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Mid-late Holocene depositional architecture and palaeoenvironmental evolution of Pisa city area from subsurface data

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Stratigraphic correlations involving MAPPA cores and selected high-quality borehole data from the Pisa plain subsurface dataset were performed along a grid of perpendicular cross-sections. These sections were used to reconstruct spatial distribution patterns of fluvio-deltaic facies associations overlying lagoon clays ("pancone") in the uppermost 15-20 meters of Pisa subsurface. High-resolution reconstruction of depositional architecture furnished new insights on the mid-late Holocene palaeogeographic and palaeohydrographic evolution of the Pisa urban and periurban area.

Keywords: Cores, facies, depositional architecture, palaeoenvironmental evolution, mid-late Holocene

1. Introduction

Holocene deposits stored beneath the modern deltaic-alluvial plains are considered excellent sedimentary archives to explore in detail the palaeogeographic and palaeoenvironmental responses of coastal areas to natural forcing factors, both allogenic (eustasy, climate) and autogenic (sediment supply, local subsidence), and to the antrophogenic impact.

Multidisciplinary studies performed on Holocene coastal sedimentary successions of the western Mediterranean have documented similar depositional evolutionary trends. Several lagoonal basins formed during the peak of marine transgression, around 8000-7000 calibrated yr BP (Fairbanks *et alii* 1989; Bard *et alii* 1996), were progressively filled in response to the combined effect of sea-level stabilization and increasing river sediment supply, promoting the development of modern deltaic-alluvial plains (Bellotti *et alii* 1994, 2004; Bruneton et *alii* 2001; Amorosi *et alii* 2004, in press). These areas suffered a lengthy and intense human land-use history since ca. 4000 cal yr BP.

In this perspective, the fluvio-deltaic successions that overlie transgressive back-barrier deposits potentially record mid-late Holocene palaeoenvironmental changes even at short time scales, comparable to those involving human civilization and society evolution. Therefore, high-resolution stratigraphic analysis of these deposits, 15-20 m-thick beneath the Pisa urban and periurban area, is a fundamental step toward an exhaustive and accurate knowledge of the recent past landscape evolution.

The development of reliable palaeogeographic maps of the Pisa area, next milestone of MAPPA project, must rely on the detailed reconstruction of temporal-spatial distribution patterns of these fluvio-deltaic facies associations, which in the study area overlie lagoonal deposits known as "pancone" (Rossi *et alii* 2011).

The coring campaign performed in the Pisa coastal plain in the context of "MAPPA project", which led to the collection of 20 sedimentary cores (9 continuous cored boreholes and 11 percussion cores; see Fig. 1 for core location), 7-20 m long, and to the acquisition of new geoarchaeological data through a cross-disciplinary approach (MapPaper 4-en, Amorosi *et alii* 2012), significantly increased our knowledge of flu-

vio-deltaic stratigraphic architecture above "pancone". Description and interpretation of the main sin- and post-"pancone" facies associations are reported further on in the text. The overall depositional architecture was reconstructed through a dense grid of stratigraphic correlations performed on a total of 18 sections (7 roughly perpendicular and 11 parallel to the modern Arno River course; Fig. 1) involving reference cores (MAPPA cores) and high-quality (high recovery percentage with accurate stratigraphic description) borehole data from the Pisa plain georeferenced subsurface dataset (see MapPaper 3-en, Anichini *et alii* 2011: 64). Sections were created using RockWare (Rockworks15) and GIS (ArcMap) softwares (MAPPAGIS; http://mappaproject.arch.unipi.it/).
The chronological framework of the studied succession benefited from 35 radiocarbon dates, accurately supported by archaeological data (mainly ceramic remains) from MAPPA cores and described in MapPaper 4-en (Amorosi *et alii* 2012).

2. Facies associations

Compared to literature data (Amorosi *et alii* 2008; Rossi *et alii* 2012; Sarti *et alii* 2012), a more detailed facies analysis was performed on the fluvio-deltaic succession buried beneath the Pisa urban and periurban area (Fig. 1). On the basis of a cross-disciplinary study carried out on reference MAPPA cores, 10 depositional facies (Figs. 2A-F) were identified and grouped into three main facies associations. Detailed facies description and interpretation in terms of depositional environments are reported below. Specific information about the analytical procedures and results from MAPPA cores (microfossil associations, palynofacies and geochemical data), along with stratigraphic descriptions, are reported in MapPaper 4-en (Amorosi *et alii* 2012).

2.1. Back-barrier facies association

2.1.1. Lagoon clays ("pancone")

This facies is composed of extremely soft grey-blue grey clays and silty clays with rare mm- to cm-thick (commonly less than 20 cm) silty-sandy layers. Abundant bioclasts and mollusc shells, mainly represented by disarticulated valves of a typical brackish species (*Cerastoderma glaucum*) are encountered along with cm-thick mollusc lags (Figs. 2A, B). Rare wood fragments are also found, especially close to facies upper boundary. High Rb e Al_2O_3 concentrations, commonly greater than 150 mg/kg and 15%, respectively, confirm the elevated content in clay minerals.

