Palaeoenvironments and palaeotopography of a multilayered city at the Etruscan-Roman transition: early interaction of fluvial processes and urban growth at Pisa (Tuscany, Italy)

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Abstract

The synergic relationship involving natural and anthropogenic processes strongly influenced the alluvial landscape evolution during the last millennia. A continuous, long-lasting record of this complex joined activity is well-documented within the depositional succession buried beneath ancient multilayered cities, where a fully integrated geoarchaeological approach can be usefully adopted.

In this work, the integration of archaeological, geomorphologic and stratigraphic data allowed the identification of the palaeoenvironments, palaeotopography and urban growth patterns of Pisa (NW Italy) at the Etruscan-Roman transition (2nd century BC-2nd century AD). During this period, Pisa saw a fast urban expansion that occurred within a dense and unstable hydrographic network. Environmental reconstructions show that wide portions of the city were characterized by poorly drained conditions until the 1st century AD, when the alluvial plain became well drained under an increasing anthropogenic pressure (Roman *Centuriatio*).Poorly drained floodplain and channel-related backswamp areas represented the lowest topographic zones of the Pisa city during early Roman times. The latter developed within an intricate pattern of palaeochannels, connected to two main rivers: the palaeoArno, which flowed in proximity of its present position, and the former palaeoSerchio river known as *Auser*. Specifically, the *Auser* showed two semi-coeval branches, one flowing in the area of Piazza Duomo located in the Northern part of the city and the other into the palaeoArno. This branch is interpreted as the course described by Strabo and never identified before. The *Auser* activity induced the development of a marked topographic high (up to 3.5 m a.s.l.) in correspondence of Piazza Duomo, where the famous Leaning Tower is located. Moreover, a wider but less prominent (about 2 m a.s.l.) relief N-S oriented occurred in the historical city centre of Pisa as a consequence of the fluvial activity since the Eneolithic period (about 2600 yr BC). Since the late Etruscan times, ancient human settlements and manufacturing sites clustered in correspondence of the topographic high close to the *Auser* river that played a crucial role in the evolution of Pisa urban context.

This geoarchaeological reconstruction provides useful data for the estimation of the archaeological potential of urban and suburban Pisa areas, furnishing a methodology that could be applied to other Mediterranean multilayered cities.

Keywords: Urban geoarchaeology; Pisa city; Roman period; palaeoenvironments; palaeotopography; Arno River

1. Introduction

During the last millennia human and natural processes have become strongly intertwined, modifying the Earth's surface and its physical, biological and chemical characters in many complex ways (Zalasiewicz et al., 2011a). The widespread stratigraphic record of intense anthropogenic perturbations, involving geochemical and sedimentary cycles as well as global biodiversity patterns, has stimulated a serious debate about the potential formalization of the Anthropocene epoch and the timing of its lower boundary (Steffen et al., 2011; Syvitski and Kettner 2011; Zalasiewicz et al., 2011a, b).

