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

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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 (7th-5th 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 1st 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.

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

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23

24 **Highlights**

25

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

31

32

33 **Abstract**

34

35 A cross-disciplinary **(sedimentological, geochemical, micropalaeontological and archaeological)**
36 examination of 12 continuous cores, up to 20 m long, integrated with **stratigraphical,**
37 **geomorphological and historical** investigations, allows for reliable delineation of the middle-late
38 Holocene environmental evolution in the Pisa old town area, with special emphasis on the Etruscan
39 age transition. Depositional facies **were identified** through integration of sedimentological **and**
40 micropalaeontological (benthic foraminifers, ostracods, phytoclasts and palynomorphs) data, **while**
41 sediment dispersal patterns **were** reconstructed on the basis of geochemical **analyses**. Facies
42 architecture **was** chronologically constrained by combined archaeological and radiocarbon **dating**.
43 The turnaround from **early Holocene,** transgressive conditions to the ensuing (middle-late
44 Holocene) phase of sea-level highstand is witnessed by a prominent shallowing-upward succession
45 of lagoonal, paludal and then poorly drained floodplain deposits **supplied by two river systems**
46 **(Arno and Serchio)**. This **'regressive'** trend, reflecting coastal progradation under nearly stable sea-
47 level conditions, was interrupted by widespread swamp development close to the Iron-Etruscan age
48 **transition**. The expansion of vast, low-lying **paludal areas** across the alluvial plain was mostly

49 induced by the intricate, short-term evolution of the meandering Arno and Serchio river systems.
50 These changes in the fluvial network, which occurred during a period of variable climate
51 conditions, strongly influenced the early Etruscan culture (7th-5th century BC) in terms of human
52 settlement and society behaviour. Conversely, a strong impact of human frequentation on
53 depositional environments is observed at the transition to the Roman age (from the 1st century BC
54 onwards), when the wetlands were drained and the modern alluvial plain started to form. Our
55 palaeoenvironmental reconstruction fits in with the original geographical descriptions mentioned in
56 Strabo's Chronicles, and provides chronologically constrained data of fluvial evolution from the
57 Pisa old town area.

58

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

60

61 **1. Introduction**

62

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

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

82 In this regard, ideal study areas to decipher human-landscape mutual relationships and their
83 effects on the environment are the Mediterranean coastal and alluvial plains, which suffered a
84 lengthy and intense human land-use history, documented by numerous archaeological sites and
85 historical sources (Butzer, 2005; Blondel, 2006). Recently, geoarchaeological investigations

86 performed on the late Holocene successions buried beneath Mediterranean deltaic-alluvial systems
87 have revealed palaeoenvironmental changes induced by both natural and anthropogenic processes
88 (Arnaud-Fassetta et al., 2003, 2010; Vött et al., 2006; Fouache et al., 2008, 2012; Bini et al., 2009,
89 2012a; Piovan et al., 2010; Bellotti et al., 2011; Carmona and Ruiz, 2011; Ghilardi et al., 2012).
90 However, their component signals cannot easily be disentangled, as natural forces (mainly climate
91 and sea level) and human forces (deforestation, agriculture and engineering works, among the most
92 important) became strongly intertwined during the last millennia, causing a synergic relationship
93 between landscape and society evolution.

94 Since **proto-historic** times, the Pisa plain, in northern Tuscany (Fig. 1A), has been one of the
95 most populated areas of the Mediterranean, as documented by a variety of archaeological sites
96 dating back up to the late Neolithic (*ca.* 5000-6000 yr cal. BP). The possible influence of a dense
97 and unstable hydrographic network on the late Holocene human settlements and on the
98 development of the Etruscan-modern age Pisa urban centre was postulated by Paribeni (2010), and
99 inferred to be related to the combined fluvial activity of Arno and Serchio rivers (Bruni and Cosci,
100 2003). These models, however, relied upon geomorphological and archaeological information only,
101 with no supporting stratigraphic or sedimentological data.

102 The aim of this work is to address on a stratigraphic basis the issue of the mutual interactions
103 between changing natural setting and evolving human society. Our focus is on the Pisa old town
104 area (*ca.* 2.5 km² wide; Fig. 1A), where archaeological evidence of early Etruscan settlements (7th-
105 5th century BC) is widespread (Paribeni, 2010). In order to frame old and new data into a high-
106 resolution chronological scheme, we used a cross-disciplinary methodology, including
107 sedimentological, micropalaeontological, geochemical, geomorphological and archaeological data
108 from cores (up to 20 m long) and aerial photo interpretation. Greater emphasis was placed on high-
109 resolution stratigraphic architecture as a fundamental tool to reconstruct landscape evolution and its
110 impact on the oldest well-framed human settlements of Pisa (Etruscan civilization).

111

112

113 **2. The Pisa plain and the study site**

114

115 As part of the wider Arno coastal plain, the Pisa plain is a flat, low-lying area, approximately
116 150 km² wide, crossed from east to west by the lower reaches of the Arno River, the 8th Italian river
117 in length, and bounded to the north by Serchio River (Fig. 1A). The town of Pisa is located in the
118 middle of the plain, *ca.* 10 km east of the Tyrrhenian Sea coast and *ca.* 5-6 km west of the Pisa
119 Mountains (Fig. 1A). It developed since **early** Etruscan times (*ca.* 2500 yr BP/600 yr BC) on the
120 banks of the Arno River (Bruni, 1998; Sarti et al., 2010). The study area, which includes the famous
121 Leaning Tower, is located in the historical centre of Pisa, north of the Arno River (Fig. 1B).