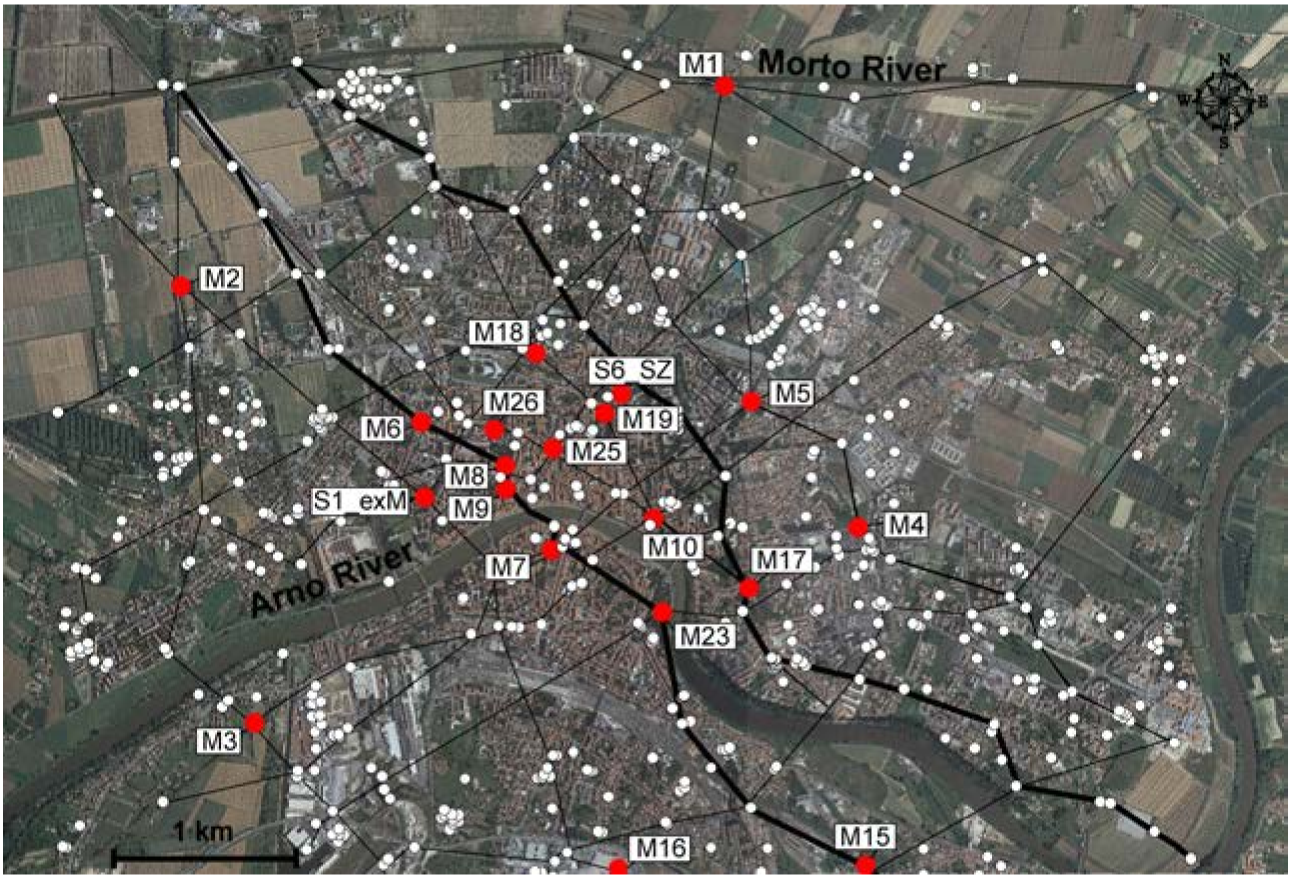

Figure 1. Location of MAPPA cores (shown as red dots) and high-quality borehole data, selected from the available subsurface dataset (shown as white dots), across the Pisa urban and periurban area. Section traces created using RockWorks15 and ArcMap softwares are also shown; bold lines indicate the two most representative sections reported in Figure 3A-B.

Ostracod and benthic foraminiferal associations (B1, B2 and B3 in MapPaper 4-en: 157) are characterized by high relative abundance (> 30%) of *Cyprideis torosa* and *Ammonia tepida-Ammonia parkinsoniana*. These opportunistic and euryhaline species are considered indicative of semi-protected, hypohaline-brackish basins subject to salinity fluctuations (Athersuch *et alii* 1989; Meisch 2000; Murray 2006). More specifically, association B1 contains an olygotypic autochthonous meiofauna mainly represented by *C. torosa*, while association B2 shows a more diversified assemblage with the occurrence as secondary taxa (usually < 10%) of typical brackish ostracods *Loxoconcha elliptica* and *Loxoconcha stellifera*, and foraminifers *Aubignyna perlucida* and *Haynesina germanica*. Association B3, exclusively recorded within the lowermost portion of the most distal cores (M2, M3 and M6 in Fig. 1), is characterized by the highest species diversity encountering several polyhaline and marine taxa as *Leptocythere ramosa, Palmoconcha turbida* and Miliolids species. Palynofacies contains marine-related elements (Dinocysts, Scolecodonts and foraminiferal linings) and various types of pollen and spores (palynofacies L in MapPaper 4-en: 158).

