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Middle to late Holocene environmental evolution of the Pisa coastal plain (Tuscany, Italy) and early human settlements

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Highlights

- We outline middle-late Holocene environmental evolution from the subsurface of Pisa
- Widespread swamp development influenced Etruscan settlement in the old town area
- Geoarchaeological evidence of human-environment interaction is reported
- We highlight the value of a cross-disciplinary methodological approach
- We found stratigraphic evidence of descriptions by Greek geographer Strabo

Abstract

A cross-disciplinary (sedimentological, geochemical, micropalaeontological and archaeological) examination of 12 continuous cores, up to 20 m long, integrated with stratigraphical, geomorphological and historical investigations, allows for reliable delineation of the middle-late Holocene environmental evolution in the Pisa old town area, with special emphasis on the Etruscan age transition. Depositional facies were identified through integration of sedimentological and micropalaeontological (benthic foraminifers, ostracods, phytoclasts and palynomorphs) data, while sediment dispersal patterns were reconstructed on the basis of geochemical analyses. Facies architecture was chronologically constrained by combined archaeological and radiocarbon dating. The turnaround from early Holocene, transgressive conditions to the ensuing (middle-late Holocene) phase of sea-level highstand is witnessed by a prominent shallowing-upward succession of lagoonal, paludal and then poorly drained floodplain deposits supplied by two river systems (Arno and Serchio). This 'regressive' trend, reflecting coastal progradation under nearly stable sea-level conditions, was interrupted by widespread swamp development close to the Iron-Etruscan age transition. The expansion of vast, low-lying paludal areas across the alluvial plain was mostly induced by the intricate, short-term evolution of the meandering Arno and Serchio river systems. These changes in the fluvial network, which occurred during a period of variable climate conditions, strongly influenced the early Etruscan culture (7^{th}-5^{th} century BC) in terms of human settlement and society behaviour. Conversely, a strong impact of human frequentation on depositional environments is observed at the transition to the Roman age (from the 1^{st} century BC onwards), when the wetlands were drained and the modern alluvial plain started to form. Our palaeoenvironmental reconstruction fits in with the original geographical descriptions mentioned in Strabo's Chronicles, and provides chronologically constrained data of fluvial evolution from the Pisa old town area.

Keywords: Depositional environment, human settlement, Etruscan age, Pisa, Holocene

1. Introduction

Landscape features have strongly influenced human settlements and activities since ancient times. However, the continuous effort of human populations to adapt their activities to changing natural environments has been always paralleled by human-induced landscape variations, giving rise to complex cause-effect-related phenomena throughout the middle-late Holocene. In Europe, the human influence started to accelerate from 6000 yr BC, long before the Industrial Revolution age, in concomitance with the Neolithic agriculture revolution and the development of the first urban centres (Hooke, 2000; Ruddiman, 2003; Kaplan et al., 2011).

Although the establishment of an Earth's time-period characterized by anthropogenic disturbance is almost globally recognized, and informally called 'Anthropocene', many issues regarding time and magnitude of humans as a geological agent still have to be resolved (Crutzen and Stoermer, 2000; Zalasiewicz et al., 2010, 2011a,b; Syvitski and Kettner, 2011). Among these: (i) the complex interaction between human and natural forcing factors, such as climate/greenhouse gas concentrations and eustacy (IPCC, 2007; Kaplan et al., 2011; Ruddiman et al., 2011), (ii) the mechanisms of direct or indirect human influence on fluvial regimes and sediment fluxes (Syvitski et al., 2005; Wilkinson, 2005; Ericson et al., 2006; Gregory, 2006; Hooke, 2006; Knox, 2006; Syvitski and Saito, 2007; Hoffmann et al., 2010; Syvitski and Kettner, 2011), and (iii) the critical transition from natural to anthropogenic-dominated environments, as recorded within different depositional archives (Dinis et al., 2006; Carmona and Ruiz, 2011; Marinova et al., 2012; Mendes et al., 2012).

In this regard, ideal study areas to decipher human-landscape mutual relationships and their effects on the environment are the Mediterranean coastal and alluvial plains, which suffered a lengthy and intense human land-use history, documented by numerous archaeological sites and historical sources (Butzer, 2005; Blondel, 2006). Recently, geoarchaeological investigations performed on the late Holocene successions buried beneath Mediterranean deltaic-alluvial systems have revealed palaeoenvironmental changes induced by both natural and anthropogenic processes (Arnaud-Fassetta et al., 2003, 2010; Vött et al., 2006; Fouache et al., 2008, 2012; Bini et al., 2009, 2012a; Piovan et al., 2010; Bellotti et al., 2011; Carmona and Ruiz, 2011; Ghilardi et al., 2012). However, their component signals cannot easily be disentangled, as natural forces (mainly climate and sea level) and human forces (deforestation, agriculture and engineering works, among the most important) became strongly intertwined during the last millennia, causing a synergic relationship between landscape and society evolution.

Since proto-historic times, the Pisa plain, in northern Tuscany (Fig. 1A), has been one of the most populated areas of the Mediterranean, as documented by a variety of archaeological sites dating back up to the late Neolithic (*ca.* 5000-6000 yr cal. BP). The possible influence of a dense and unstable hydrographic network on the late Holocene human settlements and on the development of the Etruscan-modern age Pisa urban centre was postulated by Paribeni (2010), and inferred to be related to the combined fluvial activity of Arno and Serchio rivers (Bruni and Cosci, 2003). These models, however, relied upon geomorphological and archaeological information only, with no supporting stratigraphic or sedimentological data.

The aim of this work is to address on a stratigraphic basis the issue of the mutual interactions between changing natural setting and evolving human society. Our focus is on the Pisa old town area (*ca.* 2.5 km^2 wide; Fig. 1A), where archaeological evidence of early Etruscan settlements (7^{th}-5^{th} century BC) is widespread (Paribeni, 2010). In order to frame old and new data into a high-resolution chronological scheme, we used a cross-disciplinary methodology, including sedimentological, micropalaeontological, geochemical, geomorphological and archaeological data from cores (up to 20 m long) and aerial photo interpretation. Greater emphasis was placed on high-resolution stratigraphic architecture as a fundamental tool to reconstruct landscape evolution and its impact on the oldest well-framed human settlements of Pisa (Etruscan civilization).

2. The Pisa plain and the study site

As part of the wider Arno coastal plain, the Pisa plain is a flat, low-lying area, approximately 150 km^2 wide, crossed from east to west by the lower reaches of the Arno River, the 8th Italian river in length, and bounded to the north by Serchio River (Fig. 1A). The town of Pisa is located in the middle of the plain, *ca.* 10 km east of the Tyrrhenian Sea coast and *ca.* 5-6 km west of the Pisa Mountains (Fig. 1A). It developed since early Etruscan times (*ca.* 2500 yr BP/600 yr BC) on the banks of the Arno River (Bruni, 1998; Sarti et al., 2010). The study area, which includes the famous Leaning Tower, is located in the historical centre of Pisa, north of the Arno River (Fig. 1B).

2.1. Middle-late Quaternary stratigraphy

The middle-late Quaternary subsurface stratigraphy of the Arno coastal plain consists of a cyclic alternation of continental and nearshore deposits, documenting repeated phases of transgression and regression. This peculiar facies architecture has been closely related to glacio-eustatic sea-level fluctuations falling in the Milankovitch (100 kyr-eccentricity cycles) band (Aguzzi et al., 2007; Amorosi et al., 2008). Significant fluvial incision took place in response to the post-125 kyr phase of sea-level fall, forming an incised valley broadly coinciding with the present Arno River course (Fig. 1A). The thickness of the Lateglacial-Holocene succession along the valley axis is about 50-60 m, whereas it decreases dramatically to 17 m on the interfluves. The valley fill is made up of clay-prone, estuarine deposits subdivided into three, vertically stacked transgressive-regressive millennial-scale depositional cycles, bounded by flooding surfaces (Amorosi et al., 2009). Following rapid sea-level rise, during the middle Holocene the Arno palaeovalley was progressively flooded and the interfluves submerged by the sea. The subsequent evolution of the Pisa area saw the development of a wide lagoonal environment, which was strongly controlled by the inherited palaeotopography (Rossi et al., 2011). The thick, clay-dominated, lagoonal succession, locally known as '*pancone*', acts today as a preferential, highly compressible zone of ground settlement, as best exemplified by the Leaning Tower of Pisa (Sarti et al., 2012). At time of maximum marine ingression (7.8 cal ka BP – Amorosi et al., 2013a), the shoreline was located more than 7 km inland of its present position (Mazzanti and Pasquinucci, 1983; Della Rocca et al., 1987; Sarti et al., 2008). The subsequent highstand period was characterized by repeated phases of coastal progradation, resulting in the development of the modern Arno delta, with its flanking coastal plain system. At the same time, an intricate pattern of fluvial channels attributable to both Arno and Serchio rivers built up the modern alluvial plain (Rossi et al., 2012).

2.2. Geomorphological setting

The modern Arno coastal plain is a wide sandy strandplain made up of several juxtaposed coastal beach ridges, the alignment of which records the westward migration of the shoreline over the last 3000 yr (Pranzini, 2001). Through the littoral drift, this strandplain system was supplied mostly by Arno and Serchio rivers, which frequently changed their course over time, as documented by geomorphological studies (Della Rocca et al., 1987; Marchisio et al., 2001). Indeed, the highly sinuous and low-gradient Arno and Serchio river channels were subject to recurring avulsions and lateral channel migrations, which generated a complex system of abandoned branches (Schumm, 1977; Miall, 1996). Since the Roman period (Table 1), this natural tendency was greatly thwarted by waterworks (construction of levees, canals, ditches). Several drainage channels were also constructed as part of a systematic land reclamation scheme (Roman Centuriation). Wetlands that occupied a vast portion of the Pisa plain were drained during the Etruscan-Roman period (Baldassari and Gattiglia, 2009). A renewed phase of wetland expansion occurred during the Medieval Ages, likely connected to a decrease in maintenance of drainage channels (Redi, 1991;

Martini et al., 2010). Unfortunately, only Medieval wetlands can be clearly identified by aerial photographs and remote sensing analyses (Bini et al., 2012b).

