

Pliocene-Pleistocene stratigraphic paleobiology at Altavilla Milicia (Palermo, Sicily): tectonic, climatic and eustatic forcing

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ABSTRACT - *The integration of sedimentary facies analysis, ichnology and benthic mollusc quantitative paleoecology allowed interpretation of factors that have controlled the deposition of the alluvial to marine succession outcropping in Northwestern Sicily (Southern Italy) at Altavilla Milicia, near Palermo (Imerese Basin). Two main marine units are recognised, labelled CNM and ALT, separated by an angular unconformity and formed by elementary depositional sequences (CNM1-4, ALT1-5). The succession was subdivided by means of calcareous nannoplankton biostratigraphy into upper Pliocene (Piacenzian: CNM1-4 and ALT1-4) and lower Pleistocene (Gelasian, ALT4-5), covering the onset of the Quaternary glaciation. The main asset of the succession is driven by tectonic compression and accommodation by transpressional faults, a regime that led to a change in the direction of fluvial sediment delivery, from axial (mid-Piacenzian: CNM), to transverse with respect to the basin elongation (upper Piacenzian-Gelasian: ALT). High-frequency eustatic changes drove the formation of elementary depositional sequences, the building blocks of CNM and ALT. During the late Piacenzian, a phase of gradual passage from the mid-Piacenzian warm period to the Quaternary glaciation, bioclastic production was still high, characterising the maximum flooding intervals of the two composite depositional sequences CNM and ALT. Mixed carbonate-siliciclastic lithosomes of both CNM and ALT show a good correlation with shallow marine shell-rich detrital carbonates of Northern and Southern Italy and with Mediterranean deep-water sapropel clusters, suggesting common climatic forcing. Some tropical species thought to disappear from the Mediterranean at around 3.0 Ma, including *Pecten bosniaskii*, *Macrochlamys latissima*, *Spondylus crassicosta*, *Lucina orbicularis*, *Isognomon maxillatus*, *Crassatina concentrica*, *Gastrana lacunosa*, *Callista italica*, *Circomphalus foliaceolamellosus* and *Persististrombus coronatus*, are present in the upper Piacenzian of Sicily (top of the MN16a Zone and the MN16b/17 Zone of calcareous nannofossil biostratigraphy). More data are needed to reconstruct the geographic dimension in the disappearance of the Mediterranean Pliocene macrobenthos with tropical affinities.*

INTRODUCTION

The Pliocene-Pleistocene siliciclastic succession exposed at the foothill of Altavilla Milicia has been studied since the mid-nineteenth century for the abundant remains of molluscs (e.g., Calcara, 1841; Aradas, 1846; Libassi, 1859; Seguenza, 1873-77; Cipolla, 1914; Ruggieri et al., 1959, 1967; Moroni & Paonita, 1964; Giannuzzi Savelli & Reina, 1984, 1988; Dell'Angelo et al., 2012), ostracods (D'Arpa & Ruggieri, 2004; and references therein) and foraminifers (Sprovieri, 1971). First attributed to the Zanclean-Piacenzian (Pliocene; Sprovieri, 1971; D'Arpa & Ruggieri, 2004), the 70 m-thick succession is now known to cover the Piacenzian-Gelasian (Pollina, 2012; Catalano et al., 2013: tab. III, p. 135), an interval of intense climate change, amplified oceanographic events and sea-level fluctuations at the onset of Northern Hemisphere glaciation. Neglected by recent reviews on the Quaternary of NW Sicily (Agate et al., 2017; Basilone, 2018), the Altavilla succession offers the possibility to integrate physical stratigraphy with paleobiological patterns (stratigraphic paleobiology: Patzkowsky & Holland, 2012; Dominici & Scarponi, 2020), understand what factors control the distribution of fossils and distinguish the relative role of tectonics, climate

and eustatism on deposition at a crucial time of Earth's history. The time interval covers in fact the cooling after the Mid-Piacenzian Warm Period (MPWP; De Schepper et al., 2014), with 100- to 400-kyr eccentricity maxima starting from 3.1 Ma being recorded in the Mediterranean by calcarenites and sapropel clusters (oxygen isotope stages 100-110; Lourens et al., 1996, 2004; see Roveri & Taviani, 2003), and the more intense cooling events of the Quaternary (isotope stages 96-100; Lisiecki & Raymo, 2005; Gibbard & Cohen, 2016), corresponding to three consecutive global bathymetric variations estimated to be around -70 m each (Naish, 1997; Miller et al., 2011). The Altavilla mixed carbonate-siliciclastic system is here interpreted by means of sedimentary facies analysis, ichnology, biostratigraphy, shell-bed taphonomy and quantitative paleoecology, outlining depositional patterns. Data available can be interpreted in terms of high-frequency climatic and eustatic forcing on deposition in the tectonically active setting of NW Sicily.

GEOLOGICAL SETTING

The study area represents the onshore portion of the WNW-ESE trending Imerese Basin, developing offshore

as a trough confined between the coast and a structural high at the shelf edge (Catalano et al., 2013). Below the surface, a complex chain of imbricated thrusts occurs. The basin belongs to the Maghrebian thrust belt, the most external of three structural elements that make up the collisional complex of Sicily and adjacent offshore areas (Fig. 1, inset). The orogenic belt developed from late Oligocene to Middle Pleistocene time as a south-vergent and clockwise-rotating thrust system (Oldow et al., 1990; Catalano et al., 2013). The fossiliferous gravelly-sandy deposits cropping out around Altavilla Milicia (Fig. 1), previously known as “Sabbie di Altavilla” Formation (Ruggieri et al., 1967) and ascribed to the latest Zanclean-Piacenzian (Sprovieri, 1971; D’Arpa & Ruggieri, 2004), are included in the “Marly-Arenaceous Formation of Belice” (BLC; Catalano et al., 2013; MAB; Martorana et al., 2014), a lithostratigraphic unit deposited during the Piacenzian-Gelasian (Basilone, 2018). At Altavilla, BLC rests unconformably over the Zanclean Trubi Formation and older bedrocks and is seismically characterised by internal stratigraphic concordance (Martorana et al., 2014). Two different lithofacies are recognised locally. In the basal portion, exposed at Cannamasca, about 1 km south of Altavilla Milicia (Fig. 1), fluvial conglomerates

and deltaic sediments pass upward to yellowish sandstones rich with marine macrofossils. In the upper portion, exposed on the right and left banks of the Milicia River valley (Costagrande and Altavilla sections), fossiliferous marine sandstones dominate the succession.

METHODS

We mapped sedimentary units, measured direction of stratal surfaces and thickness of the Altavilla succession at localities Cannamasca, Costagrande and at the rock cliff to the north-west of Altavilla Milicia (Fig. 1), collecting data on intervening sedimentary structures, ichnofossils and shell bed taphonomy (Fig. 2). Facies were described based on lithology, sedimentary structures, trace fossils, shell content and taphonomy, and each was referred to a specific depositional processes. Spatially and genetically related facies were grouped into associations and each association was linked to a depositional system. Whenever allowed by distinct facies associations or by the presence of diagnostic macrofossils, we determined paleoenvironmental conditions (Tab. 1). Facies associations were vertically and laterally stacked to form parasequences and elementary



Fig. 1 - (color online) Geological map of the Altavilla Milicia area, in NW Sicily, with structural setting in the inset, and position of the three sections described and sampled for this study. Two units are recognised in the Pliocene, bounded by angular unconformities. The lower Cannamasca unit (CNM) rests on Mesozoic carbonates and Cenozoic Flysch and dips towards the NNW. The upper Altavilla unit (ALT), including the limit Pliocene-Pleistocene, gently dips towards the ENE. Angular unconformities signal times of tectonic activity preceding their deposition.

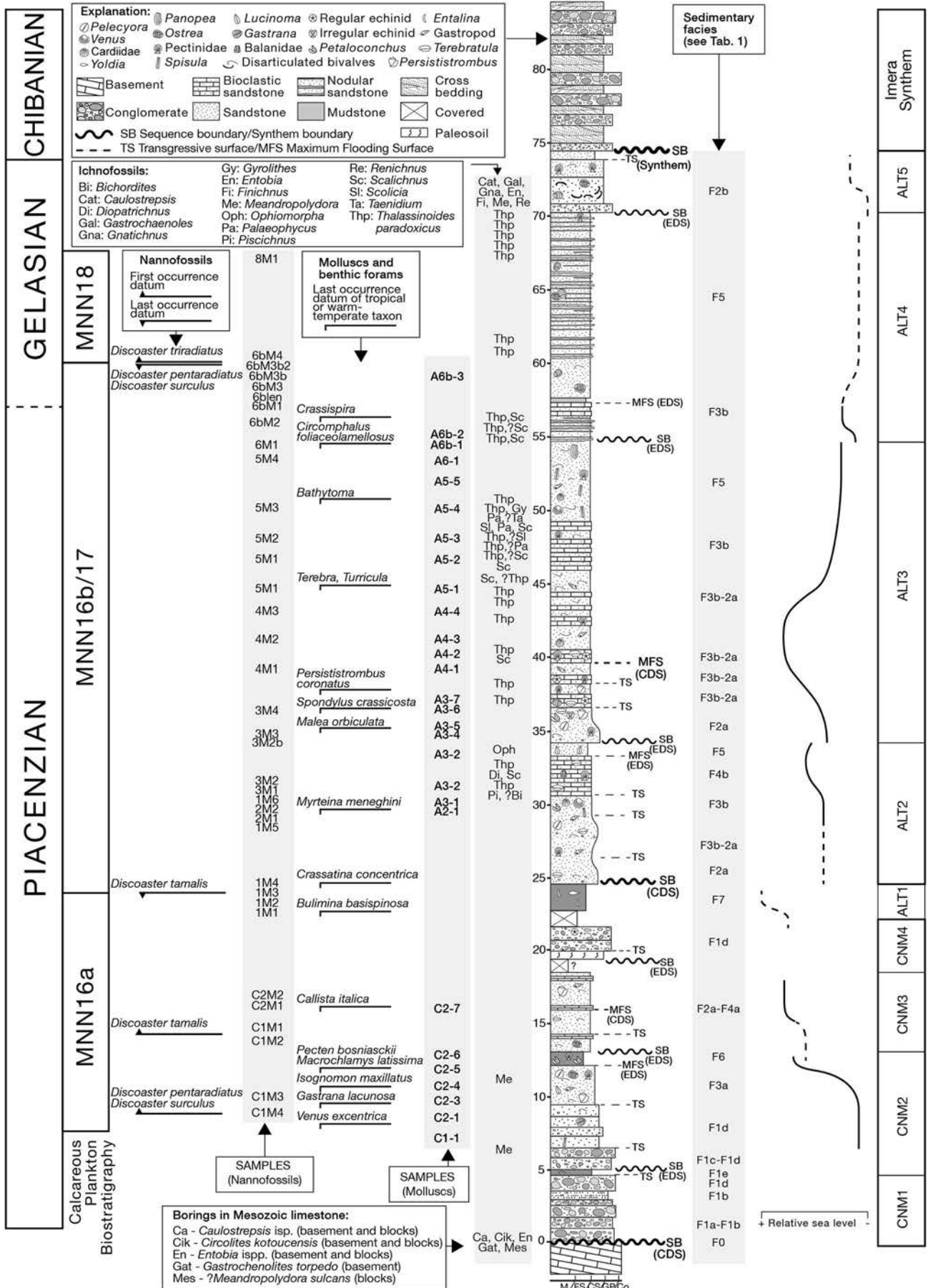
depositional sequences (EDSs, in the sense of Mutti et al., 1994), attesting to high-frequency variations of accommodation space and sediment supply. Each elementary sequence represents the building block of a composite depositional sequence (CDS; see conceptual framework in Mutti et al., 1994; Aldinucci et al., 2019). The recognition of parasequences and depositional sequences is based on intervening surfaces of sequence stratigraphic significance, namely the sequence boundary (SB), the transgressive surface (TS) and the maximum flooding surface (MFS; Fig. 2; see Mutti et al., 1994, for the significance of parasequences). These surfaces are recognised based on the stacking pattern of individual facies and on the interpretation of downlap and onlap stratal terminations studied along three transects (Figs 3-5), bearing in mind that some facies change can be the outcome of deltaic sedimentary processes of no sequence-stratigraphic significance. Two CDSs were recognised, the lowermost informally named Cannamasca unit (CNM), the uppermost Altavilla unit (ALT; Figs 2-5), separated by an angular unconformity (Fig. 1). Bulk samples for the study of calcareous nannofossils were collected at each section about every 2 m, perpendicularly with respect to bedding, some intervals being more densely sampled than others (0.25-1 m; Fig. 2). A similar spacing was adopted to study the macrofauna, resulting in a total of 29 bulk samples, nine from CNM, 20 from ALT (see Appendix, following the systematics and nomenclature proposed by WoRMS, 2019). We recognised 103 mollusc species and counted the number of specimens of each (complete fossils plus unique fragments, i.e., containing the apex, in the case of gastropods, or umbo for bivalves). After the exclusion of samples with abundances equal or smaller than 30 specimens and the exclusion of rare species occurring in only one sample, we built a database with 92 species of bivalves, gastropods, scaphopods and polyplacophorans distributed in 22 samples, for a total of 2868 specimens. Individual samples contained 34-348 specimens, with an average of 130 specimens per sample (see Appendix; stratigraphic position of samples shown in Fig. 2). To detect ecological gradients, we conducted a multivariate statistical analysis based on the Bray-Curtis similarity coefficient computed on square-transformed, percent abundance data (Patzkowsky & Holland, 2012). With the computer software package PRIMER 6 (Clarke & Warwick, 1994) we thus performed a Q-mode cluster analysis and, by grouping samples according to the results of the latter, an NMDS ordination.

