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New insights on the Quaternary stratigraphy of the Livorno area as deduced by borehole investigations

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ABSTRACT – This paper reports the main results of an integrated study of 15 boreholes drilled in the subsurface of the Livorno surroundings. Despite this area is one of the most extensively studied of the Coastal Tuscany (Central Italy), especially for the well-known Eutyrrhenian "panchina" deposits (beach rocks), the subsurface stratigraphy is still imperfectly known. The present study focused on an area which comprises the city of Livorno, located on the eustatic Livorno Terrace and the southernmost sector of the Pisa Plain. These two domains are separated by the "Gronda dei Lupi" erosional scarp. Analyses performed included lithological-sedimentological observations, macro-micropalaeontological investigations, and radiocarbon dating. Stratigraphical interpretation of the 15 investigated boreholes allowed to distinguish 7 main lithostratigraphic units, some of which can be correlated with formations outcropping in North-Western Tuscany. Particularly, in the Livorno Terrace domain we have been able to confirm the presence below the Eutyrrhenian "panchina" layer of a relatively thick marine succession belonging to the Santeranian-Emilian cycle. In addition, the Lower Pleistocene succession appears to include two units so far unrecognized in the area. Specifically, we identified brackish sediments referable to the regressive phase of the Santeranian-Emilian cycle and a second marine Lower Pleistocene cycle, which can be assigned to the Sicilian on the basis of both ostracod faunas (common occurrences of *Aurila puncticrucata*) and calcareous nannofossils ("small *Gephyrocapsa* Zone"). Finally, in a single borehole drilled in proximity of the "Gronda dei Lupi" scarp, we recorded nearshore to transitional sediments, which need further investigations, but might likely represent a cycle of probable Upper Pleistocene age (younger than the Eutyrrhenian "panchina" layer). In the Pisa Plain domain, we recorded brackish-continental sediments (with lower levels of probable Upper Pleistocene age), which are truncated by sands referable to the Versilian transgression. Historical coastal deposits close the succession. On the whole, achieved data allowed to refine the Quaternary stratigraphy of the Livorno surroundings and suggest that this area underwent a more complicated stratigraphical history than previously recognized.

RIASSUNTO – [Nuovi dati sulla Stratigrafia del Quaternario dell'area di Livorno emersi dall'analisi di sondaggi] – Vengono illustrati i principali risultati emersi dallo studio multidisciplinare di 15 sondaggi effettuati nel sottosuolo dell'area di Livorno. Sebbene quest'area sia una delle più studiate della Toscana marittima (Italia Centrale), soprattutto per i ben noti depositi Eutirreniani di "panchina", la stratigrafia del sottosuolo è a tutt'oggi ancora poco conosciuta. Questo studio interessa un'area comprendente la città di Livorno, situata sul Terrazzo eustatico di Livorno e il settore più meridionale della Pianura di Pisa. Questi due domini sono separati da una scarpata di origine erosiva nota come "Gronda dei Lupi". Le indagini effettuate includono osservazioni litologico-sedimentologiche, analisi macro-micropaleontologiche e datazioni ¹⁴C. L'interpretazione stratigrafica dei 15 sondaggi indagati ha permesso di riconoscere 7 principali unità litostratigrafiche, alcune delle quali possono essere correlate con formazioni affioranti nella Toscana Nord-Occidentale. Nel dominio del Terrazzo di Livorno è stato possibile confermare la presenza al di sotto della "panchina" Eutirreniana di sedimenti marini del ciclo Santerriano-Emiliano. Tuttavia, la successione pleistocenica risulta caratterizzata da due unità riconosciute per la prima volta. In particolare, sono stati individuati sedimenti di ambiente salmastro correlabili con la fase regressiva del ciclo Santerriano-Emiliano e un secondo ciclo marino del Pleistocene Inferiore riferibile al Siciliano sulla base delle ostracofaune (comune presenza di *Aurila puncticrucata*) e delle nannoflore ("Zona a small *Gephyrocapsa*"). Infine, in un sondaggio effettuato in prossimità della scarpata "Gronda dei Lupi", sono stati incontrati sedimenti da costieri a transizionali. Questi sedimenti, che indubbiamente necessitano di ulteriori indagini, potrebbero essere l'espressione di un ciclo di probabile età pleistocenica superiore e posteriore alla deposizione della "panchina" Eutirreniana. Nella Pianura di Pisa, sono stati individuati sedimenti continentali e di ambiente salmastro, con livelli inferiori presumibilmente riferibili al Pleistocene Superiore, che sono troncati da sabbie ascrivibili alla trasgressione Versiliana. La successione termina con depositi costieri di età storica. I dati acquisiti hanno consentito di raffinare la stratigrafia dell'area di Livorno e suggeriscono per quest'area una storia più complessa di quanto finora noto.

INTRODUCTION

The Quaternary succession of the Livorno surroundings (Tuscany, Central Italy) is one of the most extensively studied of the Coastal Tuscany (e.g. Bacci *et al.*, 1939; Malatesta, 1942; Barsotti *et al.*, 1974; Mazzanti, 1984, 1987, 1995, 2001 *cum bib.*; Lazzarotto *et al.*, 1990; Dall'Antonia & Mazzanti, 2001), especially for the well known "panchina" deposits (beach rocks) related to the marine high stand of the last interglacial (Barsotti *et al.*, 1974; Hearty *et al.*, 1986; Federici & Mazzanti, 1995; Mauz, 1999). Systematic analyses based on well data were carried

out by Galletti Fancelli (1979) and Fancelli *et al.* (1986) on Holocene deposits of the southern sector of the alluvial Pisa Plain (just North of Livorno). In particular the latter paper revised about 2000 well-logs of old boreholes, drilled for water research. These significant studies, however, are not supported by detailed palaeontological analyses and lack exhaustive chronological constrains, the only available ¹⁴C-dating being performed more than 40 years ago (Ferrara *et al.*, 1959, 1961). As a consequence, the subsurface stratigraphy of the Livorno area is still imperfectly known and controversial.

With the aim to fill this gap of knowledge, an

extensive study of 15 borehole cores was undertaken. The main results of these preliminary investigations are discussed in this paper.

GEOLOGICAL SETTING

In the North-Western Tuscany, where the study area is located (Text-fig. 1), four main morphological domains, which correspond to as much geological and structural settings (Lazzarotto *et al.*, 1990) can be easily recognized: I) the Pisa Plain made up of Upper Pleistocene-Holocene deposits; II) the "polycyclic" eustatic Livorno Terrace, formed mostly during the "Eutyrrhenian" transgression (Oxygen isotope stage, Ois 5e); III) the Livorno hills and Pisa hills comprising mainly Lower-Middle Pliocene and Lower Pleistocene marine deposits, with minor amount of continental terraced Middle-Upper Pleistocene sediments; IV) the Livorno mountains, mostly made up of Meso-Cainozoic sandstones, carbonates, argillites and ophiolites belonging to the Ligurian and Tuscan nappes.

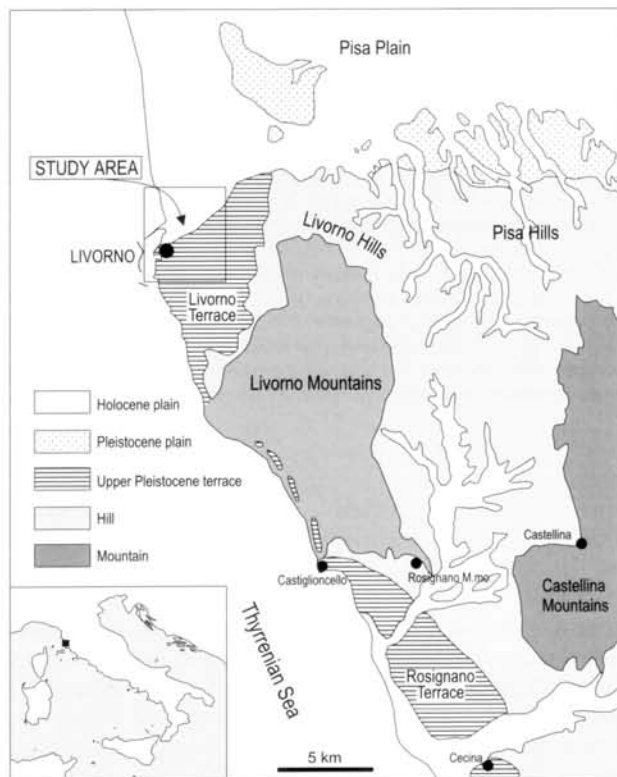
The present study focuses on a small area, which comprises the city of Livorno, located on the Livorno Terrace and the southernmost sector of the Pisa Plain. A scarp, which is locally known as "Gronda dei Lupi", separates the Livorno Terrace from the Pisa Plain. According to Lazzarotto *et al.* (1990) and Mazzanti

(2001), this scarp has a complex origin. The north-eastern sector is probably related to fluvial erosion during the marine low stand of the Last Glacial and the south-western part to marine erosion during the Holocene maximum transgression.

