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SUBSURFACE STATIGRAPHY OF MIDDLE PLEISTOCENE CONTINENTAL DEPOSITS FROM LIVORNO AREA AND BIOSTRATIGRAPHIC CHARACTERIZATION OF THE PLEISTOCENE SUBSTRATE (TUSCANY, ITALY)

Abstract - *Subsurface statigraphy of Middle Pleistocene continental Deposits from Livorno area and biostratigraphic characterization of the Pleistocene substrate (Tuscany, Italy)*. The main results of an integrated study of 4 boreholes drilled in the subsurface of Livorno (NW Italy) are reported. Stratigraphic interpretations of the cores allowed the identification of 4 main lithostratigraphic units, that were correlated with units already described in literature.
Integrating the results of the micropalaeontological (calcareous nannoplankton, foraminifers and ostracods), paleontological molluscs and lithological data, it is possible to single out the environments and biostratigraphic constrains of succession.
The micropalaeontological study of the lower lithostratigraphic unit allowed the recognition of the «cold guest» *Muellerina problematica* and *Cytheropteron testudo*, thus supporting the correlation with the lower pleistocenic Morrona Formation; in addition the top surface of this lithostratigraphic unit was also depicted.
Results highlight that the «Corea formation» shows a wider variety of depositional environments than previously documented.

Key words - Livorno, molluscs, ostracods, «Corea formation», nannoplankton, Pleistocene.

Riassunto - *Stratigrafia dei depositi continentali del Pleistocene Medio del sottosuolo dell'area di Livorno e caratterizzazione biostratigrafica del substrato Pleistocenico*. In questo lavoro sono presentati i risultati ottenuti da uno studio multidisciplinare di quattro sondaggi effettuati nell'area settentrionale del Terrazzo di Livorno. Attraverso l'analisi micropaleontologica (nannoplancton calcareo, foraminiferi ed ostracodi), paleontologica molluschi e litologica, è stato possibile caratterizzare, da un punto di vista biostratigrafico e paleoambientale, le varie successioni stratigrafiche individuate. Queste ultime vengono correlate con unità litostratigrafiche informali già note in letteratura. Lo studio micropaleontologico dell'unità litostratigrafica inferiore ha permesso la sua correlazione con la Formazione di Morrona del Pleistocene inferiore, per la presenza di alcuni fossili significativi, come *Muellerina problematica* e *Cytheropteron testudo*, considerati «ospiti freddi». Si propone inoltre il possibile andamento nel sottosuolo della superficie di tetto della suddetta formazione.
Viene inoltre messo in evidenza come la «formazione di Corea» sia caratterizzata da depositi relativi ad una più ampia varietà di ambienti deposizionali rispetto a quanto documentato precedentemente in letteratura.

Parole chiave - Livorno, molluschi, ostracodi, «formazione di Corea», nannoplancton, Pleistocene.

INTRODUCTION

During the last few years, new studies about the Quaternary sedimentary successions of the Livorno area (NW Italy) allowed the definition of a new lithostratigraphic unit, called «Corea formation» (Zanchetta *et al.*, 2006), dated to the middle-late Pleistocene (Zanchetta *et al.,* 2004; 2006). These deposits contain abundant non-marine molluscs and micromammals fauna, suggesting not fully interglacial conditions (Zanchetta *et al.*, 2006).
The present work belongs to a project that has the aim to improve the knowledge of the subsurface of Livorno by means a multidisciplinary approach,. In particular, the results of new analyses carryed out on 4 continuously-cored boreholes, including lithological, main sedimentary patterns, faunal (terrestrial and freshwater molluscs) and microfaunal content (foraminifers, ostracods and calcareous nannoplankton) analyses are reported here.
We focused especially on continental and marine deposits, relative to the «Corea formation» and Morrona Formation. These data may be useful for detailed reconstruction of the subsurface geometry of Livorno, with important implications in many fields (as protection of water resources, seismic risk assessment).

STRATIGRAPHIC FRAMEWORK

From a morphological point of view, the study area is located on the so-called «Terrazzo di Livorno» (Fig. 1), a polycyclic marine terrace developed during MIS 5 (Federici and Mazzanti, 1995), lying above marine early Pliocene - early Pleistocene deposits.
The basal layer of the «Terrazzo di Livorno» is constituted by a coastal marine (shoreface) calcarenite, with an abundant mollusc fauna (Barsotti *et al.,* 1974). This layer, containing a particular fauna (e.g. *Strombus bubonius*), can be connected with the MIS 5e (Hearty *et al.,* 1986; Federici and Mazzanti, 1995; Mauz, 1999). The calcarenite passes upward locally to brackish deposits, and to a thin continental succession containing a rich freshwater mollusc fauna (Malatesta, 1942; Barsotti *et al.,* 1974; Zanchetta *et al.,* 2004) connected with the MIS 5d (Zanchetta *et al.,* 2004). These layers are covered by a calcarenitic layer, mainly of eolian en-

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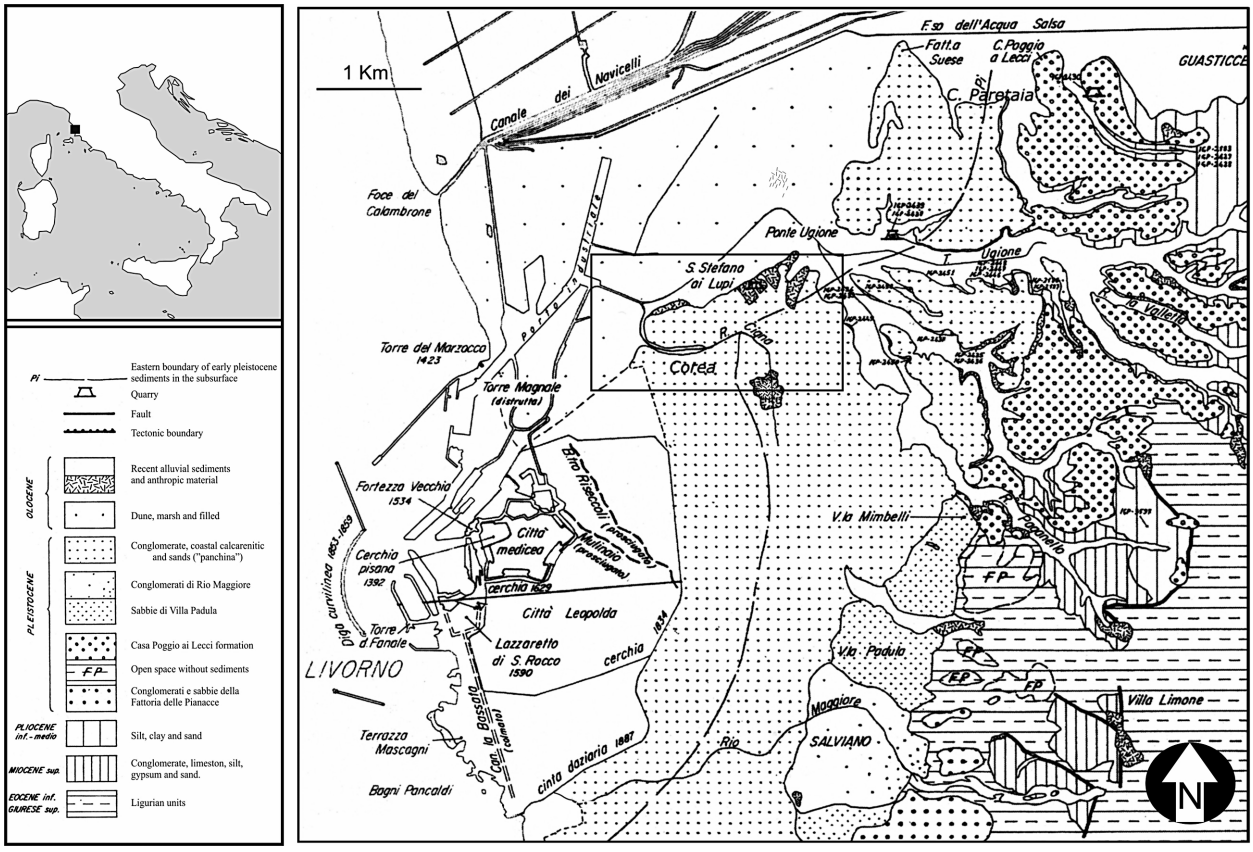

Fig. 1 - Geological sketch map (of the North-Western Tuscany) and position of the studied area (redrawn after Barsotti *et al.*, 1974).