The first reconstruction of the major fluvial landforms in the study area, based on the interpretation of aerial photographs, was carried out by Pranzini (2001) and Bruni and Cosci (2003), who focused on the Pisa suburbs and Pisa old town, respectively (Fig. 2). Although a dense network of palaeochannels was identified, the geomorphological maps were not validated (or tested for their reliability) through comparison with stratigraphic data from cores or archaeological data from excavations.

2.3. Historical and archaeological background

Past reconstructions of the Pisa ancient landscape and its fluvial evolution have also benefited from archaeological and historical data, including toponyms. Paribeni (2010) showed that the distribution of pre-Roman archaeological findings (tumulos and living structures) in the northern part of Pisa old town fits well with the past occurrence of river courses other than the Arno River. A dynamic palaeohydrographic network is also documented by the chronicles of Greek geographer Strabo (V, 2, 5, C 222), who placed the town of Pisa at the confluence of two large rivers, the Arno River and a former branch of Serchio River, known as *Auser* (Fig. 2). The etymology of the name ‘Pisa’ itself, even if its origin is still uncertain, is considered as indicative of a complex ancient alluvial landscape characterized by wetlands and river mouths.

Roman and Medieval historical sources indicate the *Auser* as the main of the three branches (*Tubra*, *Auser* and *Auserculus*) in which the modern Serchio River split at the gorge of Ripafratta (Fig. 2). The *Auser* flowed from north to south along the Pisa Mountains foothills, merging with the Arno River at Pisa. The *Auserculus* course was similar to that of modern Serchio River, although it probably forked before reaching the sea (Fig. 2). Limited information is available from Medieval sources about the course of the *Tubra* branch. According to Strabo, the Arno River was in turn split into three branches, the northernmost corresponding (albeit with higher sinuosity) to the modern course. Little is known, however, about the two southern branches (Ceccarelli Lemut et al., 1994).

To protect Pisa from floods, several waterworks were carried out since the Roman age, further modifying the intricate fluvial pattern. In particular, during the late Middle Ages (Table 1) the *Auser* was forced to flow northwards (Bruni and Cosci, 2003).

3. Methods

3.1. Data acquisition

A coring campaign performed in the context of 'MAPPA project' (http://www.mappaproject.arch.unipi.it) led to the acquisition of a total of twenty sedimentary cores. Nine cores, 10-20 m long, were performed through a continuous perforating system, which guaranteed an undisturbed core stratigraphy. Whereas eleven cores, 7-13 m long, were drilled using percussion drilling technique (Vibracorer Atlas Copco, Cobra model, equipped with Eijkelkamp samplers), which furnished smaller diameter cores, yet qualitatively similar to standard cores. All drilling sites were precisely positioned using Leica GS09 differential GPS (planimetric error ± 1 cm and altimetric error ± 2 cm).

Lithofacies description includes mean grain size, colour, sedimentary structures and accessory materials (mollusc shells and fragments; peat horizons or decomposed organic-rich layers; plant debris; wood fragments and calcareous nodules). To refine facies interpretation, the cores were sub-sampled for benthic foraminifer/ostracod (57 samples), palynological (36), geochemical (100) and radiocarbon (35) analyses. For this study, focused on the Pisa old town north of Arno River, five continuous cores and seven percussion cores were selected as reference sites (Fig. 1B). Additional continuous cores and well logs available from the Arno plain dataset (Amorosi et al., 2008; 2013a) were used for stratigraphic correlations (Fig. 1B).

Stratigraphic data from cores were matched with prominent geomorphological features (palaeochannels and wetlands) identified by integrated techniques of Remote Sensing and GIS (Bisson and Bini, 2012). For a reliable reconstruction of fluvial evolution in the Pisa urban area, multitemporal aerial photos, dated between 1943 and 2010, were analyzed (Table 2), together with multispectral images with medium-high resolution acquired from SPOT, ALOS AVNIR-2 and TERRA ASTER satellites. Morphometric elaborations carried out on a digital elevation model based on Lidar data were performed in order to detect morphological evidence of past landforms (wetlands) in the Pisa plain.

3.2. Analytical procedures

Detailed facies characterization was supported by integrated meiofauna, palynological and geochemical analyses. For benthic foraminifer/ostracod analyses, around 150-200 grams of sediments from each sample were oven-dried at 60°C for eight hours and soaked in water or water and hydrogen peroxide (35%) for highly cohesive samples. Each sample was wet-sieved through sieves of 63 μm (240 mesh) and oven-dried again at 60 °C for 1-2 days. Samples containing a well-preserved, autochthnous meiofauna were dry-sieved through sieves of 125 μm in order to concentrate adult specimens and support comparison with modern and fossil associations of the Mediterranean area. The >125 μm size fraction was semi-quantitatively analysed, following the methodology adopted by Bondesàn et al. (2006) and Aguzzi et al. (2007) for comparable and coeval associations recorded in the Po Delta and Arno plain, respectively. Three main classes of relative abundance of species (abundant: >30%; common: 10-30% and rare: <10%) were used to define two mixed benthic foraminiferal and ostracod associations, named B and F (Table 3). Another association, containing a poorly-preserved, allochthonous meiofauna, was differentiated (association R in Table 3).

Identification of species and the palaeoenvironmental significance of microfossil assemblages relied upon several key-papers, dealing with species autoecology and spatial distribution patterns of the modern Mediterranean and North Atlantic meiofauna (Athersuch et al., 1989; Albani and Serandrei Barbero, 1990; Henderson, 1990; Sgarrella and Moncharmont Zei, 1993; Meisch, 2000; Ruiz et al., 2000; Fiorini and Vaiani, 2001; Murray, 2006). In addition, a comparison was carried out with benthic foraminiferal and ostracod associations from late Quaternary deltaic and coastal deposits of the Mediterranean area (Mazzini et al., 1999; Carboni et al., 2002, 2010; Amorosi et al., 2004, 2008; Fiorini, 2004).

Standard palynological techniques (Fægri and Iversen, 1989) using hydrochloric and hydrofluoric acid for mineral dissolution were applied on 10 grams of clay and silt samples. In order to preserve all the organic components, neither oxidative nor alkali treatments were applied. Structured (phytoclasts) and unstructured (amorphous) organic matter (AOM) was qualitatively examined and described according to Batten (1996) and Batten and Stead (2005). The average palynomorph (spores and pollen, Fungi, dinoflagellate cysts, Algae, foraminiferal linings and scolecodonts) count was 200 specimens per samples. The absolute concentration was estimated by adding a tablet containing a known amount of *Lycopodium* spores. Pollen taxa were identified according to the literature (Reille, 1992, 1995, 1998 and online databases) and grouped on the basis of their ecological and climatic affinities, following the indications of previous works carried out in the Arno coastal plain (Aguzzi et al., 2007; Ricci Lucchi, 2008). Based on the presence, morphological characters and composition of the organic residues, three palynofacies (A, P and L in Table 3) were recognized.

Geochemical analyses were carried out for the reconstruction of sediment dispersal patterns, with special emphasis on the Arno and Serchio river pathways and their evolution through time. To this purpose, analyses on 80 core samples were implemented by geochemical characterization of 20 shallow (1-4 m) samples, collected using 'Cobra' equipment. These latter samples, collected few hundred metres from the modern Arno and Serchio channel axes, were used as unequivocal (end-member) indicators of sediment provenance for the interpretation of the cored samples. Twelve out of these 20 samples were collected along the modern levees of the Arno River, while eight samples correspond to modern Serchio overbank deposits. All samples were analysed at Bologna University laboratories using X-Ray Fluorescence (XRF) spectrometry (Philips PW1480 spectrometry with Rh tube). Concentration of major elements was calculated using the method of Franzini et al. (1975), whilst the coefficients of Franzini et al. (1972), Leoni and Saitta (1976) and Leoni et al. (1982) were used for trace elements. The estimated precision and accuracy for trace element determinations are better than 5%, except for those elements at 10 ppm and lower (10–15%). Loss on ignition (LOI) was evaluated after overnight heating at 950 °C.

The chronological framework of the studied succession benefited from 35 radiocarbon dates performed at CIRCE Laboratory of Caserta (Naples University). Wood fragments, charcoal and organic clay were preferred to marine mollusc shells, for which age values are commonly higher than those obtained with organic matter (reservoir effect). Conventional ages were calibrated using the CALIB5 program and the calibration curves of Reimer et al. (2009). In order to compensate for the reservoir effect, mollusc samples were calibrated using an average value of DeltaR (35±42) estimated for the northern Tyrrhenian Sea and available online (http://calib.qub.ac.uk/marine/). In this study, ages are reported as the highest probability range (yr BC/AD) obtained using two standard deviations-2σ (Table 4).

4. Facies associations

Seven major facies associations were identified within the middle-late Holocene deposits of the Pisa old town area (Fig. 3). The chronology of the studied succession, composed of fluvio-deltaic deposits overlying the '*pancone*' marker horizon (Amorosi et al., 2008; Rossi et al., 2012), was based on radiocarbon dating (Table 4) and, where available, archaeological ceramic remains. Detailed facies description (including sedimentological features, micropalaeontological content and archaeological findings) and interpretation in terms of depositional environments are reported below.

4.1. Lagoonal facies association ('pancone')

4.1.1. Description

This facies association invariably marks the lowest part of the middle-late Holocene succession in the study area. It is made up of a monotonous succession of extremely soft, blue-gray clay and silty clay, occasionally interrupted by thin (commonly < 20 cm) fine sand intercalations (Fig. 3A). Scattered plant remains, wood fragments and dark organic-rich layers are accompanied by abundant shells of *Cerastoderma glaucum*, recorded in living position and more commonly as disarticulated valves. Centimetre-thick layers made up entirely of mollusc bioclasts were also observed. An abundant, well-preserved meiofauna belonging to microfossil association B characterizes this facies association (Table 3). Abundant *Cyprideis torosa* and *Ammonia tepida*-*A. parkinsoniana* are recorded, along with common to rare *Loxoconcha elliptica*, *Loxoconcha stellifera*, *Aubignyna perlucida*, *Haynesina germanica* and *Cribroelphidium* species. In the lowest part of this facies association (Core M6 in Fig. 1B), Miliolidae species belonging to *Miliolinella*, *Quinqueloculina*, *Adelosina* and *Siphonaperta* genera are present as rare taxa, along with abundant *Leptocythere ramosa* and *Palmoconcha turbida*.