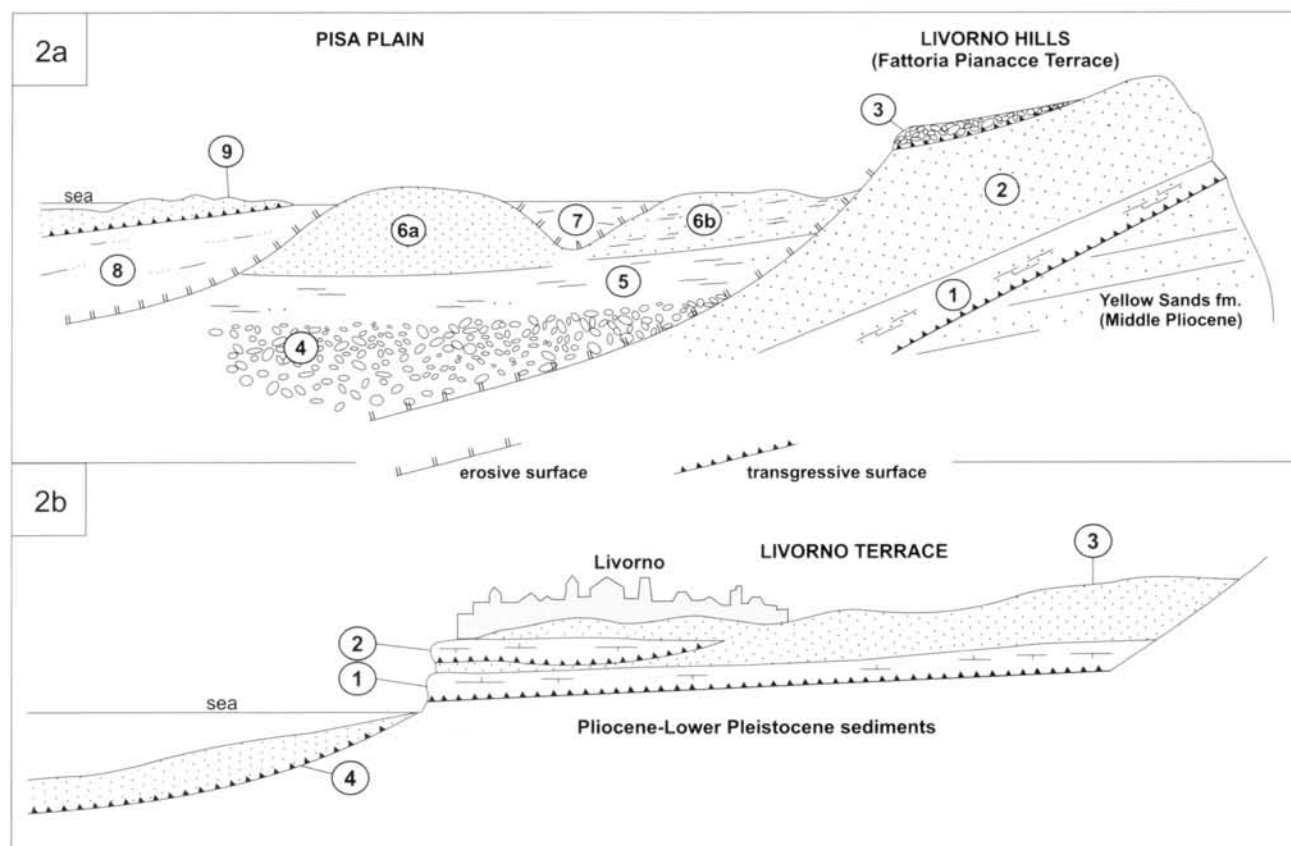
The present-day knowledge of the Pliocene-Quaternary stratigraphy of the investigated area is summarized in Text-figs 2a-b (redrawn and simplified from Mazzanti, 1987).

Text-fig. 2a shows an ideal section between the Pisa Plain and the Livorno hills. The Quaternary Livorno hills succession is characterized by three main informal formations (Barsotti *et al.*, 1974; Bossio *et al.*, 1981; Mazzanti, 1984; Lazzarotto *et al.*, 1990; Marroni *et al.*, 1990; Bossio *et al.*, 1993; Pasquinucci *et al.*, 2001). From the base they are: 1) the Lower Pleistocene (Santernian-Emilian) Sands and Clays with *Arctica islandica*, which rests transgressively on the pre-Quaternary substratum, represented by the Middle Pliocene Yellow Sands; 2) the Lower Pleistocene (Emilian) Nugola Vecchia Sands, representing the regressive phase of the Santernian-Emilian cycle; 3) the primarily continental Middle Pleistocene Fattoria delle Pianacce formation. To the North the Pisa Plain succession (Text-fig. 2a) is the result of two main sedimentary cycles separated by an erosive phase originated during the marine low stand of the Last Glacial Maximum (Mazzanti, 1987, 2001; Federici & Mazzanti, 1995). The older succession developed during the Upper Pleistocene and comprises the Arno and Serchio Gravels, the Aeolian Sands of Coltano and the Sands and Muds of Vicarello (Lazzarotto *et al.*, 1990). The younger Upper Pleistocene-Holocene succession comprises continental and marine deposits, the latter being related to the Versilian transgression and subsequent phases.

Text-fig. 2b shows the main stratigraphical features of the Livorno Terrace. As previously mentioned the Livorno Terrace formed during the marine high stand of the last interglacial, i.e. Ois 5e or Eutyrrhenian (Shackleton, 1987; Hearty *et al.*, 1986; Federici & Mazzanti, 1995; Mauz, 1999), which originated a few meter-thick calcarenitic layer ("panchina") yielding locally "Senegalese" or *Strombus* fossil community (Barsotti *et al.*, 1974). This "panchina" layer ("panchina I") is covered by thin continental deposits referred to as Ardenza Sands and Rio Maggiore Conglomerates (Lazzarotto *et al.*, 1990). A thinner second calcarenitic level ("panchina II"), mainly of aeolian facies, is locally intercalated in the continental succession. According to the recent work of Mauz (1999) at Buca dei Corvi (near Castiglioncello, about 15 km S of Livorno) and in agreement with the supposition of Federici & Mazzanti (1995), the second "panchina" layer would correspond to the Ois 5c. This succession was well documented in the spectacular section of the dry-dock of "Torre del Fanale" (Barsotti *et al.*, 1974), excavated in the harbour of Livorno about thirty years ago and no longer visible.



Text-fig. 1 - Main morphological and structural domains of North-Western Tuscany and location of the study area (redrawn from Lazzarotto *et al.*, 1990).



Text-fig. 2 - a) Ideal section between the Pisa Plain and the Livorno hills: 1) Sands and Clays with *Arctica islandica*; 2) Nugola Vecchia Sands; 3) Fattoria delle Pianacce continental deposits; 4) Arno and Serchio Gravels; 5) fluvial and marshy silts; 6a) Aeolian Sands of Coltano; 6b) Sands and Muds of Vicarello; 7) Holocene fluvial sediments; 8) Holocene silts, clays and peat; 9) sediments of the Versilian transgression (redrawn and simplified from Mazzanti, 1987).
 b) Stratigraphical features of the Livorno Terrace: 1) calcarenitic layer "panchina I"; 2) calcarenitic layer "panchina II"; 3) Ardenza Sands and Rio Maggiore Conglomerates; 4) sediments of the Versilian transgression (redrawn and simplified from Mazzanti, 1987).

In the area of the city of Livorno, which is investigated in the present study, the substratum below the first "panchina" layer is made up of Pliocene-Lower Pleistocene deposits. Notably, in the spectacular "Torre del Fanale" Section it consists of a Lower Pleistocene marine succession (ca. 15 m-thick) dipping of about 15° toward Northwest. Barsotti *et al.* (1974) assigned these basal marine sediments to the "late Calabrian" on the basis of the co-occurrence of the bivalve *Arctica islandica* (Linnaeus) and the benthonic foraminifer *Hyalinea baltica* (Schroeter). A more detailed biostratigraphical constrain was later provided by Gianelli *et al.* (1982), who referred the succession to the lower Emilian (*Helicosphaera sellii* Zone of the calcareous nannofossils).

MATERIALS AND METHODS

On the whole 15 continuously cored boreholes were investigated (Text-fig. 3). Boreholes depth varies on average from 20 to 25 m, the deepest borehole pen-

etrates down to -34 m below s.l. (depth will be throughout referred to sea level).

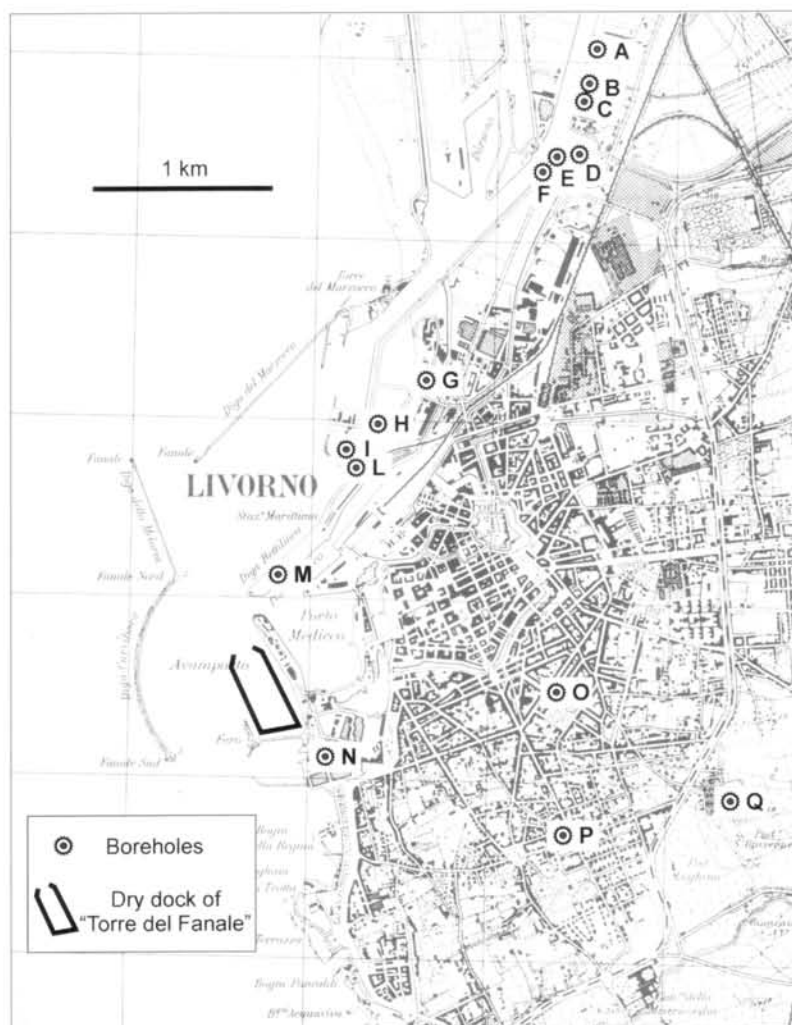
Analyses performed were primarily based on lithological-sedimentological observations, which took into account colour sediments, grain size, presence of sedimentary structures and also the macrofaunal content. Micropalaeontological analyses were carried out on a selected set of about one hundred samples, which could be considered representative of the main different lithologies recognized. Investigations were focused chiefly on ostracods, but comprised partly also benthonic foraminifers (planktonic forms are usually absent or extremely rare) and occasionally calcareous nannofossils. Data from these groups and from remains of molluscs, echinoids, charophytes, seeds, etc. were used for biostratigraphical purpose and palaeo-environmental reconstruction. Specifically, biostratigraphical significance of the ostracod fauna is based primarily upon papers by Ruggieri and co-workers. Among these there are Ruggieri (1950, 1952a, b, 1953a, b, 1954, 1972, 1973a, b, 1975a, b, 1976a,