vironment, connected with the MIS 5c (Federici and Mazzanti, 1995; Mauz, 1999; Zanchetta *et al.,* 2004).
Reddened sandy silts with Fe-Mn nodules, presenting a decimetric heavily pedogenized layer of gravels that defines a clear erosional surface, close upward the «Terrazzo di Livorno» succession. These deposits were referred to the «Sabbie di Ardenza» (Lazzarotto *et al.,* 1990) dated to the MIS 4 or 3 on the basis of the occurrence of Mousterian (Middle Palaeolithic) stone tools (Malatesta, 1940; Ciampalini & Sammartino, 2007). Deposits related to the middle Pleistocene terraces are also present in this area, the oldest of which, of marine origin, is represented by the «Conglomerati di Villa Umberto I» formation (Giannelli *et al.,* 1982; Boschian *et al.,* 2006), which overlies the «Terrazzo Fattoria delle Pianacce» (Barsotti *et al.,* 1974). Northward this terrace is covered by continental deposits, referred to the «Casa Poggio ai Lecci» formation (Lazzarotto *et al.,* 1990, Marroni *et al.*, 1990). The «Casa Poggio ai Lecci» formation was divided into two units: «San Romano» and «Cava Erta» (Zanchetta *et al.*, 1998). The upper unit (Saint Romano unit) precedes the MIS 10 and it is subsequent to the Sicilian stage (Marcolini *et al.,* 2003). On to the «Terrazzo Fattoria delle Pianacce» and between this and the «Terrazzo di Livorno», the «Sabbie Rosse di Villa Padula» formation, of eolian origin, was recognized (Giannelli *et al.,* 1982). This formation results younger than MIS 10 and older than MIS 5. Fossiliferous sands and calcarenites (Bossio *et al.,* 2008), have been recently interpreted as the marine transgression at the base of «Sabbie Rosse di Villa Padula» formation (Fig. 2). These data confirm the presence of an intermediate terrace (Salviano Terrace) between the «Terrazzo Fattoria delle Pianacce» and the «Terrazzo di Livorno», with an age that could correspond to MIS 7 or MIS 9.
The integrated study of terrestrial molluscs, Micromammals and pollens, supported by stratigraphic analysis, allowed the attribution of the «Corea formation» to the upper-middle Pleistocene (Zanchetta *et al.,* 2006). Zanchetta *et al.* (2006) recognised 2 members, the lower dominated by a gravely fluvial facies and the upper characterised by flood plain deposits. According to the proposed reconstruction, the lower unit was connected with the MIS 6 (MIS 6) while the upper one to the transition to the MIS 5.
The lower pleistocenic deposits are subdivided in three distinct successions (Dall'Antonia *et al.*, 2004). The lower marine succession is a transgressive-regres-

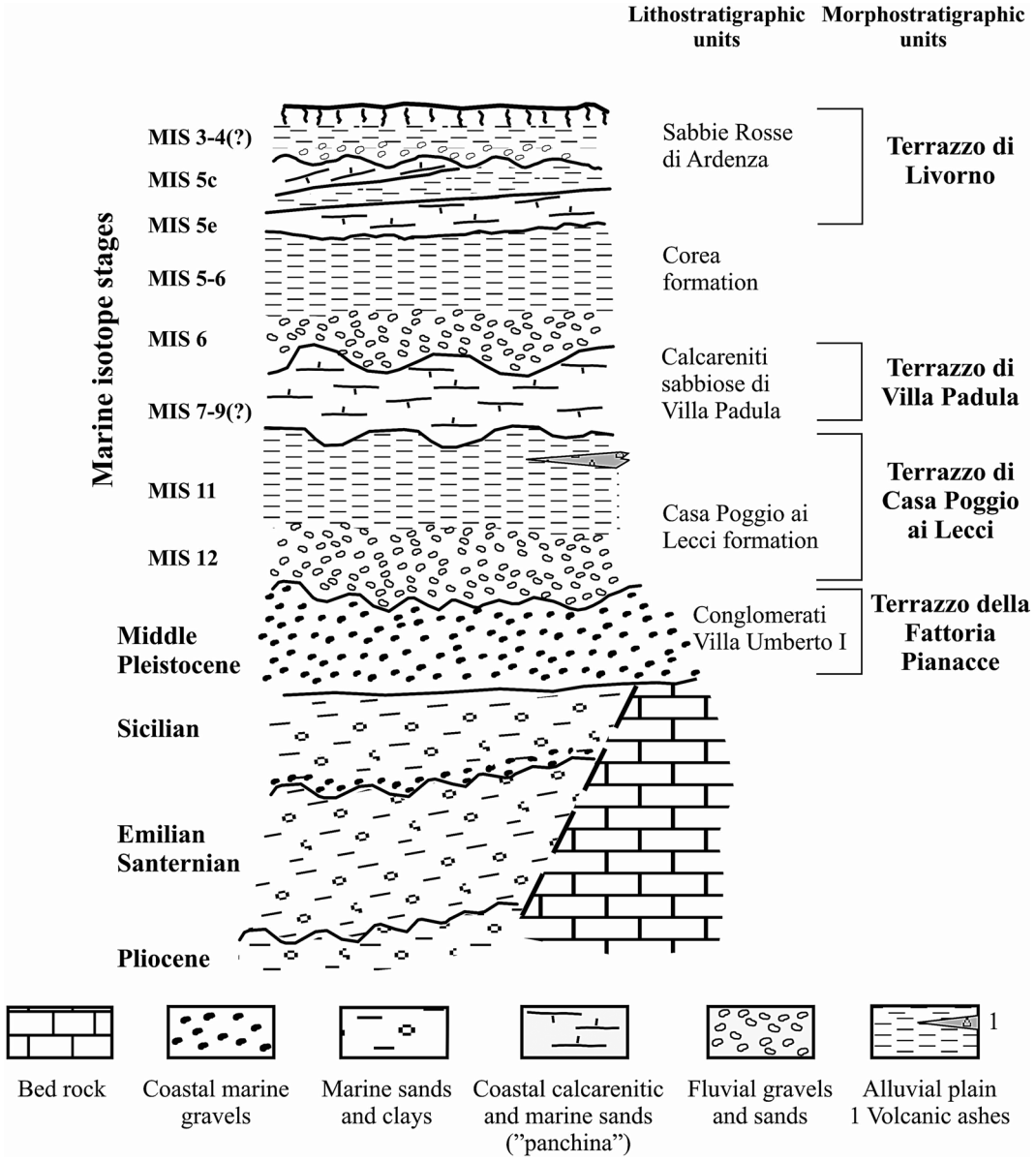

Fig. 2 - Composite stratigraphy of the Livorno area. Correlation with the marine isotope stages. The main morphostratigraphic units are also shown (Zanchetta *et al.,* 2005).

sive sedimentary wedge, mainly constituted by open marine environment (neritic zone) Santernian-Emilian sandy silts pertaining to the Morrona Formation (Boschian *et al*., 2006), followed by fine to medium-grained sands referable to the Emilian «Sabbie di Nugola Vecchia» formation (Lazzarotto *et al.,* 1990; Dall'Antonia *et al*., 2004). Above, through an unconformity, lies a succession of marine gravels and sandy silts of Sicilian age (Dall'Antonia *et al.,* 2004) referable to the Fabbriche Formation (Bossio *et al*., 1986).

Materials and methods

Three cores (P1, P2, P3) from Picchianti area (Livorno) and one from Filzi area (F1) were studied (Fig. 3). The depth of the boreholes ranges between 14 and 25 m core-depth (Fig. 4). The boreholes have been described, photographed and sampled in the field. Deposits texture and colour, type and presence of accessory materials, including, macrofossils, wood fragments, organic matter, and