Evident traces of this joined human-nature activity can be detected in long-settled city areas, where an enduring synergic relationship between landscape, ancient cultures and society evolution occurs (Butzer, 2008; Bruno et al., 2013; Ninfo et al., 2011; Schuldenrein and Aiuvalasit, 2011; Stefani and Zuppiroli, 2010; Zanchetta et al., 2013). Anthropogenic processes (i.e., land-use practices, reclamation and drainage modifications) strongly contributed to the transformation of the alluvial landscape that surrounds multilayered cities, modifying the geomorphological features and the patterns of sediment flux. They also created man-made deposits and artificial grounds, which are extremely variable in thickness, composition and subsurface spatial distribution (Price et al., 2011; Zalasiewicz et al., 2011a). However, in such an articulate geomorphological and stratigraphic context, the application of mono-disciplinary researches can furnish only partial and limited results. In contrast, a geoarchaeological approach permits the identification and mapping of historical ground layers and contributes to resolve the complexity of areas in which urbanization tends to hide geomorphological features and natural deposits (Amorosi et al., 2013a; Bini et al., 2009, 2012a; Bruneton et al., 2001; De Smedt et al., 2013; Ghilardi and Desruelles, 2009; Marriner et al. 2012; Parker et al., 2008; Price et al., 2011). Recently, the study of remote sensing images (e.g. satellite images airborne photos, LIDAR-derived digital elevation models) checked by geomorphological survey has been commonly employed as a guiding tool to identify the main geomorphological features at a larger scale (Bini et al., 2013a, b; Bisson and Bini, 2012; Butzer, 2008; Fouache et al., 2010; Ghilardi et al., 2010; Siart et al., 2008). Unfortunately, such analyses do not provide data about the sedimentological characteristics and the spatial distribution patterns of subsurface deposits, which can be directly reconstructed and quoted through continuously cored boreholes only. The integration of stratigraphic, geomorphological, geophysical and archaeological data with an accurate elevation dataset can furnish detailed insights into the three-dimensional geometry of both natural and anthropogenic sedimentary bodies, providing a solid base for palaeoenvironmental and palaeotopographic reconstructions over wide areas.

In the context of MAPPA Project (supported by PAR FAS Regione Toscana Action Line 1.1.a.3. call; www.mappaproject.org) an extensive geomorphological, stratigraphic and archaeological dataset was acquired from the multilayered city of Pisa (NW Italy, Fig. 1), furnishing a good opportunity to carry out a cross-disciplinary study.

In this work we focus on the palaeoenvironmental, palaeotopographic and urban growth patterns of Pisa at the Etruscan-Roman transition (2^{nd} century BC-2^{nd} century AD), a period that saw the development of a more structured urbanization in the environmental context of a dense and unstable hydrographic network. The reconstruction of this landscape scenario will furnish new data about human-environment interactions and dynamics during a crucial period of the Mediterranean civilization history. Specific objective is to provide and test a cross-disciplinary methodology that could be applied to other urban contexts with long human occupation history and complex subsurface stratigraphy.

2. The study area

2.1. Geomorphological and stratigraphic setting

The city of Pisa, worldwide famous for the Leaning Tower of Piazza Duomo, is placed ca. 10 km east of the Ligurian Sea coast in the middle of the Arno coastal plain (NW Tuscany, Italy), a flat low-lying area approximately 450 km^2 wide. This coastal plain, crossed from east to west by the lower reaches of the Arno River, the 8th Italian river in length, is bounded to the north by the Serchio River (Fig. 1), to the east by the Pisa Mountains and to the south by the Livorno and Pisa hills. Since protohistoric times, Arno and Serchio rivers were actively involved in the development of a wide alluvial plain, characterized by meandering river courses, passing seawards to a strandplain system (Della Rocca et al., 1987; Marchisio et al., 1999; Pranzini, 2001). These highly sinuous and low-gradient river channels frequently changed their course over time, as documented by several geomorphological studies (Bini et al., 2012a, b; Della Rocca et al., 1987). Consistent with historical sources (Ceccarelli Lemut et al., 1994; Garzella, 1990; Gattiglia, 2011), remote sensing analyses documented the presence of N-S directed palaeotraces (Bruni and Cosci, 2003; Fig. 1) connected to the activity of an ancient branch of Serchio River, known as *Auser* that merged with the palaeoArno course in the Pisa city centre (Strabo, V, 2, 5, C 222). During the late Middle Ages, the *Auser* was forced to flow northwards to prevent flooding of the urban area (Bruni and Cosci, 2003).