1977, 1978), Aruta & Ruggieri (1983) and particularly Ruggieri (1980), which provided a list of species useful for the stratigraphy of the Italian Pleistocene. Subsequent studies or unpublished research of the present authors have been taken into account to check the reliability of marker ostracod species (see appendix for details on the stratigraphical distribution of marker species). Calcareous nannofossils analyses were carried out by Dr. Agata Di Stefano (Dipartimento di Scienze Geologiche, Univ. Catania, Italy); the biozonal scheme adopted is that of Rio *et al.* (1990). Finally, 7 radiocarbon dating (AMS and conventional, performed by Centre for Isotope Research, University of Groningen, The Netherlands) from wood or mollusc shells were utilized to provide a reliable chronostratigraphical framework (Tab. 1) for the younger deposits. Dates on marine shells and remains of *Posidonia oceanica* have been corrected for the marine reservoir effect, that can be reasonably assumed to be ca. 400 yr for the whole middle-upper Holocene of the Mediterranean sea (Siani *et al.*, 2000, 2001).

The stratigraphical reconstruction herein proposed took into account the previous studies on the subsurface geology of the Livorno surroundings mentioned above and assumed as a key section the succession of the dry-dock of "Torre del Fanale" in the harbour of Livorno, described by Barsotti *et al.* (1974).

RESULTS

The multidisciplinary lithological, palaeontological and geochronological studies revealed that the 15 cores analyzed display a highly variable range of lithologies and faunal associations. However, single lithofacies have been schematically grouped into 7 main stratigraphical units, some of which can be correlated with formations outcropping in North-western Tuscany. Lithology of single borehole and stratigraphical correlation of the 7 units recognized are shown in Text-fig. 4. The units are described below from base to top; stratigraphical and palaeoenvironmental considerations are also provided.



Text-fig. 3 - Location of the 15 investigated boreholes.

Laboratory N°	Sample N°	Material	Borehole	Depth (m below s.l.)	¹⁴ C-age yr BP	δ ¹³ C _{PDB} ‰
GrN-26356	CZ12	Wood frag.	F	-19.3	> 50,300	-
GrN-26355	BZ08	Wood frag.	G	-8	> 40,700	-
GrN-26610	CL12AS1 CI	<i>Posidonia</i> <i>oceanica</i>	C	-8.4	1480 ± 40	-13.98
GrN-26611	CZ01	<i>Posidonia</i> <i>oceanica</i>	A	-3.2	1510 ± 100	-12.21
GrA-20211	CL18S2C I	<i>Posidonia</i> <i>oceanica</i>	B	-9.6	1330 ± 45	-13.23
GrA-19972	CZ06S2	Marine shells	E	-7.5	4930 ± 60	-
GrA-21608	DL01DC	Marine shells	I	-10.4	> 45,000	-

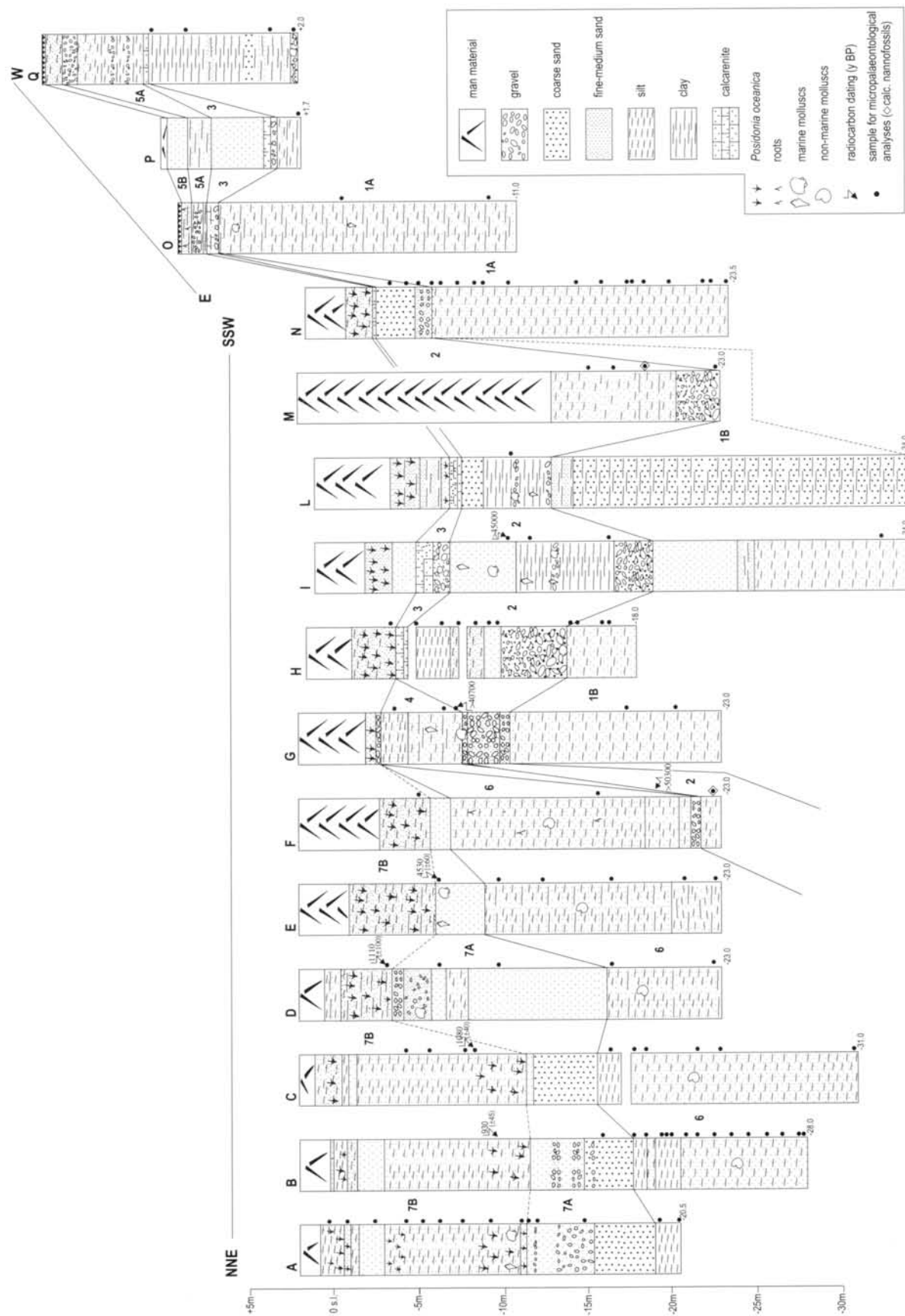
Tab. 1 - Radiometric ages technical data (¹⁴C-ages are not corrected for the marine reservoir effect).

UNIT 1

Description – Unit 1 includes two subunits (1A and 1B). Subunit 1A is characterized mainly by sandy silts (borehole N) and bluish-grey clays and silty clays (boreholes O, P, Q); the maximum cored thickness is about 17 m. Locally (borehole Q) sandy horizons with marine fossil remains (among molluscs *Nuculana*, *Turritella*, *Conus*, *Bittium*) occur. Uppermost levels of this subunit are abruptly overlain by sediments of Unit 3 and are characterized by colour banding and calcareous nodules, which suggest an episode of subaerial exposure (palaeosol). A single exception is borehole N, where Subunit 1A passes upwards to coarser sediments referable to Unit 2. Microfaunal content of Subunit 1A is not thoroughly homogeneous. Samples from borehole N usually bear scarce to moderately rich associations. Planktonic foraminifers (Globigerinida) are extremely rare; benthonic foraminifers are represented primarily by the genus *Ammonia*, including usually both *A. beccarii* (Linnaeus) and *A. tepida* (Cushman), Elphididae (*Elphidium*) and locally Miliolidae. The moderately diversified ostracod associations are characterized by the common occurrence of the euryhaline species *Cyprideis torosa* (Jones) and the marine nearshore opportunistic species *Pontocythere turbida* (Müller). *Aurila convexa* (Baird), *Cytheridea neapolitana* Kollmann, *Semicytherura incongruens* (Müller) are subordinately present; occasionally also *Callistocythere flavidofusca* (Ruggieri) and *Aurila cymbaeformis* (Seguenza) are well-represented. Many samples contain also a few specimens of the brackish species *Loxoconcha elliptica* Brady and rare representatives of the fresh water genera