122

123 *2.1. Middle-late Quaternary stratigraphy*

124 The middle-late Quaternary subsurface stratigraphy of the Arno coastal plain consists of a cyclic
125 alternation of continental and nearshore deposits, documenting repeated phases of transgression and
126 regression. This peculiar facies architecture has been closely related to glacio-eustatic sea-level
127 fluctuations falling in the Milankovitch (100 kyr-eccentricity cycles) band (Aguzzi et al., 2007;
128 Amorosi et al., 2008). Significant fluvial incision took place in response to the post-125 kyr phase
129 of sea-level fall, forming an incised valley broadly coinciding with the present Arno River course
130 **(Fig. 1A)**. The thickness of the Lateglacial-Holocene succession along the valley axis is about 50-60
131 m, whereas it decreases dramatically to 17 m on the interfluves. The valley fill is made up of clay-
132 prone, estuarine deposits subdivided into three, vertically stacked transgressive-regressive
133 millennial-scale depositional cycles, bounded by flooding surfaces (Amorosi et al., 2009).
134 Following rapid sea-level rise, during the middle Holocene the Arno palaeovalley was progressively
135 flooded and the interfluves submerged by the sea. The subsequent evolution of the Pisa area saw the

136 development of a wide lagoonal environment, which was strongly controlled by the inherited
137 palaeotopography (Rossi et al., 2011). The thick, clay-dominated, lagoonal succession, locally
138 known as ‘*pancone*’, acts today as a preferential, highly compressible zone of ground settlement, as
139 best exemplified by the Leaning Tower of Pisa (Sarti et al., 2012). At time of maximum marine
140 ingressión (7.8 cal ka BP – Amorosi et al., 2013a), the shoreline was located more than 7 km inland
141 of its present position (Mazzanti and Pasquinucci, 1983; Della Rocca et al., 1987; Sarti et al., 2008).
142 The subsequent highstand period was characterized by repeated phases of coastal progradation,
143 resulting in the development of the modern Arno delta, with its flanking coastal plain system. At the
144 same time, an intricate pattern of fluvial channels attributable to both Arno and Serchio rivers built
145 up the modern alluvial plain (Rossi et al., 2012).

146

147 2.2. *Geomorphological setting*

148 The modern Arno coastal plain is a wide sandy strandplain made up of several juxtaposed coastal
149 beach ridges, the alignment of which records the westward migration of the shoreline over the last
150 3000 yr (Pranzini, 2001). Through the littoral drift, this strandplain system was supplied mostly by
151 Arno and Serchio rivers, which frequently changed their course over time, as documented by
152 geomorphological studies (Della Rocca et al., 1987; Marchisio et al., 2001). Indeed, the highly
153 sinuous and low-gradient Arno and Serchio river channels were subject to recurring avulsions and
154 lateral channel migrations, which generated a complex system of abandoned branches (Schumm,
155 1977; Miall, 1996). Since the Roman period (Table 1), this natural tendency was greatly thwarted
156 by waterworks (construction of levees, canals, ditches). Several drainage channels were also
157 constructed as part of a systematic land reclamation scheme (Roman Centuriation). Wetlands that
158 occupied a vast portion of the Pisa plain were drained during the Etruscan-Roman period
159 (Baldassari and Gattiglia, 2009). A renewed phase of wetland expansion occurred during the
160 Medieval Ages, likely connected to a decrease in maintenance of drainage channels (Redi, 1991;

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

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

169

170 2.3. Historical and archaeological background

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

180 Roman and Medieval historical sources indicate the *Auser* as the main of the three branches
181 (*Tubra*, *Auser* and *Auserculus*) in which the modern Serchio River split at the gorge of Ripafratta
182 (Fig. 2). The *Auser* flowed from north to south along the Pisa Mountains foothills, merging with the
183 Arno River at Pisa. The *Auserculus* course was similar to that of modern Serchio River, although it
184 probably forked before reaching the sea (Fig. 2). Limited information is available from Medieval
185 sources about the course of the *Tubra* branch. According to Strabo, the Arno River was in turn split

186 into three branches, the northernmost corresponding (albeit with higher sinuosity) to the modern
187 course. Little is known, however, about the two southern branches (Ceccarelli Lemut et al., 1994).

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

191

192

193 **3. Methods**

194

195 *3.1. Data acquisition*

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

204 Lithofacies description includes mean grain size, colour, sedimentary structures and accessory
205 materials (mollusc shells and fragments; peat horizons or decomposed organic-rich layers; plant
206 debris; wood fragments and calcareous nodules). To refine facies interpretation, the cores were sub-
207 sampled for benthic foraminifer/ostracod (57 samples), palynological (36), geochemical (100) and
208 radiocarbon (35) analyses. For this study, focused on the Pisa old town north of Arno River, five
209 continuous cores and seven percussion cores were selected as reference sites (Fig. 1B). Additional

210 continuous cores and well logs available from the Arno plain dataset (Amorosi et al., 2008; 2013a)
211 were used for stratigraphic correlations (Fig. 1B).

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

220

221 3.2. Analytical procedures

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

234 association, containing a poorly-preserved, allochthonous meiofauna, was differentiated
235 (association R in Table 3).

236 Identification of species and the palaeoenvironmental significance of microfossil assemblages
237 relied upon several key-papers, dealing with species autoecology and spatial distribution patterns of
238 the modern Mediterranean and North Atlantic meiofauna (Athersuch et al., 1989; Albani and
239 Serandrei Barbero, 1990; Henderson, 1990; Sgarrella and Moncharmont Zei, 1993; Meisch, 2000;
240 Ruiz et al., 2000; Fiorini and Vaiani, 2001; Murray, 2006). In addition, a comparison was carried
241 out with benthic foraminiferal and ostracod associations from late Quaternary deltaic and coastal
242 deposits of the Mediterranean area (Mazzini et al., 1999; Carboni et al., 2002, 2010; Amorosi et al.,
243 2004, 2008; Fiorini, 2004).

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

257 Geochemical analyses were carried out for the reconstruction of sediment dispersal patterns, with
258 special emphasis on the Arno and Serchio river pathways and their evolution through time. To this

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

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

280

281

282 4. Facies associations

283

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

291

292 4.1. Lagoonal facies association ('pancone')

293 4.1.1. Description

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

307 A heterogeneous palynofacies is also encountered within these deposits (palynofacies L in Table
308 3). The organic residue is characterized by numerous orange-brown phytoclasts (few μm to 500 μm

309 in length) and sporadic granular or floccular AOM. Marine-related palynomorphs are represented
310 by dinocysts, foraminiferal linings and scolecodonts (up to 16.5%), whereas pollen and spores
311 (from 35% to 85%) and fungal spores (15-33%) represent the main components of the related
312 heterogeneous continental association. Arboreal (AP) pollen grains are more numerous than non-
313 arboreal (NAP) ones. Among the arboreal species, *Alnus* is dominating, with relative percentage up
314 to 36%. Aquatic plants may vary between 1.5% and 2.5%.