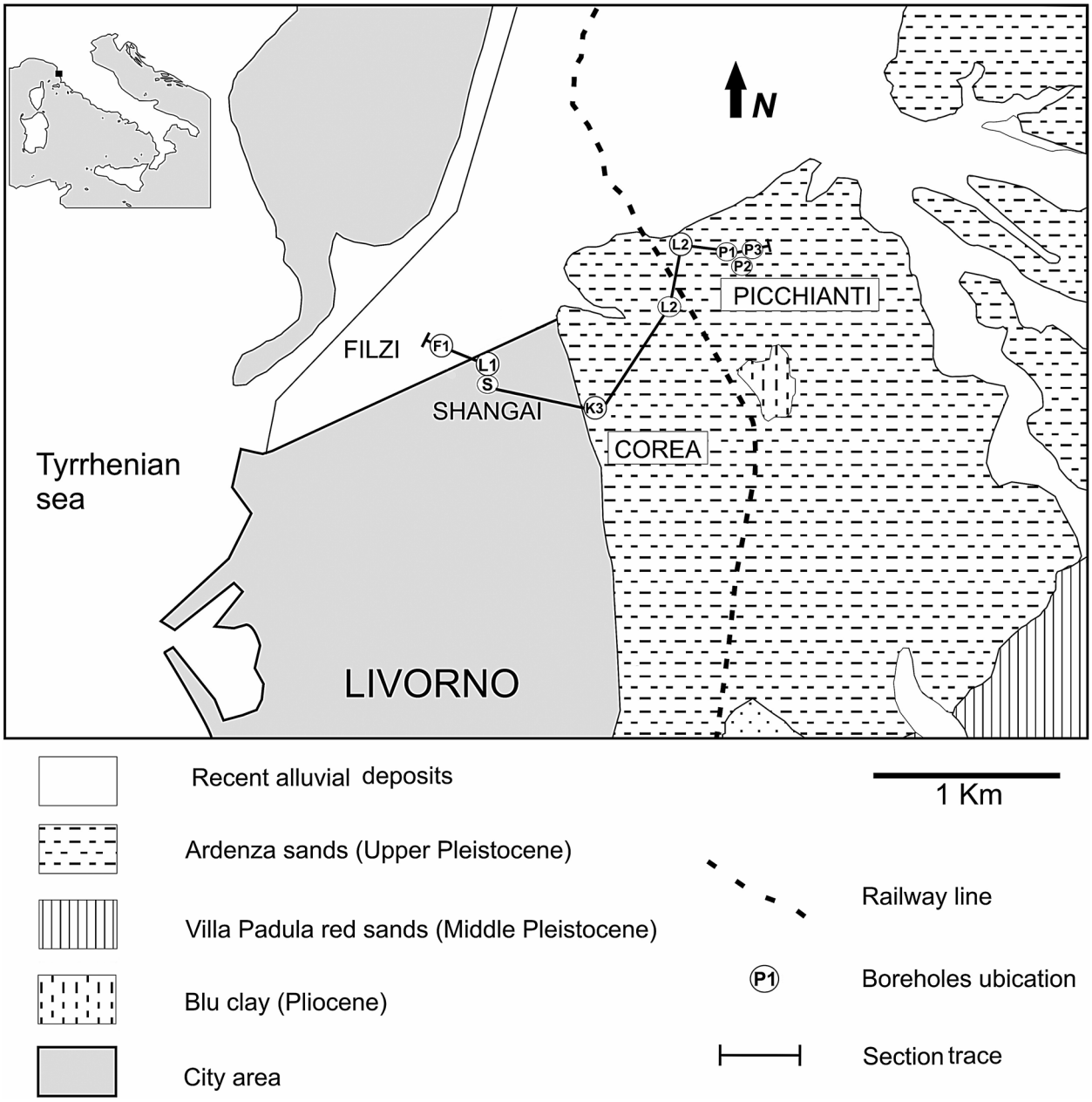

Fig. 3 - Geological sketch map of the studied area and location of the analyzed boreholes (redrawn after Lazzarotto *et al*., 1990).

palaeosols were used as basic tools for stratigraphic correlation.

Fifty-five anhydrous samples of approximately 150 g were analyzed for the microfossils content. Samples were disaggregated in warm deionised water (95°C) adding hydrogen peroxide, washed through a 63 µm sieve and finally dried in an oven at 110°C. The residue was analysed by an optical microscope to describe the micropalaeontological contents. A particular attention was required to the study of ostracofauna, in fact this group of microfossils is documented both in marine and continental environment. In order to facilitate the palaeoecologic interpretation, quantitative analysis were performed including both juvenile and adult specimens. Numerical tables, representing the number of specimens per 100 g of sediments, were generated for each core (Tab. 1). Seventeen species of ostracods have been photographed with S.E.M. (Pl. 1).

The continental molluscs found in the core drilled in the Filzi area were studied investigating 1/16 of

Tab. 1 - Distribution of the ostracods identified in Picchianti boreholes.

Samples	deep m	Acantocythereis sp.	Aglaiocypris sp.	Argilloecia aff. minor	Aurila cf. anguisfoveata	Aurila bullapunctata	Aurila convexa	Aurila cymbaeformis	Aurila cf. fastigata	Aurila fialodes	Aurila hesperiae	Aurila lanceaeformis	Aurila cf. nilensis	Aurila pigadiana	Aurila prasina	Aurila puncticruciata	Aurila spp.	Bairdia longevaginata	Bairdia sp.	Bosquetina dentata	Buntonia sp.	Buntonia sublatissima	Bythocythere puncticulata	Callistocythere flavidofusca	Callistocythere littoralis	Callistocythere lobiancoi	Callistocythere pallida	Callistocythere spp.	Candona neglecta
P1-6	6																												
P1-7	7																												3
P1-8	8																												
P1-9	9																												
P1-10	10																												1
P1-11	11																												
P1-12	12																												4
P1-13	13																												4
P1-14	14																												17
P1-14.50	14,5						3														1								
P1-15	15						3										3											1	
P1-15	15																												
P1-16	16						1	2									5												
P1-17	17																14	1											
P1-18	18			1													18	1						3				1	
P1-20	20			1			30	17					1	1			15	2				3							
P4-21	21						1										3					1							
P1-22	22			1		5	3	11	1			6	2				5						1			1	2		
P1-24	24		3														7			2									
P2-4	4																												
P2-6	6																												
P2-7	7																												
P2-8	8																												
P2-8.5	8,5																												
P2-10	10																1												
P2-11	11																												
P2-17	17			1			1	1		1					3		7			1		2							
P2-18	18						2	1		1					1														
P2-19	19					2	1								3		8												
P2-20	20													3															
P2-21	21																					1							
P2-22	22		1	1													10			1								1	
P2-23	23			5		2			1	4							20	2				1							
P2-23.30	23,3					4	15							1			5	1	1										
P2-24	24		1											2			10										1		
P3-5.4	5,4																												
P3-6	6																												
P3-7	7																												
P3-14	14																												
P3-15	15																												
P3-17	17											1					8											1	
P3-18.5	18,5	1			1		8	7		8	1	1	4	10			18	5					1?						
P3-20	20																												
P3-21	21		1			1	5			4		2	1		1		8				2	2	1					2	

Samples	deep m	Carinocythereis antiquata	Carinocythereis sp.	Caudites sp.	Costa batei	Costa edwarsi	Cyprideis torosa	Cytherella circumpunctata	Cytherella vulgata	Cytherelloidea sordida	Cytheridea neapolitana	Cytheropteron garganicum	Cytheropteron monoceros	Cytheropteron rotundatum	Cytheropteron sp.	Cytheropteron testudo	Cytheropteron vespertilio	Echinocythereis pustulata	Echinocythereis sp.	Eucythere curta	Eucytherura sp.	Grinioneis haidingeri	Hemicytherura sp.	Henryhowella asperrima	Hiltermannicythere sp.	Ilyocypris gibba	Krithe compressa	Krithe sp.	Leptocythere bacescoi
P1-6	6																												
P1-7	7						3																			4			
P1-8	8						1																						
P1-9	9						1																						
P1-10	10						4																						
P1-11	11						2																			1			
P1-12	12						2																			3			
P1-13	13						2				1															3			
P1-14	14						13																			8			
P1-14.50	14,5						2		5				1			1								5			30		
P1-15	15								1							2											25		1
P1-15	15																												
P1-16	16	1																									3		
P1-17	17												3														10		
P1-18	18								1			1				2	1	1						4			21		1
P1-20	20	6				3		3	1		1							6						4					
P4-21	21					1							1				2			1									
P1-22	22	1			2				7		2				2					1							12		
P1-24	24								1								1										4		
P2-4	4																												
P2-6	6						2																						
P2-7	7																									1			
P2-8	8																									1			
P2-8.5	8,5																												
P2-10	10										1															9			
P2-11	11																												
P2-17	17								3		1							2						4					
P2-18	18								19															5	3				
P2-19	19																												
P2-20	20																					1						2	
P2-21	21											1	1							1									
P2-22	22								2			1	1				1				1				1		10		
P2-23	23			1					19				2		1		1							14				37	
P2-23.30	23,3	4			1				1					1					1					1					
P2-24	24	1				1			2						1						1						11	1	
P3-5.4	5,4																												
P3-6	6						3																						
P3-7	7																												
P3-14	14						3																						
P3-15	15																												
P3-17	17	1							3				2		1	1							1				13		
P3-18.5	18,5					1			1		11	2									3			2			10		18
P3-20	20											11	1				8										6		
P3-21	21			1					7	2		4	1					1						8				10	