During the last glacial-interglacial period the Arno River played a dominant role in the sedimentary and geomorphological evolution of the Pisa Plain, forming a prominent incised valley system, 40-45 m thick and 5-8 km^2 wide (Amorosi et al., 2008, 2013b). This palaeovalley, developed in response to the last phase of sea-level fall culminating in the Last Glacial Maximum, was progressively filled with estuarine and paludal deposits during the Lateglacial-early Holocene transgression (ca. 13000-8000 cal yr BP). The valley-fill succession is overlain by a laterally extensive, 3-15 m thick lagoonal unit (known as "*pancone*"). This unit is composed of soft grey clays, accumulated between 6000 yr BC and 3000 yr BC (approximately 8000-5000 cal years BP) in concomitance with the Holocene maximum marine ingression and the early phase of sea-level highstand (Amorosi et al., 2008, 2013a; Benvenuti et al., 2006; Rossi et al., 2011). Upwards, a 10-15 m-thick deltaic-alluvial sedimentary wedge originated from around 3000 yr BC to Present. Eneolithic swamp clays, 1-3 m thick, form the lower portion of the late highstand fluvial succession and pass upwards to poorly-drained and then well-drained floodplain fine-grained deposits, of protohistoric and historic age, respectively. Isolated to locally amalgamated fluvial-channel sand bodies, crevasse/levee sands and sand-silt alternations occur at different stratigraphic levels (Amorosi et al., 2013a). This progradational trend was temporarily interrupted by widespread backswamp development in the Pisa city centre at the Iron-Etruscan age transition (Amorosi et al., 2013a).

2.2. Archaeological and historical background

Scattered archaeological remains, dated back to the Iron Age (9th-8th century BC), document a long-lasting history of human frequentation in the Pisa plain. Traces of human settlements became more persistent and diffuse during Etruscan times (second half 8th-first half of 1st century BC), documenting the development of the first urban centre (Paribeni, 2010; Pasquinucci, 1994).

Since the middle of the 3rd century BC the ancient Etruscan city of Pisa was under Roman control (Bruni, 1998; Corretti, 1994; Paribeni, 2011; Pasquinucci, 1993, 1995, 2003a, b; Segenni, 2003), acquiring Roman citizenship (*municipium*) after the Social War (90-88 BC; Fabiani, 2007). During the Triumviral period or Augustan Age, between 42 BC and 27 BC, Pisa became *Colonia Opsequens Iulia Pisana.* In this period the territory was divided by the *centuriatio* and the urban structure was re-organized (Pasquinucci, 1995, 2003a), showing a strong vocation for both agricultural and manufacturing production, supported by a flourishing commercial harbour activity. Indeed, a complex harbour system (Fig. 1), mainly including *Portus Pisanus* (*Itinerarium Maritimum* 501; Rutilio Namaziano, 1, 527-540; 2, 11-12) and the fluvial harbours of San Piero a Grado (the *Pisis fluvius* of *Itinerarium Marittimum)* provided trades all over the Mediterranean up to the 7th century AD (Bruni, 2003a, 2003b; Camilli and Gambogi, 2004; Ducci et al., 2005; Menchelli, 2003; Pasquinucci, 2003b, 2007). The Isola di Migliarino fluvial harbour and minor landings placed along the rivers and canals, among which the Pisa S. Rossore shipwreck site is the most famous (Benvenuti et al. 2006; Camilli and Gambogi, 2004), were also active.

The waterways were fully integrated into the road system, which put the city in a complex network of connections. These roads include the *Via Aurelia*, which was flanked by the *Via Aemilia*, the road to Florence and the road to Lucca (Ceccarelli Lemut and Pasquinucci, 1991; Coarelli, 1985-87; Fabiani, 2006; Fig. 1).

3. Materials and methods

In the context of MAPPA project, a geoarchaeological study was carried out on the mid-late Holocene alluvial succession, ca. 10 m-thick, buried beneath the urban and suburban areas of the ancient city of Pisa, covering approximately 4 km^2 (Fig. 1). Different subsurface datasets and analyses were employed and reported, as follows.

3.1. Stratigraphic data

In order to reconstruct subsurface stratigraphy in the Pisa coastal plain, a combined sedimentological and micropalaeontological study was carried out on twenty sedimentary cores, stored in a georeferenced dataset (MAPPA cores in Amorosi et al., 2013a). In this study, we focused on five continuously cored boreholes 10-20 m long, and nine cores obtained through a percussion drilling technique commonly adopted in urban geology (Atlas Copco, Cobra model, equipped with Eijkelkamp samplers). The latter reached the maximum depth of 13 metres (see Fig 2 for location).