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

319 4.1.2. Interpretation

320 Sedimentological features and the peculiar fossil content indicate that this facies association was
321 formed in a low-energy, brackish lagoonal environment. The dominance of euryhaline species, such
322 as *Ammonia tepida*-*A. parkinsoniana*, *C. torosa* and *C. glaucum* (Russel and Petersen, 1973;
323 Athersuch et al., 1989; Millet and Lamy, 2002; Murray, 2006), can be considered as a sensitive and
324 reliable indicator of semi-closed, brackish-water depositional environments subject to salinity
325 changes. Microfossil assemblages similar to association B have been reported from several modern
326 lagoons and estuaries (D'Onofrio et al., 1976; Albani and Serandrei Barbero, 1990; Montenegro and
327 Pugliese, 1996; Coccioni, 2000; Ruiz et al., 2005; Murray, 2006; Carboni et al., 2009; Nachite et
328 al., 2010), as well as from several Holocene lagoonal successions of the Mediterranean (Barra et al.,
329 1999; Carboni et al., 2002, 2010; Amorosi et al., 2004; Fiorini, 2004).

330 The higher species diversity and the relative abundance of polyhaline-marine taxa (Miliolidae
331 species, *Leptocythere ramosa* and *Palmoconcha turbida*) in the lower part of the unit suggest an
332 overall shallowing-upward trend (or increasing confinement). A consistent upward increase in
333 continental input is also documented by the relative decrease of the ratio between marine-related

334 and continental palynomorphs within palynofacies L. Finally, the remarkable percentage of typical
335 riparian taxa (*Alnus*) in the upper part of this facies association and the upward increase in light
336 coloured, irregularly shaped phytoclasts are also suggestive of increasing proximity to the source of
337 detritus.

338

339 4.2. Lower swamp facies association

340 4.2.1. Description

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

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

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

356 4.2.2. Interpretation

357 The distinctive sedimentological features (dark colour, soft consistency and the abundance of
358 woods and peat layers) and the micropalaeontological content (association F and palynofacies P),

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

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

372

373 4.3. Poorly drained floodplain facies association

374 4.3.1. Description

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

381 Samples are generally barren in microfossils; rarely, they exhibit a scarce oligotypic ostracod
382 fauna composed exclusively of *P. albicans* (association F) or *C. torosa* (association B), the latter
383 found within organic-rich layers. The presence of rounded, dark brown to black phytoclasts,

384 homogeneous in size, is the main feature of palynofacies A (Table 3). AOM is sporadically
385 abundant within organic-rich layers. The palynomorph assemblage is heterogeneous, with many
386 reworked specimens derived from either ancient sediments or adjacent lands. The aquatic species
387 vary from about 4% to 10%.

388 This facies association is locally recorded at higher stratigraphic levels (cores M10, M19 and
389 M25 - see Fig. 1B for location), where sparse brick and ceramic materials dated between the 7th and
390 3rd centuries BC, were found. Clay plaster fragments from a hut were also encountered within Core
391 M19; while ceramic materials dated between the 10th and 12th centuries AD accompanied by ashes,
392 mortar fragments and slags due to iron manufacturing occur within Core M25. Two radiocarbon
393 ages, centred around 1690 and 575 yr BC (cores M6 and M10 - Table 4), are available from the
394 lower and upper portions of this facies association, respectively.

395 4.3.2. Interpretation

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

408 Radiocarbon data generally assign a Bronze-early Etruscan age to this facies succession (Tables
409 1 and 4). However, poorly drained conditions locally persisted up to the Roman period-Middle
410 Ages, as documented by the archaeological remains found within the uppermost stratigraphic levels
411 of cores M10, M19 and M25.

412 .

413 4.4. Upper swamp facies association

414 4.4.1. Description

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

421 Several brick fragments and ceramic material (*bucchero* and coarse pottery), mostly dated to the
422 7th-5th century BC (early Etruscan age in Table 1), are recorded within these deposits, furnishing a
423 *terminus ante quem* for their formation. This is consistent with the radiocarbon dates, which
424 indicate a chronological interval between 860 and 410 yr BC (M9_5.35, M25_4 and M26_4.60 in
425 Table 3).

426 4.4.2. Interpretation

427 Similar to the lower swamp facies association, this unit records deposition of fine-grained
428 sediments and organic detritus within a stagnant, paludal environment. The distinctive palynofacies
429 P, containing numerous continental elements, is highly suggestive of ephemeral, shallow swamp
430 basins developed close to river courses during the late Iron period, and intensely frequented by
431 humans during the early Etruscan age (Table 1). A strong and enduring frequentation is testified by

432 a diffuse large amount of ceramic materials and bones of domestic animals (mainly sheep), as well
433 as by the local occurrence of sharp wood fragments.

434

435 4.5 Well drained floodplain facies association

436 4.5.1. Description

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

446 Brick fragments and ceramic material mainly dated to the late Etruscan-early Roman period (2nd-
447 1st century BC; Table 1) are commonly found within these deposits. In Core S6_SZ (Fig. 1B for
448 location) a very compact layer composed of a dark silty matrix, rich in carbon, bricks and slags was
449 also observed around 1.8 m above sea level (s.l.). One radiocarbon date performed ca. 1.5 km NW
450 of the study area (Core M2 - Fig. 1A) yielded an age of ca. 610-665 yr AD (Table 4).

451 4.5.2. Interpretation

452 The sedimentological features point to a low-energy, alluvial depositional setting subject to
453 subaerial exposure, such as a well-drained floodplain occasionally affected by river floods (sand
454 layers). This facies represents the environmental context in which human settlements developed
455 from the late Etruscan-Roman period (Table 1). The compact layer observed in S6_SZ has been
456 interpreted to represent a roughly structured walking floor. On the basis of the ceramic content

457 found within the underlying and overlying sediments, this floor can be assigned to the Roman
458 period, between 1st century BC - 1st century AD (Table 1).

459

460 4.6. *Crevasse splay and levee facies association*

461 4.6.1. *Description*

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

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

476 4.6.2. *Interpretation*

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

482

483 4.7. Fluvial/Distributary channel facies association

484 4.7.1. Description

485 This facies association, which also occurs at distinct stratigraphic levels and shows thickness of
486 2-5 m, consists of gray to yellow-brown, fine- to coarse-grained sand bodies with erosional lower
487 boundary and distinctive fining-upward trend. Organic remains (wood and other plant fragments),
488 mollusc fragments, pebbles and mud-clasts are also locally encountered. Samples collected from
489 this facies are barren or contain a transported meiofauna (association R), composed of scarce and
490 poorly preserved specimens typical of deep-marine to continental depositional settings.