One sample collected from the upper portion of this facies, recorded within core M1 (see Fig. 1 for location), furnished a radiocarbon age of 3800-3640 cal yr B.C. Literature data assign the very base of this facies back to around 6000 cal yr B.C. (8000 cal yr BP in Amorosi *et alii* 2009; Rossi *et alii* 2011).

Sedimentological and geochemical features indicate a semi-protected, low-energy depositional setting characterized by dominant settling processes, occasionally replaced by higher-energy traction processes (sand layers).

The meiofauna content is typical of a shallow, hypohaline-brackish (lagoonal) basin subject to salinity fluctuations, affected by combined riverine and marine influx. An inner-central lagoon, characterized by low to moderate marine influence (associations B1 and B2) was distinguished from an outer portion with high marine influence (association B3). The exclusive occurrence of association B3 within the lowermost portion of the most distal cores (M2, M3 and M6; Fig. 1) suggests a gradual filling trend of the Pisa lagoon basin, which started around 3700 cal yr B.C. at the northern margin of the study area (core M1; Fig. 1).

2.1.2. Flood tidal delta sands

This facies, exclusively recovered within core M3 (Fig. 1), is composed of grey medium and fine-medium sands, less than 1 m thick, containing wood fragments and minute bioclasts. Low Rb and Al_2O3 concentrations, 60-90 mg/kg and 11-13%, respectively, confirm the scarce quantity of clay minerals.

A scarce, poorly-preserved (reddish, abraded or partially broken shells/valves) meiofauna composed of typical brackish (*C. torosa* and *Ammonia tepida-A. parkinsoniana*), and shallow marine (*Ammonia beccarii* and *Nonion boueanum*) species is found (association R3 in MapPaper 4-en: 158).

According to sedimentological features (coarse-grained deposits) and micropalaeontological content (transported mixed brackish-marine meiofauna), this facies is interpreted as formed within a high-energy back-barrier environment subject to wave reworking (flood-tidal delta or washover fan). A radiocarbon age of 2890-2575 cal yr B.C. obtained from the overlying swamp deposits furnished a reliable *ante quem* chronological term for facies deposition.

2.2. Deltaic/coastal plain facies association

2.2.1. Lower swamp clays

These deposits, ranging in thickness between 1-4 m, are mainly composed of dark grey-black plastic clays and silty clays, frequently interrupted by mm- to cm-thick sandy layers. The high variability of Rb and Al_2O_3 concentrations, comprised between 100-180 mg/kg and 15-19%, respectively, confirms the remarkable textural heterogeneity.

A high organic-matter content, represented by decomposed and partially decomposed (wood and plant fragments) elements, accounts for the dark colour. Locally, mm-thick peat layers also occur (Fig. 2B). The abundance of unstructured organic matter (AOM) and fibrous phytoclasts is also confirmed by palynological analysis (palynofacies P in MapPaper 4-en: 158-159). Palynomorphs are represented by continental elements, mainly pollen and spores. Microfossil samples are barren or less frequently contain an olygotypic ostracod fauna dominated by either the oligohaline-freshwater species *Pseudocandona albicans* (association F in MapPaper 4-en: 156-157) or the euryhaline species *C. torosa* (association B1 in MapPaper 4-en: 157).

Radiocarbon data chronologically constrain these deposits to around 2900-2000 cal yr B.C. According to the progradational seaward shift of facies, a slightly younger age of 1900-1750 cal yr B.C. is obtained at distal locations (core M3; Fig. 1) at the facies upper boundary.

The high abundance of decomposed and partially decomposed organic matter, paralleled by the occasional occurrence of an olygotypic hypohaline ostracod fauna, indicates a shallow, freshwater or slightly brackish paludal basin subject to remarkable river input. The diffuse presence of AOM and the sporadic record of *P. albicans*, a species typical of stagnant waters (Henderson 1990; Meisch 2000), also suggest scarce oxygenation at the bottom. The scarcity of an autochthonous meiofauna is likely indicative of ephemeral acid conditions.

2.2.2. Subdelta sands

A 1 m-thick coarsening-upward (CU) sandy succession (grey fine to medium sands) composes this facies (Fig. 2A). Scarcity of clay minerals is confirmed by low Rb and Al_2O_3 concentrations, ranging between 60-90 mg/kg and 11-13%, respectively. Several wood fragments and a scarce ostracod fauna, exclusively formed by adult valves of *C. torosa* with evidence of abrasion and dissolution (association R2 in MapPaper 4-en: 158) are commonly encountered.

Sedimentological features (coarse-grained sediments and CU trend) and the meiofauna content, characterized by poorly preserved and size-selected valves of *C. torosa*, suggest a high-energy depositional setting formed in proximity of the innermost portion of a brackish-water basin (subdelta). A radiocarbon age of 2820-2630 cal yr B.C., derived from the overlying swamp deposits within core M1, represents an *ante quem* chronological term for the deposition of these sands along the northern margin of the study area (see Fig. 1 for core M1 location).

2.2.3. Distributary channel sands

This facies, which shows variable thickness (commonly less than 2 m) across the study area, consists of grey coarse-medium, medium-fine and fine sands organized into thin fining-upward (FU) sequences with erosional lower boundary. Coarse grain size is consistent with the very low concentration values of Rb and Al_2O_3, ranging between 60-90 mg/kg and 7-10%, respectively. Wood fragments, minute bioclasts and rare mud clasts occur (Fig. 2C). Bivalve and gastropod shells are encountered within cores M2, M6 and M7 (see Fig. 1 for location).