SEDIMENTARY- AND ICHNOFACIES ANALYSIS

The three sections represent consecutive parts that we graphically merged into one composite log (Fig. 2). Piacenzian strata at Cannamasca and Costagrande dip 20-25° towards NNW, whereas upper Piacenzian and Gelasian strata of the Altavilla section dip 8-10° towards NE. An angular unconformity therefore separates the lower part of the succession (CNM) from the upper part (ALT). A second angular unconformity separates unit ALT from overlying sub-horizontal Middle Pleistocene deposits, which form a third unit, not considered here.

Unit CNM

At Cannamasca, unit CNM reaches a thickness of about 17 m, sedimentary strata onlapping Mesozoic limestones through a steep paleorelief (Fig. 3a-b). The basal surface is an irregular surface of marine abrasion marked on top of the hill by a suite of macroborings penetrating into the basement and developed on scattered blocks that lie on the erosional surface. The ichnoassociation includes *Entobia* spp., *Caulostrepsis* sp., *Circolites kotoucensis* Mikulaš, 1992, *Gastrochaenolithes torpedo* Kelly & Bromley, 1984 and *Maeandropolydora sulcans* Voigt, 1965 (Tab. 1; Fig. 4a-e) and is diagnostic of the *Entobia* ichnofacies, typical of the long-term bioerosion of lithified carbonates (Bromley & Asgaard, 1993). The overlying CNM succession was deposited in continental and shallow marine settings during at least three relative fluctuations of sea level, as testified by intervening erosive bounding surfaces and facies allowing for a subdivision into EDSs named CNM1-3. The lower part of CNM1 is characterised by sheet conglomerates and sandstones (Tab. 1: facies F1a-1c; Figs 3b-c, 5a), recording the development of an alluvial system. This could have been a *fiumara*-like river, characterised by wide and shallow channels, or an alluvial fan. Relationship with the bedrock and bed attitude indicate that CNM1 alluvial systems prograded from SSE towards NNW. In a lateral outcrop, a poorly-exposed mudstone with sparse brackish-water bivalves (F1e in Fig. 3c; Tab. 1) rests on top of the alluvial deposits, forming the CNM1 transgressive systems tract. CNM1 is overlain through an erosional contact by basal CNM2 conglomerates from a new phase of alluvial progradation (F1c-1d). A second transgressive trend is recorded by the presence of scattered marine shell fragments and *Maeandropolydora* on isolated pebbles, bioeroded after being reworked from older marine deposits (F1d) and associated with CNM2 fluvial conglomerates, passing upward to shallow marine deposits, represented by a mollusc-rich cemented and bioturbated sandstone (F3a), with several species of tropical affinity (Tab. 1; Fig. 2), overlain by a muddy sandstone with a *Petalococonchus* bioherm (F6; Fig. 5b). The overall depositional setting is interpreted as a subtidal environment in which sandy supply (F2a, F3a) was delivered by rivers as occurring in flood-dominated delta fronts through hyperpycnal flows (in the sense of Mutti et al., 1996, 2000). The CNM2 succession defines a deepening-upward trend, from starved delta front to prodelta or inner shelf paleoenvironment. CNM2 is separated from CNM3 by an erosional surface (Fig. 3b). CNM3 is formed by rather monotonous sandstone bodies (F2a, F4a). The overall depositional setting is interpreted as a delta front (F2a) punctuated by episodes of sediment starvation, bottom cementation and occasional storm events (F4a). The uppermost portion of the section is poorly exposed, but the slope morphology suggests that CNM is angularly overlain by ALT, as observed at Costagrande (Figs 1, 5c). The CNM1-CN2 transition testifies to an increase in accommodation space and the progressive establishment of fully marine conditions, followed by a period of deltaic sedimentation keeping pace with accommodation. The angular unconformity that separates CNM from overlying ALT deposits suggests that an important tectonic event took place, uplifting the



bedrock and leading to the progressive deformation of the Pliocene succession visible at Costagrande (Fig. 1). Here partially exposed CNM deposits are characterised by graded beds of sub-angular/sub-rounded conglomerates in abundant sandy/silty matrix, passing upward to reddish pebbly sandstone (Fig. 5d). Dispersed bioclasts (rodoliths, echinids, *Ostrea*, *Spondylus*) in facies F1d are ascribed to a torrential stream fed from SSE by the dismantling of arenaceous-calcareous bedrock, colonised by hard-substrate invertebrate communities during periods of relatively high sea level and sediment starvation. Geometric relationships allow to refer these sediments to a fourth subunit, named CNM4 (Fig. 5c). Reworked fossils, the occurrence of diffuse weathering and intervening paleosols (Fig. 5d), not observed at Cannamasca, suggest that this part of CNM4 developed in a more proximal setting with respect to CNM3. Due to cover, the passage CNM3-CNM4 cannot be observed, nor the thickness of intervening sediments can be measured (Fig. 2).

Unit ALT

Sedimentary facies of the Altavilla section (Fig. 1), the thickest part of the Altavilla Milicia succession, are stacked to form five subunits (Fig. 2) separated by unconformities in the lowermost and uppermost part, but showing conformable relationships and very subtle facies change in the middle part. In the lack of marked facies contrast, a sequence boundary is recognised through onlap relationships of ALT4 on ALT3 strata. ALT 3 maximum flooding surface (MFS) is marked by a surface of downlap (Fig. 6a-b). The lowermost element of the ALT succession is a 2 m-thick massive muddy fine-grained sandstone with the scaphopod *Entalina tetragona* (Brocchi, 1814) and a micropaleontological association indicative of open marine, possibly outer shelf conditions (Dell'Angelo et al., 2012; Pollina, 2012; facies F7 in Tab. 1). Its relationship with underlying CNM4 conglomerates and sandstones outcropping at Costagrande cannot be ascertained because of cover. This element is interpreted as part of a subunit intermediate between CNM and ALT, which we subjectively assign to the overlying composite depositional sequence (ALT1). ALT2 rests on ALT1 through a covered contact that separates outer shelf sediments below, from delta front sediments above (F2a; Fig. 6b). EDSs ALT2-5 attest to the development of a deltaic system fed from SW and prograding toward the Imerese Gulf to NE. The lower part of ALT2 is characterised by a parasequence formed by a shoreface paleoenvironment (F3b) passing upward to delta front sandstone (F2a). The presence of fine gravels suggests that F3b sediments originated in a delta-front setting. Similarly to sediments of facies F3a, subsequent bioturbation in a shoreface marine environment erased all primary sedimentary structures. A new occurrence of F3b with *Petalocochnus glomeratus*

(Linnaeus, 1758) and *Venus nux* Gmelin, 1791 passes upward to a F4b partially-cemented sandstone (Fig. 7a), with a characteristic ichnoassociation of the *Cruziana* ichnofacies, including *?Thalassinoides paradoxicus* (Woodward, 1830), *Piscichnus* isp., *Bichordites* isp., *Diopatrachus* isp. and *Scalichnus* isp., the latter around large individuals of *Panopea* in life position (Fig. 7b). The presence of *Bichordites*, which is an echinoid pascichnial burrow, points to an environment with normal salinity. This backstepping parasequence set is topped by a lower shoreface sandstone with rare *Ophiomorpha* isp. and common *Lucinoma borealis* (Linnaeus, 1767) in life position (F5; Fig. 7a, c-d), which suggest a stabilisation of the sea floor and the presence of sulphide to sustain a pollution of the chemosymbiotic bivalve. Facies F3b and F4b represent times of sediment condensation during pulses of transgression, whereas the passage to F5 attests to the MFS above which coastal systems prograde during sea-level still stand. A conformable surface separates highstand bioturbated shoreface deposits of ALT2 from overlying EDS ALT3 (Fig. 7a). Above the boundary is a fossiliferous sandstone with sparse fine gravels and a 5 m-thick succession of massive calcareous sandstone, with a rich shoreface fauna (regular and irregular echinoderms, brachiopods, oysters and scallops; Fig. 7g-h) and isolated specimens of the trace fossil *?Thalassinoides paradoxicus* (Fig. 7c). These deposits are interpreted as a distal delta front (F2a) overlain by cemented strata (F3b) with a more diversified ichnoassociation of the *Cruziana* ichnofacies (*?Thalassinoides paradoxicus*, *Scalichnus* isp., *?Palaeophycus* isp., *?Scolicia* isp., *?Taenidium* isp.: Fig. 7f), testifying to lowered sedimentation rates in a lower shoreface environment. Shoreface sandstone with abundant *Spisula subtruncata* (da Costa, 1778), *Venus nux*, cardiid bivalves and occasional *Panopea* in life position, accompanied by *Scalichnus* isp. (F5), marks new progradation. Cementation and high bioclastic content in ALT3 indicate times of non-deposition during transgressive pulses. The presence of facies F2a marks higher sediment input and progradation. The MFS is tentatively placed at the passage from retrogradational to progradational stacking pattern of parasequences. The uppermost part of the progradational parasequence set is formed by a lower shoreface sandstone with monospecific *?Thalassinoides paradoxicus* (F5). The highest diversity of trace fossils is encountered at 46-50 m (F3b; Fig. 2), above the MFS thus placed. A conformable surface separates ALT3 and ALT4, with a massive fine-grained sandstone below (F5) and a nodular sandstone above. The latter is about 2 m-thick and with a richer content in carbonates in the upper part (F3b), overlain by a few decimeters of muddy sandstone. Above the fine-grained interbed, a 12 m-thick succession of thinly-bedded cemented sandstone occurs; it alternates with loose sandstone containing articulated specimens of *Ostrea edulis* Linnaeus, 1758 and *?Thalassinoides paradoxicus*. Lower ichnodiversity

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Fig. 2 - Composite sedimentary log of the study area, with a synthesis of the paleontological content of each stratigraphic unit. The lower 16 m are based on the Cannamasca outcrop, the uppermost 65 m on the Costagrande and Altavilla sections (see locations in Fig. 1). Calcareous nannoplankton biostratigraphy is based on calcareous nannofossils. Allostratigraphic units are indicated; EDS = elementary depositional sequence; CDS = composite depositional sequence. Facies labels are as in Tab. 1. Curves in the penultimate column on the right are intended as visuals of trends of relative sea-level change, prompted from the quantitative estimates based on a few diagnostic and abundant species (see text for explanation).