Samples	deep m	Leptocythere multipunctata	Leptocythere sp.	Loxoconcha bairdi	Loxoconcha elliptica	Loxoconcha sp.	Loxoconcha subrugosa	Loxoconcha tumida	Macrocypris adriatica	Microxestoleberis xenomys	Muellerina problematica	Mutilus sp.	Paracypris polita	Paracytheridea hexalpha	Paracytherois cf. mediterranea	Parakrithe sp.	Pontocythere sp.	Pontocythere turbida	Pterigocythereis jonesii	Pterigocythereis sp.	Sagmatocythere versicolor	Semicytherura acuticostata	Semicytherura alifera	Semicytherura cribriformis	Semicytherura incongruens	Semicytherura paradoxa	Semicytherura cf. ruggierii
P1-6	6																										
P1-7	7				1																						
P1-8	8																										
P1-9	9																										
P1-10	10				1													1									
P1-11	11																										
P1-12	12																										
P1-13	13																										
P1-14	14																										
P1-14.50	14,5					1	8	2	13					1		1	1			1	3						
P1-15	15	1					5	1	10					1							9						
P1-15	15																										
P1-16	16							1																			
P1-17	17							1	1												3						
P1-18	18			5			8		10					1					3				1			1	
P1-20	20						2	4			2	1		2													
P4-21	21																				1						
P1-22	22						5		5					1	1				3				1				
P1-24	24					1																					
P2-4	4				1																						
P2-6	6																										
P2-7	7																										
P2-8	8																										
P2-8.5	8,5																										
P2-10	10		1		1																						
P2-11	11																										
P2-17	17					2	1	2			2	1									2		1				
P2-18	18											5									1						
P2-19	19							3				2									1						
P2-20	20						1	2				1															
P2-21	21						2																				
P2-22	22						1	4					43		1				1		1						1
P2-23	23					3	3	6												5		2					
P2-23.30	23,3					1	3	2												1				1			
P2-24	24						2																				
P3-5.4	5,4					1																					
P3-6	6																										
P3-7	7																										
P3-14	14																										
P3-15	15																										
P3-17	17						7				2										10						
P3-18.5	18,5	3					2					3		1						1	3		2				
P3-20	20						6														15		2				
P3-21	21						12	1		1		1			2	3					5		1				

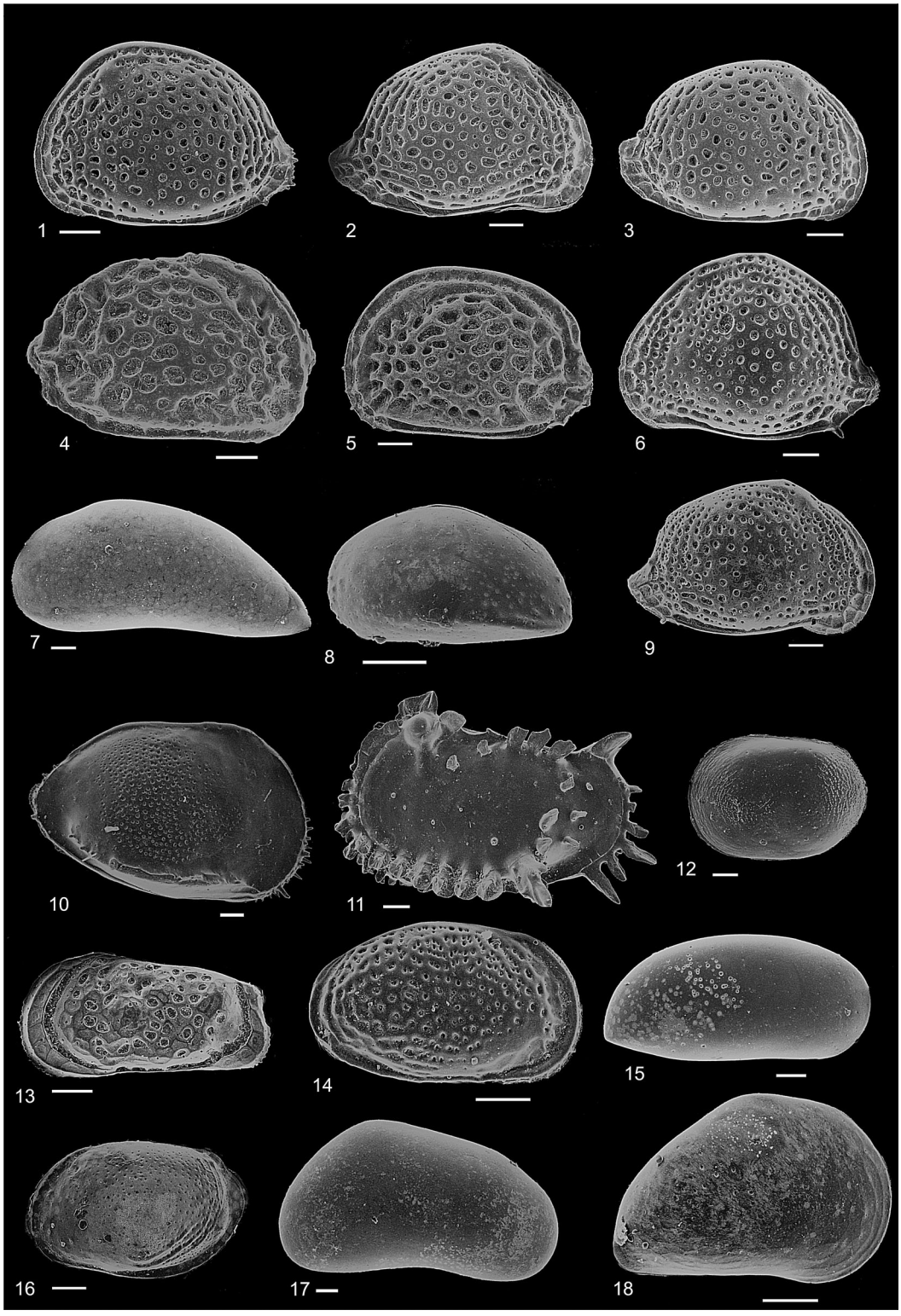

Plate 1 - Microphotographs of selected ostracods taxa. All views external lateral (scale bars =100 µm)
1. *Aurila* cf. *nilensis*, LV (Left Valve); 2. *Aurila* cf. *nilensis*, RV (Right Valve); 3. *Aurila punctata,* RV; 4. *Mutilus* sp., RV; 5. *Aurila cymbaeformis*, LV; 6. *Aurila fialodes*, LV; 7. *Propontocypris intermedia,* RV; 8. *Microxestoleberis xenomys,* LV; 9. A*urila convexa,* RV; 10. *Bosquetina carinella*, RV; 11. *Pterigocythereis jonesii*, LV; 12. *Cytherella vulgata*, LV; 13. *Muellerina problematica*, LV; 14. *Leptocythere bacescoi*, C (carapace - dorsal view); 15. *Bythocypris obtusa*, RV; 16. *Palmoconcha turbida,* LV; 17. *Candona neglecta*, C (carapace); 18. *Eucythere curta,* RV.

washed residue coming from approximately 1 kg of sediment (Pl. 2, Tab. 2). As adopted in the earliest studies on the assemblages of terrestrial fossil molluscs of the Italian peninsula (e.g. Esu, 1981; Crispino & Esu, 1995; Zanchetta *et al.*, 2006; Esu & Gianolla 2009), taxa were subdivided into ecological groups according to the scheme proposed by Ložek (1964, 1986, 1990), reflecting analogues living species assemblages (e.g. Miller & Tevesz, 2002). Following recent systematic revisions many Bithyniids shells (i.e. those comparable to *Bithynia tentaculata* Linnaeus, 1758) are here generically reported as *Bithynia/Pseudobithynia* sp. (see for instance Glöer & Bössneck 2007; Glöer *et al.,* 2007; Esu & Gianolla 2009).