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

494 4.7.2. Interpretation

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

501

502

503 5. Sediment provenance

504 Arno and Serchio river catchments display strong compositional affinity, as recently documented
505 by the geochemical characterization of stream sediments (see Dinelli et al., 2005; Cortecci et al.,
506 2008). Using modern crevasse splay/levee deposits (collected by 'Cobra' sampler) from Arno and

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

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

520

521

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

523

524 The stratigraphic architecture of the middle-late Holocene succession is best depicted by three
525 cross-sections showing consistent vertical stacking patterns of facies across the Pisa old town area
526 (Fig. 5). Soft lagoonal deposits are invariably recorded in the lower part of the study succession.
527 This geotechnically weak 'layer' (Sarti et al., 2012) corresponds to the prominent stratigraphic
528 marker ('*pancone*'), up to 15 m thick, reported by Rossi et al. (2011) at comparable depths across a
529 wide portion of the Arno coastal plain. The lagoonal deposits are overlain by a fluvio-deltaic
530 succession, 10-15 m thick, made up of paludal clays (lower swamp facies association), 1-4 m thick,
531 which in turn are overlain by poorly drained floodplain deposits. These latter show lateral transition

532 to fluvial-channel, crevasse and levee sands and sand-silt alternations. The channel bodies are
533 bounded **at their base** by erosional surfaces that may deeply cut into the underlying succession,
534 down to the ‘*pancone*’. A multiphase channel history is documented by channel clustering at
535 distinct stratigraphic levels (Rossi et al., 2012). This succession is capped by the modern alluvial
536 plain facies association.

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

541

542 **6.1 Development of *the* lagoon (ca. 6000-3000 yr BC)**

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

553

554 **6.2. Filling of the lagoon (ca. 3000-2000 yr BC)**

555 Radiocarbon dating from the preserved top of ‘*pancone*’ (Core M1 **in Fig. 1B**) constrains the last
556 phases of lagoonal development in the northern part of Pisa to around 3500 yr BC. However,

557 radiometric ages from erosionally truncated lagoonal deposits (Core M6 in Fig. 5A) allow to refine
558 the time of lagoon infilling to around 3000 yr BC. Between 3000 and 2000 yr BC the lagoon
559 evolved into a more confined paludal environment. Sedimentation in stagnant, nutrient-poor
560 wetlands reflects the development of a deltaic/coastal plain crossed by distributary channels.
561 According to Rossi et al. (2012), two main phases of drainage network organization likely occurred
562 during this period (Eneolithic age). Geochemical data from channel-related (crevasse, levee) and
563 fine-grained swamp deposits still highlight sediment provenance from two distinct source areas,
564 suggesting simultaneous influence on sediment composition by Arno and Serchio rivers.

565

566 6.3 Transition to the alluvial plain (ca. 2000-500 yr BC)

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

575 Although an earlier phase of subaerial exposure of the floodplain is documented at the eastern
576 and western margins of the study area, a clear reverse evolutionary trend is recorded in the Pisa old
577 town by the abrupt onset of swamp deposits at the transition to the early Etruscan age (upper swamp
578 facies association in Fig. 5). Starting from this period, evidence of persistent anthropic frequentation
579 becomes more frequent, and traces are left in various environmental contexts (Fig. 5; sections 4.3,
580 4.4 and 4.6).

581

582 **6.4. The modern alluvial plain**

583 Since the end of the **Etruscan** period (Table 1), the Pisa area evolved toward a subaerially exposed
584 alluvial plain, as confirmed by the abundance of **indurated horizons** (well drained floodplain in Fig.
585 **5**) and their lateral relationships with fluvial-channel sands. Geochemical data from channel-related
586 (crevasse splay) and floodplain deposits indicate stable sediment supply from the Arno River.
587 During this phase, which led to the formation of the modern Pisa plain, a pervasive human
588 frequentation, **mainly dated from the Roman period onwards, is recorded. This caused the**
589 **progressive replacement of natural deposits by a well structured anthropogenic stratification.**

590

591

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

593

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

600

601 **7.1 Fluvial landscape, sediment provenance and human frequentation**

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

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

614 Since early proto-historic times (Eneolithic age), the town of Pisa was characterized by a
615 palaeohydrographic network composed, at least, of two river branches (Fig. 6) in lateral transition
616 to paludal wetlands (lower swamp association in Fig. 5). A N-S flowing palaeochannel (palaeo-
617 Serchio?) merged in the town centre area with a river branch located about 100 m north of modern
618 Arno river (palaeo-Arno?). Consistent with previous observations and hypotheses (Bruni and Cosci,
619 2003; Paribeni, 2010; Fig. 2A-B), a more complicated palaeohydrography governed by river
620 avulsion, meander cutoff and channel reoccupation is reconstructed for the Bronze period, up to the
621 Etruscan transition (Fig. 6). Five (or six) river channels bordering poorly-drained, small floodplain
622 basin, can be recognized. N-S and E-W oriented branches formed an intricate fluvial network in the
623 Pisa old town area. A N-S directed branch, showing orientation compatible with a branch of the
624 ancient Serchio river-*Auser* (Fig. 2A), merged with the Arno channel few meters south of the
625 modern Arno river course, in the Arsenali area (Core S1_exM in Fig. 6). The confluence of the
626 palaeo-Serchio into the Arno River fits with the geographic descriptions of the historical sources
627 (Strabo's Chronicles).

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

632 M5 were fed by a separate source, likely coincident with Serchio (*Auser*) River. Thus, the river
633 branch flowing very close to Core M5 (Fig. 6) and through Core S6_SZ site (Figs. 5A and 6), is
634 likely to represent the eastward prolongation of the *Auser* channel reported by Bruni and Cosci
635 (2003) (compare with Fig. 2). The clear Arno River affinity shown by Core M7 (Fig. 4) is
636 consistent with location of Core M7 very close to the modern Arno (Fig. 6). Backswamp
637 environments presumably developed at the transition to the early Etruscan age close to, and
638 possibly confined by, the highly sinuous channels. Although wetlands appear to have been
639 compartmentalized between adjacent (though non-coeval) channel-levee systems (cores M6, M8,
640 M9, M19, M25 and M26 in Fig. 6), data density is insufficient to outline precisely their boundaries
641 (Fig. 6).