Facies	Description	Trace fossils	Body fossils	Interpretation of sedimentary process
F0	Surface of erosion on Mesozoic limestone.			Lithified substratum long exposed to waver erosion and bioerosion from a rock-dwelling fauna, in a supratidal and intertidal setting.
F1a	Pebble/cobble sized conglomerate in meter-thick tabular beds. Clast are rounded, clast-supported with abundant sandy-silty matrix. Elongated pebbles are parallel to bedding. Occasional conglomerate-sandstone bipartition.			Poorly-confined sediment-laden flows expanding in a broad fluvial channels or on a alluvial-fan surface which undergone hyperconcentration of bedload.
F1b	Horizontal planar laminated coarse-medium sandstone with floating pebbles.			Process/environment similar to Fa1 (more diluted flows).
F1c	Cobble-dominated conglomerate in meter-thick tabular beds with abundant sandy-silty matrix.			Poorly-confined subaerial hyperconcentrated flow expanding in a broad fluvial channel or on an alluvial-fan surface.
F1d	Pebble-dominated conglomerate in graded dm-m thick beds. Clasts are sub-angular to sub-rounded in abundant sandy-silty matrix. Scanty shell fragments.		<i>Gastrana fragilis</i> (Linnaeus, 1758); <i>Loripes orbiculatus</i> Poli, 1795 (CNM2); rodoliths; regular echinoids; ostreids; <i>Spondylus crassicaosta</i> (Lamarck, 1819) (CNM4).	Confined subaerial hyperconcentrated flow. Occasional shells are reworked from pre-existing marine and brackish water deposits.
F1e	Massive shelly mudstone [poorly exposed].		<i>Cerastoderma edule</i> (Linnaeus, 1758).	Brackish water, low-energy coastal environment.
F2a	Silty fine-grained sandstone with rare dispersed pebbles, in dm- or m-thick amalgamated tabular beds showing internal normal grading. Dispersed shell debris sometimes abundant, with occasional articulate bivalves not in life position. Presence of oxidised vegetal material and occasional burrowing. Occasional hummocky cross-stratification.		<i>Spondylus crassicaosta</i> ; <i>Callista italica</i> (Defrance, 1818); <i>Persististrombus coronatus</i> (Defrance, 1827).	Delta-front density currents characterised by a combined unidirectional-oscillatory structure of the flow; molluscs reworked from shallow water marine settings.

Tab. 1 - Sedimentary facies at Cannamasca, Costagrande and Altavilla Milicia.

Facies	Description	Trace fossils	Body fossils	Interpretation of sedimentary process
F2b	Massive crudely bedded pebbly sandstone rich in bioclasts. Pebbles are well rounded. Bioclasts are both dispersed and oriented parallel to the bedding.		Ostreids; pectinids; bryozoans; <i>Ditrupa</i> sp.	Delta-front high-density currents, seafloor subsequently partially bioturbated in a marine environment.
F3a	Bioclastic, locally cemented sandstone in meter-thick massive beds with scattered pebbles and abundant shell remains, frequently articulated and occasionally in life position.	<i>Meandropolydora</i> isp. (CNM); ? <i>Thalassinoides paradoxicus</i> ; <i>Bicordites</i> isp.; <i>Piscichnus</i> isp.; <i>Diopatrchnus</i> isp.; <i>Scalichnus</i> isp.; <i>Paleophycus</i> isp. (ALT2).	<i>Clypeaster pliocenicus</i> (Seguenza, 1879); <i>Persististrombus coronatus</i> ; <i>Panopea</i> sp.; <i>Gastrana lacunosa</i> ; <i>Isognomon maxillatus</i> (CNM); Spatangoids; <i>Ditrupa</i> sp.; <i>Balanus</i> sp.; <i>Pecten flabelliformis</i> (Brocchi, 1814); <i>Terebratula ampulla</i> Brocchi, 1814; <i>Malea orbiculata</i> (Brocchi, 1814); <i>Petalococonchus glomeratus</i> (Linnaeus, 1758); <i>Pelecycora islandicoides</i> (Lamarck, 1818) (ALT2).	Delta-front or shoreface deposit originally accumulated by density currents as for F2, subsequently bioturbated in a shoreface environment.
F3b	Bioclastic cemented sandstone in meter-thick massive beds with sparse fine gravels and abundant shell remains, frequently articulated and occasionally in life position.	<i>Scalichnus</i> isp.; ? <i>Thalassinoides paradoxidus</i> (ALT2); <i>Scalichnus</i> isp.; <i>Paleophycus</i> isp.; <i>Gyrolithes</i> isp.; ? <i>Thalassinoides paradoxidus</i> (ALT3).	Regular echinoids; <i>Ditrupa</i> sp.; ostreids; <i>Persististrombus coronatus</i> ; <i>Pecten jacobaeus</i> Linnaeus, 1758; <i>Aequipecten</i> spp.; <i>Mimachlamys varia</i> (Poli, 1795); <i>Spondylus crassicauda</i> ; <i>Terebratula ampulla</i> .	Delta-front or shoreface; originally accumulated by density currents as for F1, these deposits record exposure of the sea bottom under sediment starvation and winnowing, favouring bioturbation and increasing the bioclastic component.
F4a	Graded yellowish fine-, medium-grained calcarenite with hummocky cross lamination.			Subaqueous density-stratified flows under oscillatory currents.
F4b	Massive/bioturbated calcarenite-calcisiltite.			Starved shelf.
F5	Massive whitish or yellowish well-sorted fine-grained sandstone with scattered pebbles and articulated bivalves in life position.	<i>Ophiomorpha</i> isp. (ALT2); <i>Scalichnus</i> isp.; ? <i>Scolicia</i> isp.; ? <i>Thalassinoides paradoxidus</i> (ALT3).	<i>Lucinoma borealis</i> (ALT2); <i>Spisula subtruncata</i> ; <i>Azorinus chamasolen</i> (da Costa, 1778); <i>Panopea</i> sp.; cardiids; tellinids; venerids (ALT3).	Lower shoreface (wave winnowing obliterated by bioturbation).
F6	Massive greysh silty sandstone with <i>Petalococonchus</i> bioherms.		<i>Petalococonchus glomeratus</i> ; <i>Pecten bosniasckii</i> De Stefani & Pantanelli, 1878; <i>Macrochlamys latissima</i> (Sacco, 1897).	Prodelta, inner shelf.
F7	Muddy fine-grained sandstone.		<i>Entalina tetragona</i> ; <i>Yoldia</i> sp.	Outer shelf.

Tab. 1 - Continuation.



Fig. 3 - (color online) CNM sedimentary geometries and facies at Cannamasca section (see Fig. 1 for location). a) General view of the Cannamasca section, the red line indicating the bioeroded paleocliff on which inlays the Pliocene; the label SNM refers to the outcrop shown in b). b) Main outcrop of the Cannamasca section on which is based the interpretation in c). c) CNM sedimentary facies in the Cannamasca section described in Tab. 1. Erosional contacts between facies marked by an undulating thick line define the boundaries of three elementary depositional sequences (EDSs). Stratal surfaces, marked by thin red lines, show only against the Mesozoic substrate. Dashed lines indicate small faults. White arrow points to human figure for scale.

suggests a more unstable environment, possibly due to shallower depths with respect to underlying sediments or to lowered salinity under increased deltaic influence, thence showing a regressive trend with respect to ALT3. An erosional surface and a sharp facies change separates elementary sequence ALT4 from overlying ALT5, about 10 m-thick and formed in the lower part by delta front gravelly sandstone chaotically mixed with disarticulated, bioeroded and encrusted oysters (F2b; Fig. 8). The

ichnoassociation associated with the carbonate oyster substratum is extremely rich, including domichnial *Entobia* spp., *Maeandropolydora* spp., *Caulostrepsis taeniola* Clarke, 1908 and *Gastrochaenolites lapidicus* Kelly & Bromley, 1984 bored in the shells, *Renichnus arcuatus* Mayoral, 1987 and *Finichnus* isp. left by encrusters (fixichnia) and *Gnaticnus pentax* Bromley, 1975, a feeding trace left by herbivore echinoderms (pascichnia; Fig. 4f-h; David et al., 2017). The trace

fossil suite associated with the coarse-grained matrix includes *Thalassinoides paradoxicus*. The lower part of ALT5 is topped by a massive sandstone with scattered pectinid shells, showing a fining- and deepening-upward trend (Fig. 2). This subunit is interrupted by an angular unconformity preceding the deposition of the Imera synthem after a tectonic phase (Basilone, 2018; Fig. 1).

ALLOSTRATIGRAPHY

Conglomerates and shelly sandstones of the Monte Belice Formation outcropping to the west of Altavilla Milicia are subdivided into distinct unconformity-bounded stratigraphic units (UBSU in the sense of Mutti et al., 1996) and subunits (Fig. 2), hierarchically organised based on unconformities and facies transitions of different rank (see methods). Unit CNM shows stratal terminations that onlap Mesozoic limestones at Cannamasca and Oligo-Miocene Numidian Flysch at Costagrande (Figs 1, 3, 5; Catalano et al., 2013; Martorana et al., 2014). CNM is formed by four EDSs (CNM1-4), stacked to form a composite depositional sequence, showing an overall transgressive trend in the lower part (CNM1-3), regressive in the upper (CNM3-4). An angular unconformity separates CNM from unit ALT. ALT is formed by at least four EDSs (ALT2-ALT5). Outer shelf mudstones, the only outcropping part of the lowermost EDS (ALT1), are the deepest deposits of the studied succession, overlying alluvial-coastal deposits (CNM4, the contact is not visible), and underlying delta front deposits (ALT2) without visible intervening facies. This suggests that the angular unconformity separating CNM from ALT coincides with an interval of subaerial erosion and that a significant part of the record is missing, and erosion possibly renewed after the deposition of ALT1. EDSs ALT2-ALT5 are stacked to form a composite depositional sequence, with an overall transgressive trend in its lower part (ALT2-3) and a regressive trend in the upper (ALT3-5; Fig. 2). The stacking pattern of CNM and ALT is markedly different: CNM is formed by asymmetrical EDSs, each missing regressive deposits possibly due to their subsequent erosion, whereas ALT is much thicker, richer with carbonates, and formed by a symmetrical EDS in its middle part (ALT3), regressive deposits being well represented (ALT3). The overall succession is deepening-upward in the lower part (0-25 m in Fig. 2), richer with carbonates in the middle part (30-50 m), shallowing upward in the upper part (60-75 m).