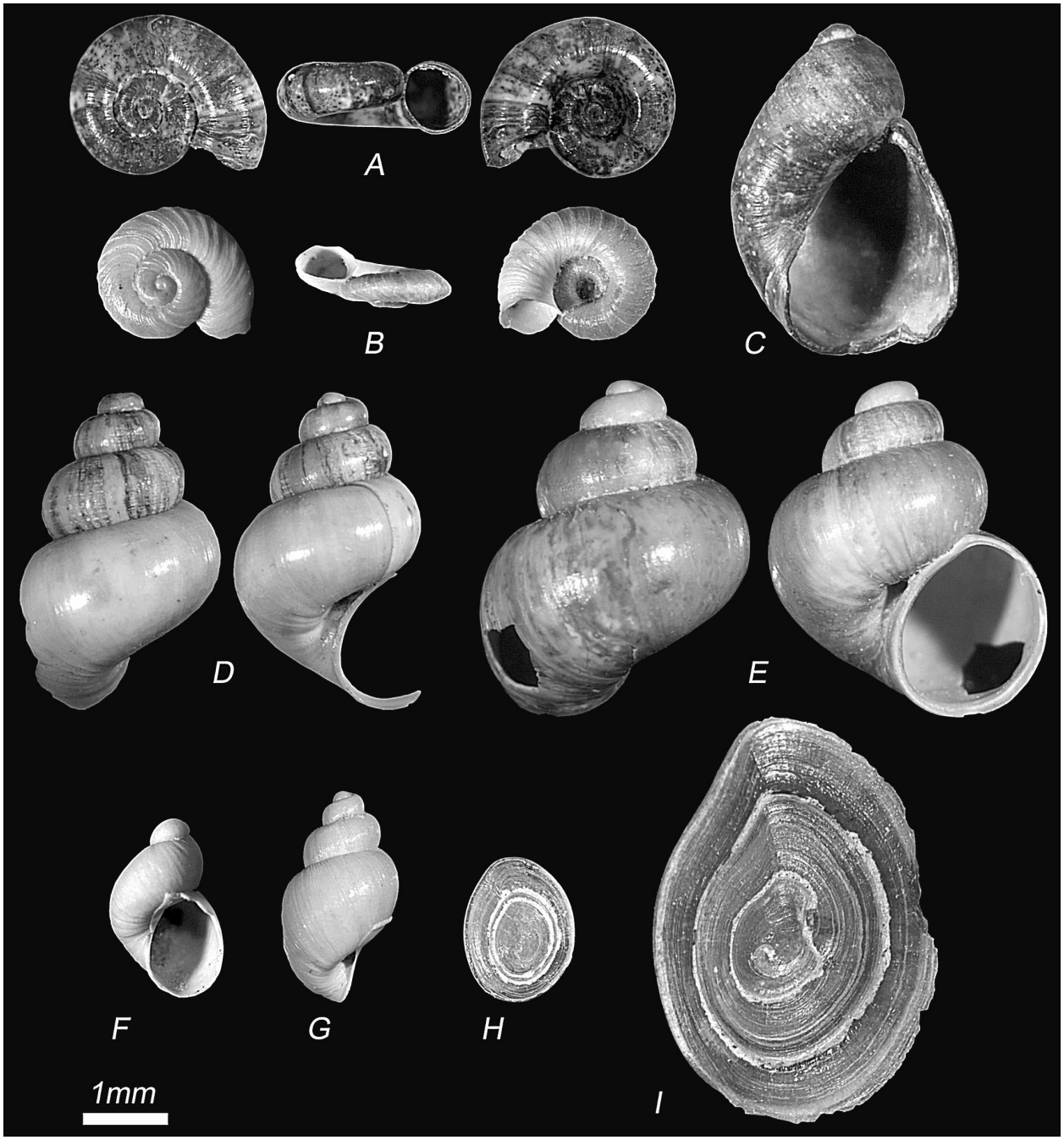

Plate 2 - *A) Valvata cristata, B) Gyraulus crista, C) Oxyloma cf. elegans; D) Bithynia* cf. *laechii; E) Bithynia/Pseudobithynia* sp.*; F) Succineidae; G) Galba truncatula; H-I) opercula of Bithynia/Pseudobithynia* sp.

Tab. 2 - List and frequency of the mollusc species. Ecological groups according to Ložek (1964) are also reported: 8-9 - Hygrophilous and strongly hygrophilous species living in very damp to wet stations; 10 - Generically freshwater species.

Species	N	%	Ecological groups
Viviparus sp.	1	1	10
Bithynia/Pseudobithynia sp.	68	39	10
Bithynia cf. *laechii* (Sheppard, 1823)	2	1	10
Valvata cristata Müller, 1774	21	12	10
Valvata piscinalis (Müller, 1774)	1	1	10
Lymnaeidae	2	1	10
Galba truncatula (Müller, 1774)	15	9	10
Planorbis sp.	9	5	10
Anisus spirorbis (Linnaeus, 1758)	31	18	10
Gyraulus crista (Linnaeus, 1758)	17	10	10
Planorbarius corneus (Linnaeus, 1758)	2	1	10
Succineidae	3	2	8 - 9
Oxyloma cf. *elegans* (Risso, 1826)	2	1	9
Pisidium cf. *casertanum* (Poli, 1791)	2	1	10
TOTAL	176		

A total of seven smear slides were analyzed for the study of calcareous nannofossils. The smear slides were prepared applying standard techniques (Bown and Young, 1999) from unprocessed samples of cores P1, P2 and P3 (Fig. 4) and analyzed at 1250 X magnification using a Leitz polarizing optical microscope. The species recognized are referenced in Perch-Nielsen (1985) and Bown (1999). The adopted biostratigraphic scheme is that of Rio *et al.* (1990), improved by Raffi *et al.* (1993) based on quantitative definition of zonal boundaries. Among the selected taxa considered in the assemblages the *Gephyrocapsa* specimens were classified according to the biometric classification established by Raffi *et al.* (1993). Three groups were considered: small *Gephyrocapsa* (< 4 μm); medium *Gephyrocapsa* (>4 μm <5.5 μm); large *Gephyrocapsa* (>5.5 μm). Data were collected applying quantitative methods by counting at least 300 specimens. The relative species abundances are presented in figure 3 and table 3.
An isobaths map representing the top of Morrona Formation was drawn, following the Thiessen polygon method (Burrough and McDonnel 1998). A total of 36 boreholes, published and unpublished, were used for this map (Fig. 5).

Results

Four informal lithostratigraphic Units (LU 1 to 4) were recognized in the cores located in the Picchianti and Shangai areas, here described from the bottom to the top (Fig. 4).

LU 1 Unit

LU 1 is mainly characterized by blue grey sandy silts including layers of fossiliferous sands and gravels (maximum grain size 6 cm) in the upper part. The minimum thickness, in the investigated boreholes, is about 10 m. The unit displays an erosional upper boundary with LU 2 unit. The planktonic foraminiferal assemblages generally include *Globigerina* spp., *Globorotalia* spp., *Sphaeroidinellopsis* spp. and *Globigerinoides* spp., showing an upwards tendency toward impoverishment and low specific diversity. Samples coming from the lower part of the unit contein *Globorotalia inflata*. The benthic foraminifers, very well represented in all samples, show rich and diversified assemblages. The arenaceous foraminifers include the genus *Dorothia*, dominant in all the interval and other genera like *Textularia, Martinottiella, Bigenerina* and *Saccammina* sporadically present only in the lower part of the unit. The Miliolids are represented by *Quinqueloculina*, characterizing all the sampled interval, *Pyrgo, Spiroloculina, Sigmoilopsis, Triloculina*. The recognized genera of Rotalids are: *Elphidium*, *Asterigerinata*, *Ammonia, Planulina, Busiltna, Cassidulina, Brizalina, Bolivina, Uvigerina*. The ostracods, mainly represented in the lower part of the unit, are generally rather rich and diversified. The lower infralittoral - circalittoral taxa as *Krithe* spp., *Cytheropteron* spp. and *Cytherella vulgata* are well represented, while *Aurila convexa*, *A. cymbaeformis*, *Callistocythere* spp. are rare. Towards the top, in agreement with the increase of grain size, the offshore assemblage is replaced by a shallow marine assemblage (upper infralittoral), characterized by the presence of *A. convexa, A. cymbaeformis, Leptocythere multipuncata* and *Muellerina problematica*.
Calcareous nannofossils are common in all samples from LU 1 showing good to moderate preservation. The main represented taxa are small specimens of *Reticulofenestra*, ranging in size from 3 to 5 mm; small specimens (>3.5 mm) of *Gephyrocapsa* containing *G. muellaere*, *G. sinuosa*, *G. oceanica*, *G. ericcsonii*, grouped as small *Gephyrocapsa*, and some medium *Gephyrocapsa* (4-5 mm); *Helicosphaera sellii*, *Helicosphaera carteri*, *Pseudoemiliania lacunosa*, *Calcidiscus leptoporus*, *Calcidiscus macintyrei*, *Coccolithus pelagicus* (Fig.6, Tab. 3). The specimens of the genera *Pontosphaera*, *Rhabdosphaera*, *Umbilicosphaera* and *Thoracosphaera* (Tab. 3) are more rare and scattered. Reworked taxa from older sediments are present with cretaceous (*Watznaueria*, *Micula*, *Aspidolithus*), paleogenic and neogenic genera (*Toweius*, *Dictyococcites*, *Discoaster*, *Sphenolithus*).

LU 2 Unit

The LU 2 comprises well rounded polygenic gravels with a grey sandy or silty matrix (subunit 2a), passing to medium-fine grey sands or grey-blue silty-clays (subunit 2b) defining a fining upward trend. Its lower boundary is marked by an irregular erosive surface. The maximum thickness, in the investigated boreholes, is about 15 m.