In core M2, this facies shows an elevated concentration of mollusc shells, accompanied by an increase in grain size (gravel and sands) and chaotic texture. A scarce, poorly preserved meiofauna, showing evidence of abrasion and dissolution (reddish, abraded or partially broken shells/valves) and composed of several euryhaline (*C. torosa, Ammonia tepida-A. par-*

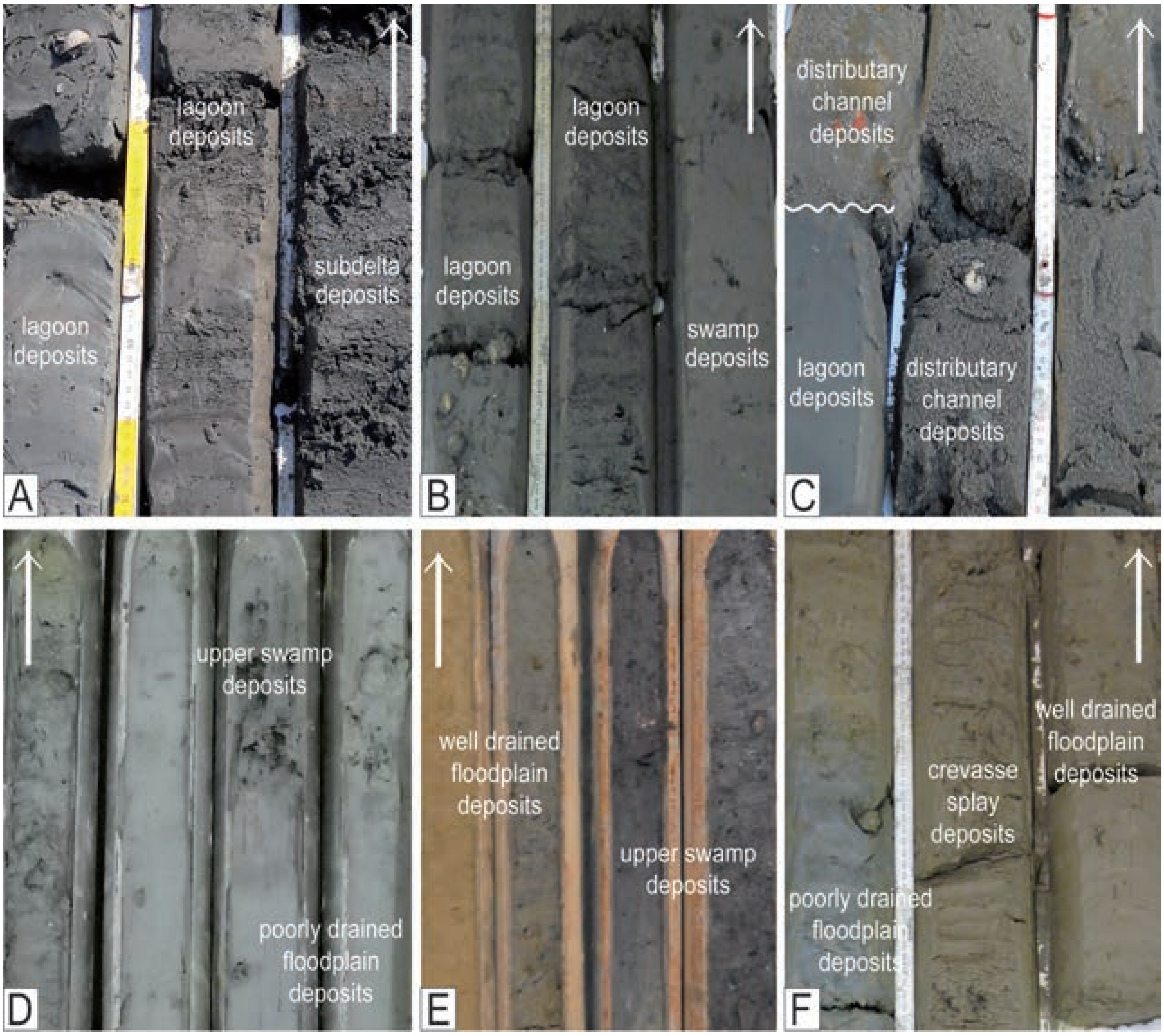

Figure 2: Representative photographs of the major depositional facies. A) lagoonal clays ("pancone") passing upward to subdelta sands (core M1); B) lagoonal clays ("pancone") overlain by swamp deposits (core M5); C) close up of distributary channel sands with mollusc shells truncating underlying lagoonal deposits (core M6); D) upper swamp deposits overlying poorly drained floodplain clays (core M26); E) upper swamp deposits passing upward to well drained floodplain clays and silts (core M9); F) poorly drained floodplain clays passing upward to a crevasse splay sandy succession overlain by well drained floodplain deposits (core M5). See Figure 1 for cores location.