Ilyocypris and/or *Candona*; rare charophyta oospores were found at -14.5 m. In borehole Q assemblages are rather rich and diversified. Fragments of marine bivalves, gastropods and echinoids are common. Planktonic foraminifers (Globigerinida and Globorotalida) are relatively well represented; marine benthonic forms are very abundant and highly diversified; Miliolidae, Elphididae, Textulariidae, Discorbidae (*Valvulineria*) and Cibicidae (*Cibicides*) are locally frequent. Ostracod assemblages consist of marine nearshore taxa and Aurilinae attain a significant portion of the fauna, among them there are *Aurila convexa*, *A. fallax* Ruggieri and subordinately *A. gr. hesperiae* Ruggieri, *A. punctata* (Münster), *A. cymbaeformis* and *A. cf. fastigata* Uliczny. In the uppermost sample, the fauna includes also frequent *Urocythereis* spp. and very few juveniles of *Cyprideis torosa* and the fresh water genus *Pseudocandona*. In boreholes O and P fragments of marine bivalves, gastropods and echinoids are widespread. Benthonic foraminifers usually dominate the microfauna, whereas planktonic foraminifers (mainly Globigerinida) are scatterly present. In borehole O foraminifers are primarily represented by Miliolidae, Discorbidae (*Valvulineria*) and *Hyalinae baltica* is notably present. In borehole P Miliolidae, Boliviniidae (*Bolivina*) and Cassidulinidae (*Cassidulina*) dominate. The major components of the usually abundant ostracod fauna are forms typical of open marine conditions. They are *Krithe praetexta* (Sars), *Cytheropteron ruggierii* Pucci, *Loxoconcha subrugosa* Ruggieri, *L. mutabilis* Ciampo and *Cytherella vulgata* Ruggieri; locally *Aurila cymbaeformis* and *Carinivalva testudo* (Namias) are relatively well represented.

Subunit 1B includes silt-sand alternations (bore-



Text-fig 4 - Lithology of single borehole and stratigraphical correlation of the 7 units recognized (1A = Subunit 1A; 1B = Subunit 1B; 2 = Unit 2; 3 = Unit 3; 4 = Unit 4; 5A = Subunit 5A; 5B = Subunit 5B; 6 = Unit 6; 7A = Subunit 7A; 7B = Subunit 7B).

holes I, G, H), fine/medium sands (borehole I) and clay-fine to coarse sand alternations (borehole L). The maximum thickness is about 20 m. Samples from this subunit yield a very scarce and moderately preserved microfauna. Assemblages are dominated by the brackish foraminifer *Ammonia tepida*, but contain also very few representatives of *Ammonia beccarii*, Elphidiidae (*Elphidium*), Nonionidae (*Florilus*) and Miliolidae. The ostracod fauna is extremely poor. *Aurila cymbaeformis*, *Costa edwardsi* (Roemer) (juveniles), *Cyprideis torosa* (juveniles), *Pontocythere turbida*, *Pseudocandona* sp. (juveniles), *Xestoleberis communis* Müller were recorded. Only a single sample (from borehole H; -14.00 m) is characterized by a relatively rich fauna with dominant *Ammonia tepida*; the ostracod fauna consists primarily of *Loxoconcha elliptica* and *Cyprideis torosa* (some specimens are tuberculate).

Stratigraphical and palaeoenvironmental remarks –

Ostracod associations recovered in Subunit 1A include a number of taxa, which are relevant for biostratigraphical purpose. These significant taxa, which usually occur patchily and in low numbers, can be divided in two distinct groups: 1) species known from the Pliocene, which disappeared by the end of the Lower Pleistocene (Sicilian), i.e. *Aurila bullapunctata extumefacta* Uliczny (very rare), *A. cymbaeformis* (rare to frequent), *A. lanceaeformis* Uliczny (very rare), *A. pigadiana* Sissingh (very rare), *A. punctata* (rare to common), *Carinivalva testudo* (rare to frequent), *Flexus triebeli* (Ruggieri) (very rare); 2) taxa, which to date are not known to occur prior to the Pleistocene, i.e. *Aurila arborescens* (Brady) (very rare), *Cytherelloidea sordida* (Müller) (very rare), *Loxoconcha elliptica* (very rare), *L. rubritincta* Ruggieri (very rare), *L. subrugosa* (rare to frequent), *Neocytherideis fasciata* (Brady & Robertson) (very rare), *Palmococoncha turbida* (Müller) (rare to frequent), *Procytherideis subspiralis* (Brady, Crosskey & Robertson) (very rare). Finally, a single sample (borehole N; -18.5 m) is characterized by the occurrence of *Aurila favorita* Ruggieri (very rare), known from the Emilian-Sicilian interval (Ruggieri, 1980).

The co-occurrence of the two groups of ostracod species mentioned above allows to refer Subunit 1A to the Lower Pleistocene. In addition, the presence of *Hyalinea baltica* allows to exclude a Santernian age for sediments encountered in borehole O (Ruggieri & Sprovieri, 1978). Finally, it is worth mentioning that no palaeontological data in favour of a Sicilian age have been recorded in Subunit 1A. It follows that this subunit can be reasonably referred to the Emilian. Comparison with the nearby and very similar succession of the dry dock of "Torre del Fanale", which has been assigned to the lower Emilian, corroborates our inference.

Faunal content of Subunit 1B is not highly suitable to provide reliable age constraints. However, the co-occurrence, although at distinct levels, of *Aurila*

cymbaeformis and *Loxoconcha elliptica* suggests a Lower Pleistocene age. Further information can derive from consideration on the stratigraphical position of this subunit. In this respect, it must be taken into account that sediments of Subunit 1A, encountered in the southernmost boreholes of the Livorno Terrace domain, dip towards Northwest (Barsotti *et al.*, 1974) and that Subunit 1B, drilled in northward boreholes, is overlain by the Sicilian Unit 2 (see below). This implies that Subunit 1B can be reasonably placed between Subunit 1A and Unit 2 and therefore assigned to the late Lower Pleistocene (Emilian).

Micro-macrofaunal content indicates that sediments of Subunit 1A formed in a shallow marine environment with predominantly normal salinities (most of the succession documented in borehole Q) and subordinate local influences of fresh-brackish waters (borehole N and top of the succession in borehole Q). Assemblages from boreholes O and P can be interpreted as reflecting a local transition to relatively deeper environments or colder bottom water conditions.

The paucity of the fauna recovered in Subunit 1B together with the dominance of *Ammonia tepida* and locally, among ostracods of *Loxoconcha elliptica* and *Cyprideis torosa*, are characteristic of unfavourable palaeoenvironmental conditions, mostly referable to a brackish water setting.

UNIT 2

Description – This unit is documented in boreholes F, H, I, L, M, N and presumably also in borehole G. Lower levels consist mainly of coarse (locally fine) sands and gravels with sparse pebbles with a thickness varying from 4 meters to a few decimetres. These coarse sediments are overlain by a fairly variable succession, which includes fine silty sands (borehole M), fine sands passing upwards to silts (borehole H) and clays, locally intercalated with gravels, followed by fine to coarse sands (boreholes I, L). Unit 2, which shows a maximum thickness of about 12 m, is documented also at the bottom of borehole F by silty sands (1 m-thick). On the basis of lithological affinities and geometric position, sands with gravels recovered from -7.7 to -10.5 m in borehole G have been included in the present unit. Unit 2 is normally abruptly overlain by calcarenitic deposits ("panchina" layer) of Unit 3.

Apart from a few exceptions, samples from this unit display a rich faunal content. Fragments of echinoids, and marine molluscs are frequent. Planktonic foraminifers (mainly Globigerinida) are occasionally present and are relatively abundant only in silty-clayey levels. Benthonic foraminifers are represented mostly by the genus *Ammonia* (predominantly *A. beccarii* and subordinately, in boreholes H, I, and N, *A. tepida*), Miliolidae and Elphidiidae (*Elphidium*). Discorbidae (*Valvulineria*) and Nonionidae (*Florilus*) can be frequent in silty-clayey sediments. Sample collected at -18.6 m in borehole

M is characterized by the presence of *Hyalinea baltica*.

Ostracod faunas are often highly diverse and comprise almost exclusively marine forms. *Aurila cymbaeformis*, *A. punctata*, *Cytheridea neapolitana*, *Loxoconcha ovulata* (Costa), *L. subrugosa*, *Krithe praetexta*, *Palmoconcha turbida* are among the most frequent and recurrent taxa. *Bosquetina dentata* (Müller), *Pterygocythereis jonesi* (Baird) and *Aurila puncticrucata* Ruggieri are particularly abundant in borehole I, H and M respectively. Rare fresh and brackish water ostracods (e.g. *Candona* sp., *Ilyocypris* sp., *Cyprideis torosa*, *Loxoconcha elliptica*) were found only in boreholes H, I, and N.

Stratigraphical and palaeoenvironmental remarks –

As for Subunit 1A, ostracod assemblages recovered in Unit 2 are indicative of a Lower Pleistocene age. This is documented by the co-occurrence of typical Quaternary species, i.e. *Loxoconcha elliptica*, *L. subrugosa*, *Neocytherideis fasciata*, *Palmoconcha turbida*, *Procytherideis subspiralis*, with Pliocene-Lower Pleistocene species (*Aurila bullapunctata extumefacta*, *A. cymbaeformis*, *A. lanceaeformis*, *A. pigadiana*, *A. punctata*, *Carinivalva testudo*, *Flexus triebeli*, *Pachycaudites attenuata* Ruggieri). Other biostratigraphical significant ostracod taxa are *Aurila puncticrucata* and *Aurila favorita*, which are restrained to the Emilian-Sicilian interval, and the “cold guest” *Muellerina problematica* (Seguenza), known only from the Lower Pleistocene (Ruggieri, 1980). These species are usually present in very low numbers, with the exception of *Aurila puncticrucata*. According to Ruggieri (1980) this species is rare in the Emilian and becomes frequent only in the Sicilian. A Sicilian age for sediments pertaining to Unit 2 is supported also by calcareous nannofossils analysis. Associations recovered in boreholes M and F are referable, although affected by reworking, to the “small *Gephyrocapsa* Zone”.