Specific sedimentological and palaeontological (meiofauna, phytoclasts and palynomorphs) information derived from MAPPA cores have been published in Amorosi et al. (2013a), to which the reader is referred for detailed methodological and facies data.

Additional palaeoenvironmental informations were furnished by archaeological remains (ceramics, mortar, brick fragments, charcoals and ashes, slags) found within the uppermost core portions. These data also support the chronological framework based on 20 radiocarbon dates performed at CIRCE Laboratory of Caserta (Naples University). Samples for radiocarbon dating correspond to wood fragments, organic clay, charcoal and mollusc shells. Conventional ages were calibrated using CALIB5 software and the calibration curves of Reimer et al. (2009). Local reservoir correction DeltaR (35±42) was applied to shell samples. In this study, ages are reported as the highest probability range (yr BC/AD) obtained using two standard deviations-2σ (Tab. 1).

The three-dimensional geometry and spatial distribution patterns of the main fluvial bodies were reconstructed through several stratigraphic sections. These sections encompass the reference MAPPA cores and the highest quality boreholes available for the Arno coastal plain dataset.

3.2. Geomorphological data

A geomorphological survey complemented by remote sensing analysis (satellite images, multitemporal photographies, lidar images, electric tomography) was undertaken in the study area. Landforms and deposits were mapped according to the guidelines adopted by the Italian Group of Physical Geography and Geomorphology of CNR and the Italian Geological Survey, Working Group for Geomorphological Mapping (*Gruppo di Lavoro per la Cartografia Geomorfologica*, 1994). Particular attention was dedicated to the identification of anthropogenic processes and to the paleohydrographic reconstruction of the Pisa urban and suburban areas. In this regard, multitemporal aerial photos, dated between 1943 and 2010, were analyzed together with multispectral images with medium-high resolution acquired from SPOT, ALOS AVNIR-2 and

TERRA ASTER satellites (Bini et al., 2012c). Variations in colour tone were mainly analyzed using 8-bit (256 grey tines) images. Spatially continuous groups of pixels with low brightness and delineating narrow, sinuous shapes may indicate zones with greater moisture content, suggesting the presence of abandoned fluvial channels.

Morphometric elaborations on a digital elevation model, based on Lidar data (density of acquisition of 0.8 or 1.6 pulse/m^2, vertical and horizontal accuracy of ± 15 cm and ± 30 cm, respectively), were undertaken in order to detect morphological evidence of past landforms. To verify the geometry of the main palaeochannels, Electric Resistivity Tomography (ERT) was acquired along 7 profiles. The ERT profiles investigate the uppermost subsurface (down to 12-18 m depth), adopting the roll-along acquisition technique, with electrodes spacing of 2 m. Schlumberger and Wenner configuration combined with dipole-dipole array were used. The 2D inversions of apparent resistivity were performed using the TomoLab software.

3.3. Archaeological data

A digital archaeological archive of the Pisa urban and suburban areas, including more than 2000 findings, was created through exhaustive research and analysis of literature data and technical documentation, such as project plans, reports and raw data (Fabiani, 2012). This dataset was first subdivided into seven chronological periods, corresponding to the main archaeological and historical growth phases of Pisa: Protohistoric; Etruscan; Roman; early Medieval, late Medieval, Modern, and Contemporary (Anichini and Gattiglia, 2012).

The archaeological findings were collected during occasional recoveries and planned excavations performed until 2011 (Fabiani, 2012). The latter were mainly performed within the declared area of archaeological interest, corresponding to the historic centre and its northern and western edges (Anichini, 2012). All the data were subdivided into typological categories on the basis of the human activity that they represent (Fabiani and Gattiglia, 2012). More than 300 catalogued and georeferenced archaeological findings referring to the last centuries of the Etruscan age (4th-1st BC) and to the centuries of the Roman age (1st BC-5th AD) were considered (Fig. 3). This broad view of the archaeological data allowed a better reconstruction and comprehension of the main human settlement features occurred around the Etruscan-Roman transition, which is the focus age of our work.

