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NEW BIOSTRATIGRAPHIC AND LITHOLOGICAL DATA ON THE NEOGENE AND QUATERNARY OF THE LIVORNO AREA (TUSCANY, CENTRAL ITALY)

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Abstract. Lithofacies analyses and datings using calcareous nannofossils, proved to be an excellent opportunity to understand the palaeoenvironmental evolution of the area of the Tuscan coast, washed up by the Ligurian Sea. A multidisciplinary approach, through lithological and micropaleontological data, collected from fifteen boreholes and one outcrop, permitted the characterization of ten stratigraphic units in the subsurface of the Livorno area. The correlations of these units depicted a stratigraphic architecture chronologically constrained. This study detected early Pliocene (Zanclean) and early Pleistocene (Gelasian) marine deposits, referable to the outer neritic zone that were dated to the calcareous nannofossil biozones MNN13, MNN14-15 and MNN18. In addition, early Pleistocene (Calabrian) marine deposits, dated to the calcareous nannofossil biozones MNN19b, MNN19d, MNN19e, which may be attributed to different bathymetric depths on the basis of benthic foraminifers and ostracods, highlighted sea level changes. Finally, the areal distribution and the stratigraphic architecture of these units permitted the recognition and the better constraining of the sedimentary dynamics impacted by major eustatic and tectonic changes.

Introduction

The Livorno area is located in the Tuscan region (Central Italy) on the Ligurian Sea coast (Fig. 1). This is a highly urbanized area with all the consequent issues, including soil pollution, saltwater intrusion, groundwater contamination and soil sealing. Tackling these problems requires knowledge about the area's geology and public administration have promoted the development of scientific research on the subsurface stratigraphy of the Livorno area. In the last decades the development of infrastructure has provided boreholes and ephemeral outcrops as new elements for the study of the subsurface stratigraphy. We took advantage of this situation taking into account new continuously-cored boreholes to investigate the Neogene-Quaternary subsurface deposits, combining lithological and micropaleontological analyses.

The area was extensively studied in the past by Barsotti et al. (1974); Ciampalini (2002); Dall'Antonia et al. (2004); Ciampalini et al. (2006); Zanchetta et al. (2004, 2006); Bossio et al. (2008); Ciampalini et al. (2013). These authors not only confirmed and enriched the stratigraphy traditionally proposed for this area, but also highlighted the complexity and the problems related to the subsurface Neogene-Quaternary successions. However, by now there have not been detailed biostratigraphic studies able to provide useful chronological constrains. In order to improve the understanding of the subsurface geology of this area, this paper

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aims to provide new biostratigraphic and palaeoenvironmental data based on the study of calcareous nannofossils, ostracods, benthic foraminifers and mollusks, on late Miocene to Holocene marine and continental successions. Stratigraphic correlations and geological reconstructions were also performed taking into account previous published and unpublished studies about the subsurface geology of the Livorno area (Barsotti et al. 1974; Dall'Antonia et al. 2004; Zanchetta et al. 2006, 2019; Bossio et al. 2008; Ciampalini et al. 2013), that are represented as a dataset of logs and sediment cores organised in GIS (Geographic Information System) by the Institute of Goescience and Georesources of CNR (IGG-DATABASE).

Geological and stratigraphic setting

The Livorno area is located between the Tuscan coast and the Apennine chain. This area has been affected by extensional tectonic processes linked to the eastward migration of the chain as consequence of the progressive opening of the Tyrrhenian Sea, which has been occurring since Tortonian (Carmignani et al. 2001). Extensional sedimentary basins were formed along normal NNW-SSE faults and were filled by late Miocene-Quaternary continental and marine sediments (Ghelardoni et al. 1968; Mariani & Prato 1988; Bossio et al. 1993; Pascucci 2005) on rocks belonging to the Tuscan and Ligurian units. In the hills surrounding the study area, Messinian lower-middle Pliocene and lower Pleistocene marine deposits and in minor amount middle-late Pleistocene continental deposits outcrop (Figs. 1-2). The Messinian is mainly represented by conglomerates, clays and gypsum (Era Morta River Clays and Gypsum formation, Cerri & Sandrelli 1994), covered by the Pliocene Blue Clay Formation. This late formation is covered by a Pleistocene marine succession, that from the base to the top comprises Santernian-Emilian open sandy silts pertaining to the Morrona Formation (Boschian et al. 2006), followed by fine to medium-grained sands referable to the Emilian Nugola Vecchia Sands (Lazzarotto et al. 1990; Dall'Antonia et al. 2004). Above this latter lies, through an unconformity, a further marine succession of gravels and sandy silts of Sicilian age referable to the Fabbriche Sands formation (Bartoletti et al. 1986; Dall'Antonia et al. 2004).

Morphological and stratigraphical studies have identified some orders of marine terraces lying at different elevations (Fig. 2, Zanchetta et al. 2019), the genesis of which was linked to the interaction between glacio-eustatic oscillations and tectonic uplift, during middle and late Pleistocene. The highest of these terraces is named Terrazzo della Fattoria delle Pianacce (Barsotti et al. 1974; Lazzarotto et al. 1990) or Terrazzo I (Federici and Mazzanti 1995). This morphostratigraphical unit is placed at a maximum altitude of 120 m a.s.l., and is overlain to north by the Poggio ai Lecci formation (Barsotti et al. 1974; Marroni et al. 1990) and to south by the Conglomerate of Villa Umbero I formation (Barsotti et al. 1974). It was attributed to MIS 11 (Marcolini et al. 2003; Zanchetta et al. 2006). The Terrazzo di Salviano (Malatesta 1942; Bossio et al. 2008), also named Terrazzo di Villa Padula (Boschian et al. 2006), is placed at an altitude of about 40 m a.s.l., its age was related to MIS9c highstand (Zanchetta et al. 2019).

The lower of these morphostratigraphical units (Fig. 2), is the Terrazzo di Livorno, also called Terrazzo II (Barsotti et al. 1974; Federici and Mazzanti 1995) that was correlated to MIS5e highstand (Hearty et al. 1986; Mauz 1999; Nisi et al. 2003; Sarti et al. 2017; Zanchetta et al. 2019). On top of these stratigraphic and morpho-stratigraphic units, the Pleistocene Ardenza Sands mainly occur (Boschian et al. 2006).

Material and methods

Fifteen boreholes, whose maximum depths range between circa -40 m and -10 m, and one outcrop, were sampled and investigated (location and details are reported in Fig. 1 and Tab. 1). Detailed stratigraphic analyses were performed through macroscopic description of sediment colour (according to the Munsell Soil Color Charts), texture, sedimentary structures, macrofossils, plant remains and organic matter. Calcareous nannofossils were used as biostratigraphic tool to date marine sediments. Ostracod and benthic foraminiferal faunas were investigated as palaeoenvironmental indicators, and ostracods also allowed the dating of the Messinian continental deposits. In figure 3 it is represented an integrated biostratigraphic scheme where we reported the calcareous nannofossil zones and events of Rio et al. (1990), and the foraminifer zones and events of Iaccarino et al. (2007), furthermore the ostracod events (from Carbonnel 1978 and Grossi et al. 2011) useful for both dating and correlation are also shown. In the scheme we propose the stage Calabrian and its substages Santernian, Emilian and Sicilian (see Rio 1982), mainly used to date Italian sediments and useful for correlation with stratigraphic units outcropping on the Tuscan coast. The Santernian corresponds to the lower part of the Calabrian (same GSSP as the Calabrian) and comprises zones MNN19a (upper part), MNN19b and MNN19c;

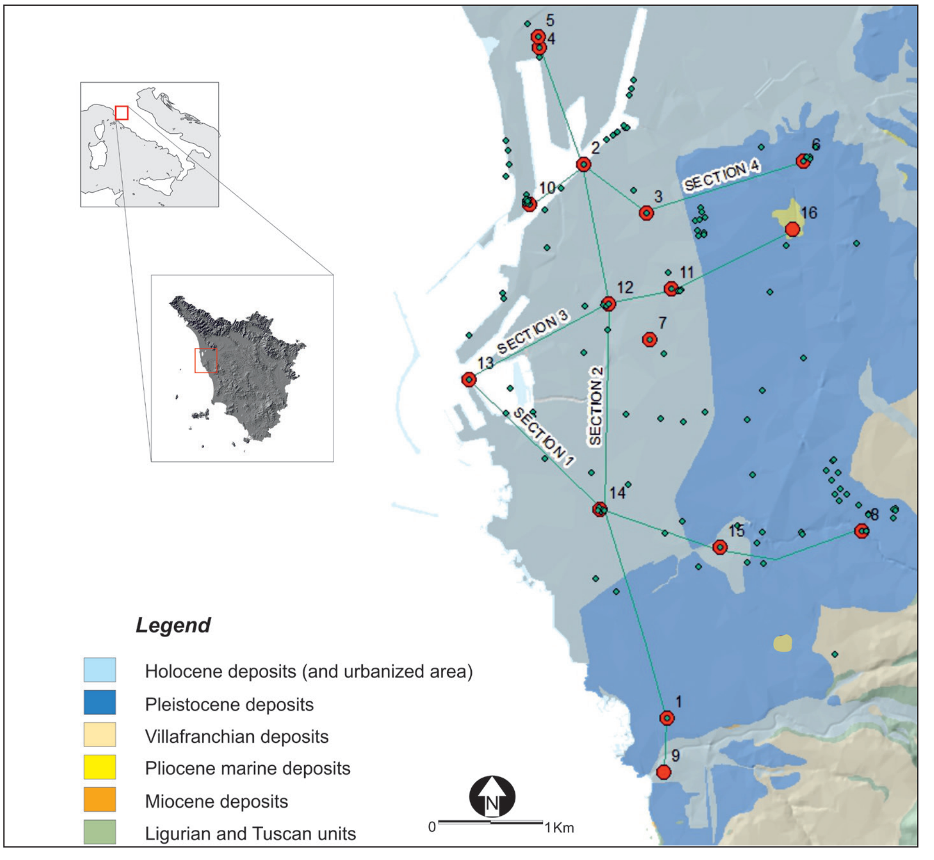

Fig. 1 - Location map of the study area and schematic geological setting. Red points indicate the location of the investigated boreholes (see Tab. 1 for geographic coordinates). Green squares indicate the borehole logs included in the IGG-DATABASE. The green lines visualize the cross sections represented in Fig. 23.

Tab. 1 - Geographic coordinates and depths of the studied boreholes.

Locality Name-Boring	Site number	Longitude	Latitude	Ground level(m a.s.l)	
Ardenza -S1	1	1606806,700000	4819106,960000	8,9	Boreholes
Calata Magnale -S7	2	1605930,209053	4824945,691973	2,0	
Via Filzi -S1	3	1606593,058260	4824437,203896	6,8	
Darsena-SA	4	1605457,490000	4826181,590000	0,4	
Paduletta	5	1605448,000000	4826294,000000	2,0	
Picchianti -S1	6	1608250,130000	4824979,340000	10,0	
Viale Carducci	7	1606631,700000	4823095,820000	8,7	
Magrignano -S22	8	1608866,000000	4821076,000000	30,5	
Banditella	9	1606770,000000	4818535,000000	4,0	
Torre Marzocco -S1	10	1605364,940000	4824525,400000	3,2	
Via Garibaldi -S2	11	1606857,000000	4823631,000000	8,9	
Via Pompilia -S3	12	1606191,900000	4823470,010000	4,2	
Porto Mediceo -S3	13	1604721,465000	4822677,483000	3,8	
Via Roma	14	1606103,328839	4821306,286674	9,2	
Salviano -S9	15	1607363,290000	4820908,850000	15,8	
Scasso	16	1608118,508000	4824265,311000	9,9	Outcrop

the Emilian corresponds to the middle part of the Calabrian, embracing zone MNN19d; the Sicilian corresponds to the upper part of the Calabrian, spanning zones MNN19e to MNN19f (lower part).

For the study of calcareous nannofossils and microfossils were chosen lithologies suitable to contain these fossil groups, so resulting in a different number of samples prepared.

The study of ostracods, benthic foraminifers and occasionally of planktonic foraminifers, was performed on 146 samples of approximately 150 g, which were disaggregated in warm water, washed through a 74 µm sieve and finally dried in an oven at 100°C. The residue was analysed through an optical microscope. Ninety-four samples that were studied in previous papers (Bossio et al. 2008; Ciampalini et al. 2013) were reanalysed. Investigations were focused mainly on microfossils but occasionally other groups (mollusks) were observed in the hand samples. The list of ostracods and foraminifers considered in this paper can be found in Appendix. The relative abundance of microfossils was evaluated on 50 g of residue. For ostracods the classes of abundance are: R (Rare, < 2), F (Few, 3-5), C (Common, 6-10), A (Abundant, >10); for foraminifers they are: R (Rare, < 10), F (Few, 10-50), C (Common, 50-100), A (Abundant, >100). Palaeocological information on taxa and assemblages and the palaeoenvironmental scheme are derived from literature (e.g. Allen 1970; Bonaduce et al. 1975; Wright et al. 1978; Athersuch et al. 1989; Sgarrella & Moncharmont Zei 1993; Yassini & Jones 1995; Meisch 2000; Smith & Horne 2002; Gliozzi & Grossi 2008; Frezza et al. 2009; Faugno et al. 2015; Adegoke et al. 2017) and summarized in figure 4.

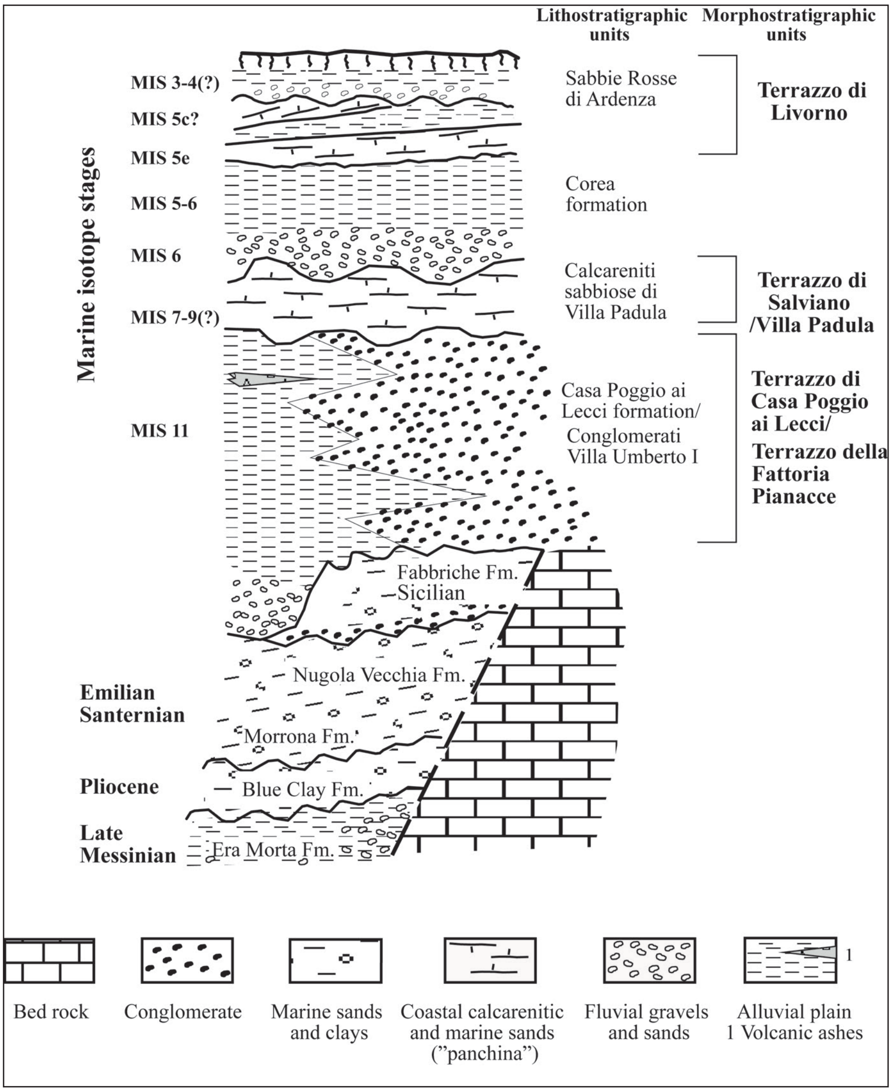

Fig. 2 - Composite stratigraphy of the Livorno area, with lithostratigraphic and morphostratigraphic units, and correlation with marine isotope stages (modified from Zanchetta et al. 2019).