kinsoniana) and shallow-marine (*A. beccarii, Nonion boueanum*) species, is also found (association R3 in MapPaper 4-en: 158).
Radiocarbon data, performed on *Cerastoderma* valves collected from core M6, furnish an age of ca. 3500-3000 cal yr B.C. Younger ages (1500-1200 cal yr B.C. and 1090-900 cal yr B.C.) were obtained from bivalve shells and wood fragments recorded within core M2.
According to the diagnostic sedimentological features (coarse-grained sediment, FU trend and occurrence of mollusc shells, bioclasts and wood fragments) and the reworked meiofauna, this facies is interpreted to reflect a high-energy depositional setting formed within a deltaic/coastal system, not far from the coastline, such as a distributary channel. However, this facies interpretation is still hypothetical for core M2 deposits and further data, including those deriving from malacological analysis, are required.
The chronological attribution of this facies is uncertain. Radiocarbon data derived from *Cerastoderma* valves within core M6 are indicative of the depositional age of "pancone" (cfr. § 2.1.1.) and do not reflect actual channel activity. The latter is better chronologically constrained by a radiocarbon age of 1750-1630 cal yr B.C., obtained from overlying swamp deposits.

2.3. Alluvial plain facies association

2.3.1. Poorly drained floodplain clays

This facies association, which shows a variable thickness ranging between 1-4 m, consists of monotonous soft light grey clays and silty clays, low in organic matter and with isolated and large (up to 3 cm) calcareous nodules (Figs. 2D, F). Abundant sharp-based, dm-to cm-thick sandy and silty layers occur. Remarkable Rb and Al_2O_3 concentrations, ranging between 120-165 mg/kg and 15-19%, respectively, confirm the high content in clay minerals.
Scattered plant remains are encountered along with few, thin-shelled mollusc fragments. Rare pulmonate gastropods and cm-thick layers made up of decomposed organic matter occasionally occur. Samples are barren, with the exception of those collected from organic-rich layers with scarce olygotypic ostracod fauna exclusively composed of *P. albicans*. About the palynofacies, AOM is sporadically present, while phytoclasts with evidence of reworking (equal size, round border, dark brown to black colour) are abundant. The pollen association is heterogeneous, with many poorly preserved specimens reworked *in situ* or derived from ancient sediments (palynofacies A in MapPaper 4-en: 159). Radiocarbon ages invariably indicate a chronological interval between 1900 and 700 cal yr B.C.
Sedimentological features and the co-occurrence of plastic consistency and calcareous nodules indicate a fully terrestrial, low-energy depositional environment (floodplain), generally below the groundwater table and subject to brief phases of subaerial exposure. This interpretation of a poorly drained floodplain environment is consistent with the rare freshwater-hypohaline ostracod fauna and the alluvial palynofacies. Frequent river floods from close active channels are documented by the occurrence of sand layers.

2.3.2. Upper swamp clays

This facies, 1-2 m thick, is formed by relatively soft, organic-rich, dark grey clays and silty clays containing abundant decomposed and partially decomposed (wood and plant fragments) organic matter. Peat layers, mm- to cm-thick, and scattered freshwater gastropods locally occur (Figs. 2D, E), while small-sized calcareous nodules are rare. These deposits show geochemical (Rb and Al_2O_3 concentrations), micropalaeontological and palynological features very similar to those observed for the lower swamp clays (cfr. § 2.2.1.). Unique exception, the occurrence of a higher amount of continental elements and a considerable local concentration (core M19; see Fig. 1 for location) of human land-use indicators. Radiocarbon ages furnish a chronological interval ranging between 860-400 cal yr B.C.
Similar to the lower swamp facies, these deposits formed within a stagnant, organic-rich subaqueous environment. The occurrence of a palynofacies with intermediate characteristics typical of both paludal and alluvial settings is highly consistent with ephemeral, shallow swamp basins developed close to river courses (backswamp), in low-lying areas surrounded by natural levee reliefs.

2.3.3. Well drained floodplain clays and silts

This facies, 1 m to 3.5 m-thick, is composed of dry, stiff, yellowish light brown clays and silty clays with low organic-matter content and evidence of subaerial exposure, including indurated horizons, calcareous nodules and yellow-brown mottles due to iron and manganese oxides (Figs. 2E, F). Scattered plant remains are encountered, while no fossils are found. Occasionally, sharp-based layers made up of fine sands, a few centimeter to decimeter-thick, can be observed. Rb and Al_2O_3 concentrations, 120-165 mg/kg and 15-19%, respectively, are consistent with the fine-grained texture. Micropalaeontological samples are barren, while the palynofacies closely resembles that described for poorly drained floodplain deposits (crf. § 2.3.1). Radiocarbon dating performed on a sample collected from core M2 (see Fig. 1 for location) gave an age of ca. 610-665 yr A.D.
Sedimentological features and palynological content indicate an alluvial depositional setting characterized by prevalent settling processes and subject to subaerial exposure, such as a well-drained floodplain occasionally affected by river floods (sand layers).