3.4. Digital Elevation Model

More than sixty points with reliable elevation values and dated to the Etruscan-Roman transition were selected from the georeferenced archaeological and stratigraphic datasets (see sections 3.1. and 3.3.) to perform a Digital Elevation Model-DEM (Figs. 2 and 3). Accurate elevation values of the archaeological data were obtained using Leica GS09 differential GPS (planimetric precision ± 1 cm, and altimetric precision ± 2 cm). Concerning core data, the elevation of the stratigraphic intervals referred to the Etruscan-Roman transition was obtained subtracting the thickness of the overlying deposits from the GPS ground level.

All points acquired were processed by statistical validation methods, with outliers detection and elimination. The final dataset (consisting of 63 points) was spatially interpolated to generate the DEM of the Pisa area at the beginning of the Roman period.

In order to minimize interpolation errors, the DEM boundary was delimitated taking into account the point distribution, and digitized internally to the distal elements of the dataset. Therefore, topography was reconstructed only for a selected area of the Pisa city centre, north of the Arno river course.

The DEM was achieved using the algorithm ANUDEM (Australian National University Digital Elevation Model. Hutchinson, 1988, 1989; http://fennerschool.anu.edu.au/research/software-datasets/ anudem). This algorithm was chosen for its better altimetric accuracy after quantitative comparison, based on reiterative cross-validation techniques with other “general purpose” methods (i.e., Spline, IDW).

4. Results and interpretation

4.1. Protohistoric-historic alluvial stratigraphy

According to previous studies (Amorosi et al., 2013a; Rossi et al., 2011; Sarti et al., 2012), the establishment of a genuine alluvial depositional system, subject to frequent flood events, is documented by the abrupt occurrence around 5 m below sea level (b.s.l.) of poorly drained floodplain clays onto laterally extensive swamp deposits. The latter are barren of archaeological findings and radiocarbon dated to the Eneolithic period (ca. 2600-2200 yr BC; Fig. 4A-C).

The monotonous alluvial clayey succession, up to 4 m thick, with local evidence of large (up to 3 cm) calcareous nodules and scattered ceramic fragments, shows genetic relationships with remarkably thick (up to 5-6 m) fluvial-channel sand bodies, whose upper boundaries mainly cluster around 5-4 m b.s.l., and levee and crevasse splay sands and silts (Fig. 4A-C) dated to the Bronze-Iron ages (Amorosi et al., 2013a; ca. 1900-700 yr BC). Upwards, more lens-shaped channel bodies, with maximum thickness of 2-2.5 m and upper boundaries clustering around 1 m b.s.l., occur in proximity of the modern Arno River course and the western city walls. In these areas and close to the NE city wall edge, correlative levee/crevasse splay coarse-grained deposits are recorded (Figs. 2, 4A-C). Radiocarbon and ceramic data chronologically constrain this phase of channel activity to the Etruscan-Roman transition (Fig. 4A-C).

In the subsurface of the historical city centre and a few metres SE of the Pisa S. Rossore site, backswamp clays and silts occur above ca. 2 m b.s.l., with lateral transition to poorly-drained floodplain and channel-related deposits (Figs. 2, 4A-C). This swamp succession, whose lower portion is dated to the late Iron Age-early Etruscan period (800-480 BC; Amorosi et al., 2013a, Fig.

4A-C), is abruptly overlain by stiff, well-drained floodplain silty clays and channel-related silty sands locally containing early Roman (1st century BC-2nd century AD) ceramic fragments. Across the study area, these deposits constitute the uppermost alluvial succession that underlies anthropogenic chaotic units, such as walking floors, ruins layers and elevation/leveling layers, with various human materials of late Roman age onwards (post-2nd century AD).