BIOSTRATIGRAPHY

The association of calcareous nannofossils found in 35 samples (Fig. 2) was generally sparse and poorly preserved, but the recognition of *Discoaster* events (mainly last appearance data, LADs; Pollina, 2012) allowed to frame the Altavilla succession in the biostratigraphic scheme devised for the Mediterranean (Rio et al., 1990). *Discoaster tamalis* Kamptner, 1967 was found in CNM2-3 at Cannamasca and ALT1 at the lowermost part of the Altavilla section, whereas it is absent in ALT2-4. Its LAD defines the upper boundary

of zone MNN16a (Piacenzian, c. 3.5-2.7 Ma; Rio et al., 1990), occurring immediately below the ALT1-ALT2 boundary. Since the latter coincides with an erosional unconformity, then the upper part of MNN16a is probably missing. The LAD of *Discoaster pentaradiatus* Tan, 1927 and *Discoaster surculus* Martini & Bramlette, 1963, 38 m from the base of the Altavilla section (Fig. 2), marks the upper boundary of the MNN16b/17 Zone (late Piacenzian-early Gelasian, c. 2.7-2.4 Ma). This boundary coincides with the first appearance datum (FAD) of *Discoaster triradiatus* Tan, 1927, a species found in ALT4. The association *Discoaster brouweri* Tan, 1927 and *D. triradiatus* and the contemporaneous absence of *D. surculus* and *D. pentaradiatus* defines the MNN18 Zone (middle-late Gelasian, c. 2.4-1.9 Ma). No biostratigraphic data are available for the uppermost part of ALT (upper part of ALT4 and ALT5; Fig. 2; Pollina, 2012). Overlying conglomerates and cross-bedded sandstones (Fig. 2) can be tentatively ascribed to the Middle Pleistocene (Chibanian) based on correlation with nearby outcrops (Garilli, 2011). This unit is referred to as “Imera synthem” in recent literature (Incarbona et al., 2016; Agate et al., 2017; Basilone, 2018).

QUANTITATIVE MOLLUSCAN PALEOBIOLOGY

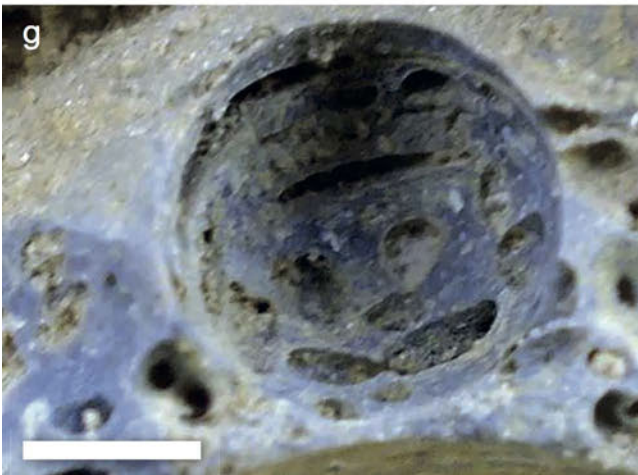
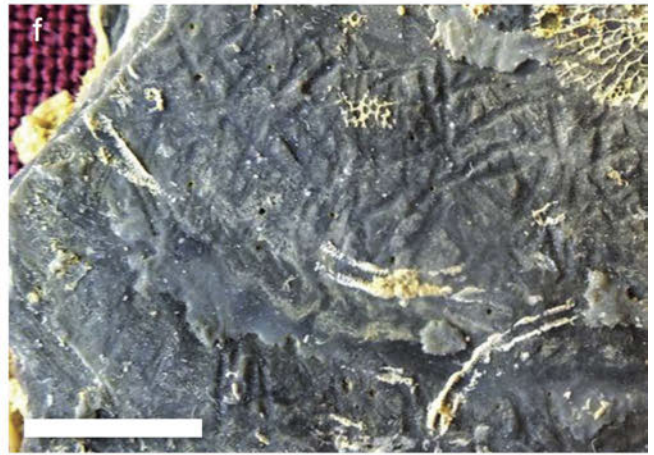
Q-mode cluster analysis highlighted three main groups, two clusters including all CNM samples (CNM2-3), with one exception, and the third cluster comprising all ALT (ALT2-4) samples. Within the latter, samples can be further grouped at higher levels of similarity (Fig. 9). Position along the main axis of the ordination (Fig. 10), mainly controlled by bathymetry (Scarponi & Kowalewski, 2004; Patzkowsky & Holland, 2012), allowed to use fossil assemblages as proxies of sea-level variation. At one end of the continuum we have a very-shallow water assemblage dominated by the bivalve *Loripes orbiculatus* (= *Loripes lucinalis* [Lamarck, 1818], *Loripes lacteus* [Linnaeus, 1758]), a fully marine infaunal species presently living in organic-rich seagrass bottoms, where it feeds on symbiotic bacteria (Taylor et al., 2016) at an average depth of 11 m (calculated on 108 observations; Dominici et al., 2018). This biofacies includes very small-sized gastropods typically dwelling in seaweeds (*Bittium*, *Alvania*, *Tricolia*). Very shallow-water associations of small-sized lucinids and small herbivores of similar significance are known from the Miocene (Dominici et al., 2019) and the Piacenzian of Tuscany (Benvenuti & Dominici, 1992; Dominici et al., 2018). Opposite in the continuum is an offshore assemblage dominated by the opportunistic suspension-feeding bivalve *Corbula gibba* Olivi, 1792 and the extinct cemented epifaunal gastropod *Petalococonchus glomeratus*. *Corbula gibba* is a hypoxia-tolerant subtidal species (Dominici, 2001; Fuksi et al., 2018; Cau et al., 2020), presently living on average at a depth of 26 m (based on 2973 observations; Dominici et al., 2018), but with a very skewed distribution, ranging from very shallow (e.g., Benvenuti & Dominici, 1992) to epibathyal water depths (Pèrès & Picard, 1964). *Petalococonchus* bioconstructions are known in the Mediterranean from the late Miocene

to the Holocene, also at a wide paleobathymetric range, from the upper subtidal to 30-50 m (Vescogni et al., 2008). Given the association with a mudstone matrix and with *Anomia ephippium* Linnaeus, 1758, a byssate epifaunal bivalve living at an average depth of 55 m (based on 225 observations; Dominici et al., 2018), it is suggested that the Cannamasca bioherm formed at the deepest part of the continuum. An analogous *Corbula-Anomia* association found in Piacenzian biocalcarenes of Northwestern Italy suggests shelf bottoms subject to periodic winnowing/high sedimentation rates (Cau et al., 2018, 2020). Both the shallowest and the deepest assemblages analysed are thus from the Piacenzian composite sequence CNM (Fig. 10; consider however that facies F7, with an open shelf marine assemblage, was not considered in the quantitative analysis due to its scarce macrofaunal content). To better characterise the gradient at intermediate depths, we excluded CNM samples and analysed the distribution of 89 species in 17 ALT collections (Piacenzian-lowermost Gelasian; Fig. 11). The shallowest assemblage is dominated by shoreface species, such as Tellinidae, *Spisula subtruncata* (the latter living on average at 13 m, calculated on 1981 observations; Dominici et al., 2018) and *Timoclea ovata* Pennant, 1777, and the deepest by muddy bottom, offshore transition species, such as *Venus nux*, the extinct gastropod *Tritia semistriata* (Risso, 1826), deposit-feeding bivalves *Yoldia* cf. *Y. nitida* (Brocchi, 1814) and *Saccella commutata* (Philippi, 1844) (average living depth of 67 m, calculated only on 36 observations) and the byssate, open marine *Anomia ephippium*. This biofacies continuum, from a shallow marine *Spisula subtruncata-Timoclea ovata* association to a deeper water *Tritia semistriata-Saccella commutata* set of species, passing through an *Anomia ephippium-Aequipecten opercularis* (Linnaeus, 1758) biofacies, closely parallels analogous mollusc associations analysed in Piacenzian shell-rich lithosome of Western Emilia, with analogous interpretations (Cau et al., 2018, 2020). The plot of estimated paleodepths along the Altavilla section (Fig. 2) highlights a deepening-upward trend from samples A2-1 to A3-2, within ALT2, and a second deepening from A3-4 to A4-3 within ALT3, the latter samples recording the interval of maximum flooding of the composite sequence. A progressive shallowing up ensues, until reaching A6b-2 (ALT4), the shallowest of all among ALT samples (Fig. 11). As for ALT2-4 sedimentary facies, estimates of paleobathymetry in the middle part of the ALT unit do not show sharp changes. These estimates, however, suggest cyclic variation consistent with high-frequency eustatic control on deposition. Another possibility is that the position of samples in the upper right of the NMDS ordination is controlled by lowered salinity. *Spisula subtruncata* is in fact known to tolerate salinity down to 7-8 per mil in estuarine settings (Wolff, 1973). The monospecific *Ostrea edulis* mollusc shell bed encountered in ALT5 could also attest to low salinities (see Gosling, 2015).

DISCUSSION

Sedimentary facies analysis, ichnology and shell-bed taphonomy allowed to reconstruct along an ideal inshore-offshore profile which genetic processes were responsible for the succession outcropping at Cannamasca, Costagrande and Altavilla. In the lower portion of Cannamasca section, textural and bedding features of the conglomerates (F1a-F1d; Tab. 1) suggest rapid deposition in subaerial heavily-charged, poorly confined flows, an hypothesis preferred to gravel reworking from wave or tide currents. This interpretation is consistent with a flood-dominated fluvio-deltaic system and with high topographic gradients of sediment source areas, such as those of modern topography. These conditioned rivers with relatively short and high-gradient transfer zones ("dirty mountainous rivers" in the sense of Milliman & Syvitski, 1992; Mulder & Syvitski, 1996; Mutti et al., 2003), particularly at times of high seasonality, when seasons of high river discharge alternates with dry seasons and times of low-base flow (see extreme examples in Plink-Björklund, 2015). Similar systems were recognised in contemporaneous succession of Northwestern Italy (Dominici, 2001; Pervesler et al., 2011; Crippa et al., 2018). The subaerial portion of the depositional system was characterised by poorly-confined sediment-laden flows expanding in broad fluvial channels and undergoing hyperconcentration of bedload. Hyperpynal flows triggered by major floods transported fine gravels and sand from delta mouths to the shelf. Due to sediment winnowing by marine currents and sediment reworking by the infauna, little or no traces were left of primary sedimentary structures typical of flood-generated delta-front sandstone lobes as described in the literature of ancient foreland basins (e.g., Mutti et al., 2003). On the other hand, sediment winnowing favoured the gradual addition of bioclastic carbonate component derived from the local shelly fauna, accompanied by bioturbation and eventual cementation of the sandy bottom at lower shoreface or inner shelf depths. At other times, hypopycnal flows carried mud to the shelf, leading to the gradual deposition of minor mudstone units. Origin from occasional resuspension processes related to storm events cannot be excluded. In theory, cyclic sedimentation within the Piacenzian-Gelasian Altavilla depositional system could result from simple climatic forcing through the alternation of dry and wet conditions, the first favouring episodic sediment transfer through a *fumara*-like fluvial channels and high-density flows at river mouths, the second favouring vegetation cover inland and thus limiting sediment transport to fines in a less-episodic fluvial regime. Relatively good bioturbation and high bioclastic content of the deposits suggest that the rate of deposition was generally lower than in other deltas. The presence of *Bichordites* and *Scolicia*, which are echinoid burrows that suggest normal salinity, marks the part of

Fig. 4 - (color online) CNM and ALT trace fossils in hard substrata. a-b) Borings in the basement limestones at Cannamasca: *Circolites kotoucensis* (a) and *Gastrochaenolites torpedo* (b). c-e) Borings in blocks and shelly substrata at the base of CNM at Cannamasca: *Entobia* ispp. (c), *Maeandropolydora* ispp. (d) and *Maeandropolydora* cf. *sulcans* on an oyster shell (e). f-h) Borings in shelly substrata of EDS ALT5 at Altavilla: *Gnatichnus pentax* (f), with encrusting serpulids and bryozoans, *Gastrochaenolites lapidicus* (g) and *Renichnus arcuatus* and *Entobia* ispp. (h). Scale bar in f-h = 1 cm.