From a palaeoenvironmental viewpoint faunal content of Unit 2 is characteristic of a nearshore marine

environment with euhaline conditions; a relatively deeper setting of deposition could be supposed for silty-clayey levels. Evidence of a fairly feeble influence of fresh-brackish waters is documented only in boreholes H, I, and N.

UNIT 3

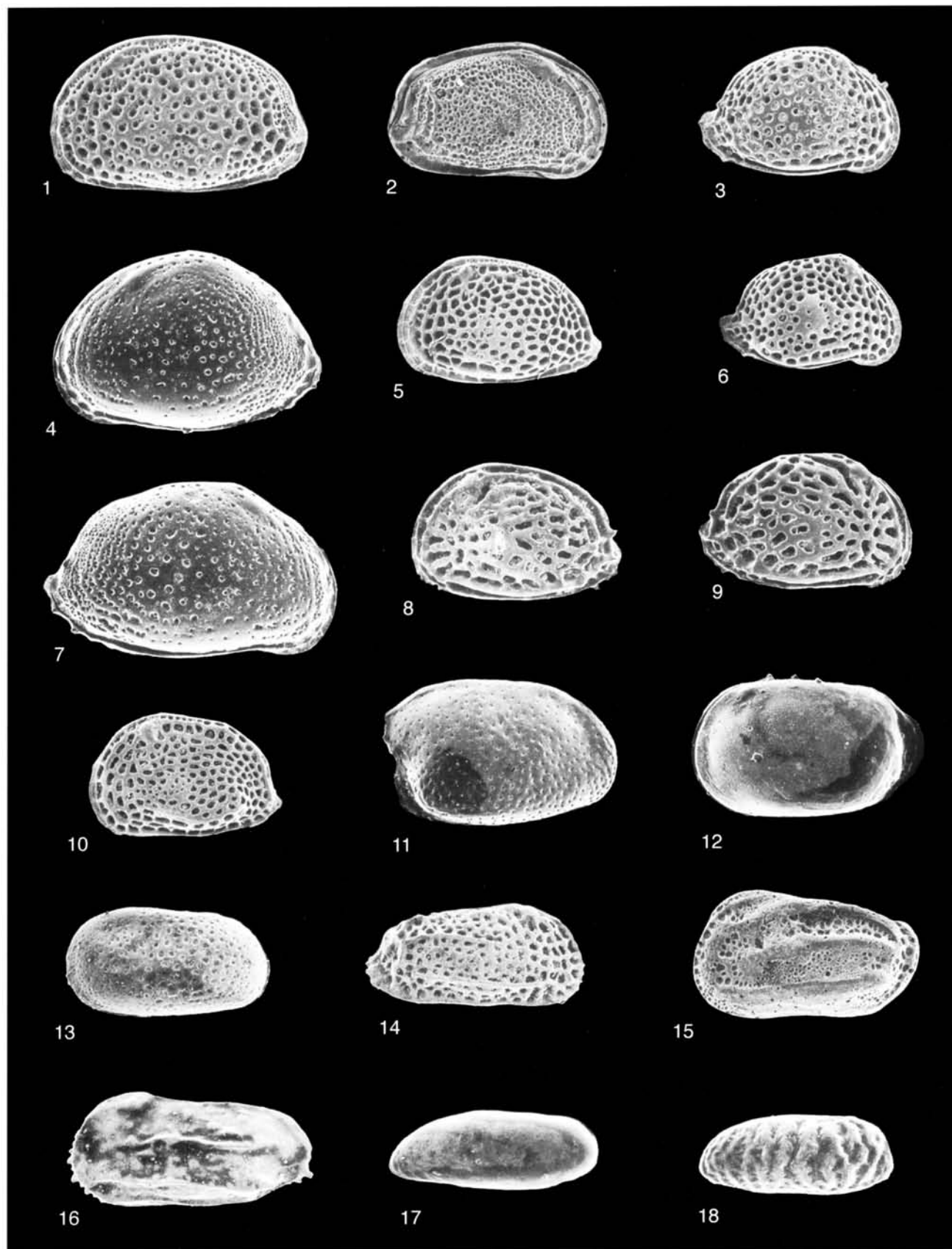
Description – This unit has been recognized in the subsurface of the Livorno Terrace (boreholes O, P, Q) and also in more seaward boreholes (boreholes H, I, L, N). It typically includes a well cemented calcarenitic layer, from a few decimetres to 1 meter thick (owing to drilling activity, this consolidated level is occasionally reduced to fragments immerse in a sandy matrix) and a basal conglomerate, from 1 to 2 meter thick (boreholes I, O, P). Abundant marine shell remains are usually present. In borehole P this unit includes also yellowish fine sands (ca. 3 m-thick) with sparse fragments of the underlain “panchina” layer and marine molluscs. Data from drilled boreholes clearly indicate a seaward increasing depth of Unit 3 (from +11 m in borehole Q to –7.5 m in borehole L). Sediments of this unit are usually not suitable for micro-palaeontological analyses; the few most favourable samples are characterized by a highly heterogeneous microfauna with frequent, clearly reworked elements.

Stratigraphical and palaeoenvironmental remarks –

Unit 3 corresponds to the Upper Pleistocene transgressive deposits (“panchina” layer) well known in the coastal strip near Livorno and particularly well studied in the dry-dock of “Torre del Fanale”. The calcarenitic layer recovered in our borehole can be correlated with the first “panchina” layer of “Torre del Fanale” (Ois 5e, ca. 125,000 yr BP). This is supported by the manifest marine origin (abundant shell remains) and consistency of depths attained in drilled boreholes with that observed in “Torre del Fanale” succession. Radiocarbon dating of *Turritella* shells from fine sands a few meters below the “panchina layer” (borehole I)

EXPLANATION OF PLATE 1

- Fig. 1 - *Aurila favorita* Ruggieri. LV (Subunit 1A borehole N; -18.5 m).
 Fig. 2 - *Aurila arborescens* (Brady). C right view (Subunit 1A borehole N; -21.5 m).
 Fig. 3 - *Aurila punctata* (Münster). RV (Unit 2 borehole M; -18.6 m).
 Figs. 4, 7 - *Aurila puncticrucata* Ruggieri. 4) LV (Unit 2 borehole M; -18.6 m); 7) RV (Unit 2 borehole M; -16.7 m).
 Fig. 5 - *Aurila lanceaeformis* Uliczny. LV (Subunit 1A borehole N; -14.5 m).
 Fig. 6 - *Aurila bullapunctata extumefacta* Uliczny. RV (Subunit 1A borehole Q; +2.1 m).
 Figs. 8-9 - *Aurila cymbaeformis* (Seguenza). 8) LV (Unit 2 borehole M; -16.7 m); 9) RV (Unit 2 borehole M; -16.7 m).
 Fig. 10 - *Aurila pigadiana* Sissingh. LV (Unit 4 borehole G; -7.3 m).
 Fig. 11 - *Bythocythere puncticulata* Ruggieri. RV (Unit 2 borehole M; -18.6 m).
 Fig. 12 - “*Bythocythere*” *minima* Bonaduce, Ciampo & Masoli (x 90). LV (Unit 2 borehole M; -18.6 m).
 Fig. 13 - *Miocyprideis italiana* Moos. LV (Subunit 7B borehole A; -2.5 m).
 Fig. 14 - *Celtia rugosa* (Costa). RV (Subunit 7B borehole A; -2.5 m).
 Fig. 15 - *Flexus triebeli* (Ruggieri). LV (Subunit 1A borehole N; -21.5 m).
 Fig. 16 - *Ruggieria tetraptera* s.l. (Seguenza). LV (Subunit 7B borehole A; -2.5 m).
 Fig. 17 - *Neocytherideis fasciata* (Brady & Robertson). LV (Unit 4 borehole G; -7.3 m).
 Fig. 18 - *Procytherideis subspiralis* (Brady, Crosskey & Robertson). LV (Subunit 1A borehole N; -23.5 m).
 S.E.M. microphotographs of selected ostracod taxa. All views external lateral (x 55 unless otherwise stated).



have provided an age greater than 45,000 yr BP and are consistent with an Upper Pleistocene age for the "panchina" layer.

UNIT 4

Description – This unit has been recovered only in borehole G. It consists of grey-bluish silty-clayey sands (3 m-thick) with disperse remains of *Turritella*, which are overlain by silty sands (ca. 1.5 m-thick). Lower levels are characterized by very abundant fragments of marine molluscs and echinoids. The microfauna consists predominantly of marine taxa, but euryhaline and brackish-fresh water forms are relatively well represented. Particularly, benthonic foraminifers are dominated by the genus *Ammonia* (prevalently *A. beccarii* and secondarily *A. tepida*) and subordinately Elphididae (*Elphidium*) and Miliolidae. Ostracod associations are quite rich and diversified, the major components being nearshore marine taxa such as *Pontocythere turbida*, *Cytheridea neapolitana*, *Loxoconchinae* (*Loxoconcha bairdi* Müller, *L. ovulata*, *L. subrugosa*, *P. turbida*), *Cistacythereis turbida* (Müller), *Costa edwardsi* and *Carinocythereis whitei* (Baird). The fauna, however, includes also *Cyprideis torosa* (common) and representatives of *Ilyocypris* and *Candona*. In the upper levels benthonic foraminifers are represented mainly by *A. beccarii*, *A. tepida*, Elphididae (*Elphidium*) and Nonionidae (*Florilus*). The ostracod assemblage is made up mostly by *Cyprideis torosa* and representatives of the genus *Ilyocypris*; marine taxa (e.g. *Costa edwardsi*, *Palmoconcha turbida*, *Semicytherura incongruens*) are present in very low numbers.