A heterogeneous palynofacies is also encountered within these deposits (palynofacies L in Table 3). The organic residue is characterized by numerous orange-brown phytoclasts (few μm to 500 μm in length) and sporadic granular or floccular AOM. Marine-related palynomorphs are represented by dinocysts, foraminiferal linings and scolecodonts (up to 16.5%), whereas pollen and spores (from 35% to 85%) and fungal spores (15-33%) represent the main components of the related heterogeneous continental association. Arboreal (AP) pollen grains are more numerous than non-arboreal (NAP) ones. Among the arboreal species, *Alnus* is dominating, with relative percentage up to 36%. Aquatic plants may vary between 1.5% and 2.5%.

No archaeological remains were found within this facies association. A radiocarbon date from the upper portion of this facies association 1.5 km north of the study area (Core M1 in Amorosi et al., 2012 - Fig. 1A) yielded an age of 3805-3639 yr BC (Table 4). Literature data assign the very base of this unit to around 6000 yr BC (8000 cal yr BP in Amorosi et al., 2009; Rossi et al., 2011).

4.1.2. Interpretation

Sedimentological features and the peculiar fossil content indicate that this facies association was formed in a low-energy, brackish lagoonal environment. The dominance of euryhaline species, such as *Ammonia tepida-A. parkinsoniana*, *C. torosa* and *C. glaucum* (Russel and Petersen, 1973; Athersuch et al., 1989; Millet and Lamy, 2002; Murray, 2006), can be considered as a sensitive and reliable indicator of semi-closed, brackish-water depositional environments subject to salinity changes. Microfossil assemblages similar to association B have been reported from several modern lagoons and estuaries (D'Onofrio et al., 1976; Albani and Serandrei Barbero, 1990; Montenegro and Pugliese, 1996; Coccioni, 2000; Ruiz et al., 2005; Murray, 2006; Carboni et al., 2009; Nachite et al., 2010), as well as from several Holocene lagoonal successions of the Mediterranean (Barra et al., 1999; Carboni et al., 2002, 2010; Amorosi et al., 2004; Fiorini, 2004).

The higher species diversity and the relative abundance of polyhaline-marine taxa (Miliolidae species, *Leptocythere ramosa* and *Palmoconcha turbida*) in the lower part of the unit suggest an overall shallowing-upward trend (or increasing confinement). A consistent upward increase in continental input is also documented by the relative decrease of the ratio between marine-related and continental palynomorphs within palynofacies L. Finally, the remarkable percentage of typical riparian taxa (*Alnus*) in the upper part of this facies association and the upward increase in light coloured, irregularly shaped phytoclasts are also suggestive of increasing proximity to the source of detritus.

4.2. Lower swamp facies association

4.2.1. Description

This facies association, which shows a variable thickness of 1 to 4 m, consists of dark soft clay and silty clay, with local presence of cm- to dm-thick sand layers. Wood fragments and peat layers are very abundant (Fig. 3B). Scattered fragments and shells of freshwater gastropods are also recorded. Samples are barren in microfossils or, less frequently, contain a scarce oligotypic ostracod fauna mainly composed of *Pseudocandona albicans* and accompanied by rare *Candona neglecta* and *Ilyocypris genetica* (association F in Table 3). No autochthonous foraminifers were encountered.

Light orange to brown/black phytoclasts of various size (mostly > 100 μm), with fibrous transparent aspect, belong to palynofacies P (Table 3). Unstructured organic matter (AOM) is locally abundant at specific stratigraphic levels. Palynomorphs are represented by continental elements (pollen, spores and fungal spores). Arboreal pollen is more abundant than non-arboreal pollen, and representatives of broadleaved trees are sporadically abundant. Aquatic plants are present in varying percentages (1.5-22%).

No archaeological remains were found in this facies association. Radiocarbon dates indicate an Eneolithic age of *ca*. 2600-2200 yr BC (compare with Tables 1 and 4).

4.2.2. Interpretation

The distinctive sedimentological features (dark colour, soft consistency and the abundance of woods and peat layers) and the micropalaeontological content (association F and palynofacies P), lacking marine-related species and palynomorphs, indicate for this facies association a fully terrestrial, wet and low-energy depositional setting, rich in wood vegetation. More specifically, the alternation of sterile horizons with a scarce association F, almost entirely composed of the ostracod species *P. albicans*, preferring slow-flowing waters (Henderson, 1990; Meisch, 2000), suggests the development of stagnant, nutrient poor, most likely acid wetlands. The large amount of unsorted phytoclasts and presence of AOM, which characterize palynofacies P, are consistent with a swamp environment, where waning energy allowed for the accumulation of organic matter, which was only partly consumed by bacteria or other organisms. Bottom-water dysoxic or anoxic conditions allowed preservation of the continental palynomorph assemblage, whereas the highest percentages of aquatic plant pollen grains indicate proximity to the vegetation source.

A freshwater-hypohaline swampland in a coastal plain/interdistributary area could account for all the above features. Individual sand layers are interpreted to reflect occasional river floods from the adjacent fluvial channels.

4.3. Poorly drained floodplain facies association

4.3.1. Description

This facies association, which ranges in thickness between 1 and 4 m, consists of a monotonous succession of light gray, soft clay and silty clay, with scarce organic matter and isolated, large (up to 3 cm) calcareous nodules. Frequently, sharp-based cm- to dm-thick sand and silt layers occur (Fig. 3B). Scattered plant remains were encountered along with few, thin-shelled mollusc fragments. Rare pulmonate gastropods and cm-thick layers formed by decomposed organic matter were occasionally observed.

Samples are generally barren in microfossils; rarely, they exhibit a scarce olygotypic ostracod fauna composed exclusively of *P. albicans* (association F) or *C. torosa* (association B), the latter found within organic-rich layers. The presence of rounded, dark brown to black phytoclasts, homogeneous in size, is the main feature of palynofacies A (Table 3). AOM is sporadically abundant within organic-rich layers. The palynomorph assemblage is heterogeneous, with many reworked specimens derived from either ancient sediments or adjacent lands. The aquatic species vary from about 4% to 10%.

This facies association is locally recorded at higher stratigraphic levels (cores M10, M19 and M25 - see Fig. 1B for location), where sparse brick and ceramic materials dated between the 7th and 3rd centuries BC, were found. Clay plaster fragments from a hut were also encountered within Core M19; while ceramic materials dated between the 10th and 12th centuries AD accompanied by ashes, mortar fragments and slags due to iron manufacturing occur within Core M25. Two radiocarbon ages, centred around 1690 and 575 yr BC (cores M6 and M10 - Table 4), are available from the lower and upper portions of this facies association, respectively.

4.3.2. Interpretation

This facies association is interpreted to reflect a fully terrestrial, low-energy depositional environment subject to short-lived phases of subaerial exposure (poorly drained floodplain), as suggested by the plastic consistency, the occurrence of calcareous nodules, the rare freshwater-hypohaline ostracod fauna (association F) and the alluvial palynofacies (palynofacies A; Batten and Stead, 2005, their Fig. 10.1). These peculiar, poorly drained conditions were likely induced by frequent river floods from active channels that prevented fine-grained flood sediments from prolonged subaerial exposition. The concomitant presence of abundant reworked pollen grains, considerable percentages of aquatic plants and abundant thin sand and silt layers supports this interpretation. Sparse human frequentation traces within the uppermost portion of this facies association are also consistent with an alluvial depositional setting. The local abundance of organic matter (AOM) combined with the presence of a slightly brackish ostracod fauna (association B) is likely to reflect channel abandonment facies.

Radiocarbon data generally assign a Bronze-early Etruscan age to this facies succession (Tables 1 and 4). However, poorly drained conditions locally persisted up to the Roman period-Middle Ages, as documented by the archaeological remains found within the uppermost stratigraphic levels of cores M10, M19 and M25.

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4.4. Upper swamp facies association

4.4.1. Description

This facies association, 1-2 m-thick, includes relatively soft, organic-rich dark gray clay and silty clay containing numerous wood fragments and scattered freshwater gastropods (Fig. 3C). Vegetal remains, cm-thick peat layers and rare small-size calcareous nodules also occur. This unit displays strong similarities with the lower swamp facies association (section 4.2.) in terms of microfossil and palynomorph/pollen content (association F and palynofacies P), except for the higher amount of continental elements and the considerable local concentration of sharp wood fragments (Core M19).

Several brick fragments and ceramic material (*bucchero* and coarse pottery), mostly dated to the 7^{th}-5^{th} century BC (early Etruscan age in Table 1), are recorded within these deposits, furnishing a *terminus ante quem* for their formation. This is consistent with the radiocarbon dates, which indicate a chronological interval between 860 and 410 yr BC (M9_5.35, M25_4 and M26_4.60 in Table 3).

4.4.2. Interpretation

Similar to the lower swamp facies association, this unit records deposition of fine-grained sediments and organic detritus within a stagnant, paludal environment. The distinctive palynofacies P, containing numerous continental elements, is highly suggestive of ephemeral, shallow swamp basins developed close to river courses during the late Iron period, and intensely frequented by humans during the early Etruscan age (Table 1). A strong and enduring frequentation is testified by a diffuse large amount of ceramic materials and bones of domestic animals (mainly sheep), as well as by the local occurrence of sharp wood fragments.

4.5 Well drained floodplain facies association

4.5.1. Description

This facies association, which represents the top of the Holocene succession, is 1 to 3.5 m thick. It is composed of dry, stiff, light brown silty clay with low organic-matter content and evidence of subaerial exposure, including indurated horizons and calcareous nodules. The occurrence of yellow-brown mottles, due to iron and manganese oxides, suggests fluctuating redox conditions likely connected to groundwater table oscillations (Figs. 3C, D). Scattered plant remains are encountered, while no microfossils are found. Occasionally, sharp-based centimetre-thick layers made up of fine sand can be observed. The palynofacies closely resembles the one described in section 4.3.1, with dark-brown to brown reworked phytoclasts and heterogeneous continental palynomorphs with many reworked specimens (palynofacies A; Table 3).