On the whole, 131 core samples and 2 outcrop samples were selected for the analyses of the calcareous nannofossils. The samples were prepared as smeared-slide using standard procedures (Bown & Young 1998). Observations were performed using a polarising light microscope at 1250X magnification. Data were collected in semi-quantitative form, the relative frequencies of index species were defined counting them in term of specimens in a prefixed area of the slide (200 fields of view, roughly corresponding to 4 mm^2). The abundance data are reported as letters, R (Rare, < 1 per mm^2), F (Few, 1-5 per mm^2), C (Common, > 5 per mm^2), A (Abundant, > 10 per mm^2). The selected taxa considered in the nannofossil assemblages are referenced in Young et al. (2017), and we listed theme in Appendix. In this paper for biostratigraphic purpose we used the scheme proposed by Rio et al. (1990), therefore we adopted the biometric subdivision proposed by the authors for the genus *Gephyrocapsa*, so "small *Gephyrocapsa*" is referred as specimens smaller than 4.0 mm in size, "medium *Gephyrocapsa*" is referred as specimens 4.0 − 5.5 mm in size, "large *Gephyrocapsa*" is referred as specimens larger than 5.5 mm in size.

Results and data

Biostratigraphy

Among the samples analysed for the calcareous nannofossil content, only 90 resulted useful to allow a reliable dating of the sediments because several samples were affected by heavily reworking with no autochthonous species observed, or resulted to be barren. In the fruitful samples were detected assemblages referable to the early Pliocene-late Pleistocene MNN biozones of Rio et al. (1990) (Fig. 3).

The early Pliocene MNN13 Zone was recognised on the occurrence of assemblages containing *Amaurolithus delicatus*, *Helicosphaera sellii, Calcidiscus macintyrei*, *Discoaster brouweri*, *Discoaster pentaradiatus*, *Discoaster surculus* and *Sphenolithus abies*. The early Pliocene combined MNN14-15 Zone was recognised on the presence of *C. macintyrei*, *Discoaster asymmetricus*, *D. brouweri*, *D. pentaradiatus*, *Discoaster tamalis*, *H. sellii*, *Pseudoemiliania lacunosa*, *Reticulofenestra pseudoumbilicus* and "small *Gephyrocapsa*".

The early Pleistocene MNN18 Zone was detected on the presence of rare *D. brouwer*i in assemblage with forms of "small *Gephyrocapsa*", *C.*

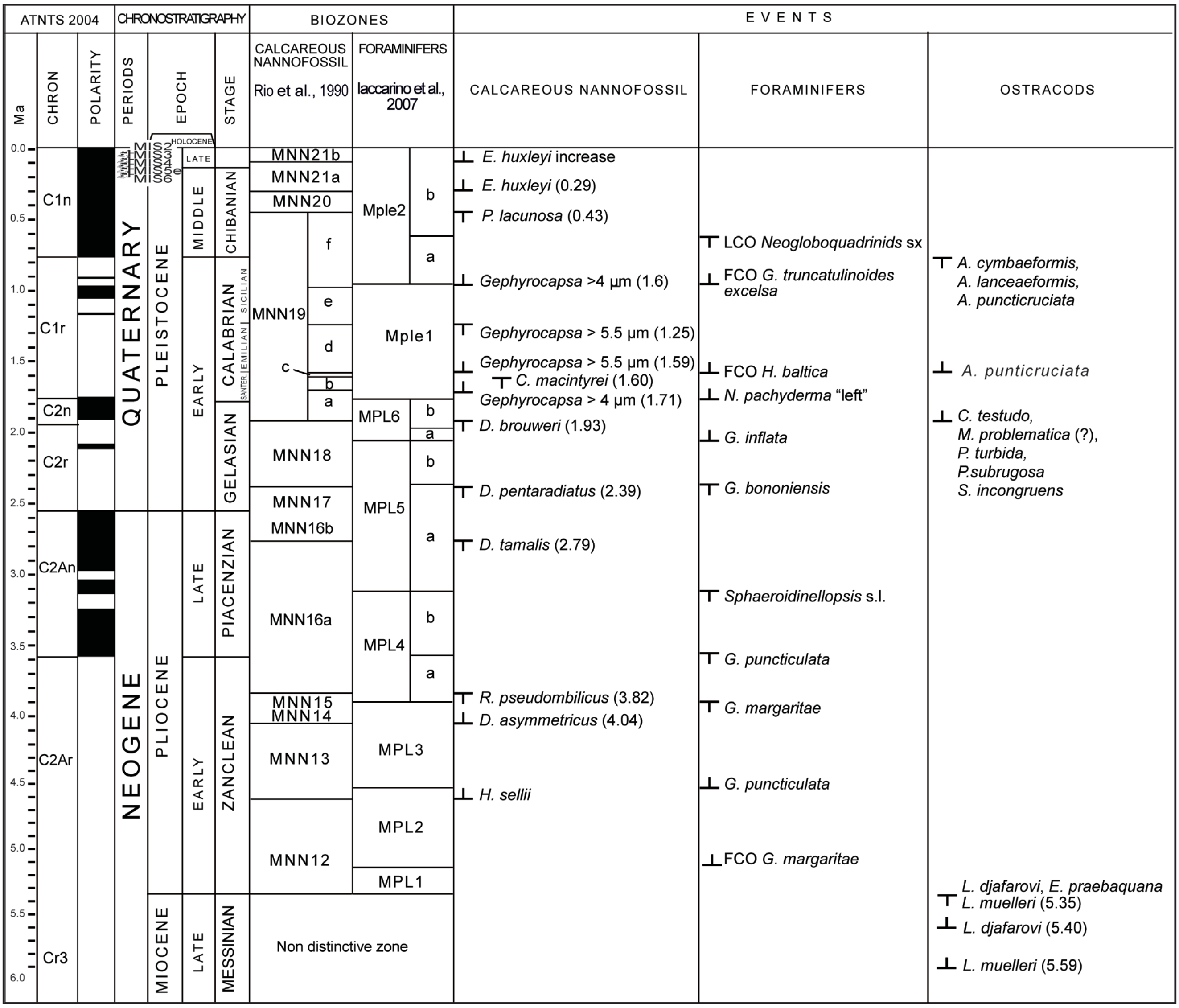

Fig. 3 - Integrated biostratigraphic scheme adopted to date the units occurring in the subsurface of the Livorno area. Biozones are plotted versus the chronostratigraphic scale and Geomagnetic Polarity Time Scale (GPTS, Lourens et al. 2004). The ages of the Marine Isotope Stages (MIS) are from LR04 ^{18}O dataset (Lisieki & Raymo 2005), MIS2=0,029-0,014 Ma, MIS3=0,057-0,029 Ma, MIS4=0,071-0,057, MIS5=0,130-0,071 Ma, MIS6=0,191-0,130 Ma. Calcareous nannofossil biochronology after Raffi et al. (2016). Foraminifer events after Iaccarino et al. (2007), ostracod events after Ruggieri (1973, 1980), Ciampo (1998), Guernet (2005), Dall'Antonia et al. (2004), Faranda & Gliozzi (2008).

macintyrei, *H. carteri*, *H. sellii* and *P. lacunosa*. The early Pleistocene MNN19b Zone was recognised on assemblages where *C. macintyrei* occurs with "medium *Gephyrocapsa*". The early Pleistocene MNN19d Zone was well characterized by the concomitant presence of "large *Gephyrocapsa*", "medium *Gephyrocapsa*" and "small *Gephyrocapsa*". The early Pleistocene MNN19e Zone was recognised on the common to abundant occurrence of "small *Gephyrocapsa*". Finally, assemblages containing rare *Emiliania huxleyi* with scarce to rare "small *Gephyrocapsa*" and "medium *Gephyrocapsa*", were attributed to MNN21a-MNN21b zones.

Stratigraphy, dating and palaeoenvironmental considerations

The boreholes investigated provided a wide range of lithologies and faunal associations that were grouped into different stratigraphic units (Fig. 5) some of which can be correlated with the outcropping formations of the nearby area (all data are summarized in Tab. 2). The units are described below from bottom to top with all the stratigraphic, biostratigraphic and palaeoenvironmental considerations derived both from data collected for this work and comparisons of data found in literature.

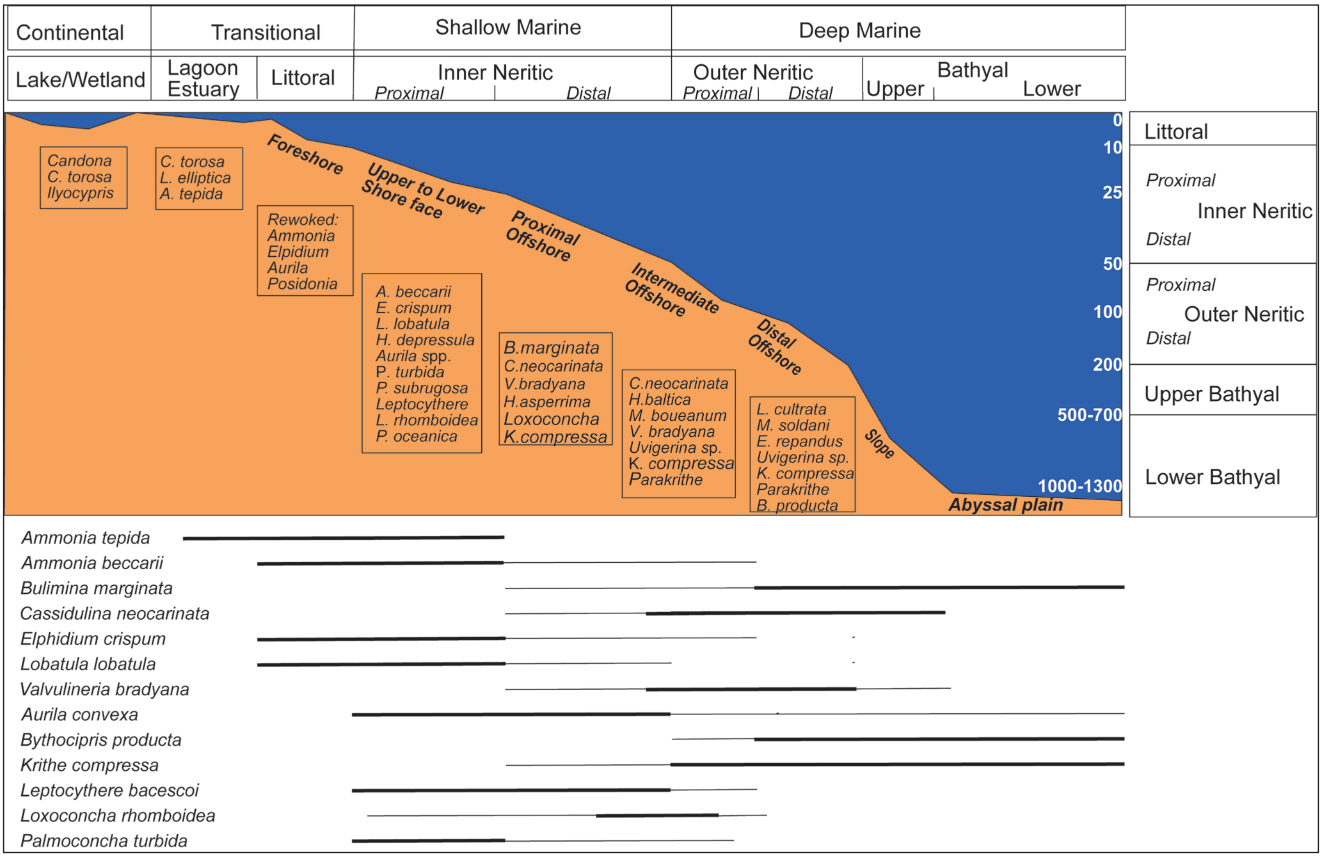

Fig. 4 - Simplified sketch showing the mainly depositional facies and palaeoenvironments (modified from Allen 1970 and Adegoke et al. 2017). The bathymetric zonation is modified from Wright et al. (1978). Ostracod and benthic foraminifer schematic assemblages and bathymetric distribution of selected taxa found out in this work are also shown (see text and table 2 for more explanations).

Unit 1 - This unit includes two lithofacies (1a and 1b). Lithofacies 1a comprises mainly brown silty sands and beige-grey silty clays, sometime with millimetric gypsum crystals. Sporadic intercalations of deposits made of heterometric gravels and sands locally cemented, constitute the 1b. Unit 1 (already described in Bossio et al. 2008), was recovered only in the south-eastern part of the Livorno area (Magrignano-S22 borehole, Fig.6), where its maximum thickness is of about 10 m. The ostracod associations are quite rich and diversified, and are characterized by the common occurrence of the mesohaline species *Loxocorniculina djafarovi*, *Euxinocythere praebaquana, Ammnicythere accicularia, Tyrrhenocythere pontica* and the euryhaline species *Loxoconcha muelleri, Cyprideis* sp. Benthonic foraminifers are represented primarily by *Ammonia tepida* and *Ammonia* spp. *Chara* oogonia and mollusks are also present. These associations indicate continental environment with oligo-mesohaline water (endoreic basin of "Lago-Mare"), as reported in Gliozzi & Grossi (2008).

The occurrence of *Cyprideis* sp. and *L. muelleri* in the lower part of the unit (up to 16 m) allows the recognition of the ostracod late Messinian *Loxoconcha muelleri* biozone of Grossi et al. (2011). The appearance (from 15.80 m) of the paratethyan taxa *L. djafarovi*, *E. praebaquana, Ammnicythere* sp. (Gliozzi 1999) permits the attribution of the upper part of the unit to the *Loxocorniculina djafarovi* biozone of Carbonnel (1978); the first occurrence of *L. djafarovi* can be also related to the astronomical age of 5.40 Ma (Grossi et al. 2011). This unit represents the upper part of the post-evaporitic interval in Italy (Cosentino et al. 2007; Grossi et al. 2011) and can be correlated with the Era Morta River Clays and Gypsum formation, which outcrops in the surrounding area (Mazzanti 2016).

Unit 2 - This unit is mainly characterized by massive grey clays and grey silty sand levels with common mollusks. It was documented in the Banditella, Ardenza-S1 and Salviano-S9 boreholes and in the Scasso outcrop (Figs. 7-10). Its maximum thickness is of about 25 m.