Stratigraphical and palaeoenvironmental remarks – Unit 4 is not easily interpretable from a stratigraphical viewpoint. Ostracod associations are characterized by typical Quaternary species (e.g. *Cytherelloidea sordida*, *Loxoconcha subrugosa*, *Neocytherideis fasciata*, *Palmoconcha turbida*). The lowermost sample (borehole G; -7.3 m) contains in very low numbers also

Pliocene-Lower Pleistocene species (i.e. *Aurila cymbaeformis*, *A. lanceaeformis*, *A. pigadiana*) and *Miocyprideis italiana* Moos, a species which does not cross the Pliocene/Pleistocene boundary (Ruggieri, 1980). The co-occurrence of the above mentioned taxa indicates reworking. On the whole, microfaunas are indicative only of a generic Quaternary age. Radiocarbon dating of wood fragments from the lowermost sample provided a minimum age of 40,700 yr BP, but it cannot be excluded that wood fragments are reworked.

Further data can derive from consideration on the geometric position of this unit. It has been recovered only in the borehole drilled in proximity of the "Gronda dei Lupi" erosional scarp, which separates the Livorno Terrace from the Pisa Plain. In this borehole, the "panchina" layer is lacking and at more or less the same depths at which it occurs in southward boreholes, we recovered sediments of Unit 4. Unit 4 is comprised between coarse sediments tentatively referred to the Sicilian Unit 2 and Subunit 7b (Holocene). As a consequence, it can be supposed that deposition of Unit 4 took place after the deposition and subsequent erosion of the Upper Pleistocene "panchina" layer and perhaps also of part of the Sicilian succession. On the whole, available data suggest that Unit 4 is younger than the "panchina" layer (Ois 5e). In addition, Unit 4 cannot be younger than Unit 6 (see below), therefore we tentatively refer this unit to the Upper Pleistocene.

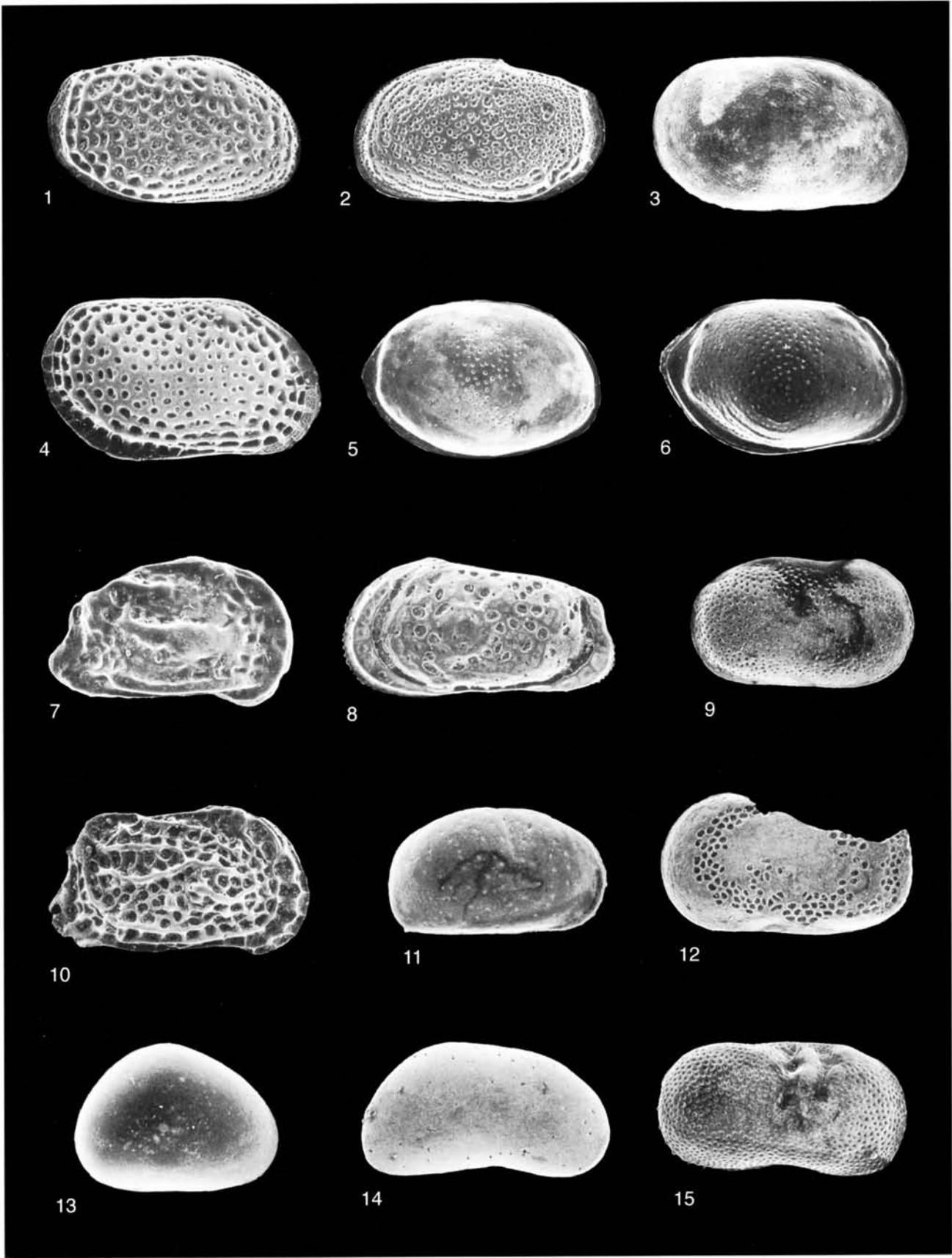
In the lower levels, the abundant shelly material and the composition of the microfauna are indicative of a very shallow marine environment with a near source of fresh water input. Upwards the dominance of fresh-brackish water forms documents a transition to a predominant brackish environment.

UNIT 5

Description – Unit 5 can be divided into two subunits (5A and 5B). Both were recovered above Unit

EXPLANATION OF PLATE 2

- Fig. 1 - *Loxoconcha rubritincta* Ruggieri. RV (Unit 2 borehole N; -5.2 m).
 - Fig. 2 - *Loxoconcha minima* Müller. LV (Unit 2 borehole I; -10.4 m).
 - Fig. 3 - *Loxoconcha elliptica* Brady. RV (Subunit 7B borehole A; -5.2 m).
 - Fig. 4 - *Loxoconcha parallela* Müller. RV (Unit 2 borehole I; -10.4 m).
 - Fig. 5 - *Palmoconcha turbida* (Müller). RV (Subunit 7B borehole A; -5.2 m).
 - Fig. 6 - *Loxoconcha subrugosa* Ruggieri. RV (Unit 2 borehole H; -6.5 m).
 - Fig. 7 - *Pachycaudites attenuata* Ruggieri (x 55). RV (Unit 2 borehole I; -11.7 m).
 - Fig. 8 - *Muellerina problematica* (Seguenza). LV (Unit 2 borehole H; -10.0 m).
 - Fig. 9 - *Cytherella thrakiensis* Stambolidis (x 55). RV (Unit 2 borehole H; -8.5 m).
 - Fig. 10 - *Tenedocythere prava* (Baird) (x 55). RV (Subunit 7B borehole F; -5.1 m).
 - Fig. 11 - *Cyprideis torosa* (Jones) (x 40). RV (Subunit 1A borehole N; -21.5 m).
 - Fig. 12 - *Cytherelloidea sordida* (Müller) (x 55). LV (Subunit 1A borehole Q; +10.6 m).
 - Fig. 13 - *Cyclocypris laevis* (Müller). RV (Unit 6 borehole B; -23.5 m).
 - Fig. 14 - *Candona neglecta* Sars (x 40). RV (Unit 6 borehole B; -26.5 m).
 - Fig. 15 - *Ilyocypris gibba* (Ramdohr) (x 55). RV (Subunit 7B borehole A; -2.5 m).
- S.E.M. microphotographs of selected ostracod taxa. All views external lateral (x 90 unless otherwise stated).



3 in boreholes drilled in the Livorno Terrace (O, P, Q boreholes). The lower Subunit 5A comprises mottled silt or clay-sand alternations with sparse carbonate glaebules and coarse sandy gravels (1-5 m-thick). The basal contact with Unit 3 is usually sharp. Subunit 5B comprises sands and reddish silty sands with millimetric nodules of manganese. Rare levels of gravelly sand are also present. Both the subunits are barren of fossils.

Stratigraphical and palaeoenvironmental remarks – The geometric position of this unit with respect to Unit 3 indicates an age younger than the Ois 5e. The environmental interpretation of Unit 5 is facilitated by sections exposed on the Livorno Terrace. Subunit 5A shows an alternation of decametric sheet-like gravelly deposits with silty sands. Some gravel bodies show fining upward organization and a concave erosive basal surface. Overall, Subunit 5A accumulated in an alluvial plain environment characterized by palaeochannels with gravelly bedload transport. Subunit 5B shows clear feature of weathered deposits; gravel levels are less frequent than in the previous subunit. It likely represents an environment dominated by superficial alteration with sporadic supply of sediments from ephemeral streams.