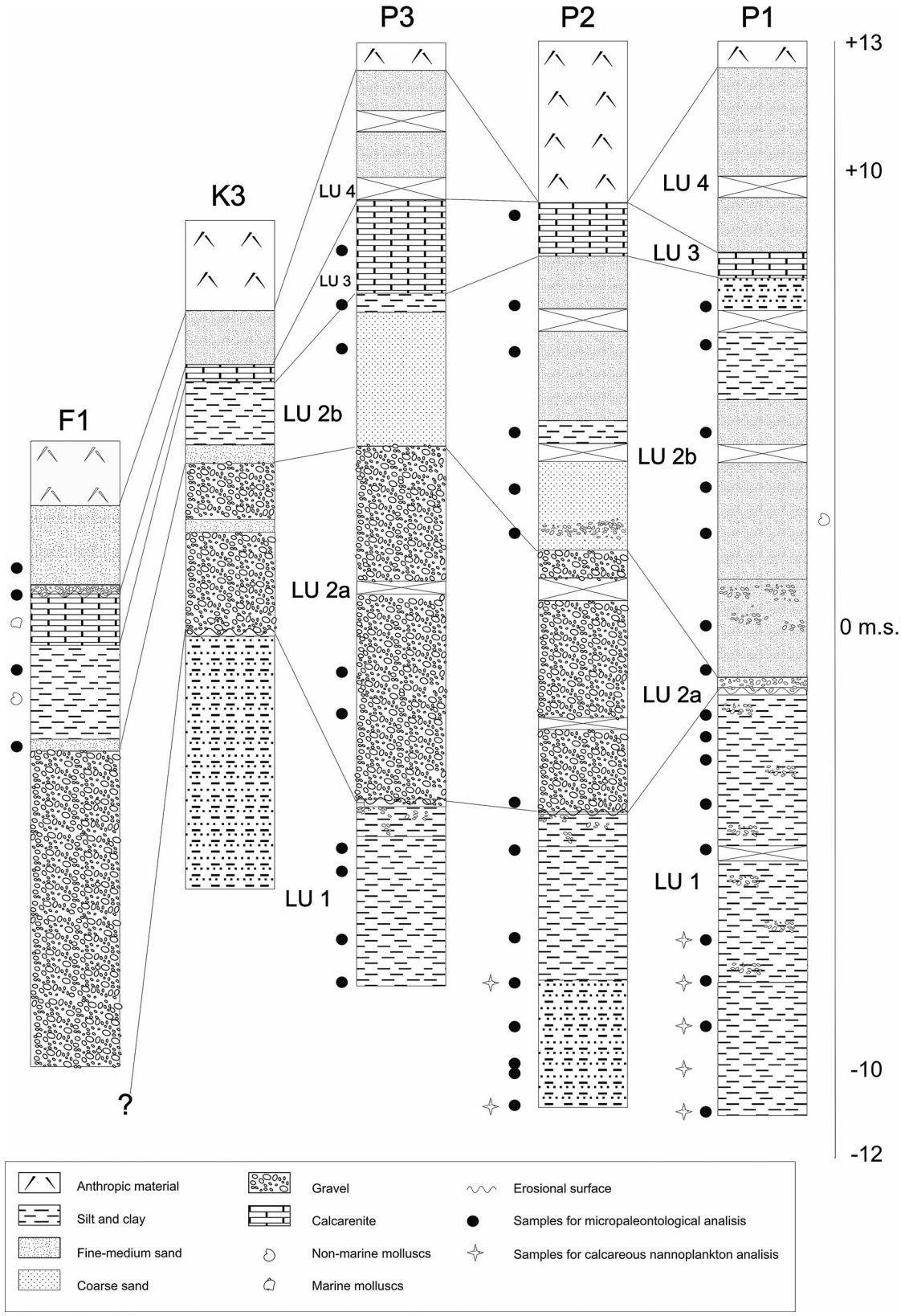

Fig. 4 - Lithologic correlation among the recognized units.

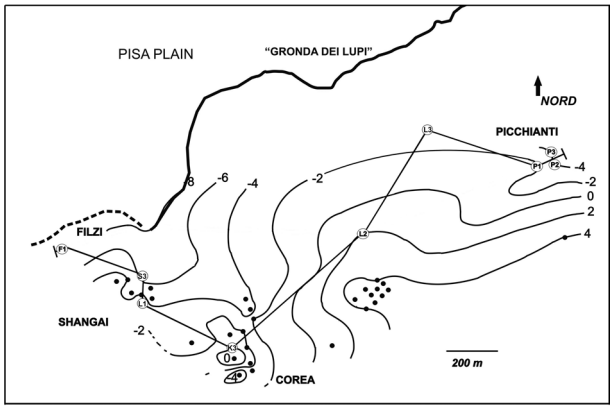

Fig. 5 - Sketch map showing the isobaths representing the top of Morrona Formation (equidistance 2 m).

The gravels contain pebbles (7-8 cm in diameter) of black chert, quartzite, jasper, sandstone and metamorphosed limestone and ophiolites. The collected macrofossils in the LU 2a are scarce and almost exclusively constituted by fragments of gastropods and marine reworked bivalves.
In the Picchianti area (P1, P2 and P3) the lower part of the subunit 2b is represented by sands with rare layers of gravels containing terrestrial molluscs (e.g. *Discus rotundatus*, recovered in the P1 borehole). Upward the sands are replaced by silt and grey-blue silty-sands, containing faunas constituted by brackish (*Ammonia tepida*, *Elphidium* sp. among the foraminifers; *Cyprideis torosa* among the ostracods) and freshwater species (*Candona neglecta*, *Ilyocypris gibba*, among the ostracods and moreover opercula of Bithyniids among molluscs).
In the Filzi area (F1 and L1) the grey sands, containing rare pulmonate gastropods (e.g. *Sphyradium doliolum*), are overlaid by grey-blue silty clays containing abundant freshwater gastropods. The specimens are strongly fragmented and include apical portions and juvenile specimens of *Galba truncatula, Anisus spirorbis, Gyraulus crista, Valvata cristata*, along with opercula of Bithyniids. The ostracods are represented by freshwater species as *Candona neglecta, Ilyocypris gibba, Erpetocypris* sp. Many *Chara* oogons and skeletal fragments, probably representative of the genus *Bufo*, were also recognized.
The upper portion of LU 2b is dark for the abundant occurrence of organic matter locally passing to a peat layers which has been recovered also in outcrop in the Shangai area, adjacent to the Filzi area (Zanchetta *et al.*, 2006).

LU 3 Unit

The LU 3 (2 m thick) is constituted by ochre-orange sandy silts and silty sands, with layers of fossiliferous calcarenite. The unit 3 has been recognized both in the Picchianti and in the Filzi areas. In the first area,

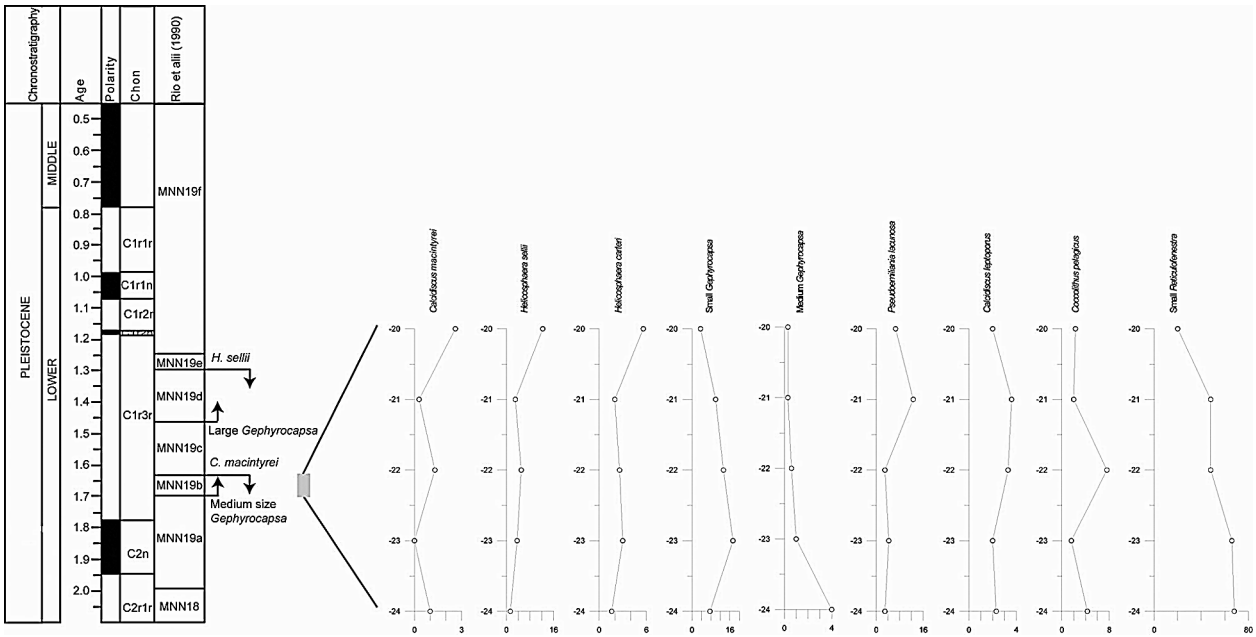

Fig. 6 - Abundance patterns of selected calcareous nannofossil taxa in Picchianti section plotted within the biostratigraphy of Rio *et al.* (1990) as improved by Raffi *et al.* (1993) and the chronostratigraphy of Lourens *et al.* (2004). The X-axis values, at the bottom of the graphs, represent the percentages relative to 300 specimens counted.