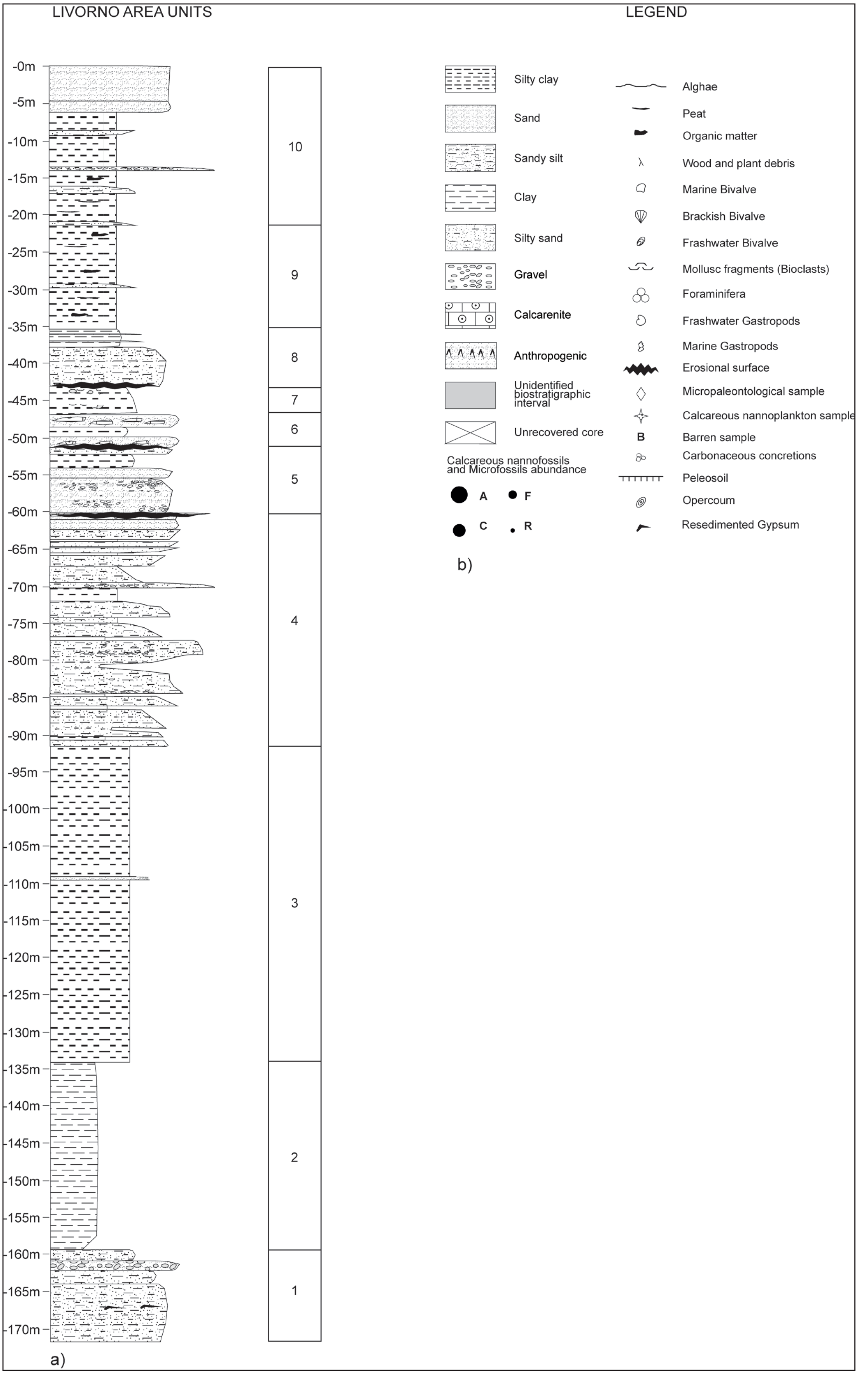

Fig. 5 - a) Schematic stratigraphic log of the units (from 1 to 10) occurring in the subsurface of the Livorno area, reconstructed from the investigated boreholes and outcrop. The thickness of each unit represents its maximum extension. b) Legend of symbols used in figure 6 to 21.

Samples from this unit yield well diversified and well preserved abundant fossils.

The calcareous nannofossils are common in all samples and show good to moderate preservation. The main represented taxa are *C. macintyrei*, *D. asymmetricus, D. pentaradiatus, D. tamalis, D. variabilis*, "small *Gephyrocapsa*", *H. carteri, H. sellii, Pontosphaera* spp., *R. pseudoumbilicus*, and *S. abies*. In the unit the Zanclean zones MNN13 (occurrence of *H. sellii* with *A. delicatus*, Fig. 7) and MNN14-15 (occurrence of *D. asymmetricus* with *P. lacunosa*, Fig. 8), and the Gelasian Zone MNN18 (occurrence of *D. brouweri* and "small *Gephyrocapsa*", see Figs. 9 and 10) were documented.

Samples taken from the clayey lithofacies of the Ardenza-S1 borehole (Fig. 8) contain rich microfossiliferous assemblages that are represented by the foraminifers *Lenticulina cultrata, Lenticulina* spp., *Melonis pompilioides*, *Uvigerina rutila*, *Planulina ariminiensis* and *Sigmoilopsis coelata*, and by the ostracods *Bythocipris obtusata*, *Krithe* spp., *Parakrithe* and *Heryhowella asperrima*. These microfossiliferous assemblages are indicative of the outer neritic zone; in particular the co-occurrence of *Bythocypris* spp. and *Krithe* spp. indicates water deeper than 250 m (Fig. 4, Sciuto et al. 2003; Sciuto & Rosso 2015) and seems to be confined to the MNN14-MNN15 Zone.

Deposits with the same lithologies, referable to MNN18 Zone, were recognised in outcrop (Scasso, Fig. 10) and in the Salviano S9 borehole (Fig.9). In outcrop (Scasso, Fig. 10), in this unit were also identified planktonic foraminifers mostly represented by *Globorotalia aemiliana, Globigerina bulloides, Globigerinoides sacculifer, Orbulina universa, L. cultrata, Siphonina reticulata, S. coelata*, and ostracods manly represented by *Argilloecia* sp., *Henryhowella asperrima, Krithe compressa, Krithe* spp., *Parakrithe* spp. The benthic foraminifers and ostracods indicate that deposition took place at the boundary between the inner and outer neritic zone (Fig. 4).

This unit can be correlated with the Blue Clays Formation that outcrops extensively in the surrounding area.

Unit 3 - This unit is characterized by sandy clays, blue grey sandy silts, with layers of gravels and sands in its lower part.

It was documented in the Magrignano-S22, Via Roma, Via Garibaldi-S2, Viale Carducci, Picchianti-S1 and Via Filzi-S1 boreholes (Figs. 6 and 11-15). Its maximum thickness is of about 40 m.

The calcareous nannofossils are common in all samples showing good to moderate preservation. On the whole, the assemblages contain *Calcidiscus leptoporus, C. macintyrei, Coccolithus pelagicus*, specimens of *Gephyrocapsa muellerae, G. sinuosa*, *G. ericsonii* and *G. oceanica* that were grouped as "small *Gephyrocapsa"* , "medium *Gephyrocapsa*" and "large *Gephyrocapsa*", *H. carteri*, *H. sellii*, *Pseudoemiliana lacunosa* and small specimens of *Reticulofenestra* (between 3.0 and 5.0 µm). Rare and scattered specimens of *Pontosphaera*, *Rhabdosphaera*, *Umbilicosphaera* and very rare specimens belonging to the calcareous dinoflagellate *Thoracosphaera* also occur. Reworking is present with Cretaceous (*Watznaueria*, *Micula*, *Aspidolithus*), and Paleogene (*Toweius, Dictyococcites, Discoaster, Sphenolithus*) taxa. Unit 3 can be attributed to the Santernian MNN 19b Zone on the occurrence of "medium *Gephyrocapsa*" along with *C. macintyrei* (Figs. 6 and 14), and to the Emilian MNN19d Zone on the occurrence of "large *Gephyrocapsa*" (Figs. 11-13 and 15).

A generic Calabrian age for Unit 3 is supported by the occurrence of the ostracods *Palmoconcha subrugosa, Cytheropteron ruggierii* and by the "cold guest" *Cytheropteron testudo*.

The lower part of the unit, referable to Zone MNN19b (Magrignano-S22 and Picchianti-S1 boreholes (Figs. 6, 14), contains *Aurila* spp., *Macrocypris adriatica*, *Urocythereis* sp., *Xestoleberis communis*, that point out the inner neritic zone (Fig. 4). The abundance variations of some taxa (e.g. *Krithe compressa*, see Picchianti-S1 borehole, Fig. 14) also testify bathymetric oscillations. Lithologies and paleobathymetries seem to indicate lower shoreface or proximal offshore. In the part of the unit referable to Zone MNN19d, we recognised a main microfossiliferous association, characterised by the common occurrence of the foraminifers *Valvulineria bradyana*, *Kassidulina neocarinata* and *Bulimina marginata*, and the ostracods *K. compressa* and *Cyrtheropteron* spp. (e.g. *C. ruggieri, C. vespertilio*). In Viale Carducci borehole (Fig. 13), Unit 3 is characterised by the occurrence of deep-water marine species that decrease numerically from the bottom to the top, while shallow-water marine species such as *Palmoconcha turbida* and *Leptocythere multipunctata* show an opposite trend. This reflects a bathymetric decrease in a depositional environment, which was interpreted as proximal offshore, also testified by the monotonous

Unit	Depositional system	Schematic lithostratigraphic description	Significant Foraminifers	Significant Ostracods	Significant calcareous nannofossils	Biozone/MIS	Age of MISs: after Lisiecki & Raimo, 2005. Age of biozonal events after Raffi et al., 2016	Epoch/Stage	Paleoenvironment	Thickness	Hypothetical correlations with nearby outcropping formations
10	Foreshore to Shoreface	Sandy silts and silts with algae. Alternating coarse sands, silts and sands	*A. beccarii, N. boueanum, E. crispum, Quinqueloculina* spp., *H. depressula, Triloculina* spp.	*Aurila* spp., *Loxoconcha* spp., *Xestoleberis* spp	*Emiliania huxleyi, Gephyrocapsa* spp.	MNN21 p.p. MIS1	11.7 ky to recent	Holocene	Marine transitional	max 15 m	Holocene deposits (Sarti et al. 2015)
9	Wetland, pound, lake	Sandy silts and silty clayey sands		*Candona neglecta, Ilyocypris gibba*		MIS3 to MIS2	57.0 to 29.0 kyr	Late Pleistocene Tyrrhenian	Continental	max 23 m	Pleistocene continetal deposits (Sarti et al. 2015)
8	Aeolic and fluvial	Yellow orange sandy silts and silty sands, with millimetric nodules of Fe-Mn				MIS4 to MIS3	71.0 to 57.0 kyr	Late Pleistocene Tyrrhenian	Continental	max 10 m	Ardenza Sands (Sabbie di Ardenza, Sabbie di Donoratico, Mazzanti 2016)
7	Alluvial Plain, fluvial channel	Silts, sands and gravels in alternating layers				MIS5d to MIS4	109.0 kyr	Late Pleistocene Tyrrhenian	Continental	max 4 m	Rio Maggiore Conglomerates (Conglomerati di Rio Maggiore, Lazzarotto et al. 1990)
6	Foreshore to shoreface	Ochre-orange sandy silts, silty sands with layers of fossiliferous calcarenites. Clays, silts and sands	*Ammonia beccarii, L. lobatula, Elphidium crispum, Quinqueloculina* spp.	*Semicytherura incongruens, Urocythereis* gr. *margaritifera*		MIS5e	123.0 kyr	Late Pleistocene Tyrrhenian	Marine and Continental	?	Panchina and continental level (Calcareniti di Castiglioncello, Mazzanti 2016)
5	Lake, alluvial plain, fluvial channel	Grey silty clays with peat layers. Grey sands or grey silty clays. Fine coarse sands. Well rounded polygenic gravels		*Candona neglecta, Ilyocypris gibba, Cyprideis torosa*		MIS6	191.0 kyr	Middle Pleistocene Chibanian	Continental	max 10 m	Corea Formation (Formazione di Corea, Zanchetta et al. 2006)
4	From upper to lower shoreface	Sands and sandy gravels. Silts and sands	*Ammonia* spp., *Bulimina marginata, Cassidulina neocarinata, D. gibbosa, Elphidium* spp., *V. bradyana*	*A. cymbaeformis, A. lancaeformis , A. punctata, A. punticruciata, Pontocythere turbida, Semicytherura incongruens*	small (<4μm) *Gephyrocapsa* spp.	MNN19e	1.25 to 1.06 Myr	Early Pleistocene Sicilian	Marine	max 20 m	Fabbriche Sands (Sabbie delle Fabbriche, Bartoletti et al. 1986)
3	From upper to lower shoreface	Grey blue clays and silty clays. Rare levels of scattered pebbles	*Ammonia* spp., *C. neocarinata, Elphidium crispum, Valvulineria bradyana*	*Aurila convexa, C. ruggierii, Krithe* spp., *Palmoconcha subrugosa, Sagmatocythere versicolor*	large (>5.5 μm) *Gephyrocapsa* spp., medium(> 4 μm) *Gephyrocapsa* spp., small (< 4 μm) *Gephyrocapsa* spp., *Helicosphaera sellii, Pseudoemiliania lacunosa*	MNN19d	1.59 to 1.25 Myr	Early Pleistocene Emilian	Marine	max 45 m	Morrona Formation (Sabbie e Argille ad *Artica islandica*, Costantini et al. 2002; Formazione di Morrona, Boschian et al. 2006)
				Aurila spp.,*Pontocythere turbida, K. compressa, S. incongruens, Urocythereis* sp., *Xestoleberis* sp.	medium > 4(μm) *Gephyrocapsa* spp., *Calcidiscus macintyrei*	MNN19b	1.71 to 1.60 Myr	Early Pleistocene Santernian-Emiliano			
2	From lower shoreface to offshore	Massive grey to blu clays. Grey siltys, fine sands with laminated levels	*P.ariminensis, Lenticulina cultrata, Siphonina reticulata, S. coelata*	*Argilloecia* spp., *Cytherella russoi, H. asperrima, Krithe* and *Parakrithe*	*Discoaster brouweri*	MNN18	2.39 to 1.93 Myr	Early Pleistocene Gelasian	Marine	max 25 m	Blue Clays (Argille Azzurre, Costantini et al. 2002)
			Lenticulina cultrata, Lenticulina spp., *Melonis soldanii, Uvigerina rotula, Planulina ariminiensis, Sigmoilopsis coelata*	*Bythocipris producta, Krithe* spp., *Henryhowella asperrima, Parakrithe* spp.	*Discoaster asymmetricus, D. brouweri, D. pentaradiatus, D.tamalis, P. lacunosa, R. pseudoumbilicus,* small(<4μm)*Gephyrocapsa* spp., *Sphenolithus abies*	MNN14/15	4.04 to 3.82 Myr	Early Pliocene Zanclean			
					Amaurolithus delicatus, Helicosphaera sellii, D. brouweri, D. pentaradiatus, D.surculus, R. pseudoumbilicus, Sphenolithus abies	MNN13	4.58 to 4.04 Myr				
1	Endoreic basin	1b. Heterometric and polygenic gravels, locally cemented				*Loxocorniculina djafarovi Zone*	5.40 to 5.33 Myr	Late Miocene Late Messinian	Continental	13 m	Clays and Gypsum of Era Morta River (Argille e gessi del F. Era Morta, Mazzanti 2016)
		1a. Beige-white silts and silty clays		*Amnicythere* spp., *Cyprideis* sp. *E. praebaquana, L. djafarovi, Loxoconcha muelleri*		*Loxoconcha muelleri Zone*					

Tab. 2 - Summary of all data collected for the units recognised in the Livorno area. The reported foraminifers and ostracods are useful to identify the different environments, calcareous nannofossils allow for recognising the biozones proposed by Rio et al. (1990) for the Western Mediterranean. The biochronology of the calcareous nannofossil events is that proposed by Raffi et al. (2016). The ages of Marine Isotope Stages (MIS) are those proposed by Lisiecki & Raymo (2005).