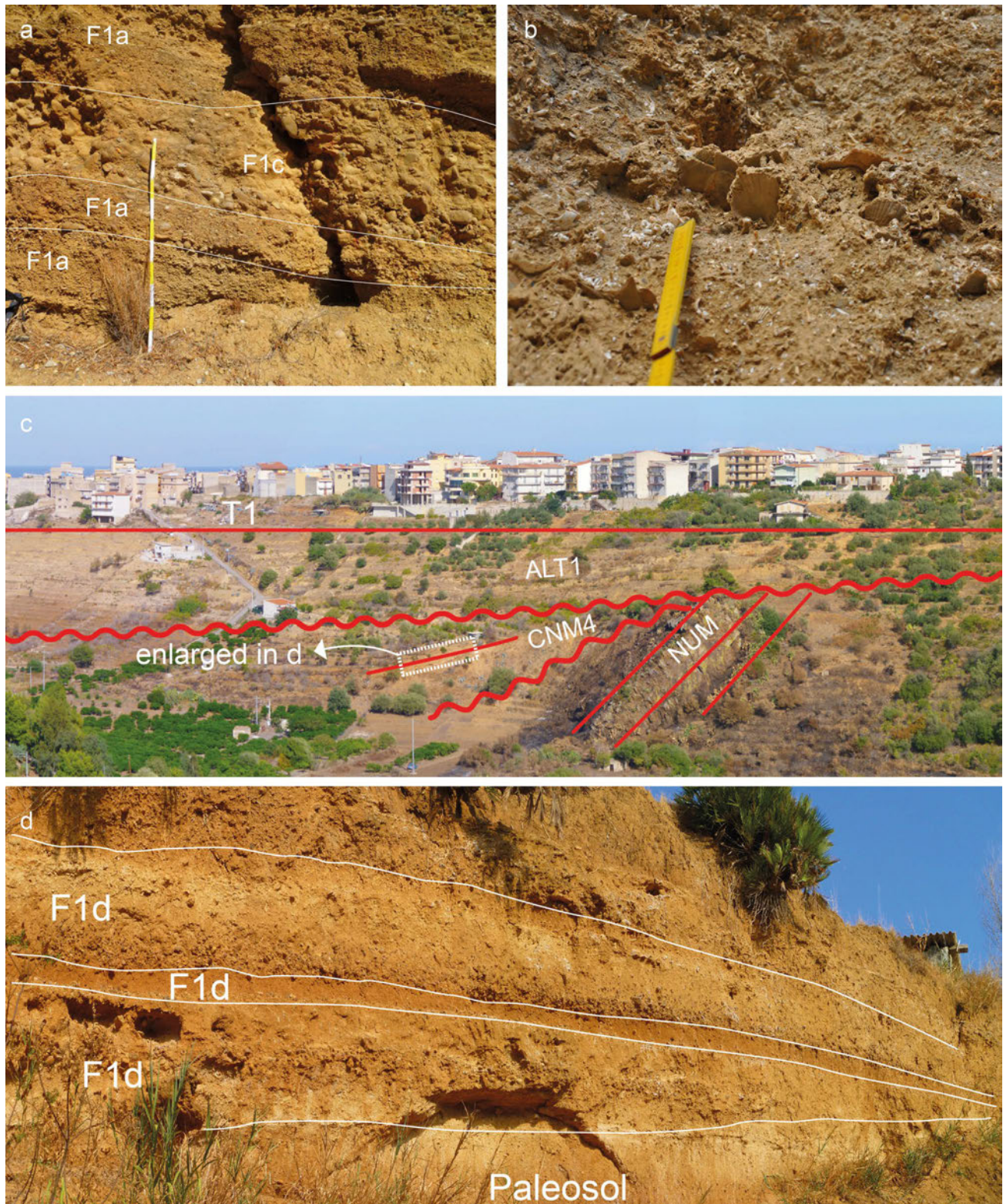


Fig. 5 - (color online) Sedimentary facies and stratal geometries of CNM. a) Detail of pebble- and cobble-dominated conglomerates in the lower portion of CNM1 at Cannamasca. b) Shells of *Petalochoncus glomeratus* and *Pecten flabelliformis* in marine mudstones of CNM2 at Cannamasca. c) Landscape view of two angular unconformities at Costagrande (see Fig. 1 for location), one separating CNM4 from the Numidian Fm. (NUM), one separating ALT from CNM4 (sequence boundaries marked by undulating red line). d) Detail of CNM4 fluvial conglomerates with reworked marine fossils, lying on top of a paleosol.

the succession where fluvial influence decreases. The quantitative analysis of shell beds suggests that high-frequency eustatic fluctuations accompanied climatic

cycles consistently with the sequence-stratigraphic interpretation based on independent characters (Fig. 2). The succession developed in a phase of tectonic activity



Fig. 6 - (color online) Stratigraphic cross section of the Altavilla unit at Altavilla (See Fig. 1 for location). a) Panoramic view of the section. b) Interpretation of sedimentary patterns, showing onlap and downlap geometries (thin red lines), sequence boundaries (ondulating lines) and surfaces of maximum flooding of individual EDSs (dashed lines); the Altavilla composite section (uppermost 65 m of the log in Fig. 2) was based on five logs measured and described along this outcrop.

following regional compression and rotation (Oldow et al., 1990; Catalano et al., 1995) and the periodicity of climatic/eustatic cycles was conditioned by at least two phases of intense tectonism recorded by angular unconformities, the first separating unit CNM from its basement and the second separating ALT from CNM. Both phases occurred during the Piacenzian, the second followed by a prolonged time of subsidence allowing for the accommodation of at least 45 m-thick shell-rich sandstone interval during the upper Piacenzian and early Gelasian. Following a rejuvenation of the topographic profile, the lowermost composite depositional sequence CNM1-4 (Piacenzian, MNN16a Zone) is characterised in its lower part by thick conglomerate partitions and later developed by the stacking of four elementary depositional sequences. The first three EDSs are stacked to show an overall deepening upward trend, from alluvial fans to delta front to open shelf paleosettings (CNM1-3). The quantitative analysis of intervening shell beds confirms this interpretation, suggesting that maximum flooding occurs in the middle part of elementary sequence CNM3. An overall regression ensues in the uppermost part of the composite sequence, testified by paleosols and alluvial fan deposits of elementary sequence CNM4 outcropping at Costagrande. CNM sandstone units have a limited thickness, suggesting sediment bypass to deeper marine settings. However, since ongoing tectonic-uplift reduced accommodation space, the regressive part of each EDS is missing due to erosional truncation, so that the relative importance of sandy deposition at shallow depths is under-appreciated. The situation changes during the deposition of unit ALT. A younger composite sequence is formed by three EDSs (ALT2-4), separated by the underlying composite sequence CNM1-4 by intervening open shelf mudstones, attributed to an intermediate elementary sequence ALT1. ALT1 is discontinuous both on underlying and overlying composite sequences, with a sharp facies change that points to erosion both before and after deposition. ALT1 belongs to the upper Pliocene (Piacenzian, MNN16a Zone), whereas composite sequence ALT2-4 ranges from the upper Pliocene to the lowermost Gelasian (MNN16b/17-MNN18 zones). Formed by shell-rich marine sandstones with very sparse fine gravels, ALT2 fines-upward, followed by ALT3, characterised by a diversified ichnoassociation and an increase in the frequency of cemented beds, marking the MFS of the composite sequence (Fig. 2). Quantitative paleobiology of molluscan shell beds confirms that the latter interval formed in a deeper setting with respect to underlying and overlying ALT strata. Depth gradually decreases, interrupted by a new slight increase in the lower part of ALT4, marked by a thin mudstone interval.

The ensuing regression is very gradual, confirming that the overall increase in accommodation space shown by the asymmetric development of ALT3 continues during deposition of ALT4, a trend interrupted before the deposition of ALT5 coarse-grained sediments in a proximal delta front. The presence of disarticulated and encrusted oyster shells, with a well-diversified trace fossil assemblage of different ethological classes (Fig. 4f-h; David et al., 2017), indicates prolonged reworking of the abundant bioclastic material by a diverse fauna of bioeroders and bioencrusters in a shallow marine, high-energy setting (ALT5).

Local tectonic forcing

The studied succession developed in a phase of intense tectonic activity related to regional compression and accommodated by transpressional faults (Event 2 in Catalano et al., 2013). The study area represents the onshore portion of the WNW-ESE trending Termini Imerese Basin developing offshore as a trough confined between the coast and a structural high coinciding with the shelf edge (Pepe et al., 2003). The sedimentary study of CNM and ALT CDSs supports the hypothesis of syn-depositional tectonic activity controlling sediment routing to the Termini Imerese Basin. CNM coarse-grained deposits suggest that, during the first part of the Piacenzian, fluvial systems drained towards the NW, i.e., axially with respect to the basin trend. Delta development during the deposition of ALT (second part of the Piacenzian) was instead fed from SSW, that is, transversally to the basin. In this perspective CNM may record the syn-depositional growth of NE-verging thrust faults which determined uplift/denudation of the southern basin shoulders with related sediment funnelled within a subsiding basin. ALT2-5 subunits may represent a stage of tectonic quiescence in the basin, with uplift/denudation concentrated in southernmost portions of the chain.

Global climatic forcing

The late Pliocene and Early Pleistocene are time intervals marked by important climatic and eustatic fluctuations undergoing a pace change, so that the hierarchy of sedimentary cycles recorded at Altavilla Milicia can be confronted with analogous signals from other Mediterranean settings (Fig. 12). Climatic forcing is recorded in correlative Pliocene-Pleistocene deposits of the Belice Basin, in western Sicily (Poggioreale and Montevago sequences; Vitale, 1997; 4th order-sequences P4a-P4b; Catalano et al., 1998; Roveri & Taviani, 2003), and Caltanissetta Basin, in the central part of the Island, where nearshore and offshore facies alternate in cyclical, high-frequency fashion (Capodarso “parasequences”;

Fig. 7 - (color online) ALT sedimentary facies, trace and body fossils at Altavilla section. a) Transgressive surface separating facies F4b below from F5 above, and maximum flooding interval of EDS ALT2, above which is the lower sequence boundary of EDS ALT3 and a gravelly sandstone (F2a) with *Pelecypora islandicoides*, *Pecten flabelliformis* and *Atrina pectinata*; bulk samples A3-4, A3-5, A3-6. b) Large, vertically oriented, bottle-shaped *Scalichnus* isp. within a thoroughly bioturbated and cemented shelly sandstone, formed during retrusive and protrusive movement of the bivalve *Panopea glycymeris*, here preserved in life position at the top of the burrow; bulk sample A5-3, F2 interval of ALT2, scale in cm. c) *Ophiomorpha* isp., F5 interval of ALT2. d) *Lucinoma borealis* in life position (white arrows), F5 interval of ALT2. e) Highstand systems tract of EDS ALT3, formed by a shell-rich calcareous sandstones with *Panopea glycymeris* in life position and a *Thalassinoides* cf. *paradoxicus* boxwork; bulk sample A6b-1. f) Underside of a 100% bioturbated calcareous sandstone with *Pecten jacobaeus* and a boxwork of *Taenidium* isp., facies F3b, regressive interval of ALT3. g) *Pecten flabelliformis* in life position (ALT3, scale in cm). h) *Pelecypora islandicoides* in life position (ALT3, pencil 12 cm long).