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

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

657

658 6.2 Factors controlling backswamp development and filling

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

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

679 Similarly, the causative role of land-use change is difficult to discern, although evidences of
680 intense early Etruscan frequentation, mainly assigned to the 7th-5th century BC, testify to a strict
681 relationship between humans and backswamp (or, more in general, alluvial) development. A very

682 rich archaeological documentation is available from swamp deposits of the Pisa area, whereas traces
683 of human frequentation become increasingly rarefied at the backswamp margins. It is not easy to
684 determine whether wetlands acted as preferential sites for early human settlements or if they simply
685 represent depositional settings with higher preservation potential.

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

690

691

692 **7. Conclusions**

693

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

701

- 702 (i) Middle-late Holocene deposits beneath the town of Pisa exhibit a consistent shallowing-
703 upward tendency, which is interpreted to have formed in response to coastal progradation
704 under stable sea-level (highstand) conditions. A thick succession of lagoonal clays,
705 locally known as *pancone*, marks the maximum marine ingressión. This is overlain by

706 vertically stacked swamp, poorly drained floodplain, and drained floodplain facies
707 associations.

708

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

714

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

720

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

727

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733 field assistance.

734

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986

987 **Figure and table captions**

988

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

996

997 Figure 2 – A) Palaeohydrography of the Pisa plain during the Etruscan period, as reconstructed on
998 the basis of geomorphological and historical/archaeological data (from Sarti et al., 2010). B)
999 Palaeohydrography of the Pisa urban area, as reconstructed on the basis of aerial photographs, and
1000 tentatively related to the Serchio river system (from <http://www.geomemories.it/>).

1001

1002 Figure 3 – Representative core photographs showing the main facies associations of the Pisa plain.
1003 A) Channel-fill sand and its erosional lower boundary onto lagoonal clay (*'pancone'* – Core M6).
1004 B) Organic-rich swamp clay (lower swamp association) with upward transition to poorly drained
1005 floodplain silty clay (Core M5). C) Organic-rich clay (upper swamp association) overlying light
1006 brown, mottled well-drained floodplain clay and silt (Core M9). D) Well-drained floodplain clay
1007 and silt overlying crevasse splay deposits (Core M5). Core top at the right up corner. See Fig. 1B
1008 for core locations.

1009

1010 Figure 4 – Discrimination between Arno and Serchio sediment supply from selected cores (M5, M6,
1011 M7 - see Figs. 1B and 6, for location) of the Pisa coastal plain. Only fluvial samples of Bronze-Iron
1012 age are plotted. Modern Arno and Serchio levee deposits are used as reference samples, i.e.
1013 compositional end-members.

1014

1015 Figure 5 – Representative stratigraphic sections depicting the middle-late Holocene facies
1016 architecture in the Pisa old town area (see Fig. 1B for section traces). Sections A and B are oriented
1017 at low angle relative to the modern Arno River course. Section C is perpendicular to the modern
1018 Arno. Reference cores are in bold. Radiocarbon data are reported as calibrated yr BC (the highest
1019 probability range; see Table 4).

1020

1021 Figure 6 – Reconstruction of the palaeodrainage network in the Pisa area during the proto-historic-
1022 early Etruscan period based on combined aerial photo interpretation and core analysis (compare
1023 palaeochannel traces with those in Fig. 2). Notice compartmentalization of swamp deposits (‘upper
1024 swamp facies association’ in Fig. 5) between non-coeval channel-levee systems. The oldest
1025 (Eneolithic) channels are also shown. Three palaeo-traces are tentatively attributed to the post-
1026 Etruscan period. Core locations and the section traces of Fig. 5 are also reported.

1027

1028 Table 1 – Archaeological chronology for the Pisa plain (from [http://www.mappaproject.
1029 arch.unipi.it](http://www.mappaproject.arch.unipi.it)).

1030

1031 Table 2 – Aerial photo sets used in this work, with year of acquisition.

1032

1033 Table 3 – Characteristic benthic foraminifer and ostracod taxa (abundant: >30%; common: 10-30%
1034 and rare: <10%) composing the three microfossil associations identified in the study area, and

1035 related palaeoenvironmental significance. For each microfossil association, the dominant taxa are
1036 reported in bold. Palynofacies characteristics in terms of phytoclast morphologies,
1037 marine/continental palynomorphs and related palaeoenvironmental attribution, are also reported.

1038

1039 Table 4 – List of the radiocarbon dates discussed in this paper. Local reservoir correction DeltaR
1040 (35±42) was applied to shell samples (*Cerastoderma glaucum* valves). Percentages associated to the
1041 calibrated age values represent the related area under probability distribution using two standard
1042 deviations-2σ.