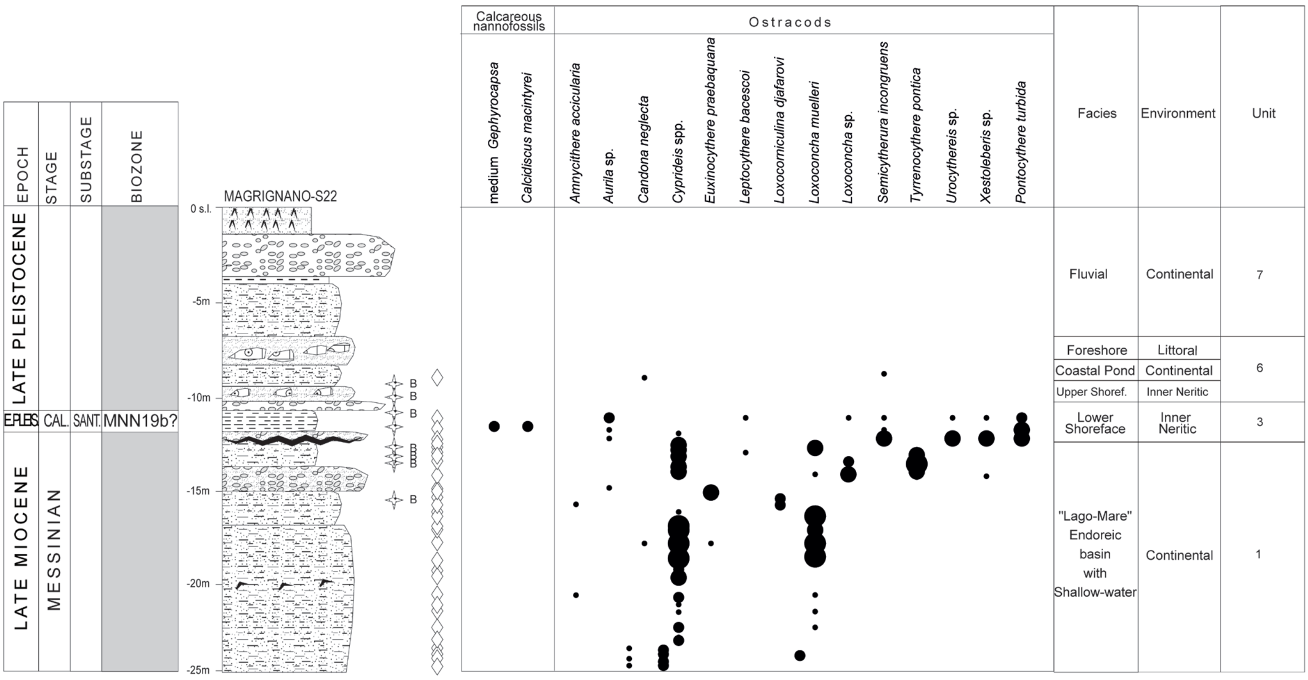

Fig. 6 - Stratigraphic log of the Magrignano-S22 borehole with the range chart of selected calcareous nannofossils and microfossils (modified from Bossio et al. 2008). For symbols see legend in Fig. 3.

fine lithologies.

Lithologies, age and microfaunal content link this unit with the Morrona Formation, consequently it is also etheropic with the Nugola Vecchia Sands (Boschian et al. 2006, and references therein).

Unit 4 - This unit is composed of sands and sandy gravels overlain by a succession of silty-sandy to clay sediments.

It was documented in the Via Pompilia-S3, Porto Mediceo-S3, Calata Magnale-S7 and Torre Marzocco-S1 boreholes (Figs. 16-19). Its maximum thickness is of about 30 m.

The most represented calcareous nannofossil specimens are "small *Gephyrocapsa*", the amount of which varies from common to abundant. This calcareous nannofossils data ascribe the unit to the Sicilian MNN19e Zone.

Fragments of echinoids, and marine mollusks are frequent. The microfaunal assemblages are characterized by abundant well diversified foraminifers (e.g. *Ammonia beccarii, A. tepida, Elphidium crispum, Hyalinea baltica*, *Nonion boueanum*) and common ostracods (*Aurila cymbaeformis, A. lancaeformis*, *A. punctata* and *A. punticruciata* gathered as *Aurila* spp*., Bosquetina dentata, Cytheridea neapolitana, K. compressa, Loxoconcha ovulata, Muellerina problematica, Neocytherideis fasciata, P. subrugosa, P. turbida* and *Pterygocythereis jonesi*). In particular, two main biofacies can be distinguished. In the first one benthic foraminifers occur with abundant *A. beccarii, Quinqueloculina seminula*, and common *Ammonia parkinsoniana, E. crispum, Lobatula lobatula* and *N. boueanum*, while ostracods mainly consist of *P. turbida, Pontocyhere turbida* and *Aurila convexa.* These microfauna are characteristic of the proximal inner neritic zone, and the mostly sandy lithology in which they occur, is indicative of upper-lower shoreface (Fig. 4, Tab. 2). In the second biofacies, shallow-water taxa (e.g. *Aurila, Ammonia, Elphidium, Lobatula*) are numerically less represented and in association with frequent specimens of *C. neocarinata*, *V. bradyana*, *Bosquetina carinella* and *P. jonesii.* This assemblage indicates the distal inner neritic zone, and the lithological characters are indicative of proximal offshore (Fig. 4, Tab. 2). The presence of *A. cymbaeformis, A. lancaeformis, A. punctata, A. punticruciata* and *Hyalinea baltica* allows the attribution of the unit to the early Pleistocene (Fig. 3).

Age and lithologies allow the correlation of this unit with the Fabbriche Sands formation (Bartoletti et al. 1986; Boschian et al. 2006 and references therein).

Unit 5 - This unit comprises well rounded polygenic gravels with a grey sandy or silty matrix, passing upward and laterally into grey sands or grey

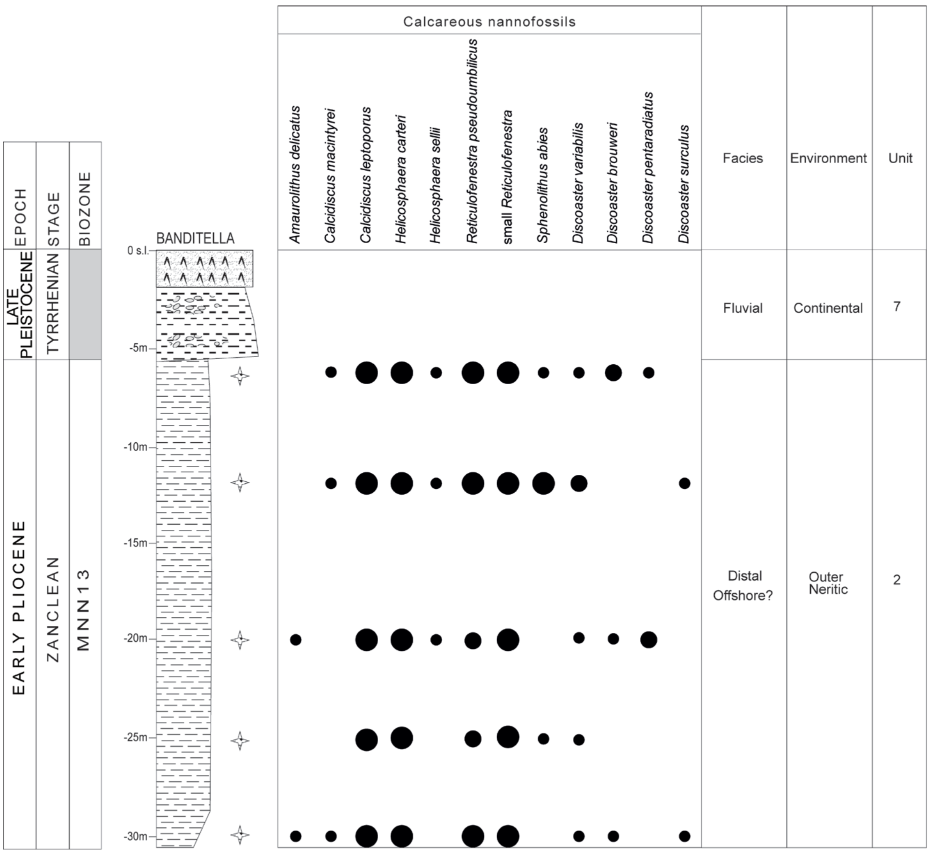

Fig. 7 - Stratigraphic log of the Banditella borehole with the range chart of selected calcareous nannofossils. For symbols see legend in figure 5.

silty clays. In the upper portion of the unit there are dark organic clays locally passing to a peat layer.

This unit was recorded in the Picchianti-S1 and Via Filzi-S1 boreholes, where its maximum thickness is of about 10 m (Figs. 14-15).

In this unit it is present a microfauna represented by ostracods (*Candona neglecta, Ilyocypris gibba* and *Cyprideis torosa*), and a macrofauna represented by mollusks (*Galba truncatula, Anisus spirorbis, Gyraulus crista, Valvata cristata* and *Bithynia*).

Fauna and lithological characters, found in the sandy sediments of this unit (Picchianti-S 1 borehole, Fig. 14), allow us to infer an estuarine system that moves towards a continental environment. In the Via Filzi borehole (Fig. 15), this unit is represented by sandy gravel sediments, with a fining-upward sequence, that are interpreted as fluvial deposits passing to freshwater lake deposits (Fig. 4).

On the basis of lithological and micro-macrofaunistical similarities, this unit may correspond to the middle-late Pleistocene Corea formation of Zanchetta et al. (2006), dated to MIS6 and its transition to MIS5 (Fig. 22).

Unit 6 - It consists of calcarenitic layers, grey and orange sands, and locally clayey silts levels.

This unit was documented in the Magrignano-S22, Ardenza-S1, Salviano-S9, Via Roma, Picchianti-S1, Via Filzi-S1 and Torre Marzocco-S1 boreholes (Figs. 6, 8, 9, 11, 14, 15 and 19).

Its maximum thickness is of about 4 m.

On the whole, the unit is represented by lithologies unsuitable for micropaleontological analyses (Dall'Antonia et al. 2004); however, we were able to prepare few samples from not cemented lithologies that contain a fauna rich in ostracods, represented by *Aurila* spp., *Loxoconcha elliptica, N. fasciata, N. subspiralis, P. subrugosa, Po. turbida, Semicytherura incongruens* and *S. rarecostata*, and foraminifers, which are mostly represented by *A. beccarii, E. crispum* and *L. lobatula*. In the calcarenitic layers present in in the subsurface of the harbour area (Torre Marzocco-S1, Fig. 19), marine mollusks (e.g. *Vermetus* and *Lithodomus* holes) were also found. These assemblages are typical of littoral environment (Fig. 4).

The occurrence of *P. turbida* and *S. incongruens* allows the attribution of the unit to a generic Quaternary. However, thanks to the presence of the characteristic calcarenitic layers, this unit may be linked to the "Panchina I" (corresponding to the "Calcareniti di Castiglioncello" of Mazzanti 2016), that was attributed to the middle-late Pleistocene

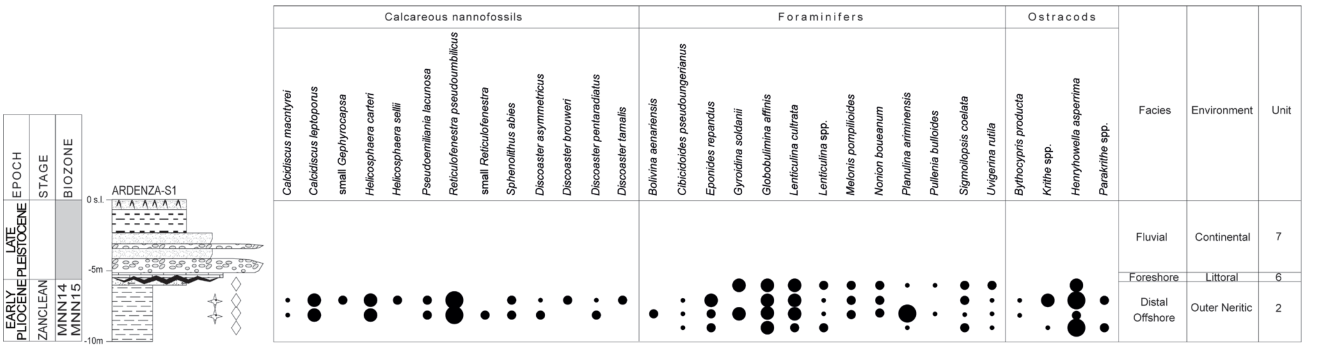

Fig. 8 - Stratigraphic log of the Ardenza-S1 borehole with the range chart of selected calcareous nannofossils and microfossils (benthic foraminifers and ostracods). For symbols see legend in figure 5.

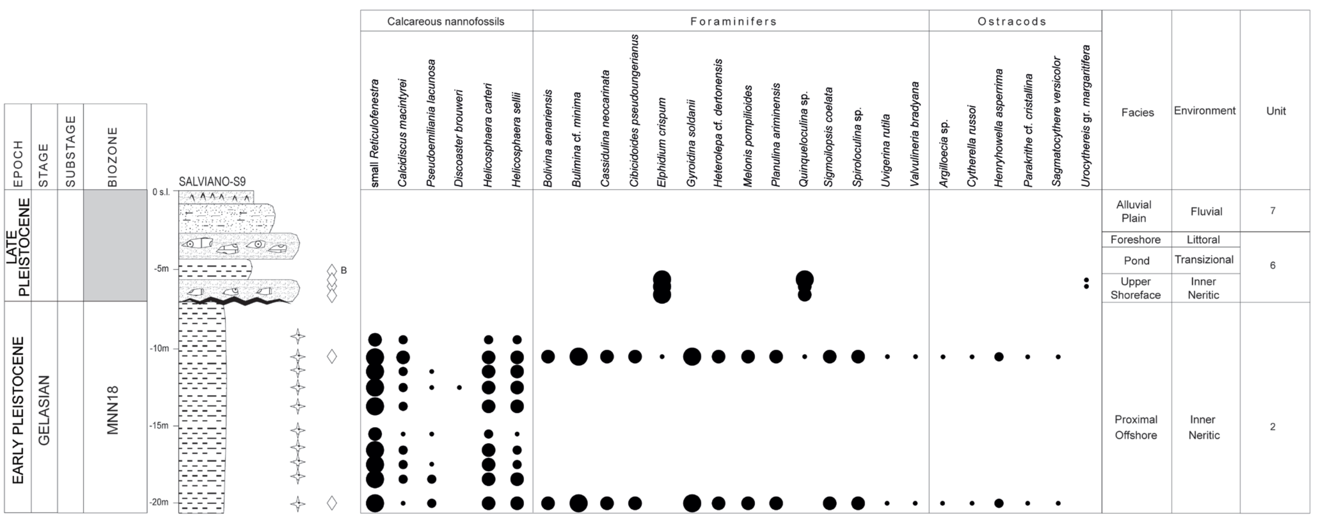

Fig. 9 - Stratigraphic log of the Salviano-S9 borehole with the range chart of selected calcareous nannofossils and microfossils (benthic foraminifers and ostracods). For symbols see legend in figure 5.

MIS5e (Fig. 22; Zanchetta et al. 2004; Zanchetta et al. 2006 and references therein).

For what regards the calcarenitic layer that occurs in the Magrignano-S22 borehole (Fig. 6), its altitude above sea level, which now results to be at about 20 m, and its stratigraphic position, led some authors to correlate these deposits with the Villa Padula Calcarenite formation (dated to MIS 7 or MIS9c hightstand by Bossio et al. 2008).

