settings, both driven by orbital parameters. We propose

that these deposits occur in opposite hemicycles of the precessional curve, characterised by climate oscillations producing significant changes in the source-to-sink system. According to this model, sapropels and shallow-water mudstones formed during the warmer-wetter precession minima, while biocalcarenes and deep-water marls formed during the colder-drier precession maxima.

#### ACKNOWLEDGEMENTS

Thanks to Stefano Dominici (Museo di Storia Naturale, Università di Firenze) for his review and editorial handling. Ronald Nalin (Loma Linda University, California, USA) and an anonymous reviewer are acknowledged for their constructive comments and suggestions that improved an early version of the paper. We thank Alessandro Freschi, Gianluca Raineri (Riserva Geologica del Piacenziano e dello Stirone) and Carlo Francou (Museo Geopaleontologico "G. Cortesi", Castell'Arquato) for their assistance with sample collection. This is ISMAR CNR, Bologna, scientific contribution n. 1950.

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Manuscript received 15 November 2019  
 Revised manuscript accepted 14 March 2020  
 Published online 10 April 2020  
 Editor Stefano Dominici