Brick fragments and ceramic material mainly dated to the late Etruscan-early Roman period (2nd-1st century BC; Table 1) are commonly found within these deposits. In Core S6_SZ (Fig. 1B for location) a very compact layer composed of a dark silty matrix, rich in carbon, bricks and slags was also observed around 1.8 m above sea level (s.l.). One radiocarbon date performed *ca.* 1.5 km NW of the study area (Core M2 - Fig. 1A) yielded an age of *ca.* 610-665 yr AD (Table 4).

4.5.2. Interpretation

The sedimentological features point to a low-energy, alluvial depositional setting subject to subaerial exposure, such as a well-drained floodplain occasionally affected by river floods (sand layers). This facies represents the environmental context in which human settlements developed from the late Etruscan-Roman period (Table 1). The compact layer observed in S6_SZ has been interpreted to represent a roughly structured walking floor. On the basis of the ceramic content found within the underlying and overlying sediments, this floor can be assigned to the Roman period, between 1st century BC - 1st century AD (Table 1).

4.6. Crevasse splay and levee facies association

4.6.1. Description

This facies association, which occurs at various stratigraphic levels with overall thickness of about 1 m, is either made up of silty sand and fine sand with characteristic coarsening-upward trend or includes a rhythmical sand-silt alternation (Fig. 3D). Scattered plant remains, wood and small-sized, unidentifiable mollusc fragments are commonly observed along with rare calcareous nodules and yellow-brown mottles due to iron and manganese oxides. A scarce and poorly preserved meiofauna, including species from the deep-marine to the continental realm, is locally observed (association R; Table 3).

Brick and ceramic fragments are locally recorded in the upper part of this facies association. Ceramic materials dated to the 8th-7th century BC and 7th-6th century BC were found around 2.5 m and 1 m below s.l. in Core S6_SZ (a pot handle fragment) and Core S1_exM (cooking pot fragments along with stones and two large pig's bone fragments), respectively. Medieval ceramic material (10th-11th century AD) was encountered around 2.2 m above s.l. in the Core M10 area. A slightly younger radiocarbon age (1170-1260 yr AD) was obtained from this facies association around 2 m above s.l. within Core M9.

4.6.2. Interpretation

On the whole, this facies association is interpreted as channel-related deposits within a deltaic or fluvial depositional system. More specifically, the coarsening-upward sand bodies correspond to crevasse splays or subdeltas (deltaic lobes within the lagoon basin), whereas the sand-silt alternations are likely to reflect levee aggradation. These alluvial deposits formed natural high-grounds, locally frequented from the early Etruscan age up to medieval times (Table 1).

4.7. Fluvial/Distributary channel facies association

4.7.1. Description

This facies association, which also occurs at distinct stratigraphic levels and shows thickness of 2-5 m, consists of gray to yellow-brown, fine- to coarse-grained sand bodies with erosional lower boundary and distinctive fining-upward trend. Organic remains (wood and other plant fragments), mollusc fragments, pebbles and mud-clasts are also locally encountered. Samples collected from this facies are barren or contain a transported meiofauna (association R), composed of scarce and poorly preserved specimens typical of deep-marine to continental depositional settings.

Two radiocarbon dates derived from *Cardium* shells, collected within a 5 m-thick sandy body from Core M6, 8 m and 6 m below s.l., respectively, furnished an age interval of *ca*. 3550-3080 yr BC (Table 3).

4.7.2. Interpretation

On the basis of its diagnostic sedimentological features (lithology; vertical grain size variations-FU trend; lower erosional surface) and the reworked fossil content, this facies association is interpreted as (fluvial or distributary) channel bodies cutting the fluvio-deltaic succession above the '*pancone*' marker horizon at various stratigraphic levels. Locally (Core M6), channels could erode the '*pancone*' itself, removing *Cardium* shells from its top. As a consequence, the ages derived from these reworked shells date the upper portion of the '*pancone*', rather than channel activity.

5. Sediment provenance

Arno and Serchio river catchments display strong compositional affinity, as recently documented by the geochemical characterization of stream sediments (see Dinelli et al., 2005; Cortecci et al., 2008). Using modern crevasse splay/levee deposits (collected by 'Cobra' sampler) from Arno and

Serchio rivers, as well as shallow (1 m deep), hand-drilled samples from the Pisa area (Amorosi et al., 2013b) as reference samples, we were able to detect subtle, but consistent geochemical indicators of Arno *versus* Serchio sediment provenance (Fig. 4): these allowed the differentiation of detritus supplied by these distinct two source areas. The binary diagram MgO/Al_2O_3 vs CaO (Fig. 4), in particular, appears as an efficient discriminating factor, and offers a consistent differentiation between Arno-supplied sediment (with relatively low MgO/Al_2O_3 and high CaO values) and Serchio-derived material (higher MgO/Al_2O_3 and lower CaO values). This characteristic geochemical signature has been interpreted to reflect primarily the different type and quantity of carbonate detritus available in the respective source areas. Sediment mixing can be envisaged where samples plot in an intermediate position relative to the two end members.

Plots of fluvial deposits from the study area (cores M5, M6, and M7 in Fig. 1B) onto the modern dataset enable provenance assignments on the basis of the overlap between individual core samples and the fields diagnostic of Arno and Serchio river provenance, respectively.

6. Middle to late Holocene palaeoenvironmental evolution of the Pisa coastal plain

The stratigraphic architecture of the middle-late Holocene succession is best depicted by three cross-sections showing consistent vertical stacking patterns of facies across the Pisa old town area (Fig. 5). Soft lagoonal deposits are invariably recorded in the lower part of the study succession. This geotechnically weak ‘layer’ (Sarti et al., 2012) corresponds to the prominent stratigraphic marker (‘*pancone*’), up to 15 m thick, reported by Rossi et al. (2011) at comparable depths across a wide portion of the Arno coastal plain. The lagoonal deposits are overlain by a fluvio-deltaic succession, 10-15 m thick, made up of paludal clays (lower swamp facies association), 1-4 m thick, which in turn are overlain by poorly drained floodplain deposits. These latter show lateral transition to fluvial-channel, crevasse and levee sands and sand-silt alternations. The channel bodies are bounded at their base by erosional surfaces that may deeply cut into the underlying succession, down to the '*pancone*'. A multiphase channel history is documented by channel clustering at distinct stratigraphic levels (Rossi et al., 2012). This succession is capped by the modern alluvial plain facies association.

Combining detailed facies characterization and geochemical data into a chronologically constrained stratigraphic framework provides additional insights into the depositional history of the Pisa coastal plain. On the basis of this integrated dataset, we reconstructed four separate phases of middle-late Holocene environmental evolution.

6.1 Development of the lagoon (ca. 6000-3000 yr BC)

The widespread occurrence of '*pancone*' clays at the very base of the study succession indicates that at the turnaround from transgressive to early highstand conditions (around 8000 cal yr BP - Amorosi et al., 2008, 2012 - corresponding to *ca*. 6000 yr BC) the study area was occupied by a laterally extensive lagoonal system. This topographic depression, broadly coincident with the area formerly occupied by the post-glacial Arno palaeovalley, is interpreted to have formed due to higher compaction of the less indurated valley fill relative to the adjacent, stiff Pleistocene substratum (Rossi et al., 2011; Sarti et al., 2012). Geochemical characterization of this facies association (section 5) reveals a two-fold sediment supply from Arno and Serchio catchments, thus suggesting that at time of maximum marine ingression both fluvial mouths were built into the same lagoon.

6.2. Filling of the lagoon (ca. 3000-2000 yr BC)

Radiocarbon dating from the preserved top of '*pancone*' (Core M1 in Fig. 1B) constrains the last phases of lagoonal development in the northern part of Pisa to around 3500 yr BC. However, radiometric ages from erosionally truncated lagoonal deposits (Core M6 in Fig. 5A) allow to refine the time of lagoon infilling to around 3000 yr BC. Between 3000 and 2000 yr BC the lagoon evolved into a more confined paludal environment. Sedimentation in stagnant, nutrient-poor wetlands reflects the development of a deltaic/coastal plain crossed by distributary channels. According to Rossi et al. (2012), two main phases of drainage network organization likely occurred during this period (Eneolithic age). Geochemical data from channel-related (crevasse, levee) and fine-grained swamp deposits still highlight sediment provenance from two distinct source areas, suggesting simultaneous influence on sediment composition by Arno and Serchio rivers.

6.3 Transition to the alluvial plain (ca. 2000-500 yr BC)

The upward transition to poorly drained floodplain deposits documents the establishment in the study area of a genuine alluvial depositional system, subject to overbank processes, between the Bronze Age and the early Etruscan period. Isolated to locally amalgamated fluvial-channel sand bodies, encased within predominantly fine-grained sediment, represent the major stratigraphic feature of this period (Rossi et al., 2012). Two main phases of channel activity likely occurred in the study area during the Bronze Age and before the Iron-Etruscan transition (Fig. 5; Table 1). Vertical changes in sediment provenance across distinct channel fills (Core M7 at the southern margin of the study area - Fig. 1B), testify to channel reoccupation by different river courses through time.

Although an earlier phase of subaerial exposure of the floodplain is documented at the eastern and western margins of the study area, a clear reverse evolutionary trend is recorded in the Pisa old town by the abrupt onset of swamp deposits at the transition to the early Etruscan age (upper swamp facies association in Fig. 5). Starting from this period, evidence of persistent anthropic frequentation becomes more frequent, and traces are left in various environmental contexts (Fig. 5; sections 4.3, 4.4 and 4.6).