Unit 7 - This unit comprises alternating layers of silts, sands and gravels. It was documented in the Banditella, Ardenza-S1, Salviano-S9, Via Roma and Via Pompilia-S3 boreholes (Figs. 7-9, 11 and 16). Its maximum thickness is of about 3 m.

It is barren of fossils. This unit may correspond to the late Pleistocene Rio Maggiore Conglomerates and to all those fluvial deposits related to the fluvial activity of the late Pleistocene in the surrounding area (e.g. Ardenza and Cignolo streams), which are related to the MIS5d (Fig. 22), because of their stratigraphic position on top of the "Panchina I" (Ciampalini et al. 2006; Bossio et al. 2008).

Unit 8 - This unit includes well rounded sands and reddish silts and silty sands, with millimetric nodules of Fe-Mn. Silts and sands are barren of fossils and locally appear pedogenized. It was documented in the Via Garibaldi-S2, Picchianti-S1 and Via Filzi-S1 boreholes (Figs. 12, 14 and 15) and in the Scasso outcrop (Fig. 10). Its maximum thickness is of about 5 m.

Lithologies are barren of fossils and interpreted as eolian and fluvial deposits.

Stratigraphic and lithological considerations,

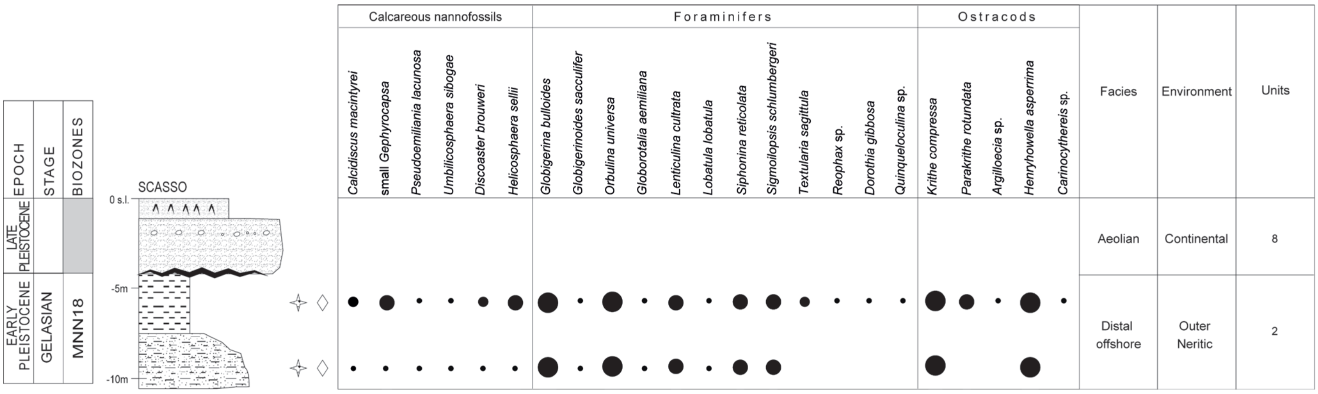

Fig. 10 - Stratigraphic log of the Scasso outcrop with the range chart of selected calcareous nannofossils and microfossils (foraminifers and ostracods). For symbols see legend in figure 5.

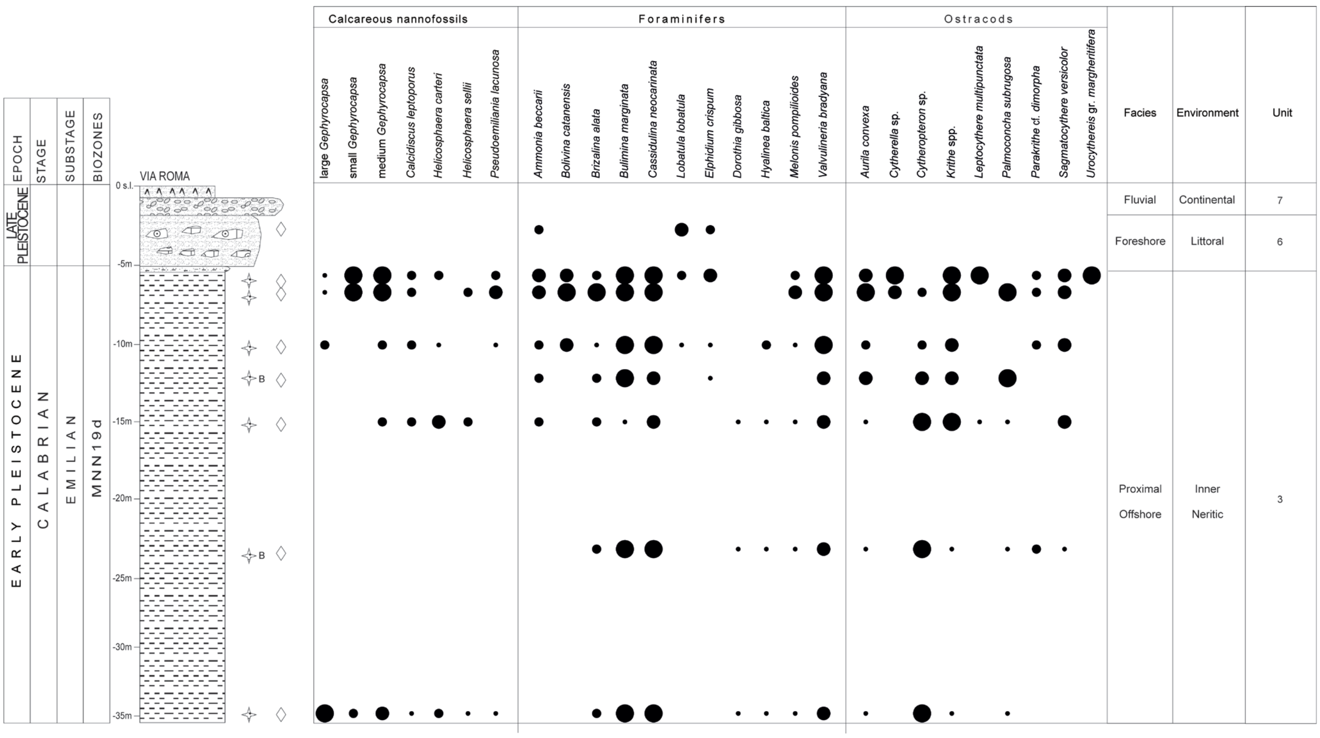

Fig. 11 - Stratigraphic log of the Via Roma borehole with the range chart of selected calcareous nannofossils and microfossils (benthic foraminifers and ostracods) taxa. For symbols see legend in figure 5.

mostly based on the characteristic presence of millimetric nodule of Fe-Mn, for intense pedogenesis, allow the correlation of the unit with the Ardenza Sands (Ciampalini et al. 2006; Bossio et al. 2008) and the Donoratico Sands (see Boschian et al. 2006), and its attribution to the late Pleistocene. Ciampalini & Sammartino (2007), on the presence of Mousterian tools (Middle Paleolithic), linked the Ardenza Sands to the late Pleistocene MIS4 to MIS3 isotopic stages (Fig. 22), which embrace great part of the Wurm glacial stage. Due to this correlation we could infer a similar age for Unit 8.

Unit 9 - This unit includes sandy silts and silty-clayey sands. It was documented in the Calata Magnale-S7, Darsena-SA and Paduletta boreholes (Figs. 18, 20 and 21). Its maximum thickness is of about 22 m.

The ostracofauna analysed in the Darsena-SA borehole, consists of *Candona neglecta* and *Ilyocypris gibba* with very rare benthic foraminifera specimens reworked. This micropaleontological assemblage indicates a freshwater or oligohaline continental palaeoenvironment (Fig. 4, Tab. 2). The macrofauna are mostly represented by fresh water mollusks (e.g.

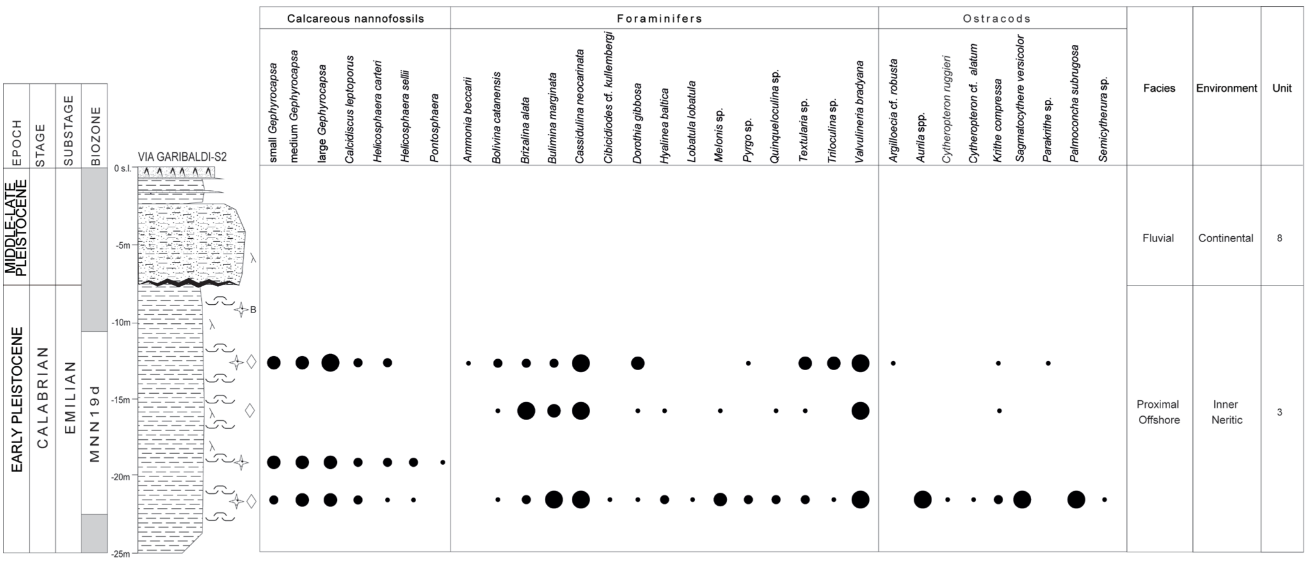

Fig. 12 - Stratigraphic log of the Via Garibaldi-S2 borehole with the range chart of selected calcareous nannofossils and microfossils (benthic foraminifers and ostracods) taxa. For symbols see legend in figure 5.

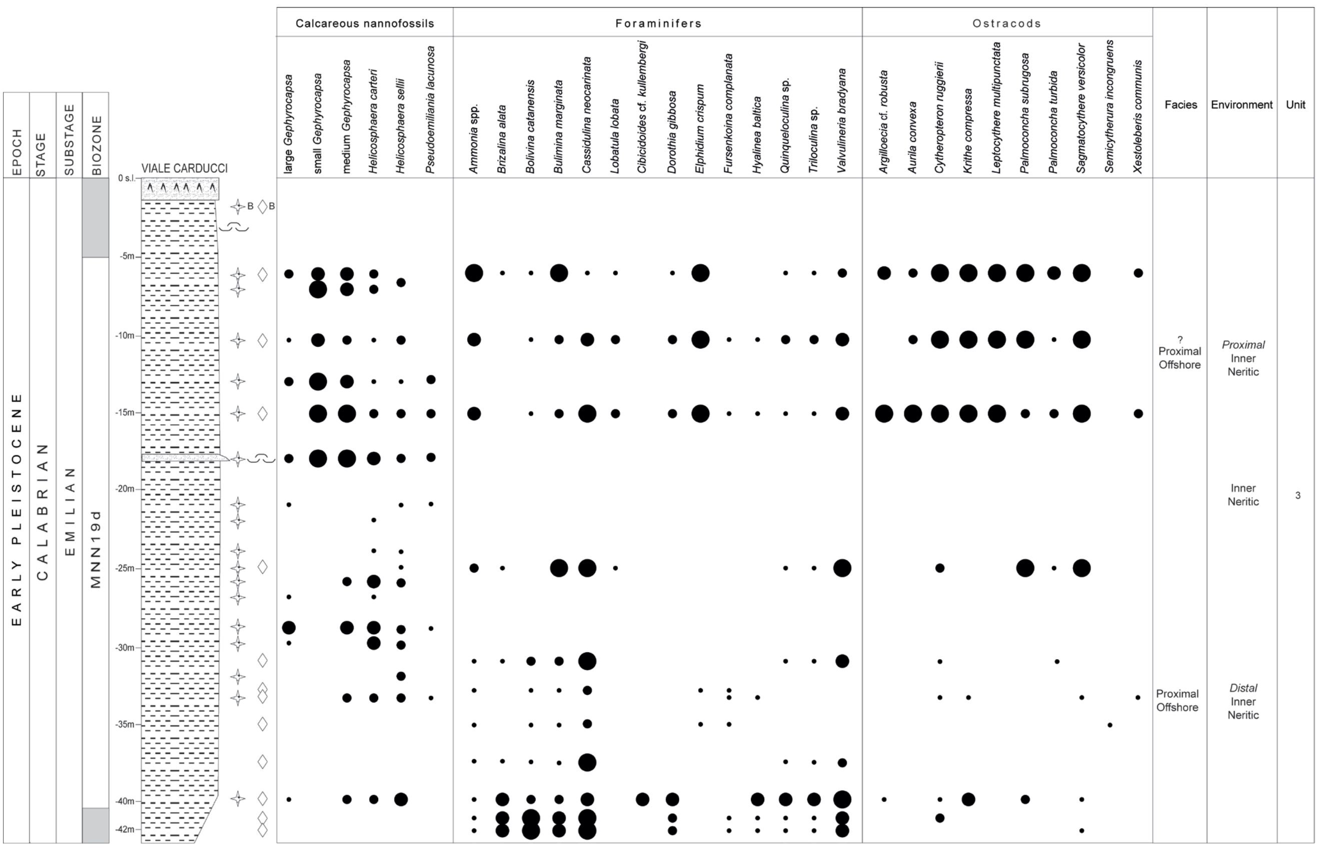

Fig. 13 - Stratigraphic log of the Viale Carducci borehole with the range chart of selected calcareous nannofossils and microfossils (benthic foraminifers and ostracods) taxa. For symbols see legend in figure 5.

Ancylus, Bithynia and *Pisidium*) and land snails mollusks (e.g. *Carychium, Punctum* and *Vallonia*).