2.3.4. Crevasse splay and levee sands and silts

This facies association is made up of fine sands and silts, displaying a 1 m-thick CU trend, or a rhythmical alternation (Fig. 2F). Grain size is consistent with Rb and Al_2O_3 concentrations ranging between

90-110 mg/kg and 11-17%, respectively. Scattered plant remains, wood and unidentifiable small-sized fragments of mollusc are commonly observed along with rare calcareous nodules and yellow-brown mottles due to iron and manganese oxides. Samples are barren or, less commonly, contain scarce and poorly preserved meiofauna composed of species typical of different environments, from deep marine to coastal marine and continental areas (association R1 in MapPaper 4-en: 158).
Radiocarbon data furnish different ages in relation to sample-depth collection. ^{14}C samples collected at positive elevation with respect to sea level (s.l.), within core M7 and core M9, give a chronological interval of 1040-1260 yr A.D. Radiocarbon data obtained from a sample collected 3 m below s.l., within core M10, furnished an older age ranging between 2350-1625 cal yr B.C.
On the whole, this facies association is interpreted to reflect an alluvial setting characterized by energy fluctuations and located close to active river courses, from which mixed reworked meiofauna derived. More specifically, CU sandy sequences correspond to crevasse splays while alternations of sands and silts reflect levee aggradation.

2.3.5. Fluvial channel sands

Fine to coarse sands organized into FU sequences with an erosional lower boundary compose this facies. The coarse grain size is confirmed by the very low values of Rb and Al_2O_3 concentrations. Wood fragments, bioclasts and mollusc shells are not present. Samples are barren.
These sand bodies are interpreted as fluvial-channel fills. Compared with distributary channel sands (cfr. § 2.2.3.), the main distinctive features is the absence of fossils and wood fragments.

3. Mid-late Holocene depositional architecture

The interdisciplinary approach used to analyze MAPPA cores significantly increased our knowledge of the shallow (15-20 m) subsurface architecture in the Pisa area. By means of stratigraphic correlations along a dense grid of sections, oriented perpendicular to each other (Fig. 1), the temporal-spatial distribution patterns of fluvio-deltaic facies overlying "pancone" were reconstructed in more detail than before (Fig. 3). Similar to previous works in the area, the lower portion of the mid-late Holocene succession is shown to be constituted invariably by an extremely soft and homogeneous lagoonal clayey horizon ("pancone"; § 2.1.1.). Along most of the studied sections (see Fig. 1 for section traces), "pancone" is overlain by paludal fine-grained sediments (lower swamp facies; § 2.2.1.) or subdelta sands (§ 2.2.2.) through a stratigraphically continuous surface, generally identified between 6-9 m b.s.l. (Fig. 3). Channel-fill sands (distributary channel facies; § 2.2.3) may locally overlie "pancone" through prominent erosional truncations, which deeply cut the underlying lagoonal succession taking its upper boundary down to almost 15 m b.s.l. (Fig. 3).

Isolated to locally amalgamated distributary channel-fill bodies are observed to cluster at specific depth intervals (Fig. 3), showing lateral transition to paludal deposits (lower swamp facies; § 2.2.1.) dated to the Eneolithic age (about 2900-2000 cal yr B.C). Although reoccupation of previous channels and local changes in accommodation due to subsidence and sediment compaction cannot be ruled out, channel upper boundaries represent useful stratigraphic markers to discriminate different channel generations, as recently documented for the Pisa plain by Rossi et al. (2012). Top-of-distributary channel bodies mainly cluster at about 8 m and 5-6 m below s.l., recording two main phases of deltaic/coastal plain development.

Around 5 m below s.l., swamp deposits are abruptly replaced by a poorly drained floodplain succession, which shows variable thickness ranging between 1-4 m (cfr. § 2.3.1.). Floodplain deposits are associated, at different stratigraphic levels, to crevasse splay-levee facies (§ 2.3.4.) and channel-fill sands (fluvial channel facies; § 2.3.5.), forming an articulate alluvial plain depositional system.

Poorly drained floodplain clays mostly accumulated during the Bronze-Iron ages (1900-700 cal yr B.C.), with the exception of the historical centre of Pisa (M10, M19 and M25; Fig. 1), where poorly drained conditions locally persisted up to the Roman period (MapPaper 4-en: 170; 175 and 177). Within the floodplain succession, at least two major phases of fluvial activity are recorded by the spatial distribution of channel bodies (Fig. 3). Between 0-2 m below s.l. poorly drained floodplain deposits are overlain by a variety of alluvial facies including well drained floodplain clays and silts and crevasse splay/levee sands (Fig. 3). A different stacking pattern of facies is recorded in the historical city centre, north of the modern Arno River course, where widespread swamp sedimentation (upper swamp facies; § 2.3.2.) is recorded around 2 m below s.l. (Fig. 3B). South of the Arno River course and in periurban areas, these paludal deposits of late Iron-early Etruscan age (ca. 860-400 cal yr B.C.) show lateral transition to crevasse sands and overbank fines (Fig. 3B).

Well drained floodplain deposits, dated by integrated radiocarbon and archaeological data to the Roman and post-Roman period (MapPaper 4-en: 188-189), cap the mid-late Holocene succession across the study area. In the historical Pisa centre, swamp (M25) and poorly drained floodplain clays (M10, M19 and M25) are locally recorded up to the transition to anthropic structures.
Few isolated channel-fill bodies, whose upper boundaries cluster at positive quotes with respect to s.l., are exclusively recorded in correspondence of the modern Arno River course (Fig. 3). The recent alluvial plain succession is overlain by anthropic structures at various depths.