6.4. The modern alluvial plain

Since the end of the Etruscan period (Table 1), the Pisa area evolved toward a subaerially exposed alluvial plain, as confirmed by the abundance of indurated horizons (well drained floodplain in Fig. 5) and their lateral relationships with fluvial-channel sands. Geochemical data from channel-related (crevasse splay) and floodplain deposits indicate stable sediment supply from the Arno River. During this phase, which led to the formation of the modern Pisa plain, a pervasive human frequentation, mainly dated from the Roman period onwards, is recorded. This caused the progressive replacement of natural deposits by a well structured anthropogenic stratification.

7. Natural environments and early human settlement in the Pisa old town area

The late Iron-early Etruscan period (800-480 yr BC; Table 1) saw the establishment in the Pisa area of a complex, alluvial depositional setting, where subaerially exposed flood basins were in lateral transition to natural topographic reliefs formed by channel-levee complexes, and backswamp low-lying zones ('upper swamp facies association' in Fig. 5). This articulate fluvial landscape inevitably influenced the development and organization of the earliest, permanent human settlements that led to the foundation of Pisa during the Etruscan period (Bruni, 1998).

7.1 Fluvial landscape, sediment provenance and human frequentation

A dense fluvial network is documented from the Pisa area on the basis of aerial photo interpretation; however, this technique alone may not be able to assign each channel a specific age (Bini et al., 2012c). Through integration of purely morphological criteria with subsurface high-resolution stratigraphy and historical maps we provide for the first time a reliable reconstruction of the palaeoenvironmental scenario of the Pisa old town area (Fig. 6).

Channel-fill deposits with upper boundaries around 7-6 m and 4-2 m below s.l. (Fig. 5) likely developed during the first phases of lagoon infilling (*ca.* 3000-2000 yr BC; Eneolithic age in Table 1) and floodplain construction (*ca.* 2000-800 yr BC; Bronze-Iron Age in Table 1), respectively. Scarcity of younger (higher altitude) channel bodies from the available subsurface dataset (Fig. 5) hampers at present precise reconstruction of the Etruscan and Roman fluvial network. This is likely due to inhomogeneous core distribution (Fig. 1B), although possible relation with extensive anthropic channelization performed from Roman times cannot be ruled out.

Since early proto-historic times (Eneolithic age), the town of Pisa was characterized by a palaeohydrographic network composed, at least, of two river branches (Fig. 6) in lateral transition to paludal wetlands (lower swamp association in Fig. 5). A N-S flowing palaeochannel (palaeo-Serchio?) merged in the town centre area with a river branch located about 100 m north of modern Arno river (palaeo-Arno?). Consistent with previous observations and hypotheses (Bruni and Cosci, 2003; Paribeni, 2010; Fig. 2A-B), a more complicated palaeohydrography governed by river avulsion, meander cutoff and channel reoccupation is reconstructed for the Bronze period, up to the Etruscan transition (Fig. 6). Five (or six) river channels bordering poorly-drained, small floodplain basin, can be recognized. N-S and E-W oriented branches formed an intricate fluvial network in the Pisa old town area. A N-S directed branch, showing orientation compatible with a branch of the ancient Serchio river-*Auser* (Fig. 2A), merged with the Arno channel few meters south of the modern Arno river course, in the Arsenali area (Core S1_exM in Fig. 6). The confluence of the palaeo-Serchio into the Arno River fits with the geographic descriptions of the historical sources (Strabo's Chronicles).

Provenance data from the Bronze age deposits are consistent with our observations, confirming a combined influence of Arno and Serchio rivers on Pisa landscape evolution, up to the early Etruscan transition (Fig. 4). The Arno River appears to have acted as the major sediment source for swamp and alluvial deposits of cores M6 and M7 (Fig. 5A), whereas correlative deposits from Core

M5 were fed by a separate source, likely coincident with Serchio (*Auser*) River. Thus, the river branch flowing very close to Core M5 (Fig. 6) and through Core S6_SZ site (Figs. 5A and 6), is likely to represent the eastward prolongation of the *Auser* channel reported by Bruni and Cosci (2003) (compare with Fig. 2). The clear Arno River affinity shown by Core M7 (Fig. 4) is consistent with location of Core M7 very close to the modern Arno (Fig. 6). Backswamp environments presumably developed at the transition to the early Etruscan age close to, and possibly confined by, the highly sinuous channels. Although wetlands appear to have been compartmentalized between adjacent (though non-coeval) channel-levee systems (cores M6, M8, M9, M19, M25 and M26 in Fig. 6), data density is insufficient to outline precisely their boundaries (Fig. 6).

Over this fluvial landscape, characterized by natural topographic highs and lows, permanent human settlements propagated pervasively, especially upstream the Arno-Serchio (*Auser*) river confluence, which was plausibly located close to the Arsenali zone (Fig. 6). Several archaeological findings and traces of human frequentation dating back to the 8^{th}-5^{th} century BC have been observed in distinct depositional sub-environments (section 4), suggesting different types of human land-use. Evidence of episodic frequentation has been found above natural reliefs (crevasse splay and levee deposits). For example, traces of food preparation and eating activities (hearth?), dated by ceramics to the 7^{th}-6^{th} century BC, are recorded within Core S1_exM (Figs. 5B, 6). Scattered ceramics dating between the end of the 8^{th} and the beginning of the 7^{th} centuries BC occur at Core S6_SZ site (Figs. 5A, 6).

On the other hand, intense and continuous traces of human frequentation characterize the low-lying backswamp areas and their margins (Fig. 5). Specifically, domestic activities (meal remains and sharp wood fragments) and human settlements (hut), dated by ceramics to the 7^{th}-5^{th} century BC, are recorded at M25 and M19 core sites (Fig. 5A), documenting the first step toward a well-structured Pisa urban fabric.

6.2 Factors controlling backswamp development and filling

As shown in Fig. 6, the widespread backswamp development in the Pisa old town area at the transition to the early Etruscan age appears to be strictly connected with the Arno-Serchio fluvial network evolution. The significant role played by palaeohydrography and related fluvial landforms is documented by the invariable occurrence of paludal environments on the inside of an intricate river channel pattern, dated to the Bronze-Iron period (Fig. 6). This complex landscape evolution created an ideal low-topographic setting, where fine-grained flood sediments and organic matter preferentially accumulated, surrounded by natural levee reliefs. The subsiding context of the Pisa plain (Pascucci, 2005) and the differential land subsidence rates (Sarti et al., 2012), reflecting the lower compressibility of fluvial sandy bodies relative to the adjacent, soft poorly-drained clays (Fig. 5), likely favoured the formation and preservation in the study area of these depositional niches, which persisted for *ca.* 300-400 years, between the 9th and 5th centuries BC (radiocarbon dates from cores M9, M25 and M26 - Table 3).

Although we do not have clear documentation of climate change at the transition to the early Etruscan age, the potential influence of climate on backswamp development in the study area cannot be excluded *a priori*. For example, pollen data from pre-Roman deposits at Pisa S. Rossore archaeological site, just 200 m west of Pisa old town (Fig. 1), indicate wetter and cooler climate conditions (Mariotti Lippi et al., 2007). Furthermore, a semi-coeval (2800-2500 cal yr BP, corresponding to *ca.* 850-550 yr BC) prominent climatic event, marking the Subboreal-Subatlantic boundary and characterized by cooler conditions and an increase in humidity, has been recorded across Northern Europe (Van Geel et al., 2000; Mayewski et al., 2004; Wanner et al., 2008).

Similarly, the causative role of land-use change is difficult to discern, although evidences of intense early Etruscan frequentation, mainly assigned to the 7th-5th century BC, testify to a strict relationship between humans and backswamp (or, more in general, alluvial) development. A very rich archaeological documentation is available from swamp deposits of the Pisa area, whereas traces of human frequentation become increasingly rarefied at the backswamp margins. It is not easy to determine whether wetlands acted as preferential sites for early human settlements or if they simply represent depositional settings with higher preservation potential.

On the other hand, a more incisive anthropogenic forcing can be hypothesized for the ensuing Roman period, when important waterworks and a systematic land reclamation scheme (Roman Centuriation) caused the end of swamp sedimentation, and certainly had profound impact on the landscape.

7. Conclusions

The subsurface of Pisa conceals witness of a succession of landscapes of late Iron-Etruscan age, in which fluvial sedimentation influenced human activities, but at the same time man impressed his action on natural environments. In this study, we demonstrate the value of a cross-disciplinary methodological approach, involving coring and sedimentological, micropalaeontological (benthic foraminifers, ostracods, phytoclasts and palynomorphs) and geochemical analyses, by reconstructing the middle-late Holocene environmental evolution of the Pisa area. The major outcomes of this work can be summarized as follows:

(i) Middle-late Holocene deposits beneath the town of Pisa exhibit a consistent shallowing-upward tendency, which is interpreted to have formed in response to coastal progradation under stable sea-level (highstand) conditions. A thick succession of lagoonal clays, locally known as *pancone*, marks the maximum marine ingression. This is overlain by vertically stacked swamp, poorly drained floodplain, and drained floodplain facies associations.

(ii) Extensive swamp development is documented from wide sectors of Pisa old town during the early Etruscan transition. Wetland formation took place at the confluence of Arno and Serchio river channels, in low-lying areas bounded by higher levees, and had profound impact on the Etruscan settlements. Autogenic processes (channel avulsion and meander cutoff events) were the main controlling factors on river development.

(iii) The reciprocal influence between natural environment and human settlement is illustrated for the Etruscan period. The impact of human frequentation on palaeoenvironments can be seen at the rapid transition from paludal to well-drained alluvial areas. This environmental change is interpreted to reflect human control at the Etruscan/Roman transition, when swamps were drained and the modern alluvial plain began to form.

(iv) Sediment dispersal pathways were reconstructed (and Arno *versus* Serchio sediment sources differentiated) on the basis of combined geomorphological (aerial photograph), historical and geochemical data. By refining previous work on palaeoenvironmental evolution, this study provides, for the first time, stratigraphic evidence of Strabo's descriptions, documenting the simultaneous presence of the Arno River and of a branch (*Auser*) of Serchio River in the Pisa old town area.