Figure 1
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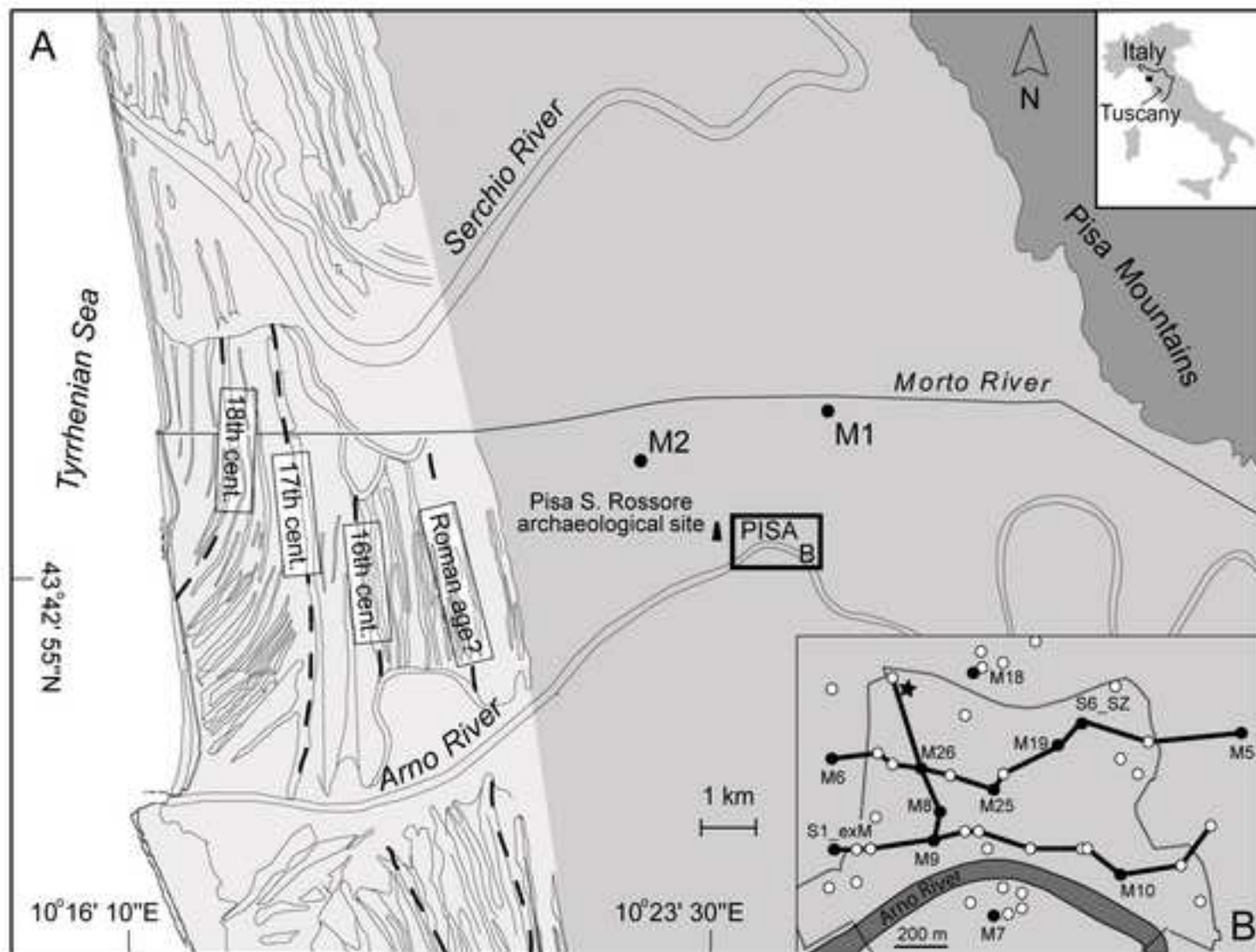


Figure 2
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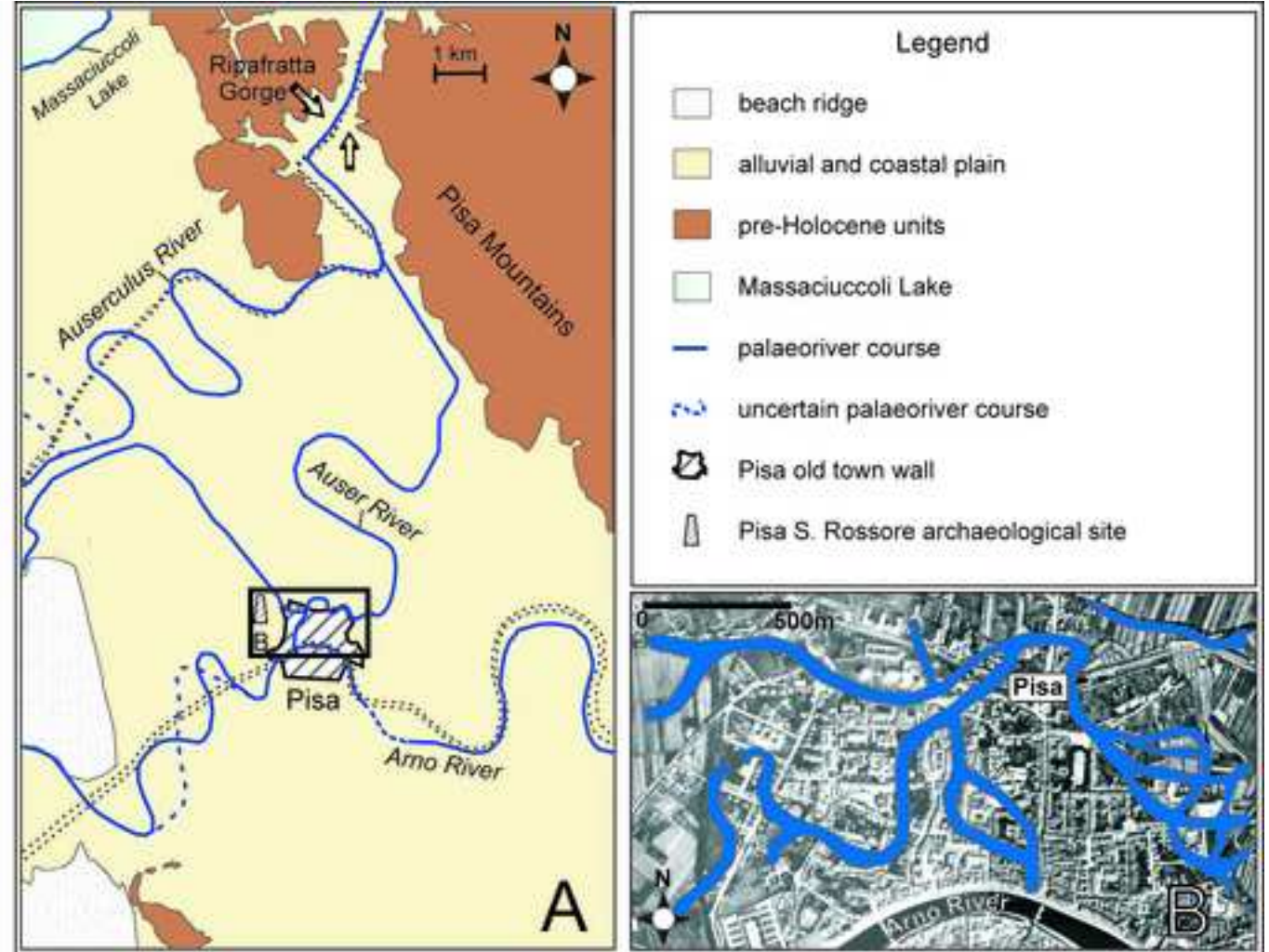