The litholocical and faunal features, match very well with those of other continental deposits reported in literature (Federici 1993; Antonioli et al. 2000; Dall'Antonia et al. 2004). Stratigraphic

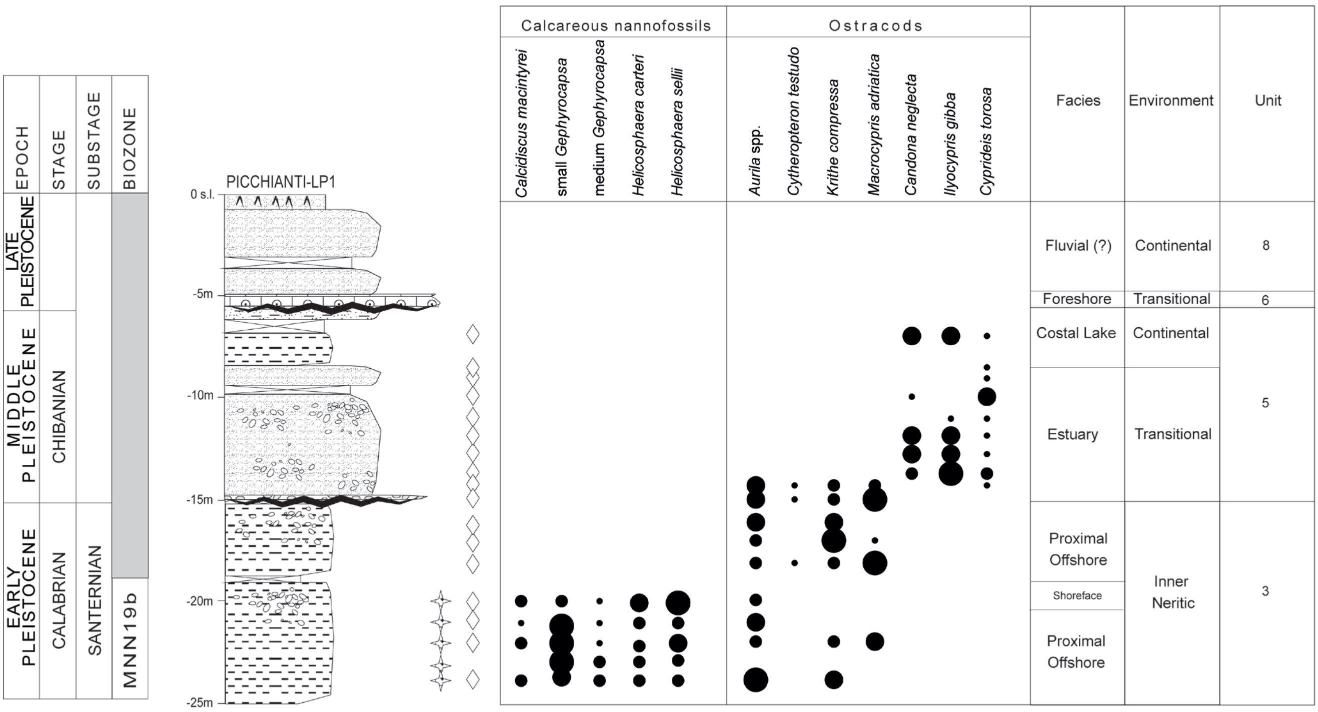

Fig. 14 - Stratigraphic log of the Picchianti-S1 borehole with the range chart of selected calcareous nannofossils and microfossils (ostracods) taxa (modified from Ciampalini et al. 2013). For symbols see legend in figure 5.

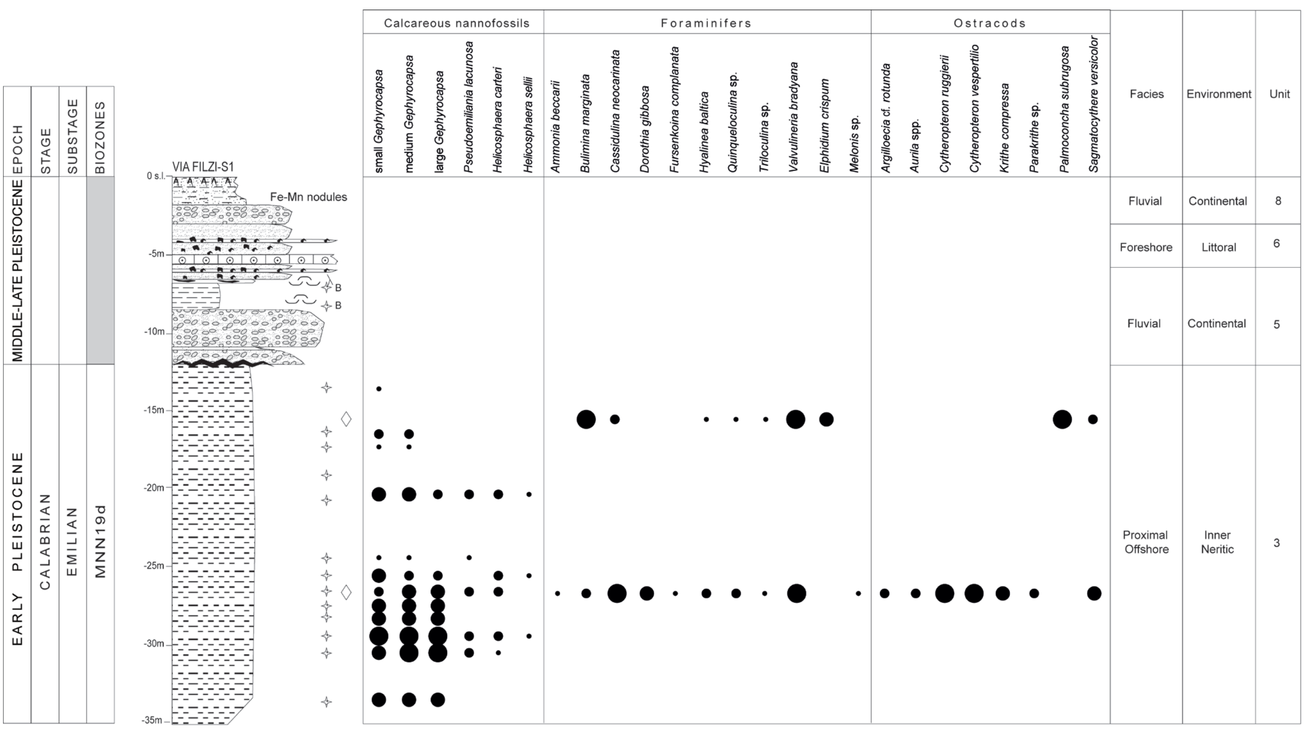

Fig. 15 - Stratigraphic log of the Via Filzi-S1 borehole with the range chart of selected calcareous nannofossils taxa. For symbols see legend in figure 5.

considerations and correlation with near boreholes suggest a late Pleistocene age, probably linked with MIS2 (Dall'Antonia et al. 2004).

Unit 10 - This unit consists of fine to coarse sands, alternating silts and sands, locally with metric levels of *Posidonia oceanica*. It was detected in the

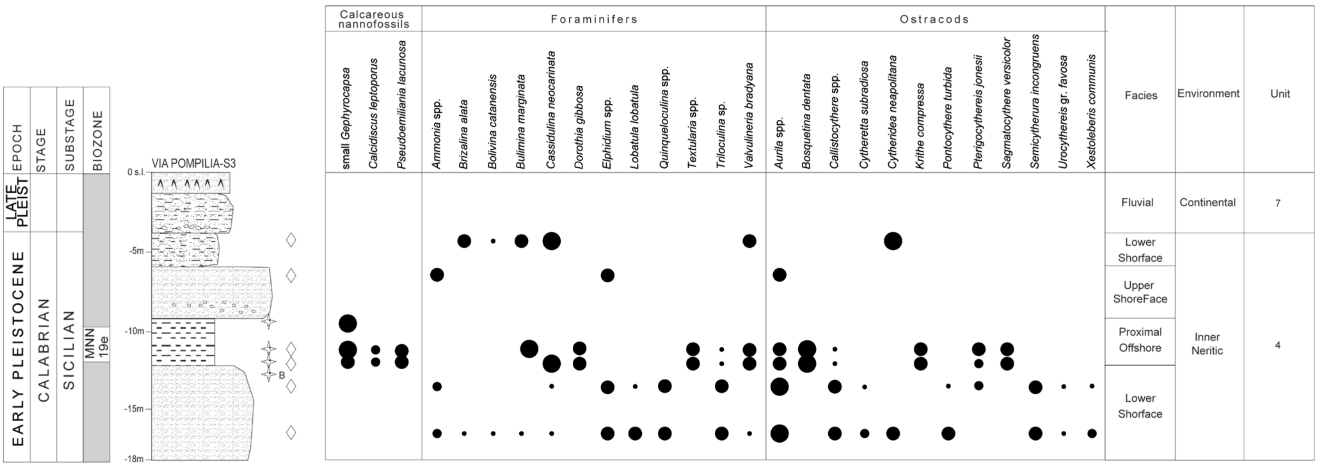

Fig. 16 - Stratigraphic log of the Via Pompilia-S3 borehole with the range chart of selected calcareous nannofossils and microfossils (benthic foraminifers and ostracods) taxa. For symbols see legend in figure 5.

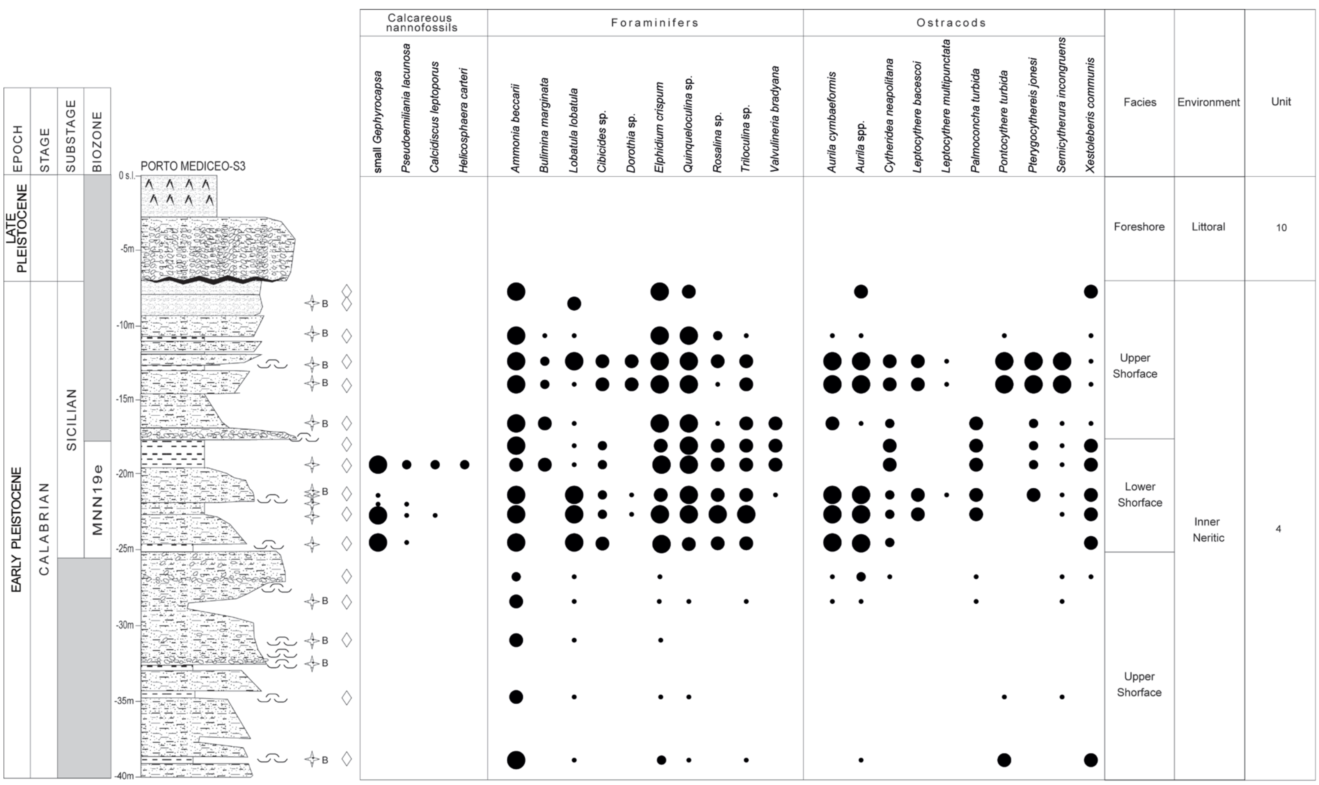

Fig. 17 - Stratigraphic log of the Porto Mediceo-S3 borehole with the range chart of selected calcareous nannofossils and microfossils (benthic foraminifers and ostracods) taxa. For symbols see legend in figure 5.

Porto Mediceo-S3, Calata Magnale-S7, Torre Marzocco-S1, Darsena-SA, and Paduletta boreholes (Figs. 17-21). Its maximum thickness is of about 15 m.

Few samples, containing scarce calcareous nannofossils represented by *E. huxleyi* with "small *Gephyrocapsa*" and "medium *Gephyrocapsa*", permit us to refer the unit to an interval of time corresponding to the middle-late Pleistocene-Holocene MNN21a-MNN21b zones.

The ostracodfauna are mostly represented by *Aurila* spp., *Loxoconcha* spp., *Xestoleberis* spp. The main represented foraminifers are *A. beccarii*, *N. boueanum*, *E. crispum*, *Quinqueloculina* spp., *Haynesina depressula* and *Triloculina* sp. Marine molluska (e.g. *Chlamys*, *Venus, Nucula* and *Tellina*) also occur. These fossil assemblages characterise the proximal inner neritic zone (Fig. 4).

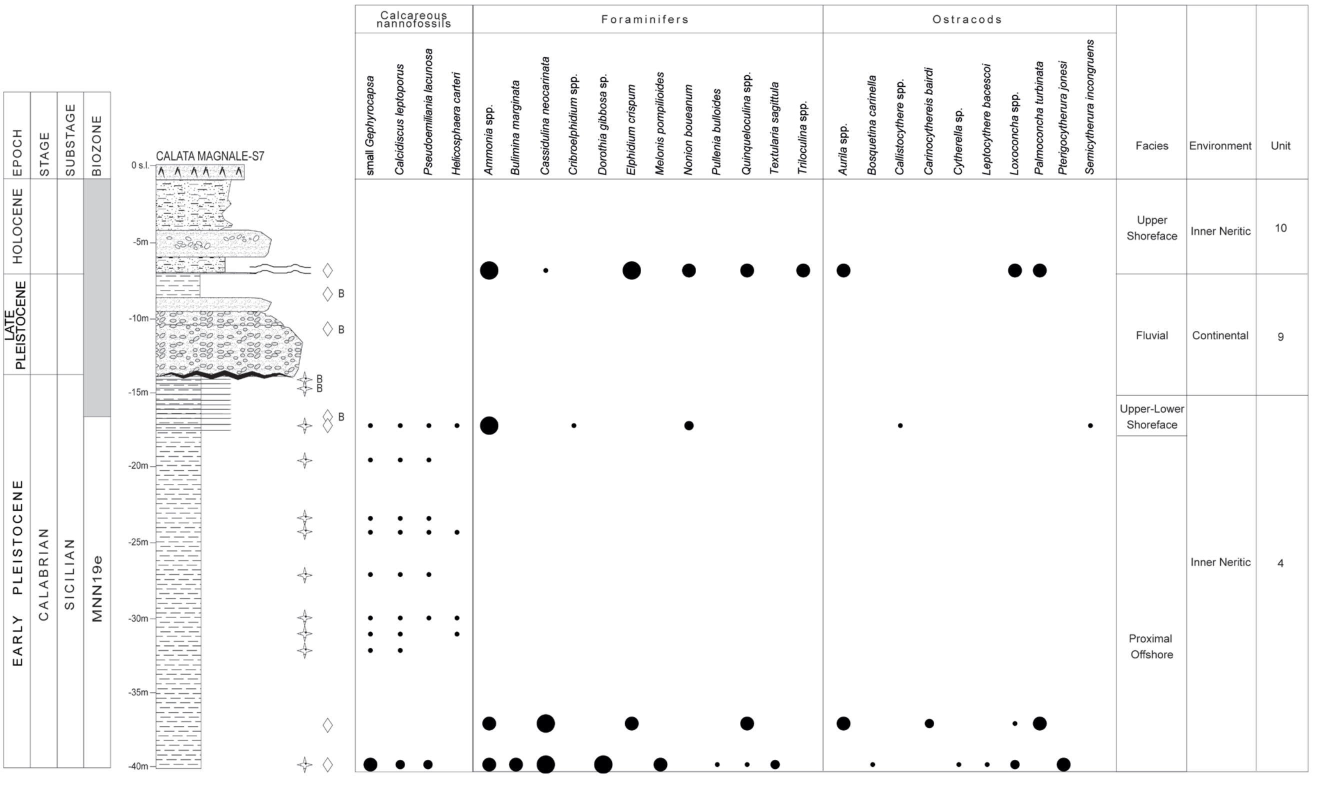

Fig. 18 - Stratigraphic log of the Calata Magnale-S7 borehole with the range chart of selected calcareous nannofossils and microfossils (benthic foraminifers and ostracods) taxa. For symbols see legend in figure 5.