Tab. 3 - Distribution of calcareous nannofossil taxa in Picchianti section.

sample	metres	counted specimens	*Braarudosphaera bigelowi*	*Calcidiscus macntyrei*	*Calcidiscus leptoporus*	*Coccolithus pelagicus*	*Gephyrocapsa* small	*Gephyrocapsa* medium	*Helicosphaera carteri*	*Helicosphaera sellii*	*Pontosphaera discopora*	*Pontosphaera japonica*	*Pseudoemiliania lacunosa*	*Rhabdosphaera clavigera*	*Rhabdosphaera procera*	*Reticulofenestra* small	*Scyphosphaera dilatata*	*Thoracosphera* sp.	*Umbilicosphaera foliosa*	*Umbilicosphaera rotula*	*Umbilicosphaera sibogae*	Palegene-Neogene reworking	Cretaceous reworking
P1-20	-20	300	0,3	2,6	2,0	2,3	3,6	0,3	5,6	12,3	0,6	0,3	6,6	0,0	0,0	20,0	0,0	0,3	0,0	0,0	0,0	2,6	2,0
P1-21	-21	300	0,0	0,3	3,6	2,0	10,0	0,3	2,0	3,0	1,3	1,0	12,6	0,0	0,3	48,0	0,0	0,0	0,6	0,3	1,3	7,6	3,3
P1-22	-22	300	0,3	1,3	3,3	7,6	13,3	0,6	2,6	5,0	1,3	0,3	3,0	0,0	0,0	48,0	0,0	0,0	0,0	0,0	0,0	9,3	5,0
P1-23	-23	300	0,0	0,0	2,0	1,6	17,3	1,0	3,0	3,6	0,6	1,0	4,3	0,3	1,3	66,0	0,3	0,0	0,3	0,0	0,0	1,3	0,0
P1-24	-24	300	0,0	1,0	2,3	4,3	7,6	4,3	1,6	1,3	0,3	0,6	3,0	0,0	0,0	68,0	0,0	0,0	0,0	0,0	0,0	5,6	3,3

sample	metres	counted specimens	*Braarudosphaera bigelowi*	*Calcidiscus macntyrei*	*Calcidiscus leptoporus*	*Coccolithus pelagicus*	*Gephyrocapsa* small	*Gephyrocapsa* medium	*Helicosphaera carteri*	*Helicosphaera sellii*	*Pontosphaera discopora*	*Pontosphaera japonica*	*Pseudoemiliania lacunosa*	*Rhabdosphaera clavigera*	*Rhabdosphaera procera*	*Reticulofenestra* small	*Scyphosphaera dilatata*	*Thoracosphera* sp.	*Umbilicosphaera foliosa*	*Umbilicosphaera rotula*	*Umbilicosphaera sibogae*	Palegene-Neogene reworking	Cretaceous reworking
P2-21	-21	300	0,0	0,0	3,0	9,6	0,6	1,3	2,3	1,0	0,3	0,0	5,0	0,0	0,0	66,0	0,0	0,0	0,0	0,6	0,0	14,0	8,0
P2-24	-24	300	3,0	0,6	3,0	2,0	6,3	0,0	11,6	16,6	3,0	0,3	0,3	0,0	0,6	26,0	0,0	1,0	0,0	0,3	0,0	12,6	8,6

it consists of fragments of calcarenite, ochre yellow sands and sandy silts containing abundant spicules of porifera, eroded fragments of gastropods (*Cerithium* and *Murex*), marine bivalves (*Arca*), remains of bryozoans and echinoids. foraminifers are represented by the genera *Elphidium* and *Cribroelphidium*. In the Filzi area, instead, the ochre-orange sands are characterized by tiny fragments of molluscs. The sands are associated with layers of pebbles and slabs of calcarenite containing well preserved marine fossils, represented by gastropods (*Cerithium, Alvania, Murex*) and bivalves (Pectinids, *Arca*, *Nucula*).

LU 4 Unit

The LU 4 comprises yellow orange sandy silts and silty sands, with millimetric nodules of Fe-Mn (max 3-4 mm). In the Filzi area, rounded calcareous pebbles have been observed at the base. The LU 4, rarely exceeding one meter thickness, covers the «Terrazzo di Livorno» and is referable to the Ardenza Sands s.s. (Lazzarotto *et al.,* 1990). Silts and sands are barren of fossils and appear pedogenized (Inceptisoils) (Mazzanti and Sanesi, 1987).

Discussion

Considerations on LU 1

The LU 1 presents rich and diversified microfossil assemblages. The benthic foraminifers (*Dorothia, Textularia, Martinottiella, Bigenerina, Saccammina, Busiltna, Cassidulina, Brizalina, Bolivina, Uvigerina, Elphidium, Ammonia*) are indicative of the marine infralittoral environment (neritic zone), and the Plankton-Benthos (P/B) ratio is < 1.

Particularly *Elphidium* and *Ammonia,* recovered only in the sample at –23.3 m of depth, are referable to shoreline environment, in which do not occur genera such as *Bolivina*, *Bulimina*, *Brizalina*, characteristic of muddy poor oxygenized conditions.

In the lower part of the LU 1 the typical ostracods of open sea *Krithe* spp., *Loxoconcha subrugosa, Cytheropteron ruggierii, Cytherella vulgata* occur, while the shallower water genera *Aurila*, *Callistocythere*, *Loxoconcha* are under-represented. The exception is the sample collected at –23.3 m of depth in the P2 borehole, where the species *Aurila convexa* is dominant; it

is associated with other shallow marine (upper infralittoral) taxa as *Carinocythereis, Aurila, Loxoconcha*. These species probably indicate a bathymetric decrease, that is also confirmed by the increasing grain size in the corresponding layer and by the strong decrease in the P/B ratio (sample at –23.3 m). Towards the top, the typical open sea assemblage is replaced by an inner neritic assemblage, characterized by the presence of *Aurila convexa*, *A. cymbaeformis*, *Leptocythere multipunctata* (P3). The presence of *Muellerina problematica* (P1, P2 and P3) and *Cytheropteron testudo* (P3) («cold guests» of the Mediterranean), together with *Sclerochilus contortus* (P3), could suggest a cooling phase. This interpretation may explain the presence, in some samples, of *Krithe* spp., a deep sea taxon which may rise to shallower water during episodes of cooling. Interest is to note that the pollen analysis, carried out on the samples of the LU 1 recovered from the K3 borehole in the Corea locality, confirms a climatic deterioration, suggested not only by the increment of percentage of *Abies* and *Betula,* but even by the abundance peak of *Picea* to the depth of –10,50 m (Zanchetta *et al.,* 2006).

The presence of *Globorotalia inflata* (Gelasian-Present), from the base of the section (–24,00 m). and among the ostracods of *Loxoconcha subrugosa* (Pleistocene-Present) and *Muellerina problematica* (early Pleistocene), allows the attribution of the LU 1 to the early Pleistocene. This age is also confirmed by the presence of *Cytheropteron testudo* (early Pleistocene-Recent) (Aiello *et al.,* 1996). Therefore, the LU 1 can be correlated with the Morrona Formation that represents the substrate of the «Terrazzo di Livorno» (Boschian *et al.,* 2006).

The analysis of the calcareous nannoplankton confirms this attribution and allows to refer the LU 1 to a time interval corresponding to the zones MNN 19b of the early Pleistocene (Rio *et al.* 1990), comprised between the highest occurrence of specimens of *Gephyrocapsa* larger than 3.5 mm, and the highest occurrence of *Calcidiscus macintyrei*, respectively dated to circa 1.73 My and 1.66 My in the Mediterranean (Raffi *et al.,* 2006). The stratigraphic record of the LU 1 should be included within this interval of time.

Considerations on LU2

In the Picchianti area, the presence of polygenic gravels, maximum 6-7 m thick, in the lower part of the LU 2 (LU 2a subunit), is interpretable as produced by fluvial channel deposits.

The pebbles of black chert, quartzite, jasper, sandstone and metamorphosed limestone probably come from the Pisa Mountains and pebbles of ophiolites probably come from the Livorno Mountains.

In the P1 and P2 boreholes, sandy silts of freshwater environment (confirmed by the presence of specimens belonging to *Candona* and *Ilyocypris* genera) are present above the gravels (LU 2b subunit). Upward the sandy silts passes gradually to clayey silts interpreted as probably coastal paleoenvironment with a sure marine influence, for the presence by terrestrial molluscs, of *C. torosa* and *L. elliptica* among the ostracods and by *Ammonia* and *Elphidium* among the foraminifers. In the P3 borehole, the gravels are overlaid by coarse-grained sands, with scarce brackish faunas (*C. torosa*), possibly referable to mouth bar environment (Amorosi *et al.,* 2003).

In the Filzi area the situation is partially different (Fig. 4-7). Although a lower layer of channel fluvial gravels with a thickness ranging from 3-4 m to 7 m, and a thin layer of grey sands of alluvial plain, are still present, the LU 2b subunit is represented by grey clays deposited in stagnant freshwater environment as evidenced by molluscs content. The significant number of continental molluscs, present in a sample from F1 borehole (Pl. 2, Tab. 2), allowed a more detailed study on the non-marine fauna.