Figure 3
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Figure 4

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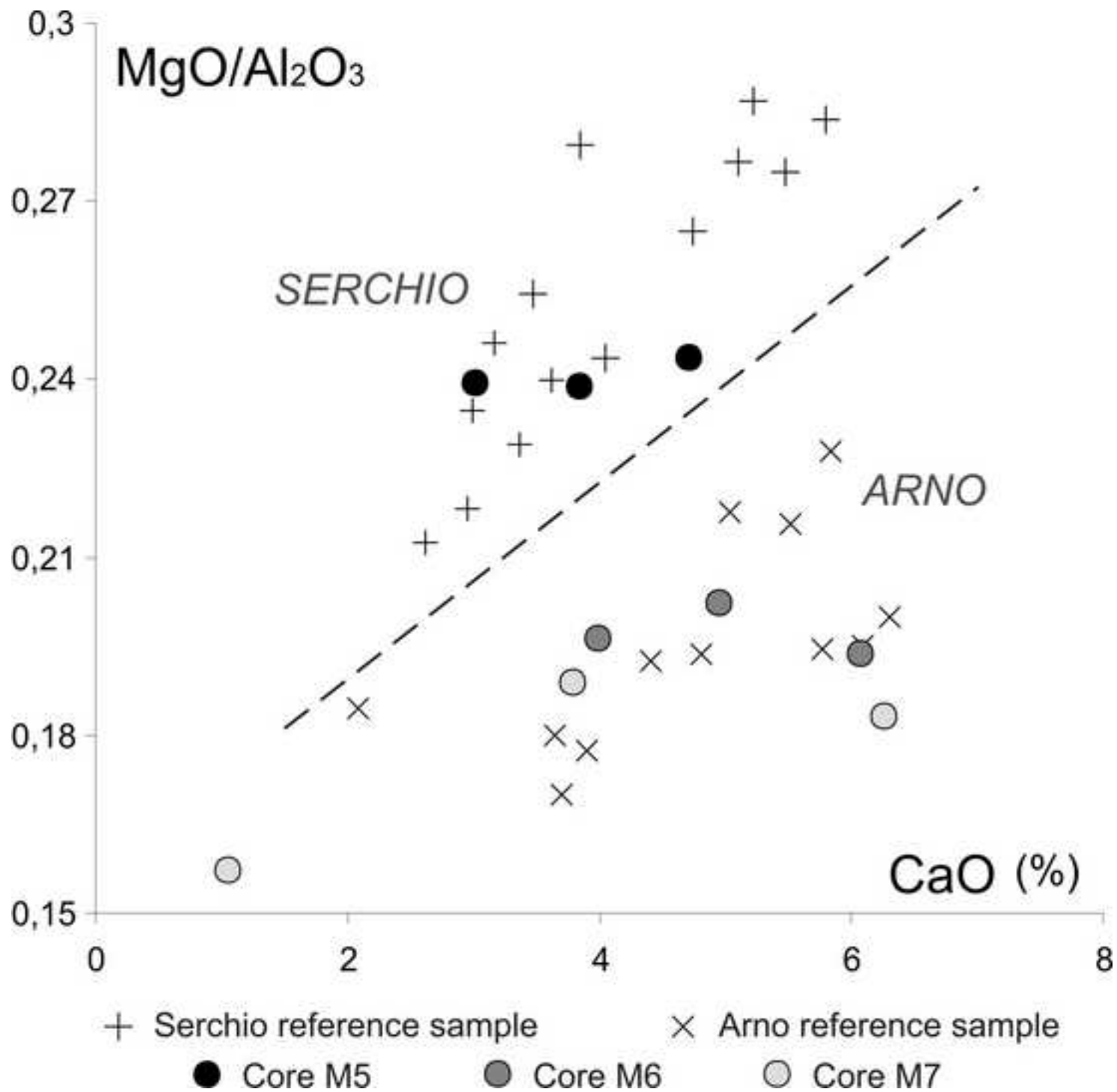


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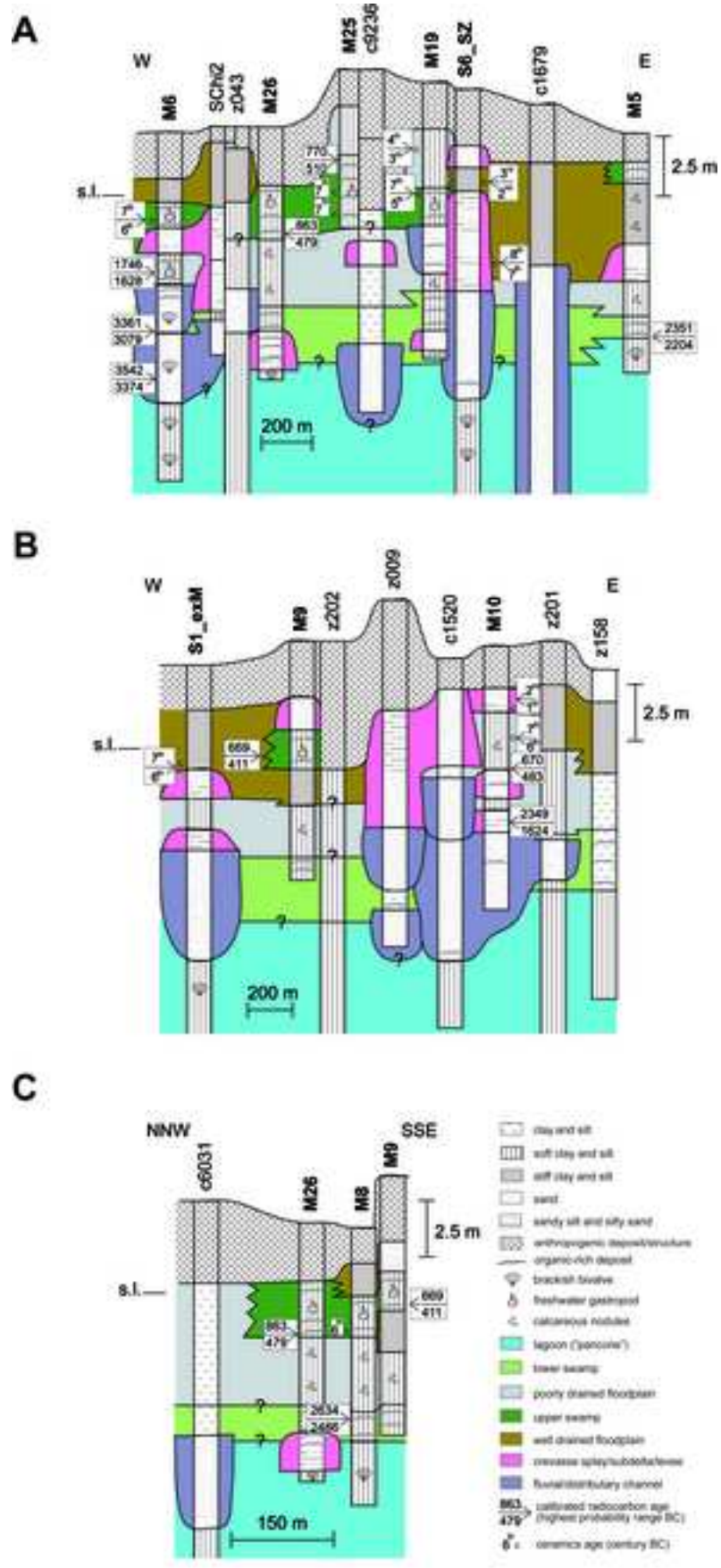