UNIT 6

Description – This unit comprises sandy silts and silty-clayey sands recovered from -7 to -31 m in the northern boreholes (boreholes A, B, C, D, E, F); the maximum cored thickness is about 15 m. Carbonate glaebules, plant remains, non-marine shells are common throughout; charophyta oospores are often present. Unit 6 is sharply overlain by Unit 7. In boreholes D, E and F lower levels of this unit are usually characterized by fresh water molluscs (e.g. *Bithynia*, *Ancylus*, and *Pisidium*) and land snails (e.g. *Carychium*, *Vertigo*, *Vallonia*, *Punctum*, *Limax*, and *Testacella*). Fresh water ostracods are locally well represented; they belong mainly to *Ilyocypris* and *Candona*, including *Pseudocandona compressa* (Koch), and subordinately to *Cyclocypris laevis* (Müller) and *Pseudocandona* spp. In the upper levels, land snails are still present; they are represented mainly by *Carychium* and to a lesser extent by *Vallonia*, *Discus* and *Monacha*, whereas fresh water ostracods become extremely rare. The only fresh water mollusc species is *Lymnaea*.

Faunal content of boreholes B and C differs only slightly from that above described. Remains of fresh water gastropods (*Bithynia* and *Valvata*) and land snails (*Carychium* and *Limax*) were found patchily also in these boreholes. Microfaunas are usually very poor and include marine and brackish (e.g. *Ammonia tepida*, *Protelphidium*) benthonic foraminifers and very rare, reworked planktonic forms; ostracods comprise fresh-brackish water taxa and locally very rare marine forms.

Only two samples (borehole B; -26.5 m and borehole C; -16.4 m) yielded a rich fresh water ostracod fauna (comprising adults of *Candona neglecta* Sars). Fairly abundant benthonic foraminifers with dominant *Ammonia tepida* were recovered at -22.9 m in borehole C and at -24.5 m in borehole B.

Stratigraphical and palaeoenvironmental remarks – Radiocarbon dating from wood fragments collected in the lower levels of this unit (borehole F; -19.3 m) indicates an age greater than 50,300 yr BP. The stratigraphy of this unit indicates that it is older than Holocene deposits (Unit 7) and younger than Unit 2 of Sicilian age (see borehole F); furthermore, it is probably also younger than Unit 3 and Unit 4. Therefore, we infer that Unit 6 is still Upper Pleistocene in age.

Fossil assemblages recovered in this unit are indicative of an alluvial plain environment with ephemeral water bodies. In the northern boreholes, the irregular alternation of non-marine and brackish faunas is considered to reflect temporary exchange between continental and marine waters.

UNIT 7

Description – This unit includes two subunits (7A and 7B). The lower one (Subunit 7A) consists of fine to coarse sands (boreholes A, B, C, D, E, F) with local concentrations of gravels (boreholes A, B, D), recovered from a maximum depth of -19.0 m to a minimum depth of -3.8 m. The upper subunit (Subunit 7B) comprises alternations of silty sands and sandy silts often rich in *Posidonia oceanica* remains and locally marine shells. Subunit 7B has been recognized in most of the investigated boreholes (boreholes A, B, C, D, E, F, G, H, I, L, N), where it occurs from a maximum depth of -11.6 m to +1.0 m.

With the exception of the uppermost levels, which can display concentration of marine shells, sands of Subunit 7A are almost barren of fossils. They occasionally include (borehole A) rare remains of echinoids and very scarce microfaunas, with possible local mixing of marine, brackish and fresh water elements.

Faunal content of the upper subunit is variable. Levels with *Posidonia oceanica* remains are usually rich in marine gastropods (e.g. *Alvania*, *Calliostoma*, *Cerithium*, *Cerithiopsis*, *Cryptospira*, *Cythara*, *Gibbula*, *Hinia*, *Jujubinus*, *Tricolia*, *Rissoa*, *Bittium*, *Turritella*) and subordinately bivalves (e.g. *Acanthocardia*, *Chlamys*, *Dosinia*, *Leda*, *Pectunculus*, *Venus*, *Venerupis*, *Nucula*, *Tellina*). Microfaunas are abundant and comprise highly diverse, shallow marine foraminifers and ostracods (e.g. *Aurila convexa* (Baird), *Aurila fallax* Ruggieri, *Bairdia longevaginata* Müller, *Bythocythere minima* Bonaduce, Ciampo & Masoli, *Costa batei* (Brady), *C. edwardsi*, *Carinocythereis whitei*, *Caudites calceolatus* (Costa), *Cytherelloidea sordida*,

Loxoncha ovulata, *L. rhomboidea* (Fisher), *Phlyctocythere globosa* (Schornikov), *Pontocythere turbida*, *Tenedocythere prava* (Baird), *Xestoleberis communis*, *X. decipiens* Müller).

Remaining sediments locally yielded microfaunas characterized by a mixing of marine, brackish and fresh water forms. Ostracods can include rare reworked specimens pertaining to *Celtia rugosa* (Costa), *Flexus triebeli*, *Miocyprideis italiana*, and *Ruggieria tetraptera* (Seguenza).

Stratigraphical and palaeoenvironmental remarks – Radiocarbon dating from shell remains collected at the top of Subunit 7A (borehole E; –6.2 m) provided an age of $4,530 \pm 60$ yr BP and allowed to attribute this subunit to the late “Versilian transgression”. Radiometric ages of *Posidonia oceanica* remains from lower levels of Subunit 7B range between 930 ± 45 yr and 1110 ± 100 yr BP, indicating that deposition of these sediments persisted till historical age. It is worth mentioning that bottom of Subunit 7A displays a northward increasing depth (from –7.0 m in borehole F to –19.0 m in borehole A); on the whole, this holds true also for Subunit 7B (from –5.8 m in borehole F to about –11.5 m in boreholes A and B).

On the whole, Unit 7 is interpreted as transgressive deposits related to the onset of a sandy shore coastal system. Sands with local gravel horizons can be considered to represent beach-ridge deposits; silty sands and sandy silts with *P. oceanica* may have accumulated both in a shoreface environment and in a shallow marine setting (Della Pietà, 1984). The local occurrence of brackish-fresh water microfaunas mixed with shallow marine associations and reworked elements suggests the existence of zone influenced by fluvial discharge.

CONCLUSIONS

The multidisciplinary study (lithological and palaeontological analyses and radiocarbon dating) of 15 boreholes allowed to refine the Quaternary stratigraphy of the Livorno surroundings and suggested that this area underwent a more complicated stratigraphical history than previously known (Text-fig. 5).

Particularly, in the southernmost boreholes pertaining to the Livorno Terrace domain we have been able to confirm the presence below the Eutyrrhenian “panchina” layer (Unit 3) of a relatively thick marine succession belonging to the Santernian-Emilian cycle (Subunit 1A). This succession has been relatively well documented in the past literature and, as previously mentioned, it has been correlated to the transgressive Santernian-Emilian Sands and Clays with *Arctica islandica* or considered as transitional between these and the regressive Emilian Nugola Vecchia Sands (Barsotti *et al.*, 1974; Giannelli *et al.*, 1982). The transition between these formations is still not well

constrained. Stratigraphical inferences on the Nugola Vecchia Sands formation, which outcrops about 18 km ENE of Livorno, derive only from a likely correlation with the “Montescudaio Limestones” formation, known from the Rosignano basin (about 20 km S of Livorno). The latter formation has been referred to the Emilian by Galiberti *et al.* (1982) and Bartoletti *et al.* (1986). On the whole, marine sediments of the Santernian-Emilian cycle investigated in the present study can be reasonably referred to the Emilian.

In addition, the Lower Pleistocene succession of the Livorno subsurface appears to include two sedimentary units so far unrecognized in the area.

Specifically, we identified brackish sediments (Subunit 1B) most likely referable to the regressive phase of the Santernian-Emilian cycle and thus correlatable to the Nugola Vecchia Sands formation. As previously discussed stratigraphical considerations on this brackish succession derives mostly on its geometric position and in none of the investigated boreholes we have been able to document a direct transition between Subunit 1A and Subunit 1B.

We have been able to well document a second marine Lower Pleistocene cycle (Unit 2), which can be assigned to the Sicilian on the basis of both ostracod faunas (common occurrences of *Aurila puncticrucata*) and calcareous nannofossils (“small *Gephyrocapsa* Zone”). In most of the examined boreholes (boreholes G, H, I, L), marine Sicilian sediments rest on the regressive phase of the Santernian-Emilian cycle (Subunit 1B) and only in a single borehole (N) they overlie marine sediments of Subunit 1A. In coastal Tuscany, marine Sicilian sediments were previously known only from the Rosignano area; they are represented by the Fabbrie Sands formation (about 30 m thick), which rests transgressively on the Emilian “Montescudaio Limestones” formation (Bartoletti *et al.*, 1986).

Finally, in a single borehole drilled in proximity of the “Gronda dei Lupi” erosional scarp (borehole G), we recorded nearshore to transitional sediments (Unit 4) comprised between coarse sediments tentatively referred to the Sicilian cycle and Holocene sediments with *Posidonia oceanica* remains. On the whole, achieved data seem to suggest that these sediments, which undoubtedly need further investigations, would represent a cycle of probable Upper Pleistocene age (younger than the “panchina” layer).