Generally the assemblage is polytypic and primarily represented by freshwater species (Ecological group 10), in which fragmented shells and opercula of *Bithynia/Pseudobithynia* sp. are dominant (Pl. 2; Tab. 2). In particular this taxon depicts an environment prevalently consisting of calm or slow-moving waters, in which *Bithynia* cf. *laechii*, *Gyraulus crista*, *Planorbis* sp., *Planorbarius corneus, Pisidium casertanum* may also inhabit. The appreciable percentage of *Anisus spirorbis*, *Valvata cristata* and *Galba truncatula* also suggest shallow waters rich of vegetations. The presence of Succineids shells and *Oxyloma* cf. *elegans* (Ecological group 8-9) suggests the neighbourhood of occasionally flooded zones, swamps and very wet areas. Also ostracods (e.g. *Candona neglecta, Ilyocypris gibba*) indicate freshwater environment. On the basis of the available literature, data about the ecology of the recovered taxa would suggest temperate climate (e.g. Bedulli *et al.,* 1995; Bodon *et al.,* 1995a, b).

The investigated samples of clay grey sands of the Shangai section have provided gastropods (e.g. *Vallonia enniensis, Vertigo antivertigo, Bythinia* sp.) and bivalves (*Pisidium* sp.), suggesting flood plain environment with running waters (e.g. Girod *et al.*, 1980; Kerney and Cameron, 1987). On the contrary the samples recovered from the Filzi core, contain species of stagnant waters (e.g. Girod *et al.,* 1980) probably referable to a lake. The ostracods of the Shangai area are qualitatively identical to those recovered in the core F1,but with a smaller specific abundance.

The LU 2, is lithologically and stratigraphically equivalent to the «Corea formation», recently defined in the northern part of the «Terrazzo di Livorno» (Zanchetta *et al.,* 2006). The «Corea formation» has been currently recognized only in the northern part of the «Terraz-

zo di Livorno», even though continental deposits, probably referable to the «Corea formation» and assigned to the middle Pleistocene through stratigraphic relations, have been recognized in the Villa San Giorgio area (Livorno) (Zanchetta *et al.,* 2004).
In order to provide a better understanding of the relationships between the «Corea formation» (LU 2) and the underlying Morrona Formation (LU 1), the isobaths of the top of this later formation have been drawn, using all the published and unpublished stratigraphic data available for the area (Fig. 5).
The isobaths analysis, despite the inhomogeneous distribution of the data, evidences a general deepening trend towards north-west, ending in the erosive scarp of the «Gronda dei Lupi» (Targioni Tozzetti, 1768; Barsotti *et al.,* 1974). A more accurate analysis shows a complex geometry of the substrate, with important changes on small distances (see also Fig. 7). The erosive surface, as shown above, corresponds to an erosive phase probably connected to a lowering of the sea level (MIS 6).

Considerations on LU 3

In the study areas, the LU 2 is covered by the LU 3. This unit, considered representative of a transgressive coastal environment («panchina»), can be assimilated to the Castiglioncello Sandy Calcarenites (Lazzarotto *et al.,* 1990) and therefore correlated to the MIS 5e. The sands and the «panchina» layers can be considered the evolution of the LU 2, that from sands and silts of fresh water environment (fluvial deposits, alluvial plain), passes gradually to brackish deposits which culminate with the marine transgression of the late Pleistocene (Tyrrhenian).

Considerations on LU 4

The LU 4 consists mostly of continental environment deposits (Lazzarotto *et al.,* 1990), even if detailed studies of this units are still necessary.
The LU 4 lies above the Tyrrhenian calcarenites through an unconformity; this unconformity corresponds to an stratigraphic hiatus related to the MIS 4, that in the Filzi area is marked by a gravel layer. In the near «Santo Stefano ai Lupi» (Malatesta, 1940) and in the Picchianti locality (Ciampalini and Sammartino, 2007) Mousterian stone tools were found in the upper part of these deposits (corresponding to MIS 3-4).

Conclusions

This multidisciplinary study provides new data about the subsurface of Livorno and in particular: i) the

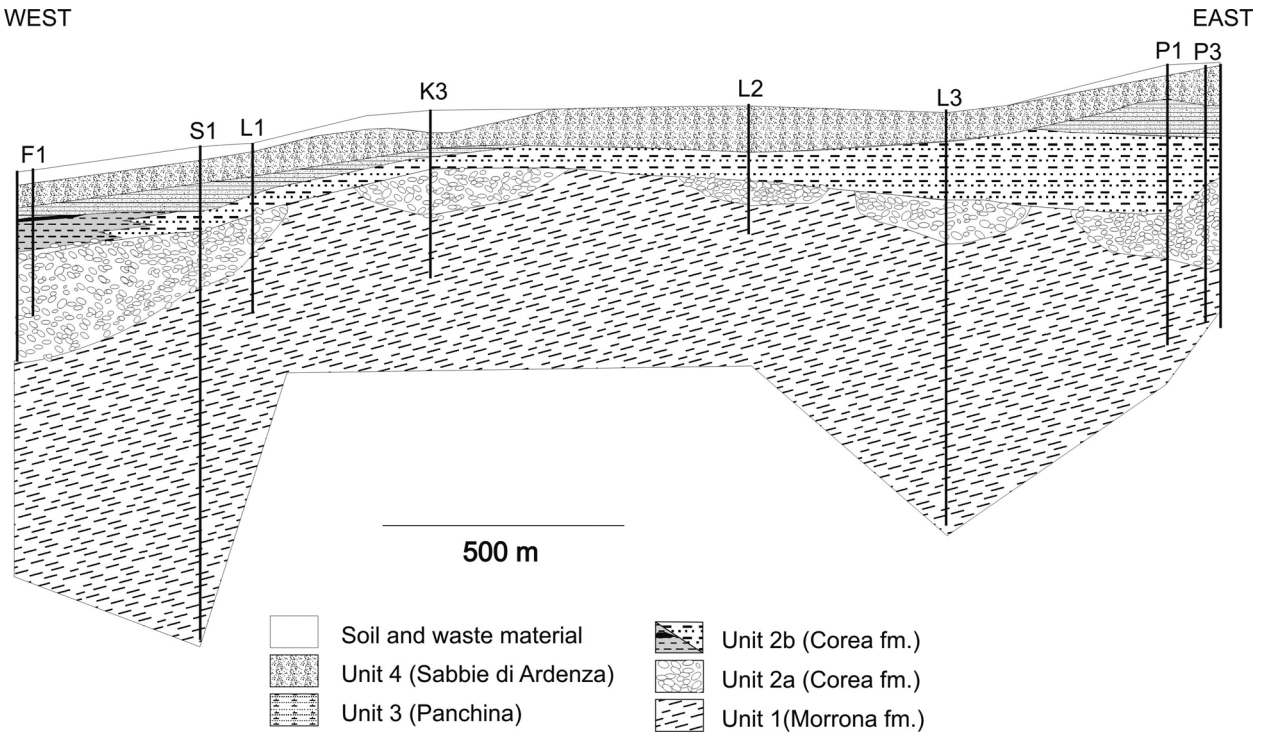

Fig. 7 - Schematic geological section across the north sector of Livorno area.

«Corea formation» is detailed and its distribution enlarged, and a rich fresh water malacofauna is described; ii) on the basis of the new data the top of the Plio- early Pleistocene marine substrate of the studied area, is better delineated and chronologically constrained.

Four lithological informal units are recognized (Fig. 4): The LU 1, on the basis of micropalaeontological data, is referable to the Morrona Formation and datable to the zone MNN19b of the calcareous nannoplankton zonation. The presence in the upper part of this unit of *Muellerina problematica* and *Cytheropteron testudo*, «cold guests» of the Mediterranean Sea, supplies indications of cooling in the depositional environments.

The LU 2 (maximum thickness of 6-7 m) includes a basal layer of sands and sandy gravels of fluvial environment lying on the LU 1 with an erosive lower boundary. In the Picchianti area gravels pass upward to grey sands of fresh-brackish environment, and to sandy silts, with gastropods, referable to an flood plain. In the Filzi area the uppermost sediments are replaced by grey sands and clayey silts, of fresh water environment. On the basis of stratigraphic position and paleontological data the whole LU 2 is attributed to the middle-late Pleistocene and correlated with the «Corea formation». Within the «Corea formation» it was also possible distinguish different depositional environments not detailed before.

Besides the isobaths analysis of the LU 1 evidences a complex geometry of the substrate with a general deepening trend towards NW (Fig. 5).

The base of the LU 1 corresponds to a bedload river probably formed during regression phase of sea level. The erosive surface may have performed during the maximum decrease of the sea level in the MIS6.

The LU 2b can represent a first phase of the sea level rise with diminishing sedimentary supply. If this reconstruction is correct the phase of the definitive marine transgression and highstand is represented by the overlying calcarenites (LU 3).

The LU 3 is composed of ochre silty sands associated with levels of calcarenites of coastal marine environment, dated to the late Pleistocene. This unit is referred to the Castiglioncello Sandy Calcarenites.

The LU 4, referable to the «Ardenza Sands», consists of orange silts and silty sands of the late Pleistocene. In the Filzi and Shangai areas, at the base of this unit there is a conglomeratic level, which indicates a probable erosive event between the units 3 and 4.

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