4.2. Palaeohydrography at the Etruscan-Roman transition

The most prominent palaeohydrographic features of the study area were mapped by remote sensing analysis (aerial photos and satellite images), on the basis of evident chromatic changes.

More than 30 fluvial diachronic traces were identified on an overall surface of around 4 km^2, documenting the significant contribution of the fluvial network to the geomorphological development of this area. These features were checked through the integration with Electric Resistivity Tomography (ERT; Fig. 5) and subsurface stratigraphic data (Fig. 4A-C), allowing identification of the palaeotraces chronologically referred to the Etruscan-Roman transition (top of the fluvial sand bodies around 1 m b.s.l.; see sub-section 4.1. and Fig. 4A-C).

The fluvial network consists of two main courses lengthwise crossing the Pisa area with a sinuous pattern (meandering fluvial style), consistent with the low-gradient alluvial plain (Fig. 6). The southernmost river course, close to modern Arno River, is interpreted as the Etruscan-Roman transition palaeoArno branch. The other course flowing ca. 600 m northwards, is reasonably related to the palaeoSerchio (*Auser*) river system, which was involved in the development of the Pisa plain till the late Middle Ages (Bruni and Cosci, 2003).

The northward migration of the palaeoArno meander, supported by palaeotraces alignments (Fig. 6), is well-documented by core data, which show decreasing depths of the top of fluvial sand bodies toward the modern Arno river course (Fig. 4A). Consistent with this interpretation, channel-related sediments (crevasse splay/levee sands and silts) stratigraphically connected to the Etruscan-Roman meander are recorded lateral to the channel (see sub-section 4.1. and Fig. 4A-B). Moreover, widespread ceramic materials of late Etruscan-early Roman age (1st century BC-1st century AD; see core M9 in Fig. 4A) are found within the northern crevasse-levee complex.

A more articulated fluvial pattern is documented for the *Auser* course flowing from the eastern edge of the study area to Piazza Duomo, where it seems to split into two main branches not strictly coeval. The *Auser* branch bordering Piazza Duomo to the north, in correspondence of the medieval walls, was mainly active during the Roman period and presumably reached the sea about 6 km north of the modern Arno River mouth, as testified by historical sources (Garzella, 1990; Gattiglia, 2011). The other branch, mainly active during the late Etruscan centuries, flowed few tens of metres south of Piazza Duomo, roughly following an east-west direction and crossing the shipwreck site of Pisa S. Rossore (Benvenuti et al., 2006).

Recently acquired stratigraphic data also indicate the presence of a third branch, flowing north-south, which likely reached the Arno ca. 1 km west of the Ponte di Mezzo (Figs. 4C and 6).

This palaeohydrographic scenario is consistent with the ETR profile of Figure 5, showing stratigraphy beneath Piazza Duomo medieval wall (see Fig. 2, for location). The profile shows the occurrence of a high-resistivity stratigraphic interval with values around 130 a.u. and upper boundary about 2 m below ground level (ca. 0 m b.s.l.). This area, corresponding to a fluvial-channel sand body, is interpreted as the northern *Auser* branch described above (Fig. 6). Below, a laterally continuous low-resistivity interval (2-35 Oh x m), consistent with the vertical stacking of clay-prone (floodplain-swamp-lagoon) deposits (compare with Fig. 4A-C, and Amorosi et al., 2013a; Sarti et al., 2012;), is detected (Fig. 5). A narrow high-resistivity area (around 450 Oh x m), ascribable to an older palaeotrace (see core c6031 in Fig. 4C and Amorosi et al., 2013a), occurs few metres north of the Leaning Tower (Fig. 5).