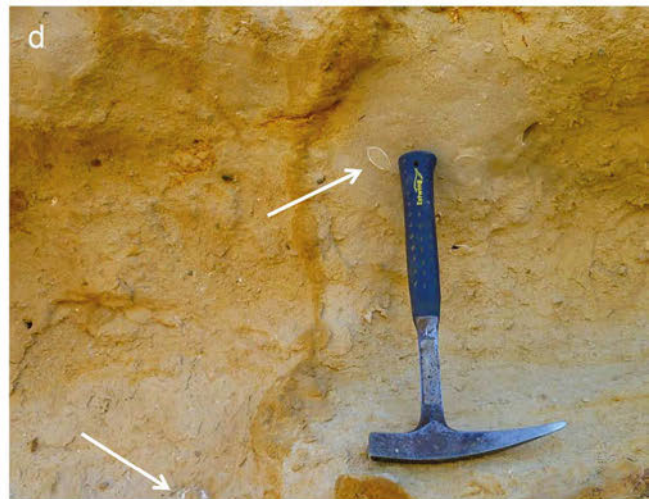
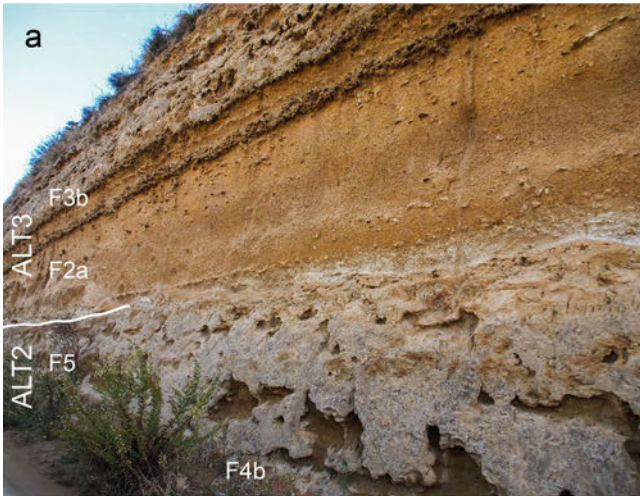




Fig. 8 - (color online) Delta-front deposits of EDS ALT5, formed by a gravelly sandstone with tightly-packed, medium-sized, generally sorted and disarticulated *Ostrea edulis* (F2b); shells are bioeroded by clionaid sponges and other hard-substrate dwellers and bioencrusted by red algae, membraniporiform bryozoa and balanids (see also Fig. 4f-h).

Lickorish & Butler, 1996; 4th order sequence P4c according to Catalano et al., 1998; P4b in an alternative hypothesis of Roveri & Taviani, 2003). Belice sequences P4a-P4b (MNN16a-MNN16b/17; Catalano et al., 1998; Roveri & Taviani, 2003) are time correlative with Cannamasca CNM1-4 and the lower part of the Altavilla unit (EDSs ALT1-3). The carbonate-rich interval ALT2-ALT3, in particular, is correlative in Sicily with the Montevago succession in the Belice Basin, and possibly with the Capodarso succession (zone MNN16b/17 according to Roveri & Taviani, 2003). Shell-rich detrital carbonates

were developing at the same time in other Mediterranean settings, confirming a global climatic forcing. The best studied is the Castell'Arquato calcarenite in the Western Emilia, correlating basinward to rodolithic layers and to the sapropel interval "A" (Roveri & Taviani, 2003; Cau et al., 2018, 2020). In the hypothesis that the Capodarso sedimentary cycles belong to the MNN18 Zone (Catalano et al., 1998), possibly marking the early Pleistocene 41-ky cyclicity recorded in shallow marine successions worldwide (e.g., Naish & Kamp, 1997), then these could be instead partly correlative with Altavilla cycles ALT4-5.

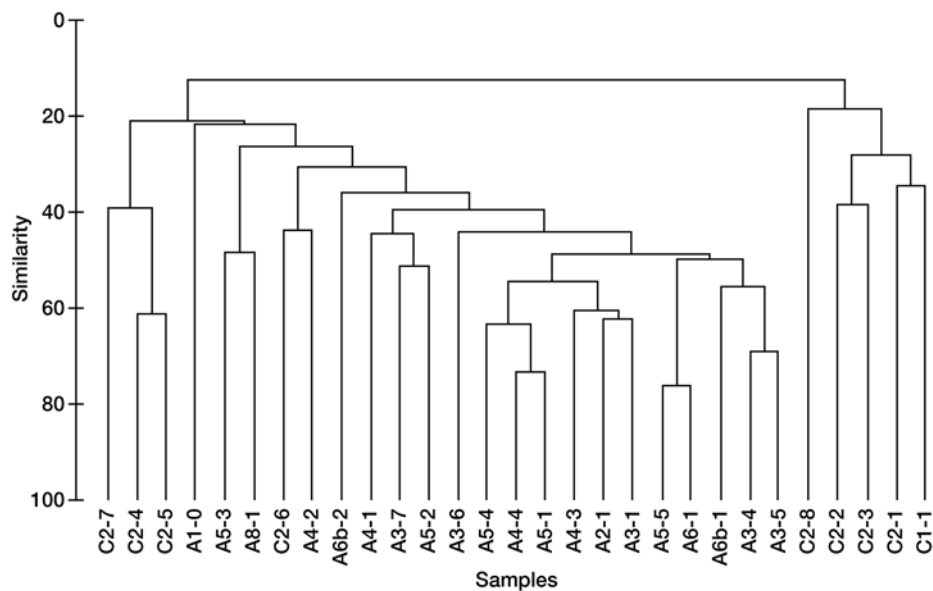


Fig. 9 - Q-mode cluster analysis carried out on a dataset restricted to 22 samples and 92 species, after the exclusion of samples $n < 30$ specimens. Samples were standardised by total, and square-root transformed. Resemblance S17 Bray Curtis Similarity.

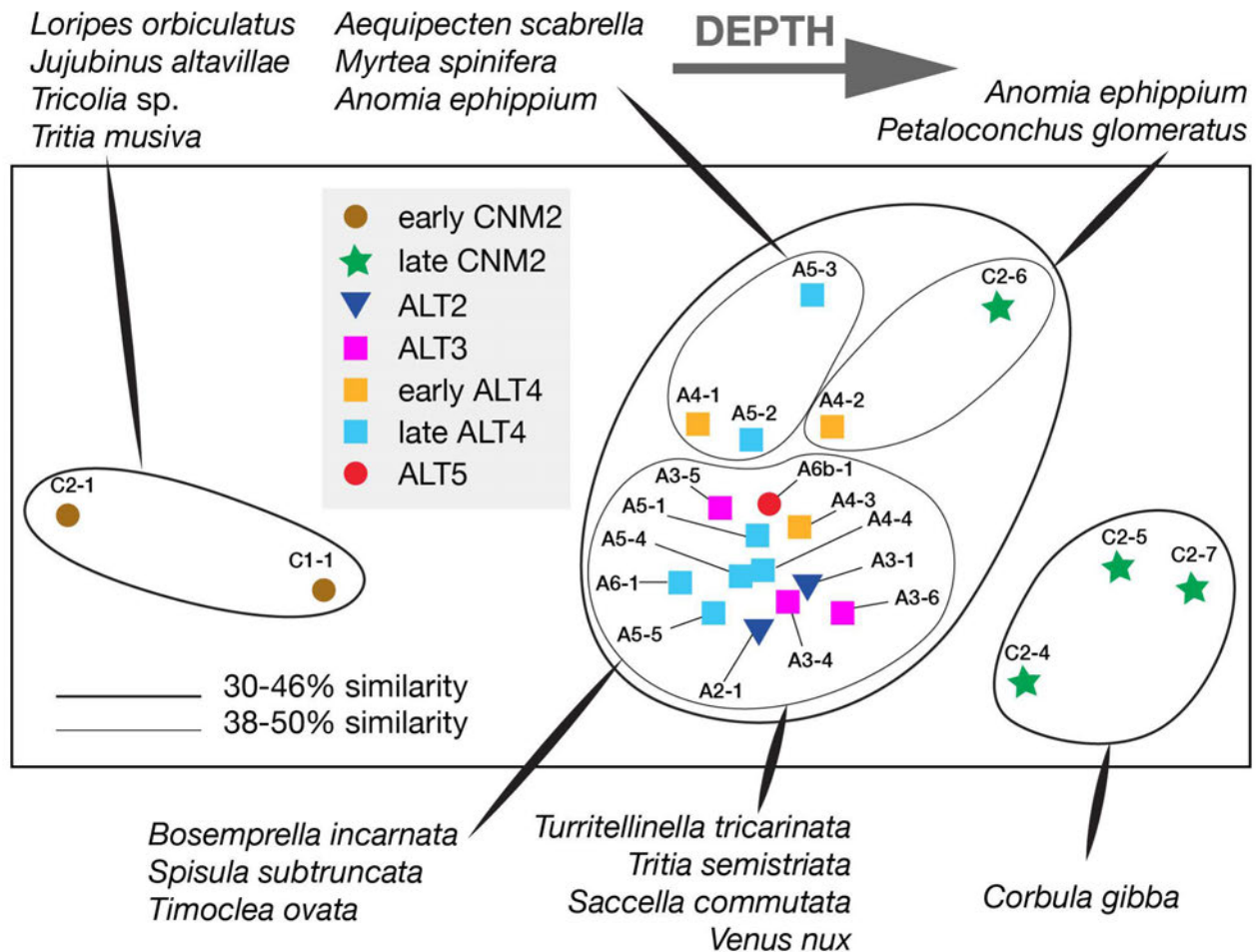


Fig. 10 - (color online) Non-metric multidimensional scaling (NMDS) carried out on a dataset of 22 samples and 92 species collected in composite sequences CNM and ALT (see Fig. 2 for the stratigraphic position of bulk samples); the main axis of the ordination can be interpreted as an expression of the paleobathymetric gradient.

These EDSs prelude to Gelasian and Calabrian sedimentary cycles, triggered by climatic and eustatic cycles of higher amplitude. High-frequency signals are in fact recorded in Mediterranean successions by distinct and locally sharp facies changes, both in nearshore settings, such as in the Croton Basin (Gelasian; Capraro et al., 2006; Zecchin et al., 2012; Calabrian; Capraro et al., 2014) and in Western Emilia (Calabrian; Dominici, 2001; Stefanelli, 2004; Cau et al., 2020; Crippa et al., 2018), and offshore settings, such as in Lucania (Calabrian; D'Alessandro et al., 2003; Ciaranfi et al., 2009). Accordingly, sedimentary cycles with a carbonate-rich component comparable to the Altavilla lithosomes characterise the Marsala synthem of Calabrian age, outcropping on the left side of the Milicia river (locality Stazzone, "Upper Member"; Pollina, 2012) and in many areas of Northwestern Sicily (Agate et al., 2017: fig. 5).