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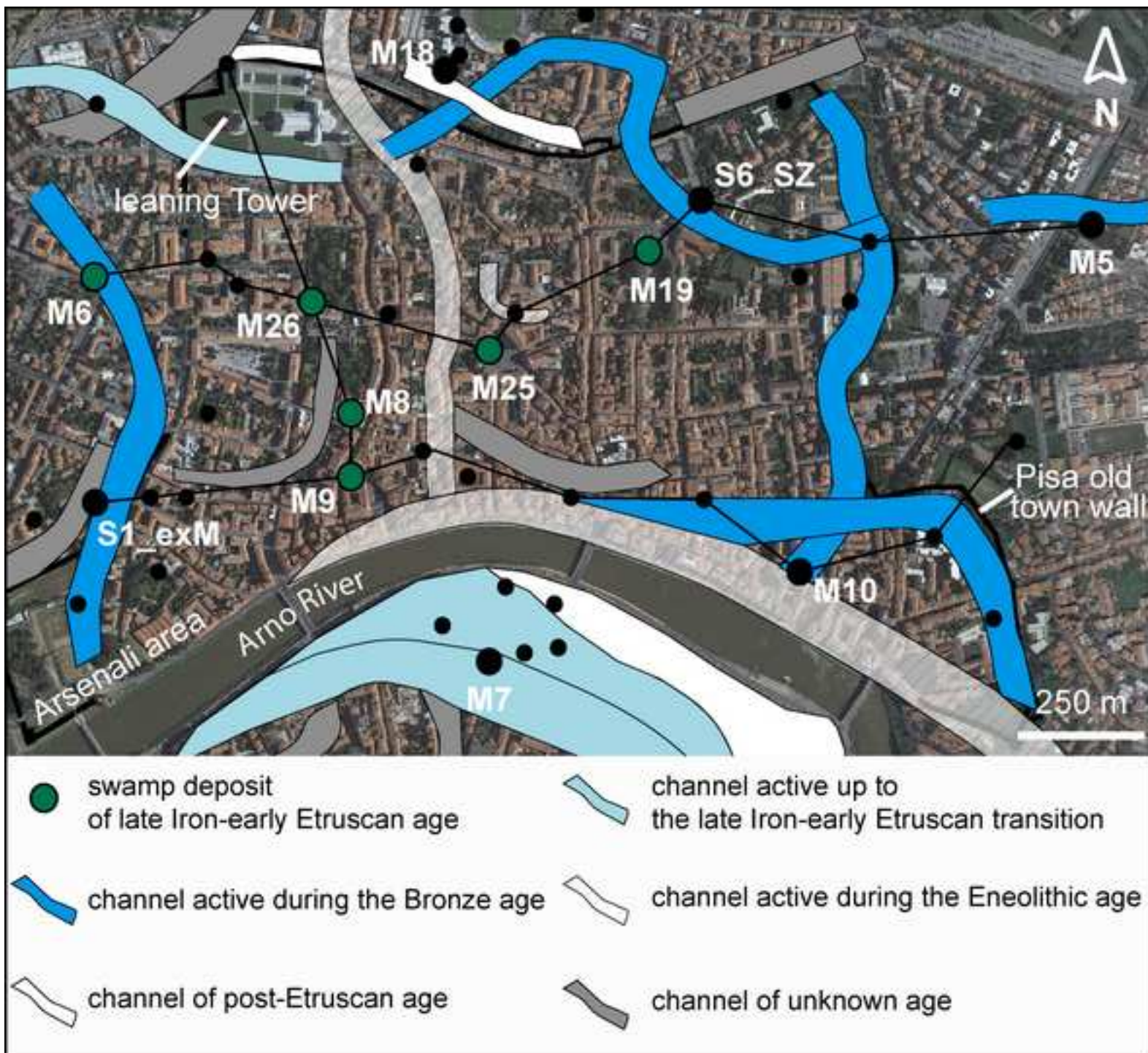


Table 1
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Chronology		Time range (yr BC/AD)	Time range (cal yr BP)	
Prehistoric age	Neolithic	(5500-3300 BC)	ca. (7500-5300)	
Proto-historic ages	Eneolithic	(3300-1900 BC)	ca. (5300-3800)	
	Bronze Age	(1900-901 BC)	ca. (3800-2850)	
	Iron Age	(900-721 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 <i>Ammonia tepida</i> and <i>A. parkinsoniana</i> . As secondary species, common to rare <i>Haynesina germanica</i> (Ehrenberg, 1840), <i>Aubygnina perlucida</i> (Heron-Allen and Earland, 1913) and <i>Criboelphidium</i> species. Rare Miliolidae species	Abundant <i>Cyprideis torosa</i> (Jones, 1850). Common to rare <i>Loxoconcha stellifera</i> (G.W. Müller, 1894) and <i>Loxoconcha elliptica</i> (Brady, 1868b). Rare <i>Leptocythere ramosa</i> (Rome, 1942) and <i>Palmoconcha turbida</i> (G.W. Müller, 1912)	Brackish-water environment with moderate to high marine influence (central-outer lagoon)
F	Absent	Abundant <i>Pseudocandona albicans</i> (Brady, 1868). Rare <i>Candona neglecta</i> (Sars, 1887) and <i>Ilyocypris</i> 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%)



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

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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.