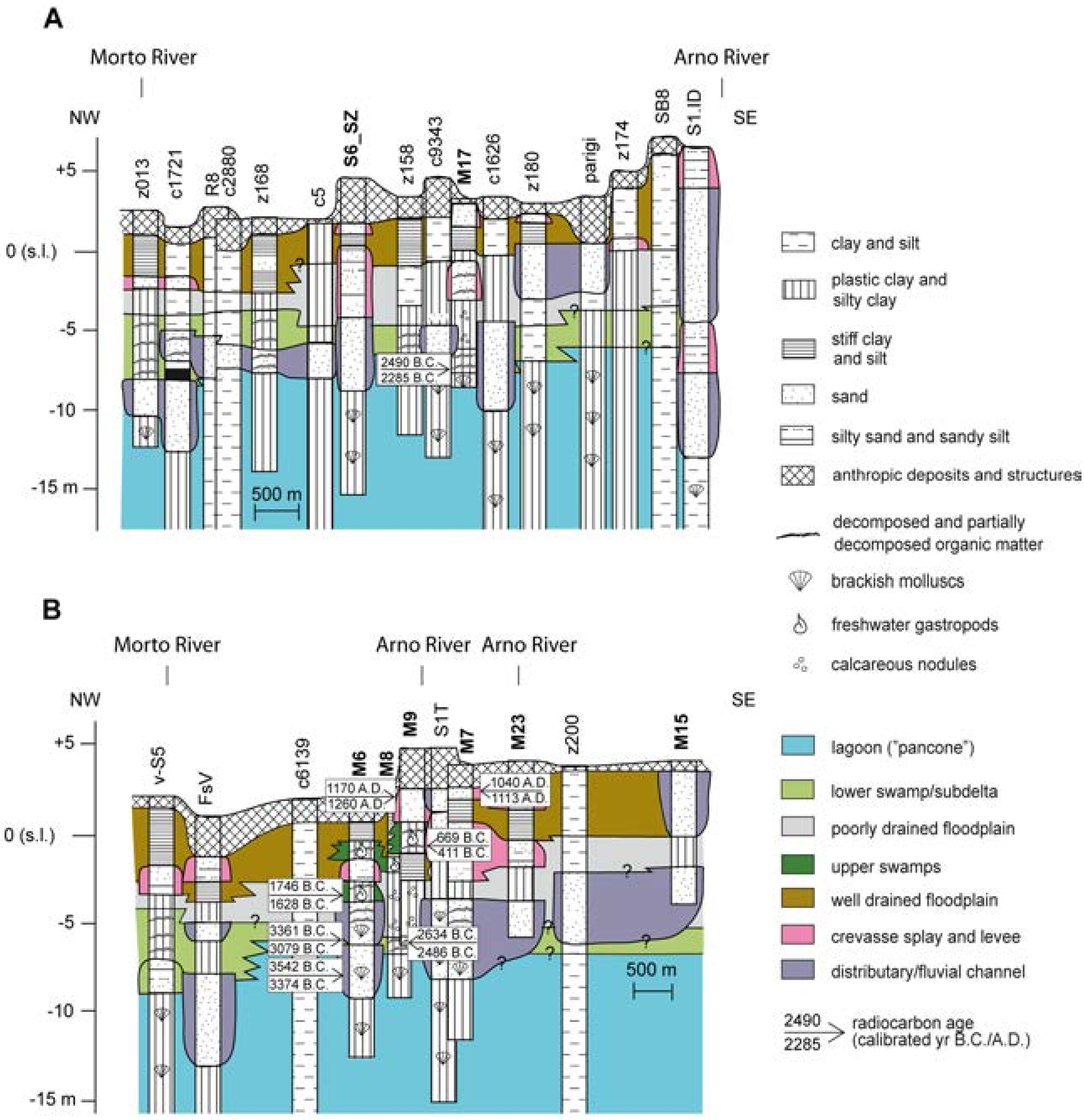

Figure 3. Cross-sections perpendicular to the modern Arno River course (see Figure 1 for section traces) depicting facies distribution patterns and stratigraphic architecture in the Pisa subsurface at proximal locations, east of the historical city centre (A) and around the historical city centre (B).

4. Palaeoenvironmental evolution: from a lagoon system to the Pisa alluvial plain

The depositional and palaeoenvironmental evolution of the Pisa plain during the last 6000-5000 cal yr B.C. was strongly influenced by the worldwide deceleration in sea-level rise (Fairbanks *et alii*, 1989; Bard *et alii*, 1996) and the increase in sediment supplied by the two main fluvial systems (Arno and Serchio) flowing in the study area since historical times (Bruni and Cosci 2003).

As documented by literature data (Benvenuti *et alii* 2006; Amorosi *et alii*, 2008; Rossi *et alii* 2011), the widespread spatial distribution of "pancone" in the lowermost portion of the mid-late Holocene succession (Fig. 3) documents the development of a lagoonal basin at the turnaround from the maximum marine transgression (ca. 6000 cal yr B.C.) to the subsequent highstand phase. Geochemical analyses at this stratigraphic level reveal a two-fold sediment provenance, from both Arno and Serchio catchments, and a mixed contribution to the lagoon system (MapPaper 4-en: 183).