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Figure and table captions

Figure 1 – A) Geological sketch map of the Pisa coastal plain, with indication of the study area (boxed). B) Pisa old town (dotted line) and the subsurface dataset used in this paper. The bold lines indicate the three stratigraphic cross-sections of Fig. 5. Reference cores are reported as black dots: cores M5-7, S1_exM and S6_SZ were performed through a continuous perforating system, whereas the other cores were drilled using a percussion drilling technique. White circles represent stratigraphic data from the Arno plain georeferenced dataset (Amorosi et al., 2013a); the black star indicates the Leaning Tower.

Figure 2 – A) Palaeohydrography of the Pisa plain during the Etruscan period, as reconstructed on the basis of geomorphological and historical/archaeological data (from Sarti et al., 2010). B) Palaeohydrography of the Pisa urban area, as reconstructed on the basis of aerial photographs, and tentatively related to the Serchio river system (from http://www.geomemories.it/).

Figure 3 – Representative core photographs showing the main facies associations of the Pisa plain. A) Channel-fill sand and its erosional lower boundary onto lagoonal clay ('*pancone'* – Core M6). B) Organic-rich swamp clay (lower swamp association) with upward transition to poorly drained floodplain silty clay (Core M5). C) Organic-rich clay (upper swamp association) overlying light brown, mottled well-drained floodplain clay and silt (Core M9). D) Well-drained floodplain clay and silt overlying crevasse splay deposits (Core M5). Core top at the right up corner. See Fig. 1B for core locations.

Figure 4 – Discrimination between Arno and Serchio sediment supply from selected cores (M5, M6, M7 - see Figs. 1B and 6, for location) of the Pisa coastal plain. Only fluvial samples of Bronze-Iron age are plotted. Modern Arno and Serchio levee deposits are used as reference samples, i.e. compositional end-members.

Figure 5 – Representative stratigraphic sections depicting the middle-late Holocene facies architecture in the Pisa old town area (see Fig. 1B for section traces). Sections A and B are oriented at low angle relative to the modern Arno River course. Section C is perpendicular to the modern Arno. Reference cores are in bold. Radiocarbon data are reported as calibrated yr BC (the highest probability range; see Table 4).

Figure 6 – Reconstruction of the palaeodrainage network in the Pisa area during the proto-historic-early Etruscan period based on combined aerial photo interpretation and core analysis (compare palaeochannel traces with those in Fig. 2). Notice compartmentalization of swamp deposits ('upper swamp facies association' in Fig. 5) between non-coeval channel-levee systems. The oldest (Eneolithic) channels are also shown. Three palaeo-traces are tentatively attributed to the post-Etruscan period. Core locations and the section traces of Fig. 5 are also reported.

Table 1 – Archaeological chronology for the Pisa plain (from http://www.mappaproject.arch.unipi.it).

Table 2 – Aerial photo sets used in this work, with year of acquisition.

Table 3 – Characteristic benthic foraminifer and ostracod taxa (abundant: >30%; common: 10-30% and rare: <10%) composing the three microfossil associations identified in the study area, and

related palaeoenvironmental significance. For each microfossil association, the dominant taxa are reported in bold. Palynofacies characteristics in terms of phytoclast morphologies, marine/continental palynomorphs and related palaeoenvironmental attribution, are also reported.

Table 4 – List of the radiocarbon dates discussed in this paper. Local reservoir correction DeltaR (35±42) was applied to shell samples (*Cerastoderma glaucum* valves). Percentages associated to the calibrated age values represent the related area under probability distribution using two standard deviations-2σ.

Figure 1
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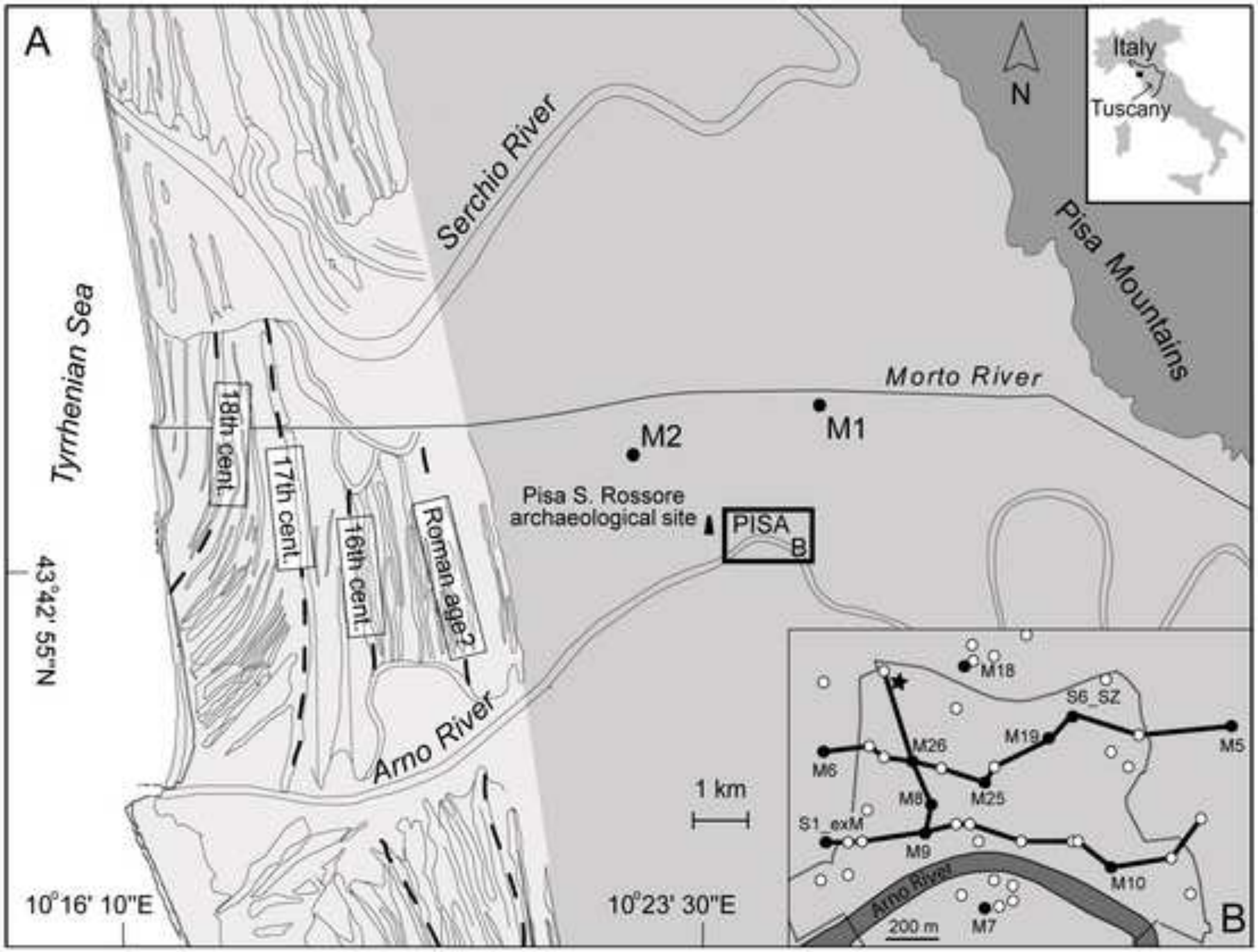

Figure 2
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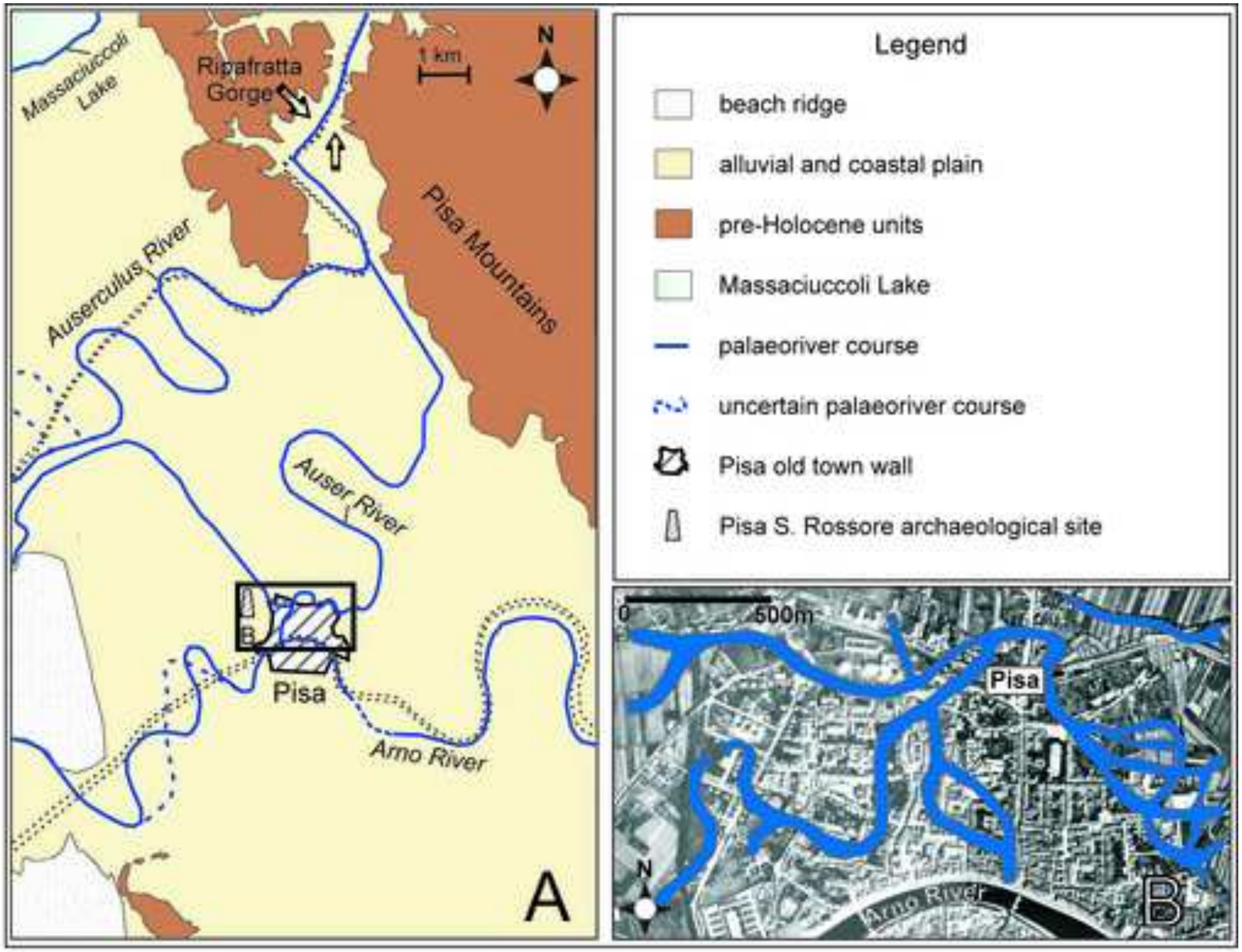