Pliocene-Pleistocene mollusc disappearance/extinction events

Major climatic changes of the Northern Hemisphere, respectively at 3.0, 2.5 and 2.1, have been approximated to boundaries of four Mediterranean Pliocene Molluscan Units (MPMUs), defined on the basis of the stratigraphic

distribution of 365 species of bivalves and a few key gastropod species (Monegatti & Raffi, 2001, 2007). The MPMU1-MPMU2 boundary, occurring in the late middle part of the MN16a Zone of calcareous nannofossil biostratigraphy (*D. tamalis* Zone; Rio et al., 1990) at around 3.0 Ma, is marked by the disappearance in the Mediterranean of thermophilic species, including, among others, *Pecten bosniasckii* (De Stefani & Pantanelli, 1880), *Macrochlamys latissima* (Sacco, 1897), *Spondylus crassicosta* (Lamarck, 1819), *Lucina orbicularis* (Linnaeus, 1758), *Isognomon maxillatus* (Lamarck, 1801), *Crassatina concentrica* (Dujardin, 1837), *Gastrana lacunosa* (Chemnitz, 1782), *Callista italica* (Defrance, 1818), *Circomphalus foliaceolamellosus* (Dillwyn, 1817) and *Persististrombus coronatus* (Defrance, 1827) (Monegatti & Raffi, 2001; see Appendix). The last appearance datum (LAD) of the above species lies at Altavilla presumably at the late MN16a Zone, or definitely in the MN16b/17 Zone (*D. pentaradiatus* Zone; Rio et al., 1990; Fig. 2), meaning that some of these thermophilic taxa certainly survived longer than previously supposed. Because of the nature of the sedimentary rock record, estimates of diversity measured simply by summing up the numbers of species recorded from successive

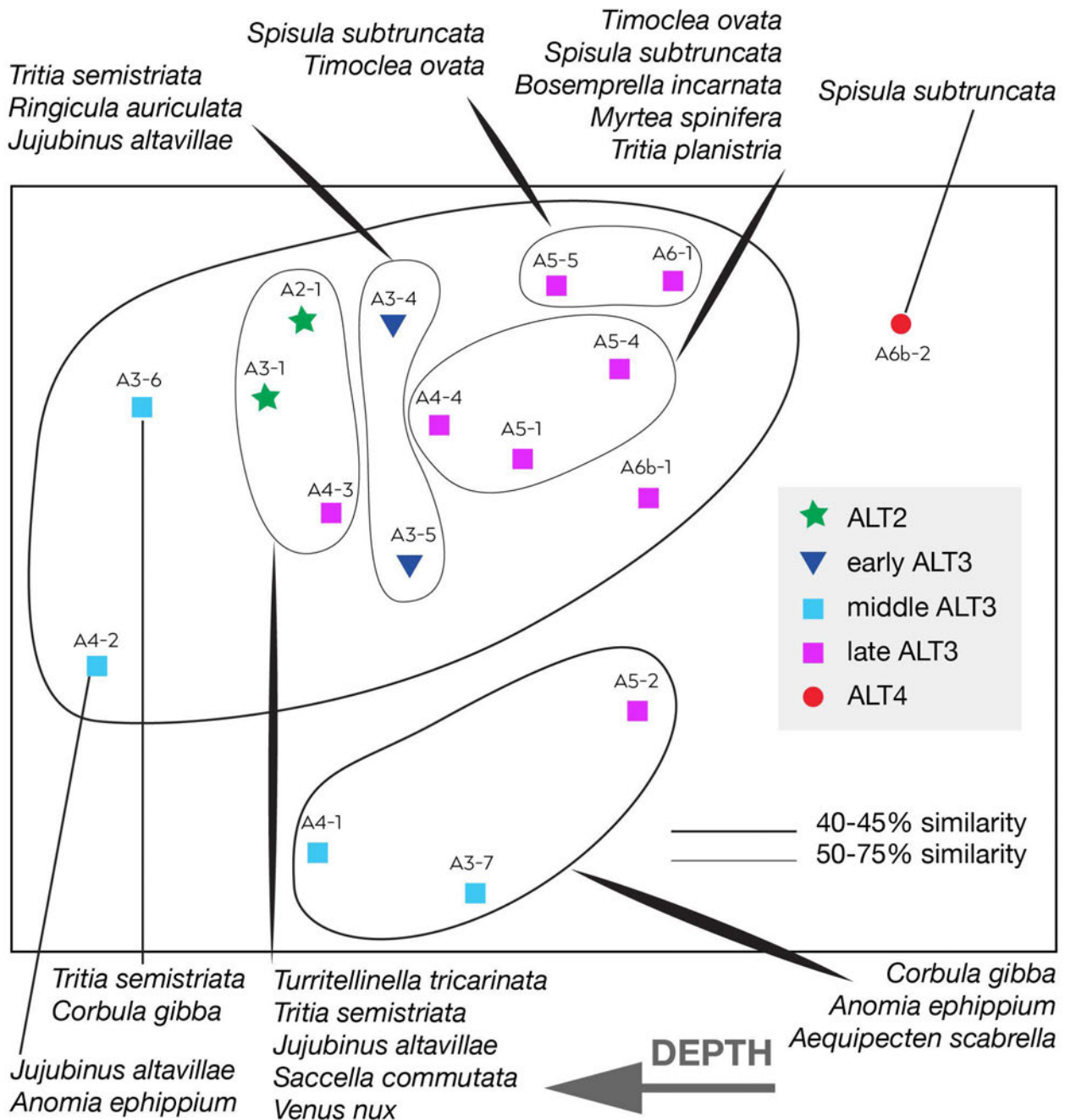


Fig. 11 - (color online) Non-metric multidimensional scaling (NMDS) carried out on a dataset of 17 samples and 89 species collected in composite sequence ALT; the main axis of the ordination can be interpreted as an expression of the paleobathymetric gradient.

geological time intervals brings to crude approximation that may be subject to a number of biases. Two important such biases in the case of the Mediterranean Neogene and Quaternary are facies control on fossil assemblage composition (e.g., Dominici et al., 2019) and an unbalanced sampling effort which favours the NW sector of the basin (see Monegatti & Raffi, 2001, 2007). The SE sector is on average warmer, potentially offering refuges to thermophilic molluscs during times of climatic cooling, resulting in different stratigraphic ranges with respect to what expected from existing literature, as demonstrated in the Quaternary (Garilli, 2011). A significative case is represented by terebrids, a

typical tropical group of shallow-water gastropods that were regarded as extinct in the Mediterranean in the early Gelasian (Monegatti & Raffi, 2001) but actually survived to the climatic deterioration occurred in that Basin at the base of the Calabrian (Malatesta, 1960-1963; Reina, 1985; Ruggieri, 1987; Garilli, 2011). A remarkable example of biogeographic dynamics at the species level in support of the refuge model is represented by *Terebra corrugata* Lamarck, 1822 (= *T. acuminata* Borson, 1820), which was recorded from the Calabrian of South Italy (Seguenza, 1880; Malatesta, 1960-63) and the Late Pleistocene MIS5e of Ionian Greece (Garilli, 2011).

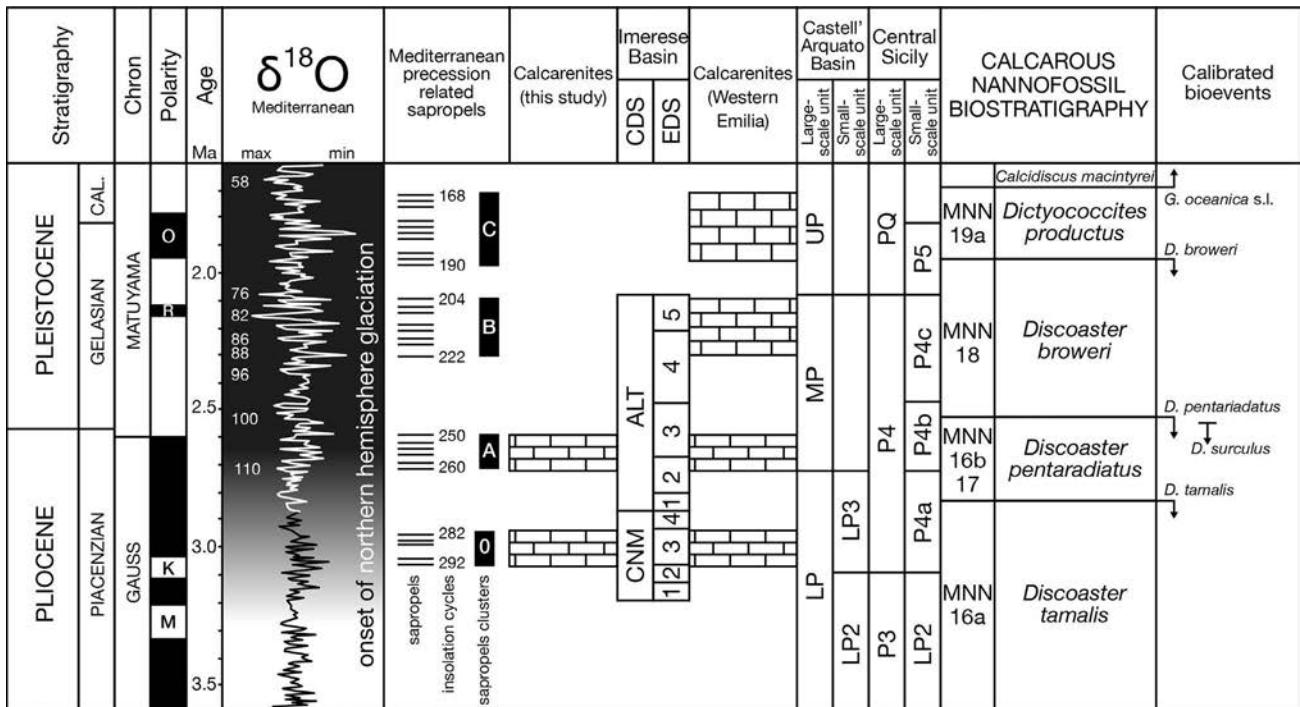


Fig. 12 - Pliocene-Pleistocene stratigraphic chart showing the time distribution of sapropels, some well-known Mediterranean calcarenites and their relationship to isotopic stages and astronomic cyclicity (see references in Roveri & Taviani, 2003).

The present study is a further evidence that Pliocene-Pleistocene successions of Sicily, a region forming a gateway between NW and SE sectors of the Mediterranean, allow to better frame the timing of disappearance, or extinction, of tropical taxa. This is particularly true of shallow marine paleosettings, where most of the change occurs (Tomašových et al., 2014; Dominici et al., 2019; and references therein).