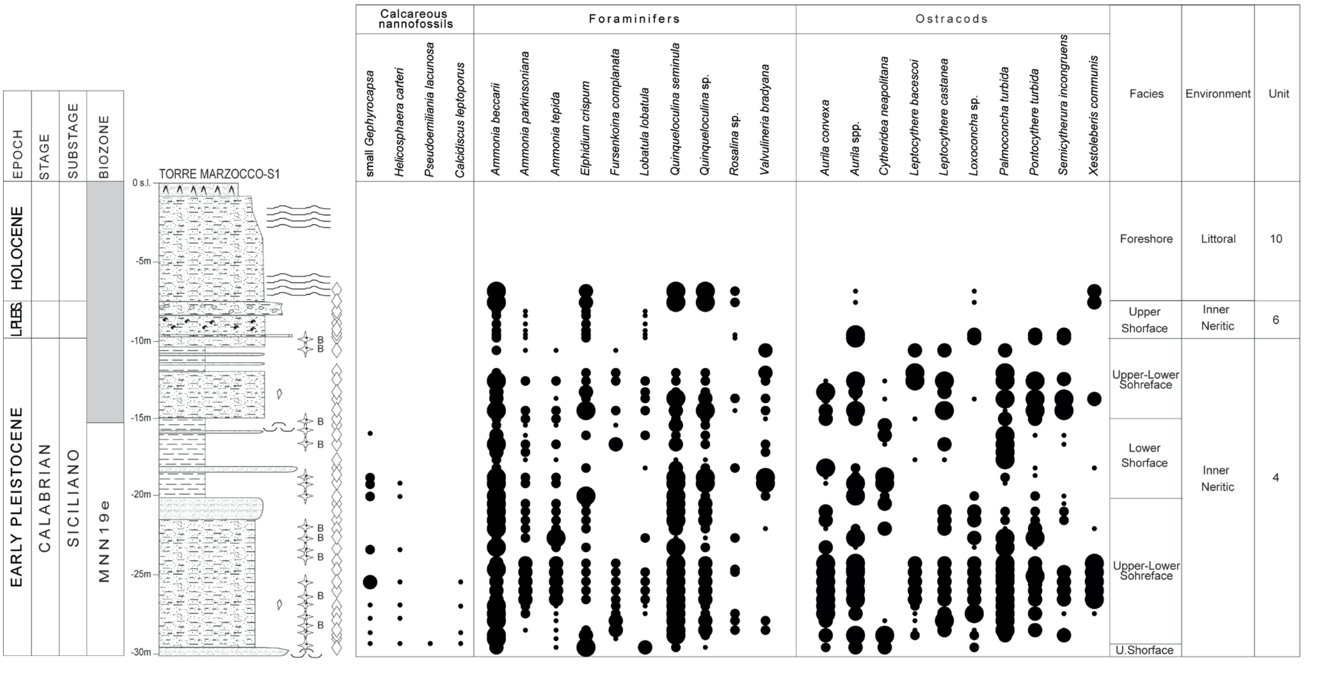

Fig. 19 - Stratigraphic log of the Torre Marzocco-S1 borehole with the range chart of selected calcareous nannofossils and microfossils (benthic foraminifers and ostracods) taxa. For symbols see legend in figure 5.

The palaeoenvironment, the lithologies and the richness of *Posidonia oceanica* remains, allow us to relate the Unit 10 to the Holocene sediments of the Versilian transgression (Dall'Antonia et al. 2004), which brought the sea to the present-day level, starting from the end of the last glacial maximum (transition from MIS2 to MIS1, Fig. 22).

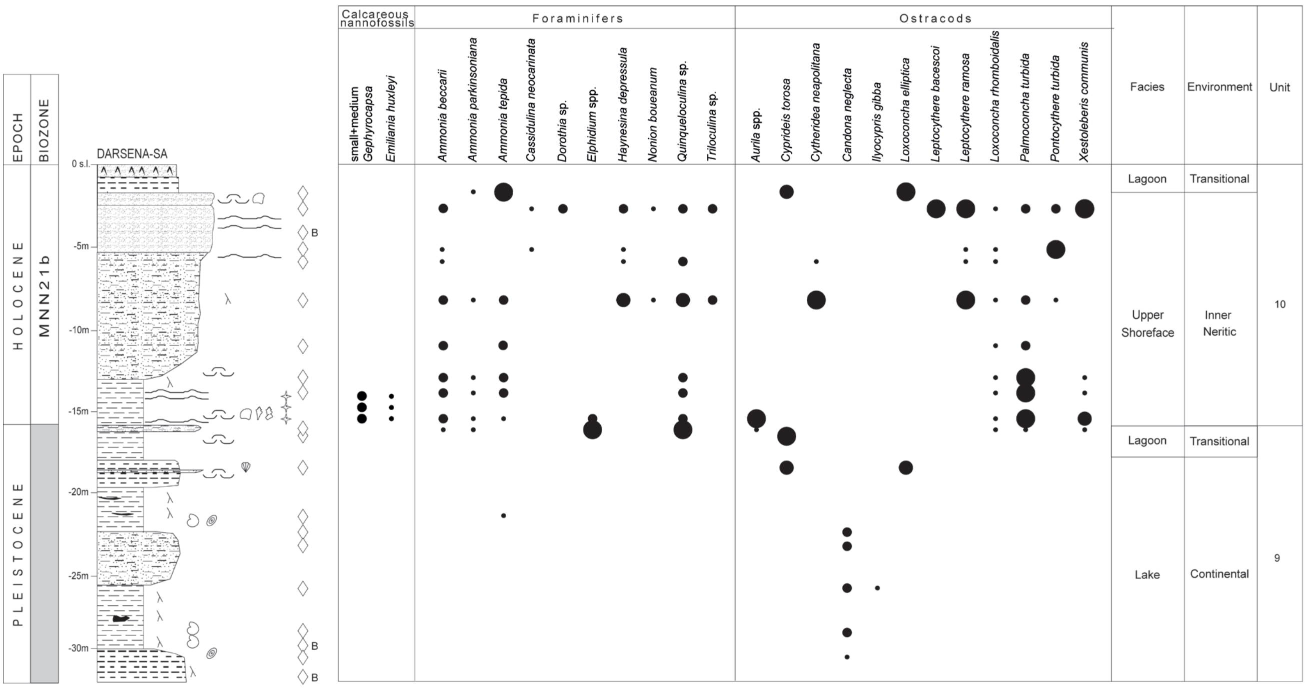

Fig. 20 - Stratigraphic log of the Darsena-SA borehole with the range chart of selected calcareous nannofossils and microfossils (benthic foraminifers and ostracods) taxa. For symbols see legend in figure 5.

Discussion and conclusion

The different units were characterised through lithofacies analysis, taking into account lithology, micropalentological and macropaleontological content. In addition, where it was possible, they were biostratigraphically constrained. Furthermore, on the basis of their lithologies and faunal and floral contents they were correlated to lithostratigraphic units described in literature and outcropping in the surrounding area. So, we can tell a reliable palaeoenvironmental story of this area spanning the late Messinian to Holocene time interval (Tab. 2). For the subsurface stratigraphic study of the Livorno area, a data set of continuous logs of cores derived from the IGG-DATABASE was also used (location in Fig. 1). On the basis of these data, we performed four schematic geological cross-sections, which depict the stratigraphic architecture (Fig. 23).

The continental deposits of Unit 1, were found exclusively in the south-eastern area of Livorno (Section 1, Fig 23). Micropaleontological content and lithologies show that an endoreic basin, with oligo-mesohaline waters, developed during the late Messinian, as it occurred in other areas of the Mediterranean (Caruso et al. 2020 and reference therein).

The transition to the overlying Pliocene sediments was not documented, but only supposed to have occurred in the area between Magrignano-S22 and Salviano-S9 boreholes, on the basis of the reconstructed cross-sections (Section 1, Fig. 23).

Marine deposits confined into Unit 2, and referable to the early Pliocene MNN13 and MNN14-15 zones and the early Pleistocene MNN18 Zone, occur from South to North in an inner belt with semicircular pattern (Sections 1-3, Fig. 23). These deposits are characterised by microfaunal assemblages that testify palaeoenvironments referable to the inner and outer neritic zones. The accepted stratigraphic model for the Tuscan area, argues that during the Gelasian and early Calabrian time interval (corresponding to zones MNN18-MNN19a) there was no marine sedimentation (Bossio et al. 1986; 1993). On the contrary, our data extend the presence of the Pliocene marine cycle to the early Pleistocene (Gelasian MNN18), and allow us to exclude that the Livorno area took part in the general epirogenic uplift that interested the rest of Tuscany, during the late Pliocene-early Pleistocene time span. In addition, unpublished calcareous nannofossil data, collected from boreholes drilled in the Tuscany coastal area (offshore and inland), referable to zones MNN16a, MNN16b-MNN17 and MNN18

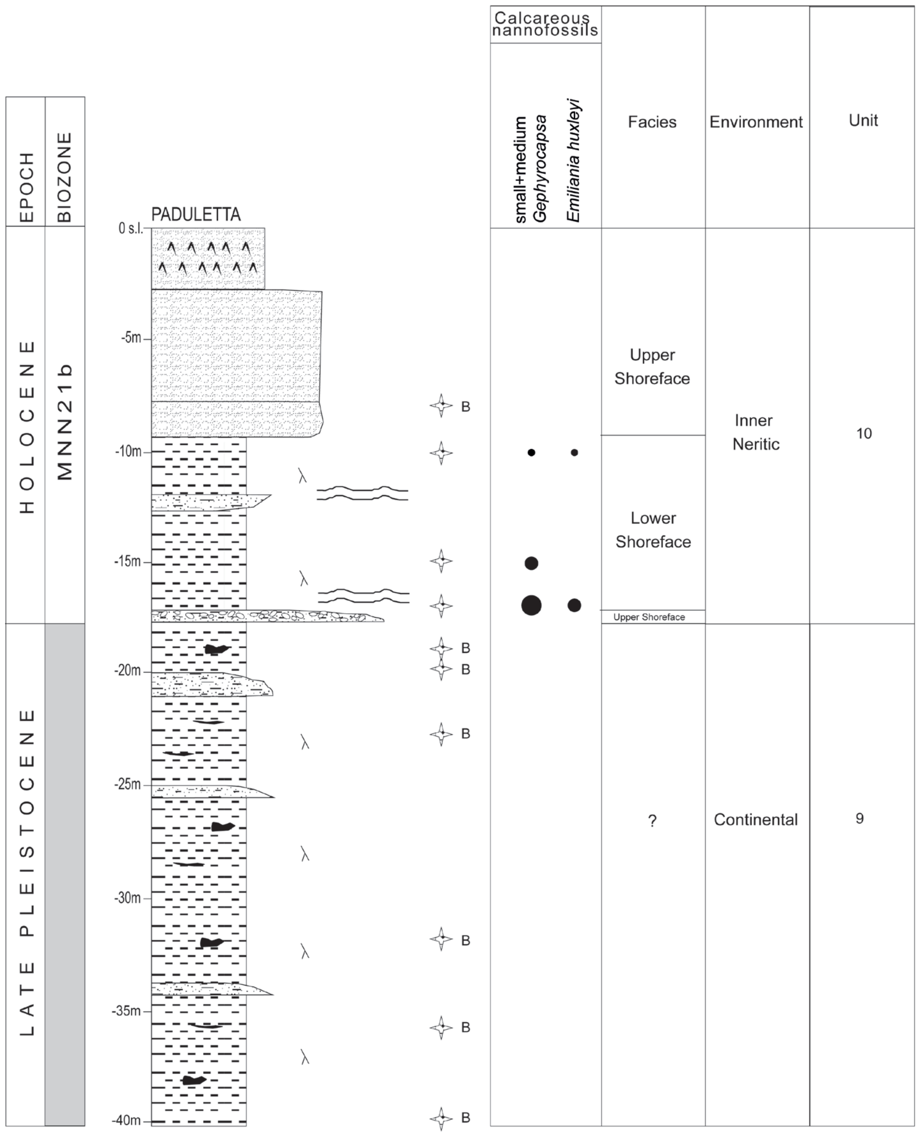

Fig. 21 - Stratigraphic log of the Paduletta borehole with the range chart of selected calcareous nannofossils taxa. For symbols see legend in figure 5.

(IGG-Database), allow us to recognise a continuous marine sedimentation during the Pliocene to early Pleistocene time interval.

Data collected so far do not record sediments referable to the uppermost Gelasian-lowermost Calabrian MNN19a Zone, confirming emersion during this time interval as reported in literature for the western side of the Northern Apennines (e.g. Bossio et al. 1998) and our study did not even record the lower Calabrian MNN19c Zone, probably because this zone represents a very narrow interval of time (Fig. 3). Instead, we recognised marine sediments in Unit 3, which were dated to the Calabrian (Santernian p.p. to Emilian) MNN19b and MNN19d zones. Microfauna found in sediments related to zones MNN19b show a transgressive trend. In fact, during Zone MNN19b, the sea level reached the inner parts of the Livorno area overlying deposits of the Messinian Unit 1 (section 1, Fig. 23), probably due to a tectonic lowering. During MNN19d, the sea reached the outer zones of the area (sections 2 and 3, Fig. 23) expressing depths that characterised a distal inner neritic zone. Furthermore, in the upper part of the Viale Carducci borehole (Fig. 13), we can observe the regressive trend of the marine cycle dating to MNN19d Zone, testified by the transition from distal to proximal neritic zone. As a whole, Unit 3 seems to reach a greater depth from E-SE to W-NW (Fig. 23).