Figure 3
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Figure 4

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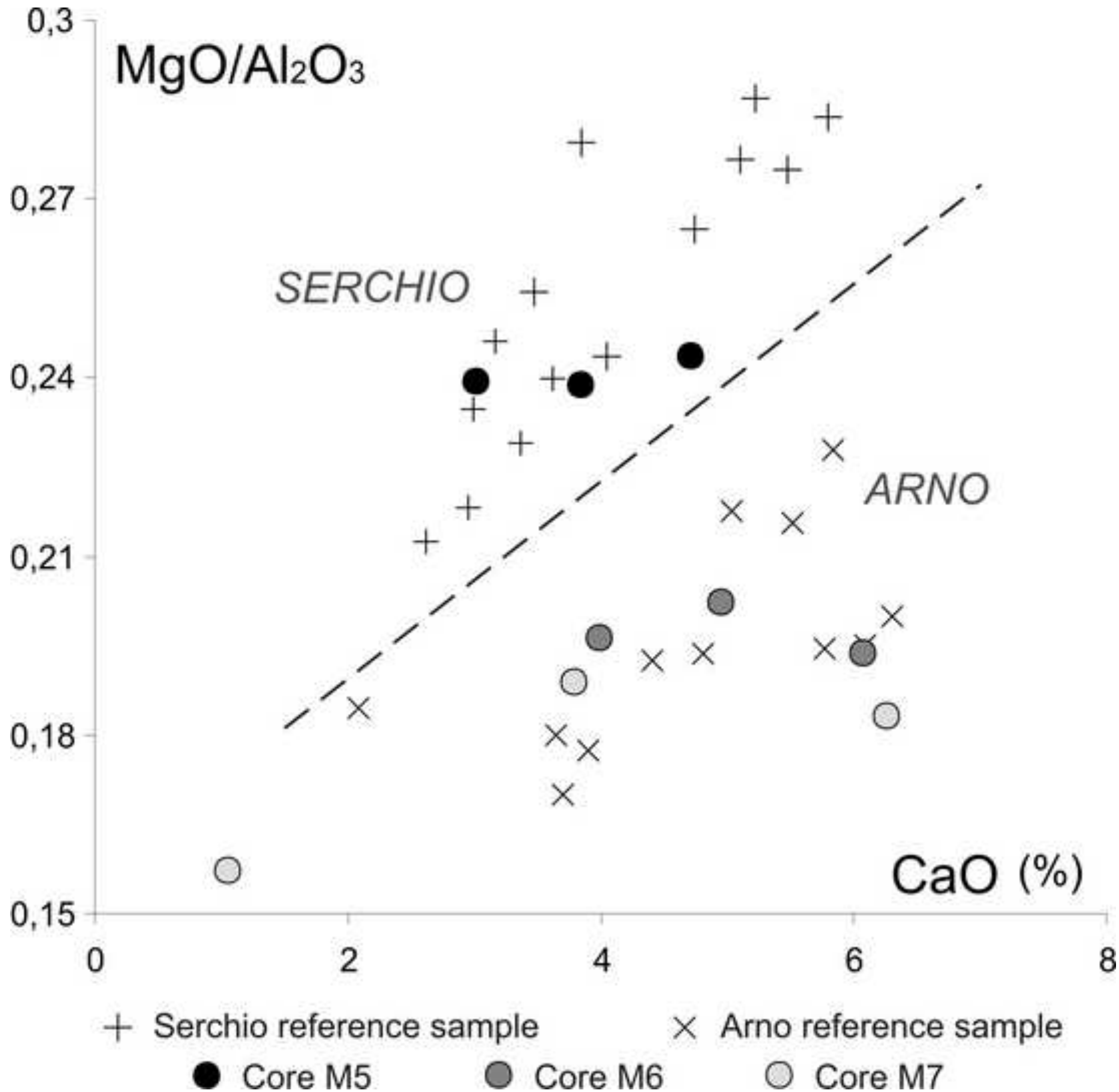

Figure 5

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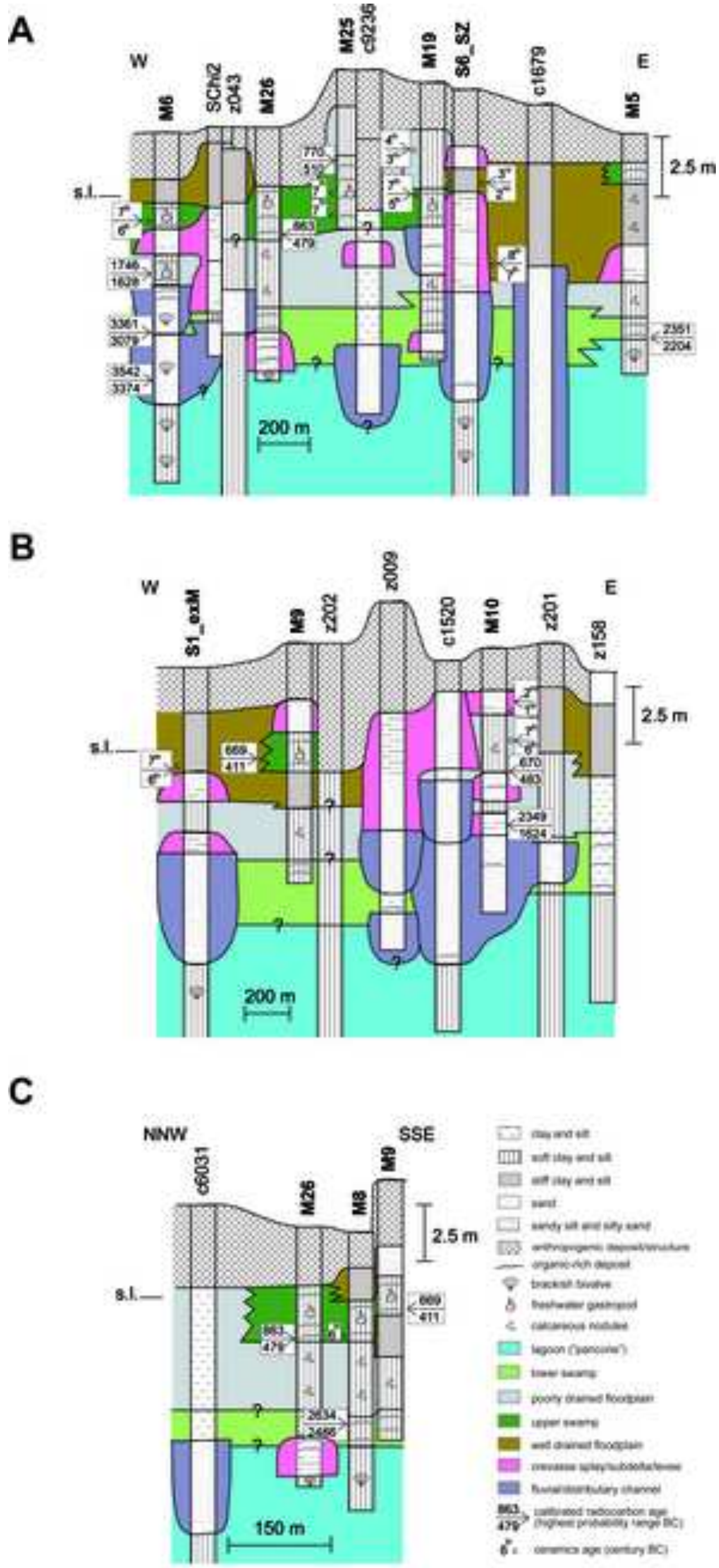