CONCLUSIONS

The Altavilla Milicia succession, near Palermo (NW Sicily, Italy), has long been studied for its rich mollusc shell beds and the microfauna, but uncertainties about its age and the lack of clear-cut facies changes in its thickest and most fossiliferous part have hindered the interpretation of controlling factors. We improved this knowledge by a detailed analysis of sedimentary facies and geometry of stratal surfaces, allowing for a sequence-stratigraphic interpretation of the succession. The qualitative and quantitative analyses of trace and body fossils allowed to collect independent evidence on factors controlling deposition. Two large unconformity-bounded composite depositional sequences are recognised, named Cannasca unit (CNM) and Altavilla unit (ALT). Outcrop conditions do not allow to see facies change along the depositional profile, but the joint analysis of the two units suggest that deposition took place in a fluvio-deltaic system dominated by hyperpycnal floods, where wave and tidal influence was secondary, influenced on a large scale by tectonics and climate, on a small scale by high-frequency cycles of relative sea-level change. Calcareous nannoplankton biostratigraphy allowed to recognise both upper Pliocene and Lower Pleistocene deposits, covering the transition

from the warm mid-Piacenzian to the cooler Quaternary. Acting on a regional scale, syn-depositional tectonic activity controlled a change in the direction of fluvial clastic input, from axial (CNM) to transverse (ALT) with respect to basin trend. After the warm mid-Piacenzian climatic optimum, carbonate bioclastic production at shelf depths was still important, peaking at Altavilla during the uppermost Piacenzian, at a time of tectonic quiescence. High-frequency cycles of relative sea-level variation resulted in the formation of elementary depositional sequences, the building blocks of composite depositional sequences. CNM is formed by four elementary depositional sequences stacked in an overall deepening-upward trend, from alluvial fans to delta front, to open shelf paleosettings. The quantitative analysis of intervening shell beds confirms this trend, suggesting that maximum flooding occurs in proximity of elementary sequence CNM3. An overall regression ensues, as testified by paleosols and alluvial fan deposits occurring in elementary sequence CNM4. An angular unconformity separates CNM from overlying sediments of the Altavilla unit, testifying to an important tectonic event occurring, putting in contact open shelf sediments with underlying continental deposits, suggesting that an important part of the record is missing due to erosion. Composite sequence ALT2-4, of upper Piacenzian and lower Gelasian age, is thicker than CNM and formed by more symmetric elementary depositional sequences. Shell-rich carbonate lithosomes are particularly well-developed around the MFS of the composite sequence, an interval deposited immediately before the Quaternary glaciation. Mixed carbonate-siliciclastic lithosomes of both CNM and ALT show a good correlation with shallow marine shell-rich detrital carbonates recognised in Northern and Southern Italy, which in turn correlate with the deep-water sapropel clusters "0" and "A" found in the Mediterranean,

confirming common forcing related to astronomically-driven climate and oceanographic changes at both low- (100-400 kyr: eccentricity-controlled) and high-frequency scales (20-41 kyr: precession- or obliquity-controlled). The stratigraphic distribution of thermophilic mollusc species extends known ranges of some taxa that define the boundaries separating Mediterranean Pliocene Molluscan Units (MPMUs), particularly concerning species known to disappear or become extinct at the boundary between MPMU1 and MPMU2.

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	C1-1	C2-1	C2-4	C2-5	C2-6	C2-7	A2-1	A3-1	A3-4	A3-5	A3-6	A3-7	A4-1	A4-2	A4-3	A4-4	A5-1	A5-4	A5-5	A6-1	A6b-1	A6b-2
<i>Loripes orbiculatus</i> Poli, 1795	4	39	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Lucinoma borealis</i> (Linnaeus, 1767)	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	2	0	0	0
<i>Myrtea spinifera</i> (Montagu, 1803)	0	0	0	0	0	0	26	7	8	6	1	1	5	1	3	20	10	7	4	4	3	3
<i>Loripinus fragilis</i> (Philippi, 1836)	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	1	0	0	0	0	0	0
<i>Lucinella divaricata</i> (Linnaeus, 1758)	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	2	3	0	0	0	0	0
<i>Centrocardita aculeata</i> (Poli, 1795)	0	0	0	0	5	0	0	0	0	0	1	0	10	2	0	0	0	0	0	0	0	0
<i>Cyclocardia astartoides</i> (Martens, 1878)	0	0	11	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Acanthocardia echinata</i> (Linnaeus, 1758)	0	0	9	0	0	0	6	2	1	0	0	0	0	1	0	0	5	3	4	2	1	2
<i>Papillicardium minimum</i> (Philippi, 1836)	0	0	0	0	0	0	8	6	3	0	3	0	2	1	0	3	4	2	3	2	0	0
<i>Papillicardium papillosum</i> (Poli, 1791)	3	0	1	1	0	0	0	0	9	4	0	0	0	3	0	3	2	2	0	0	1	0
<i>Laevicardium crassum</i> (Gmelin, 1791)	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Spisula subtruncata</i> (da Costa, 1778)	0	0	19	5	0	0	5	0	20	7	0	1	2	0	2	25	18	34	54	52	10	11
<i>Ervilia castanea</i> (Montagu, 1803)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	6	21	4	4	0	0
<i>Phaxas pellucidus</i> (Pennant, 1777)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
<i>Oudardia compressa</i> (Brocchi, 1814)	0	0	0	0	0	0	0	0	1	0	2	0	0	0	0	2	0	4	0	0	1	3
<i>Bosemprella incarnata</i> (Linnaeus, 1758)	0	0	0	0	0	0	12	4	3	2	0	0	0	0	2	13	14	17	5	5	3	4
<i>Gari uniradiata</i> (Brocchi, 1814)	0	0	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0	0	0	0	1	0
<i>Abra prismatica</i> (Montagu, 1808)	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	3	2	0	1
<i>Abra alba</i> (W. Wood, 1802)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	3	1
<i>Azorinus chamasolen</i> (da Costa, 1778)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	2	0	0
<i>Venus nux</i> Gmelin, 1791	0	0	21	0	0	0	24	3	2	0	0	0	0	0	1	3	2	3	6	2	0	0
<i>Gouldia minima</i> (Montagu, 1803)	0	0	0	0	3	0	2	1	1	0	0	0	1	4	2	2	2	5	0	0	1	1
<i>Pitar rudis</i> (Poli, 1795)	0	0	7	6	0	0	1	3	3	0	9	0	0	1	0	0	0	2	0	0	0	0
<i>Chamelea gallina</i> (Linnaeus, 1758)	2	0	0	0	0	0	0	0	0	0	0	0	0	1	2	1	4	11	0	0	0	0
<i>Timoclea ovata</i> (Pennant, 1777)	1	0	3	2	3	3	3	3	2	5	6	0	2	4	5	22	6	17	6	3	3	4
<i>Corbula gibba</i> (Olivi, 1792)	0	0	76	46	7	101	9	102	27	21	22	2	6	7	19	30	20	11	5	4	12	0

	C1-1	C2-1	C2-4	C2-5	C2-6	C2-7	A2-1	A3-1	A3-4	A3-5	A3-6	A3-7	A4-1	A4-2	A4-3	A4-4	A5-1	A5-4	A5-5	A6-1	A6b-1	A6b-2
<i>Hiatella arctica</i> (Linnaeus, 1767)	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	1	3	1	0	0	0	0
<i>Pandora inaequalis</i> (Linnaeus, 1758)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0
<i>Cuspidaria cuspidata</i> (Olivi, 1792)	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0
<i>Cardiomya costellata</i> (Deshayes, 1835)	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Paradentalium sexangulum</i> (Gmelin, 1790)	1	0	0	0	0	0	2	2	1	1	0	1	2	1	1	2	1	0	0	0	0	0
<i>Fustiaria jani</i> (Hörnes, 1856)	0	0	0	0	0	0	3	5	0	0	1	0	1	0	3	4	1	1	0	0	0	0
<i>Cadulus gadulus</i> (Doderlein, 1862)	0	0	0	0	0	0	2	9	1	3	1	0	3	0	1	1	0	0	0	0	0	0
<i>Diodora italica</i> (Defrance, 1820)	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0
<i>Calliostoma granulatum</i> (Born, 1778)	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0	0
<i>Steromphala cf. varia</i> (Linnaeus, 1758)	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Jujubinus striatus</i> (Linnaeus, 1758)	8	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Jujubinus altavillae</i> Giannuzzi-Savelli & Reina, 1987	0	0	0	0	0	0	11	6	9	11	3	1	9	6	2	5	0	3	6	6	0	0
<i>Turitellina tricarinata</i> (Brocchi, 1814)	0	0	0	0	0	0	32	29	4	1	11	2	1	0	3	9	1	4	4	0	3	0
<i>Helminthia varicosa</i> (Brocchi, 1814)	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Petalocochlus glomeratus</i> (Linnaeus, 1758)	0	0	0	4	23	0	4	2	0	0	2	5	0	2	6	0	0	0	0	0	0	0
<i>Bittium reticulatum</i> (da Costa, 1778)	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
<i>Bittium latreillii</i> (Payraudeau, 1826)	33	0	0	0	0	0	7	1	0	0	0	0	0	0	6	3	0	0	3	1	5	0
<i>Cerithium vulgatum</i> Bruguière, 1792	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Monophorus</i> sp.	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Calyptraea chinensis</i> (Linnaeus, 1758)	0	0	0	0	0	0	25	2	0	0	0	0	0	1	1	6	8	6	5	1	0	0
<i>Aporrhais uttingerianus</i> (Risso, 1826)	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	1	0	0	0
<i>Euspira</i> sp.	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Euspira macilenta</i> (Philippi, 1844)	0	0	0	0	0	0	1	16	0	1	3	0	0	0	2	2	2	0	0	0	0	0
<i>Notocochlis tigrina</i> (Röding, 1798)	3	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Cochlis raropunctata</i> (Sasso, 1827)	0	0	0	0	0	0	1	0	0	0	2	0	0	0	0	2	0	0	0	0	0	0
<i>Tritia angulatus</i> (Brocchi, 1814)	0	0	0	0	0	0	1	0	0	0	1	0	0	0	2	3	2	0	0	0	0	2

	C1-1	C2-1	C2-4	C2-5	C2-6	C2-7	A2-1	A3-1	A3-4	A3-5	A3-6	A3-7	A4-1	A4-2	A4-3	A4-4	A5-1	A5-4	A5-5	A6-1	A6b-1	A6b-2
<i>Tritia chlatratus</i> (Born, 1778)	0	0	2	0	0	0	2	0	4	2	3	0	0	0	1	0	0	0	0	0	0	0
<i>Tritia planistria</i> (Brugnone, 1876)	0	0	0	0	0	0	4	15	0	0	1	0	0	0	1	36	25	2	1	0	0	0
<i>Tritia prismaticus</i> (Brocchi, 1814)	0	0	0	0	0	0	0	0	0	0	2	0	0	2	0	0	0	0	0	0	0	0
<i>Tritia semistriata</i> (Brocchi, 1814)	0	0	4	0	0	0	18	12	32	19	22	0	0	0	1	5	0	0	5	2	3	1
<i>Tritia musiva</i> (Sismonda, 1847)	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
<i>Tritia serraticosta</i> (Bronn, 1831)	0	0	0	0	0	0	0	1	0	0	1	0	0	0	3	4	2	0	0	0	0	0
<i>Raphitoma echinata</i> (Brocchi, 1814)	1	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	0
<i>Cerodrillia sigmoidea</i> (Bronn, 1831)	0	0	0	0	0	0	0	2	0	0	1	0	0	0	0	1	0	1	0	1	0	0
<i>Mangelia scabriuscula</i> (Brugnone, 1862)	0	0	0	0	0	0	1	1	2	0	0	0	0	0	0	4	1	0	0	0	0	0
<i>Mangelia tenuicostata</i> (Brugnone 1868)	0	0	0	0	0	0	1	2	1	0	1	0	0	0	1	2	0	0	0	0	0	0
<i>Sorgenfreispira brachystoma</i> (Philippi, 1844)	0	0	0	0	0	0	1	4	0	1	0	0	0	1	2	3	2	1	0	0	0	1
<i>Megastomia conoidea</i> (Brocchi, 1814)	4	0	0	0	0	0	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Turbonilla lactea</i> (Linnaeus, 1758)	1	0	0	0	0	0	0	1	2	1	0	0	0	0	0	0	0	0	0	0	0	0
<i>Acteon semistriatus</i> (Basterot, 1825)	0	0	0	0	0	0	0	2	1	2	0	0	0	0	0	5	3	0	0	0	1	1
<i>Ringicula auriculata</i> (Ménard de la Groye, 1811)	1	0	0	0	0	0	0	1	5	1	2	0	0	0	0	0	0	0	2	0	1	0
<i>Ringicula ventricosa</i> (J. Sowerby, 1824)	0	0	0	0	0	0	0	3	2	2	2	1	0	1	2	2	1	0	1	1	3	1
<i>Roxania utriculus</i> (Brocchi, 1814)	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1
Total abundance:	92	53	168	79	91	105	272	348	166	108	146	34	70	80	107	275	175	184	136	102	65	38