Progradation of subdelta bodies, dated around 3600-3500 cal yr B.C. along the northern margin of the study area (M1; Fig. 1), represents the oldest sedimentological-stratigraphic evidence of lagoon filling. However, ultimate lagoon siltation occurred only 5-6 centuries later, around 3000 cal yr B.C., as documented by widespread swamp sedimentation. These stagnant, nutrient poor, almost acid wetlands (§ 2.2.1.) crossed by distributary channels (§ 2.2.3.) record the development of a delta plain. The depositional architecture of deltaic-coastal plain facies documents the occurrence of two main phases of drainage network reorganization (Fig. 3; § 3.), which likely occurred during the Eneolithic age (3000-2000 cal yr B.C.) involving simultaneously both Arno and Serchio palaeochannels (MapPaper 4-en: 184). Within a general Arno River provenance context, geochemical data recognize a palaeo-Serchio river branch flowing along the northern margin of the study area in correspondence of the modern Morto river course (M1; Fig. 1). This channel is probably related to the old branch of Serchio River known as *Oseri*, which flowed southward from the Pisa Mountains, reaching the sea close to the present Serchio river mouth (Bruni and Cosci 2003).

An intricate drainage network related to Arno and Serchio rivers also characterized the subsequent phase of alluvial plain construction, started around 1900 cal yr B.C. Following a gradual progradational trend, swamplands progressively emerged and turned into poorly drained floodplain areas (§ 2.3.1.) fed by several palaeochannels active during the Bronze-early Etruscan period (ca. 1900-700 cal yr B.C.). Fluvial architecture documents a highly dynamic protohistoric fluvial system characterized by three main phases of channel activity (§ 3.) and mainly fed by the Arno River catchment. Geochemical data (MapPaper 4-en: 181) also suggest the activity of two palaeo-Serchio branches in the study area, likely related to the *Oseri* palaeochannel (M1 in Fig. 1) and the *Auser* palaeochannel, the latter flowing from NE toward the historical centre of Pisa (M7 and M5; Fig. 1). As documented by historical documents and aerial photographs interpretation (Bruni and Cosci 2003), the *Auser* likely merged with the Arno River between Ponte di Mezzo and Ponte della Cittadella.

Since the late Etruscan-Roman age, a general phase of subaerial exposure took place across the study area, leading to the development of the modern alluvial plain. Peculiar to the historical Pisa city centre, north of the modern Arno River course, was the presence of early Etruscan (860-400 cal yr B.C.) small-sized swamp areas formed within low-lying zones surrounded by coeval and semi-coeval natural levee reliefs (Amorosi *et alii* in press). This articulate palaeomorphology, connected to fluvial network dynamics, also induced the local persistence of poorly drained conditions (M10, M19 and M25; Fig. 1) up to the diffusion of anthropic structures of medieval ages (MapPaper 4-en: 187).

5. Conclusions and future perspectives

The interdisciplinary approach used to analyze MAPPA cores (MapPaper 4; Amorosi *et alii* 2012) and their stratigraphic correlations along a dense grid of cross-sections led to the improved reconstruction of the depositional architecture in the subsurface of the Pisa urban and periurban area.

Two additional depositional facies (poorly drained floodplain and upper swamp deposits) were identified with respect to previous work, and a more accurate definition of architectural patterns was achieved, laying the foundation for the reconstruction of mid-late Holocene landscape changes.

The wide lagoonal basin that occupied the entire study area from the Pisa Mountains foothills to the outcropping beach-ridges started to silt up around 3500-3000 cal yr B.C., triggering the development of the Pisa deltaic-coastal plain. Interdistributary areas were formed by swamp deposits of Eneolithic age (3000-2000 cal yr B.C.) mainly fed by the Arno palaeochannels; unique exception, an east-west flowing river branch interpreted as the palaeo-Morto River (*Oseri*?) and attributable to Serchio River system. Over about one millennium the Eneolithic drainage network of Pisa plain was subject, at least, to two main phases of reorganization.

A gradual siltation and emersion of swamplands started around 1900 cal yr B.C., leading to the formation of an alluvial system characterized by initially poorly drained and then well drained floodplain areas. The protohistoric drainage network, which underwent three main reorganization phases, showed an articulate fluvial pattern characterized by two active Serchio palaeochannels corresponding to the palaeo-Morto River (*Oseri*?) and the river branch known as *Auser*. The latter flowed from the northeast, bordering the Pisa Mountains and merging with the palaeo-Arno at Pisa, consistent with historical chronicles. A clear reverse depositional evolution trend took place in the Pisa old town centre, north of the Arno River course, as documented by the abrupt onset of swamp deposits at the transition from the Iron age to the early Etruscan age (860-400 cal yr B.C.) in low-lying areas bounded by higher levees.

The new stratigraphic framework illustrated in this report, integrated with geomorphological evidence from the major fluvial landforms (Bini *et alii*, 2012) and archaeological data (MAPPAGIS; http://mappaproject.arch.unipi.it/?page_id=452) form the basis for the accurate reconstruction of the main palaeonvironmental and human settlement scenarios of the Pisa city area during the mid-late Holocene period.

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