Figure 6
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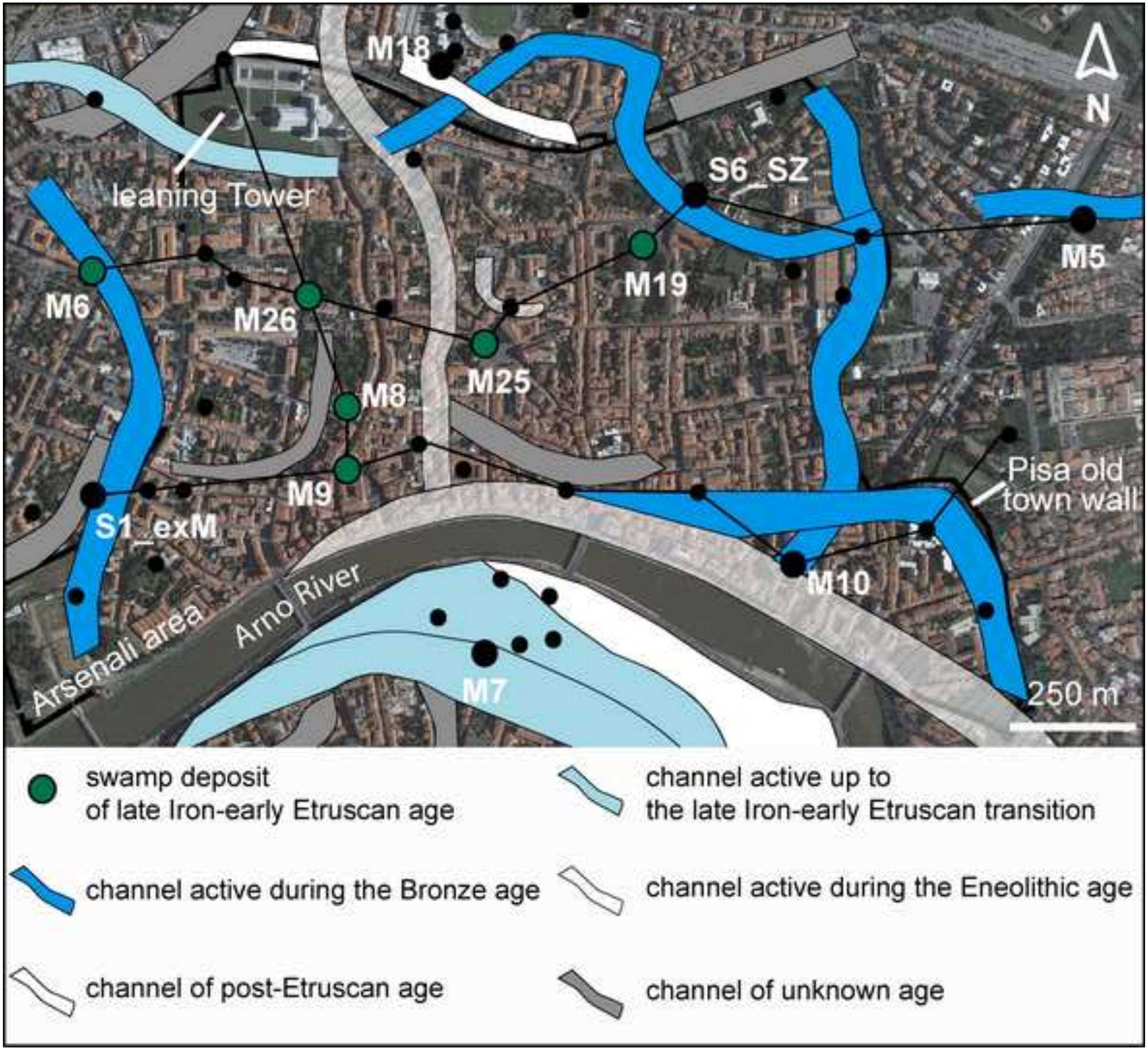

Table 1

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Chronology			Time range (yr BC/AD)	Time range (cal yr BP)
Prehistoric age	Neolithic		(5500-3300 BC)	ca. (7500-5300)
Proto-historic ages	Eneolithic		(3300-1900 BC)	ca. (5300-3800)
	Bronze Age		(1900-901 BC)	ca. (3800-2850)
	Iron Age		(900-721 BC)	ca. (2850-2700)
Historical ages	Etruscan period	Early	(720-481 BC)	ca. (2700-2400)
		Late	(480-90 BC)	ca. (2400-2000)
	Early Roman period		(89 BC-192 AD)	ca. (2000-1750)
	Late Roman period		(193-600 AD)	ca. (1750-1350)
	Early Middle Ages		(601-1000 AD)	ca. (1350-950)
	Late Middle Ages		(1001-1491 AD)	ca. (950-450)
	Modern Age		(1492-1814 AD)	ca. (450-150)
	Contemporary Age		(1815 AD-present)	ca. (150-present)

Table 2
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Acquisition	Authority owner
2010	Provincia Pisa
2009	I.G.M.
2007	I.G.M.
2005	I.G.M.
2003	I.G.M.
1999	I.G.M.
1996	I.G.M.
1988	I.G.M.
1986	Regione Toscana
1983	M. Cosci
1978	Regione Toscana
1954	I.G.M.
1953	I.G.M.
1943	R.A.F

Table 3

Microfossil Association			Depositional environment
Name	Benthic Foraminifers	Ostracods	
B	Abundant ***Ammonia tepida*** and ***A. parkinsoniana***. As secondary species, common to rare *Haynesina germanica* (Ehrenberg, 1840), *Aubygnina perlucida* (Heron-Allen and Earland, 1913) and *Cribroelphidium* species. Rare Miliolidae species	Abundant ***Cyprideis torosa*** (Jones, 1850). Common to rare *Loxoconcha stellifera* (G.W. Müller, 1894) and *Loxoconcha elliptica* (Brady, 1868b). Rare *Leptocythere ramosa* (Rome, 1942) and *Palmoconcha turbida* (G.W. Müller, 1912)	Brackish-water environment with moderate to high marine influence (central-outer lagoon)
F	Absent	Abundant ***Pseudocandona albicans*** (Brady, 1868). Rare *Candona neglecta* (Sars, 1887) and *Ilyocypris* species	Organic-rich, freshwater-slightly brackish environment (swamp)
R	Few, poorly-preserved brackish, shallow to deep-marine foraminifers and freshwater ostracods		High-energy, river-dominated environment (crevasse splay, distributary/fluvial channel)
Palynofacies			**Depositional environment**
Name	Phytoclasts	Palynomorphs	
L	Orange-brown phytoclasts (from a few µm to 500 µm). AOM sporadically present, in granular or floccular form	Common (up to 16.5%) marine-related elements (dinocysts, foraminiferal linings and scolecodonts). Pollen and spores as main component (35-85%) of the continental association. AP more abundant than NAP	Marine influenced environment (lagoon)
P	Abundant light orange to brown/black phytoclasts (generally > 100 µm) and AOM. Most abundant phytoclasts with light brown transparent colour and fibrous aspect	Marine-related elements absent. Pollen and spores (34-56%) and spores of Fungi (27-31%) as main components of the continental association. AP more abundant than NAP	Shallow, organic-rich environment (swamp), with dysoxic/anoxic conditions at the bottom.
A	Equally sized, round-bordered and dark brown to black phytoclasts. AOM sporadically present	Heterogeneous continental (spores/pollen) association with abundant reworked palynomorphs from older deposits. NAP more abundant than AP	Alluvial environment fed by fluvial channels (floodplain)

Table 4

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Core sample depth (m)	Dating materials	Conventional age (yr BP)	Calibrated age (2_sigma cal yr BC/AD)
M1_10.10	mollusc shells	5148±35	3805-3639 BC (99,5%)
M2_1.34	organic matter	1395±23	609-664 AD (100%)
M5_8.76	organic clay	3842±24	2351-2204 AD (81,9%)
M5_4.77	wood fragments	———	< 1950 AD
M6_10.75	mollusc shells	4915±35	3542-3374 BC (76,4%)
M6_8.70	mollusc shells	4708±47	3361-3079 BC (97,6%)
M6_6.04	peat	3395±25	1746-1628 BC (100%)
M8_8.30	wood fragments	4050±26	2634-2486 BC (94,5%)
M9_5.35	wood fragments	2456±41	669-411 BC (75,3%)
M9_2.75	wood fragments	827±23	1170-1260 AD (100%)
M10_7.85	organic clay	3613±137	2349-1624 BC (98,8%)
M10_5.30	charcoal	2465±27	670-483 BC (59,8%)
M25_4	charcoal	2485±26	770-510 BC (98,8%)
M26_4.60	wood fragments	2563±75	863-479 BC (94,8%)

*Detailed Response to Reviewers

DIPARTIMENTO DI SCIENZE BIOLOGICHE, GEOLOGICHE E AMBIENTALI

March, 7th 2013
Editor -in-Chief N.R.Catto
Quaternary International

Dear Editor,

Please enclosed find the revised version of the paper “Middle to late Holocene environmental evolution of the Pisa coastal plain (Tuscany, Italy) and early human settlements” by A. Amorosi, M. Bini, S. Giacomelli, M. Pappalardo, C. Ribecai, V. Rossi, I. Sammartino, G. Sarti (Manuscript Reference Number QUATINT-D-12-00358).

We are strongly indebted to both reviewers for their careful review of our manuscript.
All comments and remarks are fully taken into account in the revised version.
In the file “Revision, changes marked”, changes are highlighted in gray. The revised version was prepared strictly in accordance with the journal style.

We address the comments made by the reviewers as follows.

If some replays to reviewers comments are unclear, please do not hesitate to contact me.

Best regards,

Alessandro Amorosi

Alessandro Amorosi

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DIPARTIMENTO DI SCIENZE BIOLOGICHE, GEOLOGICHE E AMBIENTALI

"Middle to late Holocene environmental evolution of the Pisa coastal plain (Tuscany, Italy) and early human settlements"

A. Amorosi, M. Bini, S. Giacomelli, M. Pappalardo, C. Ribecai, V. Rossi, I. Sammartino, G. Sarti

General comment

In order to address the major critiques and issues raised by the reviewers, we removed repetitions of data and concepts rewording the discussion sections (6 and 7). Data and interpretations were separated by removing the section on geochemical data (sediment provenance; section 5) from the discussion. A new table (Table 3) regarding meiofauna and palynological data was added (comments by Reviewer #2).

Reviewer #1

- As suggested by Reviewer #1, the organization of the paper was improved subdividing the discussion into two sections (6 and 7), where the palaeoenvironmental evolution of the Pisa plain (section 6) and the environment-human settlement interactions (section 7) are separately discussed.
- We agree with Reviewer #1, who suggested that more attention should be paid to the archaeological significance of our data and, on the whole, to the use of the word "geoarchaeology". In this respect, we added archaeological data into sections 4 (Facies associations) and 7.1. (Fluvial landscape, sediment provenance and human frequentation), using a more appropriate terminology about the historical time periods (see also Table 1) and replacing the word "geoarchaeology" with "human settlement" in the keywords. We now specify in both text and highlights that we used a cross-disciplinary approach involving stratigraphical, geochemical, geomorphological and archaeological data to reconstruct environmental changes and investigate human-environment interactions, in the framework of the geoarchaeological project "MAPPA".

Reviewer #2

- Reviewer #2 asks for an additional figure supporting the stratigraphic framework (section 2.1). We think that there is no reason to duplicate cross-sections from previously published material, to which we make wide reference.
- We inserted new text in the 'Methods' and 'Facies associations' sections and added a new table (Table 3) to present more accurately our meiofauna and palynological data.
- We re-organized the text in order to eliminate repetitions and added a "Sediment provenance" section, which now precedes the discussion (see also response to Reviewer #1).

All minor remarks from both reviewers were accepted and incorporated in the revised version.

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