Subunit 5A, recovered above the “panchina” layer in boreholes drilled on land in the Livorno Terrace, may be tentatively correlated to the “Rio Maggiore Conglomerates” (Lazzarotto *et al.*, 1990). Subunit 5B is well correlatable with the “Ardenza Sands” (Lazzarotto *et al.*, 1990). These authors suggested that this formation is partly related to aeolian deposition, but today exposed outcrops do not show clear evidences of this. Overall, Unit 5 can be assigned to a generic Upper Pleistocene. This attribution is corroborated by

UNIT	SUBUNIT	Biostratigraphical significant faunal data (Ostracoda = O; Foraminifera = F; calcareous nanofossils = N) (rate = r, c = common)		Radiocarbon dating (yr BP)	Inferred age	Palaeo-environment		Correlations with outcropping nearby formations
		Known distribution				transgressive deposits of a sandy shore coastal system	shoreface or shallow marine beach-ridge	
UNIT 7	SUBUNIT 7B	Biostratigraphically insignificant shallow marine mollusc, foraminifer and ostracod taxa		lower levels (P. oceanica) between 930 ± 45 and 1110 ± 100	HOLOCENE			Sediments of the "Versilian transgression" and historical coastal deposits
	SUBUNIT 7A	Top with marine molluscs Almost barren of fossils		top (marine shells) 4,530 ± 60				
UNIT 6		Biostratigraphically insignificant continental (land snails) and fresh-water (molluscs and ostracods) faunas		> 50,300 (wood fragments)	UPPER PLEISTOCENE	alluvial plain with freshwater bodies		Continental sediments of the Pisa Plain
	SUBUNIT 5B	Barren of fossils			UPPER PLEISTOCENE?	alluvial plain		"Ardenza Sands" (Upper Pleistocene)
UNIT 5	SUBUNIT 5A	Barren of fossils						"Rio Maggiore Conglomerates" (Upper Pleistocene)
UNIT 4		A. cymbaeformis, A. lanceaeformis, A. pigadiana	Plioc.-Lower Pleist.		UPPER PLEISTOCENE?	very shallow marine with influences of fresh water (palaeoshore?)		
		O C. sordida, L. subrugosa, N. fasciata, P. turbida	Pleistocene-Recent	> 40,700 (wood fragments)				
		Miocypriideis italiana (reworked)	Pliocene					
UNIT 3					EUTYRRHENIAN (Os 5e)	transgressive lower "panchina layer" (beach rock) of the dry-dock of "Torre del Fanale"		
UNIT 2		A. b. extumefacta, A. cymbaeformis, A. lanceaeformis, A. pigadiana, C. testudo, F. triebeli, Pachycaudites attenuata	Plioc.-Lower Pleist.	> 45,000 (Turritella shells)	SICILIAN	Shallow marine with feeble influences of freshwater water		Fabbritche Sands Fm. (Sicilian) known only from the Rosignano area (ca. 20 km south of Livorno)
		L. elliptica, L. subrugosa, N. fasciata, P. turbida, P. subspiralis	Pleistocene-Recent					
		Muellina problematica	Lower Pleistocene					
		Aurilia favorita	Emilian-Sicilian					
		Aurilia puncticulata (common)	Emilian (r)-Sicilian (c)					
	F	Hyalinea baltica	Emilian-Recent					
	N	Associations referable to the "small Gephyrocapsa zone"						
		A. cymbaeformis	Plioc.-Lower Pleist.					
UNIT 1	SUBUNIT 1B	L. elliptica	Pleistocene-Recent		EMILIAN	Brackish		Nugola Vecchia Sands Fm. (Emilian)
		Aurilia bullapunctata extumefacta, A. cymbaeformis, A. lanceaeformis, A. pigadiana, A. punctata	Plioc.-Lower Pleist.		EMILIAN	Shallow marine		Clays and Sands with A. islandica Fm. (Santernian-Emilian) or transitional between these and the Nugola Vecchia Sands Fm. (Emilian)
		Caniovalva testudo, Flexus triebeli						
		Aurilia arborescens, Cytherelloidea sordida, Loxoconcha elliptica, L. rubritincta, L. subrugosa, Neocytherideis fasciata, Palaeoconcha turbida, Procytherideis subspiralis	Pleistocene-Recent					
	SUBUNIT 1A							
	F	Hyalinea baltica	Emilian-Recent					

Text-fig. 5 - Summary of the main data achieved on the Quaternary stratigraphy of the Livorno area (Biostratigraphical significant faunal data and radiocarbon dating are reported).

frequent discoveries of Middle Palaeolithic Flintstones in Subunit 5B (Ciampalini, 2002).

In the northernmost boreholes belonging to the alluvial Pisa Plain dominated by the Arno River influence, the present study allowed to confirm the presence of brackish-continental sediments with lower levels of probable Upper Pleistocene age (Unit 6). These sediments are truncated by sands (Subunit 7A), which can be ascribed to the Versilian transgression (radiometric age of their top is 4530 ± 60 yr BP) followed by historical coastal deposits (Subunit 7B).

It is worth mentioning that the stratigraphy of Pisa Plain here discussed shares some interesting features with the subsurface deposits of the Versilian Plain. Particularly, a recent revision of old boreholes of the Versilia Plain (Federici, 1993) and the study of a new drilling (Antonioli *et al.*, 2000) indicate the presence of a thick continental succession below the marine-sands of the Versilian transgression. This continental succession can be correlated with our Unit 6.

Further future refinement of the stratigraphy of the Pisa Plain will permit a better reconstruction of the subsiding history of the various sectors of this plain and its relationships with the nearby Versilia Plain.

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APPENDIX

TAXONOMIC AND STRATIGRAPHICAL NOTES ON SELECTED OSTRACOD TAXA

- Aurila arborescens* (Brady) = *Cythere arborescens* Brady, 1865
Synonymy and discussion in Athersuch *et al.* (1985)
Distribution: Pleistocene (Santerian)-Recent *fide* Ruggieri (1980) [as *Aurila woodwardii* (Brady, 1868)]
- Aurila bullapunctata extumefacta* Uliczny, 1969
Distribution of *Aurila bullapunctata* s.l.: Pliocene-Lower Pleistocene (Sicilian) *fide* Ruggieri (1980)
- Aurila cymbaeformis* (Seguenza) = *Cythere cymbaeformis* Seguenza, 1883
Distribution: Pliocene-Lower Pleistocene (Sicilian) *fide* Ruggieri (1980)
- Aurila favorita* Ruggieri, 1975b
Distribution: (Emilian-Sicilian) *fide* Ruggieri (1980)
- Aurila lanceaeformis* Uliczny, 1969
Distribution: Pliocene (Uliczny, 1969; Ciampo, 1992)-Lower Pleistocene (Ciampo, 1976)
- Aurila pigadiana* Sissingh, 1972
Distribution: Pliocene-Lower Pleistocene (Sicilian) *fide* Ruggieri (1980)
- Aurila punctata* (Münster) = *Cythere punctata* Münster, 1830
Distribution: Pliocene-Lower Pleistocene (Sicilian) *fide* Ruggieri (1980)
- Aurila puncticrucata* Ruggieri, 1975b
Distribution: Lower Pleistocene (Emilian/rare-Sicilian/frequent) *fide* Ruggieri (1980)
- Carinivalva testudo* (Namias) = *Cythere testudo* Namias, 1900

- Distribution (Mediterranean): Neogene-Lower Pleistocene (Sicilian) *fide* Ruggieri (1980)
- Celtia rugosa* (Costa) = *Cytherina rugosa* Costa, 1853
Distribution: Pliocene-Pleistocene *fide* Mostafawi, 1989
- Cytherelloidea sordida* (Müller) = *Cytherella sordida* Müller, 1894
Distribution: Pleistocene (Emilian)-Recent *fide* Ruggieri (1980)
- Flexus triebeli* (Ruggieri) = *Eucytheretta triebeli* Ruggieri, 1962
Synonymy and discussion in Ruggieri (1992)
Distribution: Pliocene-Lower Pleistocene *fide* Ruggieri (1992)
- Loxococoncha elliptica* Brady, 1868
Synonymy and discussion in Athersuch & Whittaker (1976)
Distribution: Pleistocene-Recent *fide* Athersuch & Whittaker (1976)
- Loxococoncha rubritincta* Ruggieri, 1964
Distribution: Pleistocene (Emilian)-Recent *fide* Ruggieri (1980)
- Loxococoncha subrugosa* Ruggieri, 1976b
Distribution: Pleistocene-Recent *fide* Ruggieri (1978)
- Muellerina problematica* (Seguenza) = *Cythere concinna*? var. *problematica* Seguenza, 1884
Distribution: Lower Pleistocene ("cold guest"? *fide* Ruggieri (1980, 1992)
- Miocyprideis italiana* Moos, 1962
Distribution: Pliocene *fide* Ruggieri (1980)
- Neocytherideis fasciata* (Brady & Robertson) = *Cytherideis fasciata* Brady & Robertson, 1874
Distribution: Pleistocene (Santerian)-Recent *fide* Ruggieri (1980)
- Pachycardites attenuata* Ruggieri, 1980
Distribution: Pliocene-Lower Pleistocene (Sicilian) *fide* Ruggieri (1980)
- Palmococoncha turbida* (Müller) = *Loxococoncha turbida* Müller, 1894
Distribution: Pleistocene (Santerian)-Recent *fide* Ruggieri (1980)
- Procytherideis subspiralis* (Brady, Crosskey & Robertson) = *Cytherideis subspiralis* Brady, Crosskey & Robertson, 1874
Distribution: Pleistocene-Recent *fide* Ruggieri (1978)
- Ruggieria tetraptera* s.l. (Seguenza) = *Cythere tetraptera* Seguenza, 1880
Distribution: Miocene-Pliocene *fide* Ruggieri, 1980

ADDENDUM. RECORDS SIGNIFICANT TO EXTEND THE STRATIGRAPHICAL DISTRIBUTION OF SOME OSTRACOD SPECIES

- Cytherella thrakiensis* Stambolidis, 1980: recovered in borehole H Unit 2-Sicilian; cited from the Recent (Stambolidis, 1980; Aiello *et al.*, 1996).
- Loxococoncha minima* Müller, 1894: recovered in borehole I Unit 2-Sicilian; cited from the Recent (e.g. Müller, 1894; Puri *et al.*, 1964; Bonaduce & Pugliese, 1976; Bonaduce *et al.*, 1976; Barra, 1991 *cum bib.*).
- Loxococoncha parallela* Müller, 1894: recovered in boreholes I, H and N Unit 2-Sicilian; cited from the Recent (Müller, 1894; Puri *et al.*, 1964; Bonaduce *et al.*, 1976), but reported as *Loxococoncha* cf. *parallela* from the Sicilian of Southernmost Apulia (South Italy) by Bossio *et al.* (1989).

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