Sediments referable to the Calabrian (Sicilian) MN19e Zone, which constitute Unit 4, were detected exclusively around the Livorno harbour zone and in the corresponding inner part (Fig. 23). The microfauna observed allows the recognition of evident bathymetric variations and consequently of the transgressive phase that marks the beginning

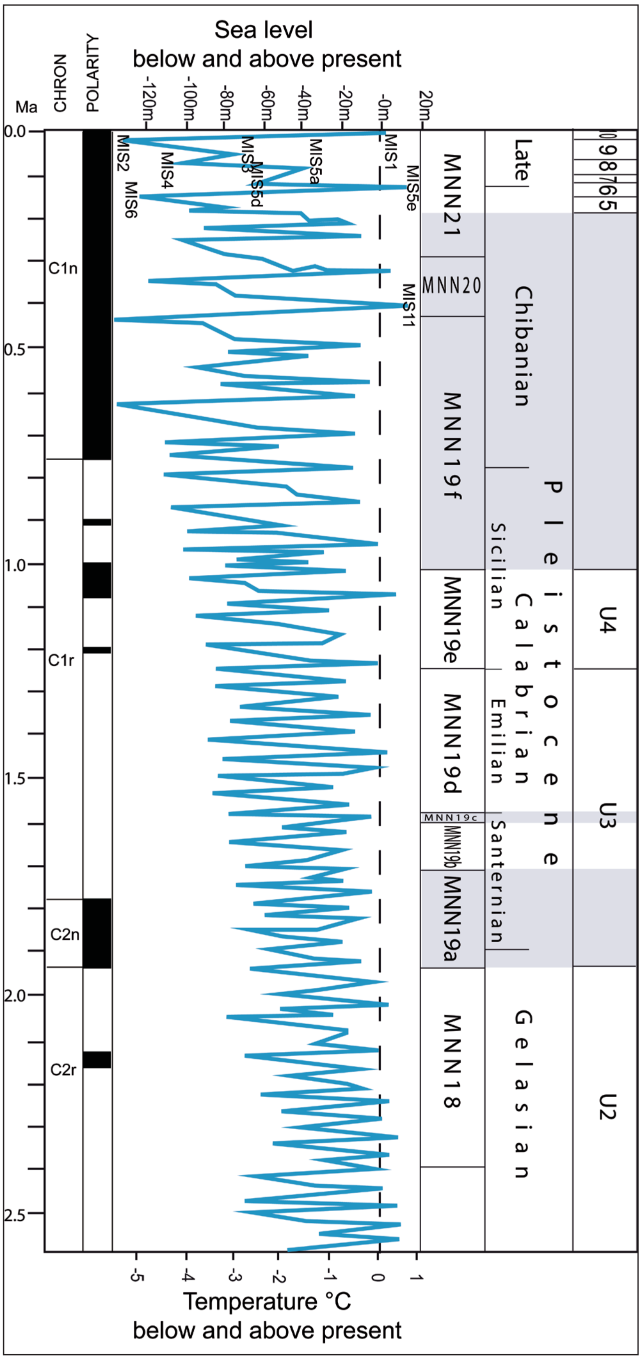

Fig. 22 - Livorno area subsurface units, plotted against the calcareous nannofossil biostratigraphy and the $\delta^{18}O$ stack of Lisiecki & Raymo (2005), with sea-level and temperatures estimates for the Pleistocene. In grey the undocumented interval of time.

of the second Calabrian marine transgressive-regressive cycle, cited in the literature (Dall'Antonia et al. 2004). Actually, in the Via Pompilia-S3, Porto Mediceo-S3, Marzocco-S1 boreholes (Figs. 16, 17 and 19), from the bottom to the top of the stratigraphic successions, it is possible to distinguish environments that move from proximal inner neritic to distal inner neritic and return to proximal inner neritic. In addition, overall, the thickness of the deeper bathymetric levels, represented by offshore proximal deposits, and referable to the distal inner neritic zone, have different thicknesses in different boreholes. For example, in the Calata Magnale-S7 borehole (Fig. 18), these deposits have a thickness of more than 20 m, while in the Via Pompilia-S3 borehole (Fig. 16) they are reduced to a few meters. This could be explained with the presence of a particularly articulate Pleistocene sedimentary basin, whose origin should be investigated, but that could be related to tectonic dynamics. Sediments attributed to the Sicilian are very rare in Tuscany and limited to small outcrops and very few boreholes (Bartoletti et al. 1986; Dall'Antonia et al. 2004). So, our paper confirms the presence of these sediments in the Livorno subsurface and shows an area of distribution wider than that reported in literature (Boschian et al. 2006). In addition, the micropaleontological analyses allowed us to identify sedimentary environments deeper than those known for the Sicilian succession (Bartoletti et al. 1986; Boschian et al. 2006).

Our data do not record the late Calabrian (Sicilian)-Chibanian MNN19f-MNN20 zones. Actually, there are not marine sediments related to this interval of time that is only testified by the patchy occurrence of the coastal deposits of Villa Battaglia Conglomerates or Villa Umberto I Conglomerates (Boschian et al. 2006; Zanchetta et al. 2006; Zanchetta et al. 2019). The unrecorded Sicilian-Chibanian sediments lead us to suppose that the coastal plain could have been exposed to erosion by tectonic uplift, since the warmer conditions characterising at least the MNN20 Zone (MIS11 and MIS13, Fig. 22) would require sea-level high stand.

The first marine sediments overlaying the Sicilian sediments are transgressive deposits referable to Unit 6 (Fig. 23), which are datable to the late Pleistocene MIS5e. The subsequent sediments of units 7 to 9, testify transitional and continental conditions during the late Pleistocene MIS5d, MIS4 and MIS3, linked to glacio-eustatic control.

Holocene lagoonal and marine sediments of Unit 10 are found in the northern and western part of the study area (section 2, Fig. 23). This unit, in the Darsena-SA borehole (Fig. 20), shows a complete depositional sequence with a progressive passage from transitional to marine environment that testifies the Versilian transgression (Federici 1993),

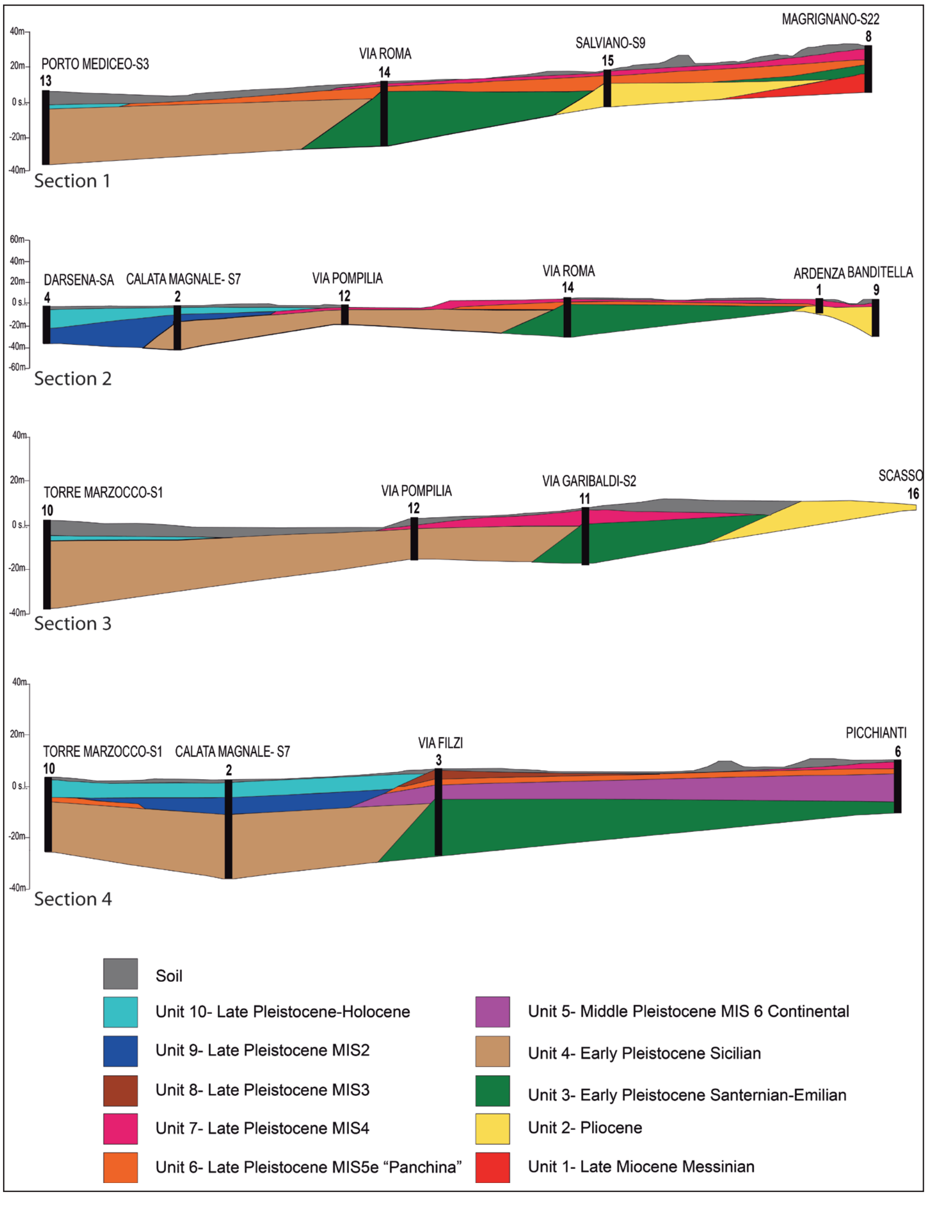

Fig. 23 - Straight-line stratigraphic cross sections showing stratigraphic correlations among selected boreholes and outcrops. The different units can be visualized. Location of boreholes (red points and numbers) and sections are reported in Fig. 1.

occurred during MIS2 to MIS1 transition.

For what concerns the marine terraces (Fig. 2), their different altitude above sea level and different age indicate a general uplift of the area from the Quaternary (Zanchetta et al. 2019). The Livorno Terrace is placed at an altitude of about 20 m a.s.l. and related to the Eutyrrhenian transgression (MIS5e, Federici & Mazzanti 1995; Hearty et al. 1986; Mauz 1999; Nisi et al. 2003).

The second order of marine terraces (Villa Padula and Salviano Terraces) is placed at an altitude of about 40 m a.s.l. and was related to middle Pleistocene MIS7- 9(?) (Zanchetta et al. 2019).

The Salviano Terrace, which was doubtfully attributed to the middle Pleistocene by Bossio et al. (2008), in our paper is better constrained in the Magrignano-S22 borehole (Fig. 6) because of the presence of the early Calabrian (Santernian) MN-N19b Zone in the underlying sediments.

The highest terrace order, named Terrazzo della Fattoria Pianacce, which was related to the middle Pleistocene MIS11 (Zanchetta et al. 2006), is constituted by a tilted surface ranging from about 120 m to 20 m a.s.l. (Zanchetta et al. 2019).

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APPENDIX A
Taxonomic Appendix

CALCAREOUS NANNOFOSSILS
Amaurolithus delicatus Gartner and Bukry, 1975
Calcidiscus macintyrei (Bukry and Bramlette, 1969) Loeblich and Tappan, 1978
Calcidiscus leptoporus (Murray & Blackman 1898) Loeblich & Tappan, 1978
Discoaster asymmetricus Gartner, 1969
Discoaster brouweri Tan, 1927, emend. Bramlette and Riedel, 1954
Discoaster pentaradiatus Tan, 1927
Discoaster surculus Martini and Bramlette, 1963
Discoaster tamalis Kamptner, 1967
Discoaster variabilis Martini and Bramlette, 1963
Emiliania huxleyi (Lohmann 1902) Hay & Mohler, in Hay et al. 1967
Gephyrocapsa Kamptner, 1943
Helicosphaera carteri (Wallich 1877) Kamptner, 1954
Helicosphaera sellii (Bukry and Bramlette, 1969) Jafar and Martini, 1975
Pontosphaera Lohmann, 1902
Pseudoemiliania lacunosa Kamptner, 1963 ex Gartner, 1969
Rhabdosphaera Haeckel, 1894
Reticulofenestra Hay, Mohler & Wade, 1966
Reticulofenestra pseudoumbilicus (Gartner, 1967) Gartner, 1969
Sphenolithus abies Deflandre in Deflandre and Fert, 1954
Umbilicosphaera sibogae (Weber - van Bosse 1901) Gaarder, 1970

CALCAREOUS DINOFLAGELLATE
Thoracosphaera Kamptner, 1927

OSTRACODS
Amnicythere accicularia (Olteanu)
Argilloecia cf. *A. robusta* Bonaduce, Ciampo & Masoli, 1976
Aurila convexa (Baird, 1850)
Aurila cymbaeformis (Seguenza, 1883)
Aurila lanceaeformis Uliczny, 1969
Aurila punctata (Muenster, 1830)
Aurila punticruciata Ruggieri, 1975
Bosquetina carinella (Reuss, 1850)
Bythocypris obtusata producta (Seguenza, 1880)
Callistocythere pallida (Mueller, 1894)
Candona neglecta Sars, 1887
Carinocythereis bairdi Uliczny, 1969
Cyprideis torosa (Jones, 1850)
Cytherella russoi Sissingh, 1972
Cytheretta subradiosa (Roemer, 1838)
Cytheridea neapolitana Kollmann, 1960
Cytheropteron cf. *C. alatum* Sars, 1866
Cytheropteron ruggierii Pucci, 1956
Cytheropteron testudo Sars, 1869
Cytheropteron vespertilio (Reuss, 1850)
Euxinocythere praebaquana (Livental, 1956)
Henryhowella asperrima (Reuss, 1850)
Ilyocypris gibba (Ramdohr, 1808)
Krithe compressa (Seguenza, 1880)
Leptocythere bacescoi (Rome, 1942)
Leptocythere castanea (Sars, 1866)
Leptocythere multipunctata (Seguenza, 1883)
Leptocythere ramosa (Rome, 1942)
Loxoconcha rhomboidea (Fischer, 1855)
Loxoconcha elliptica Brady, 1868
Loxoconcha muelleri (Mehes, 1908)
Loxoconcha ovulata (Costa, 1853)
Loxocorniculina djafarovi (Schneider, 1956)
Macrocypris adriatica (Breman, 1975)
Muellerina problematica (Seguenza, 1884)
Neocytherideis fasciata (Brady & Robertson, 1874)
Neocytherideis subspiralis (Brady, Crosskey & Robertson, 1874)
Palmoconcha subrugosa (Ruggieri, 1977)
Palmoconcha turbida (Müller, 1894)
Parakrithe cf. *P. cristallina* (Reuss, 1850)
Parakrithe cf. *P. dimorpha* Bonaduce, Ciampo & Masoli, 1976
Parakrithe rotundata Aiello, Barra, abate & Bonaduce 1993
Pontocythere turbida (Müller, 1894)
Pterygocythereis jonesi (Baird, 1850)
Sagmatocythere versicolor (Müller, 1894)
Semicytherura incongruens (Müller, 1894)
Semicytherura rarecostata Bonaduce, Ciampo & Masoli, 1976
Tyrrenocythere pontica (Livental, 1961)
Urocythereis gr. *U. margaritifera* (Müller, 1894)
Xestoleberis communis Müller, 1894

FORAMINEFERS
Ammonia beccarii (Linnaeus, 1758)
Ammonia parkinsoniana (d'Orbigny, 1839)
Ammonia tepida (Cushman, 1926)
Bolivina aenariensis Costa, 1856
Bolivina catanensis Seguenza, 1862
Brizalina alata (Seguenza, 1862)
Bulimina cf. *B. minima* Tedeschi & Zanmatti, 1957
Bulimina marginata d'Orbigny, 1826
Cassidulina neocarinata Thalmann, 1950
Cibicidoides cf. *C. kullembergi* (Parker, 1958)
Cibicidoides pseudoungeriana (Cushman, 1922)
Dorothia gibbosa (d'Orbigny, 1826)
Elphidium crispum (Linnaeus, 1758)
Eponides repandus (Fichtel & Moll, 1798)
Fursenkoina complanata (Egger, 1893)
Globigerina bulloides d'Orbigny, 1826
Globigerinoides sacculifer (Brady, 1877)
Globobulimina affinis (d'Orbigny, 1839)
Globorotalia bononiensis Dondi, 1963
Globorotalia aemiliana Colalongo & Sartoni, 1967
Gyroidina soldanii d'Orbigny, 1826
Haynesina depressula (Walker & Jacob, 1798)
Heterolepa cf. *H. dertonensis* (Ruscelli, 1954)
Hyalinea baltica (Schroeter, 1783)
Lenticulina cultrata Montfort, 1808)
Lobatula lobatula (Walker & Jacob, 1798)
Melonis pompilioides (Fichtel & Moll, 1798)
Nonion boueanum (d'Orbigny, 1846)
Orbulina universa d'Orbigny, 1839
Planulina ariminensis d'Orbigny, 1826
Pullenia bulloides (d'Orbigny, 1846)
Quinqueloculina seminula (Linnaeus, 1758)
Sigmoilopsis coelata Costa, 1855
Sigmoilopsis schlumbergeri (Silvestri, 1904)
Siphonina reticulata (Cžjžek, 1848)
Textularia sagittula Defrance, 1824
Uvigerina rutila Cushman and Todd, 1941
Valvulineria bradyana (Fornasini, 1900)

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