4.3. Pisa ground level at the beginning of the Roman period

The topography of Pisa at the beginning of the Roman period involves an area of about 1.5 km2. The reconstructed DEM, with a density of 42 points/km2, shows a mean elevation value of 0.55 m a.s.l., with minimum and maximum values of -2,7 m and 3.5 m a.s.l. (Tab. 2), respectively. The ancient ground level was significantly different from the current topography derived by LIDAR, and located approximatively 2 m below the ground level (Fig. 7). A topographic rise, with average height of 2 m a.s.l. and areal extension of 1 km^2 characterized the central part of the study area. The highest elevation value of 3 m a.s.l. was coincident with the NW edge of Pisa historical city centre, strictly corrisponding to the small area of Piazza Duomo (Fig. 7). On the contrary, the topographically lowest areas, around 0 m-1 m b.s.l . were situated at the southern and western margins of the study area. Moreover, a small-sized lowland is attested few metres NE of Piazza Duomo.

4.4. Human traces during the late Etruscan-early Roman ages

In the study area, 106 archaeological findings dating back to the late Etruscan age (Fabiani et al., 2013a) were recovered, mostly in the northern part of the historical city of Pisa, close to Piazza Duomo (Fig. 8A). The majority of these findings corresponds to undifferentiated tracers of human frequentation (ca. 60%). Among the categorized archaeological remains, generic structures and necropolis represent about 11% and 8% of total findings, respectively (Fig. 8A). Public and private buildings, infrastructures, agricultural and manufacturing areas cover the remaining 20% (Fig. 8A).

More than 200 early Roman remains were found, mostly along the northern boundary of the study area (Fabiani et al. 2013a; Fig. 8B). Undifferentiated tracers of human frequentation are the most recorded findings (ca. 40%), with the secondary occurrence of agricultural areas (ca. 20%) and generic structures (ca. 13%). Slightly lower percentages (ca. 8%) are recorded for infrastructures and private buildings, while public buildings, necropolis and manufacturing areas, are attested each below 5% (Fig. 8B).

5. Discussion

5.1. The palaeoenvironmental and palaeotopographic scenario

At the Etruscan-Roman transition (2nd century BC-2nd century AD), a remarkably complex palaeoenvironmental and palaeotopographic scenario, with a variety of alluvial depositional environments and fluvial landforms, characterized the Pisa historical town (Figs. 6, 9A).

The previous and coeval activity of palaeoArno and palaeoSerchio (*Auser*) rivers, crossing the city area, strongly influenced the spatial distribution of natural environments and reliefs. Flooding events from a N-S oriented channel, interpreted as the Eneolithic palaeo*Auser* in Amorosi et al. (2013a), likely favoured the development of a 2 m-high landform in the middle of Pisa historical centre (Fig. 7). Over centuries the recurring accumulation of overbank deposits, connected to the Pisa Plain multiphase channel history (see Fig. 6 and Amorosi et al., 2013a), enhanced the aggradation of this relief, which acted as divide between the palaeoArno and *Auser* watersheds, (Fig. 9) up to the Modern Age.

A less extensive, but more prominent relief, up to 3.5 m a.s.l. high, was present in correspondence of Piazza Duomo. This relief was likely related to the activity of two E-W flowing, non-coeval branches of *Auser* (Fig. 9). A few metres south, another branch of the *Auser* system merged into the palaeoArno River (Fig. 9) following a NE-SW direction, according to Roman age literary sources (Strabo, 5.2.5; Pliny, N.H. 3.5.50; Scolio a Tolomeo, 3.1.4; Rutilio Namaziano, 1.566).

Relatively lowland areas, apart from those connected to the channel network, were located between the *Auser* branches and north of the Piazza Duomo relief (Fig. 9). These areas, hosting soft grey clays and silts indicative of poorly-drained conditions, characterized wide portions of the Pisa plain, up to the beginning of the Roman period (Fig. 4A-C).

Diffuse poorly-drained conditions are likely favoured by the proximity to the coeval shoreline, ca. 7 km west of city centre (Della Rocca et al., 1987).

Moreover, shallow paludal basins occurred between the palaeoArno and the *Auser* river courses on both sides of the inherited reliefs and, more extensively, between the E-W and NE-SW *Auser* branches, as attested by stratigraphic data (Figs. 4, 9). These basins reasonably represented the topographically lowest areas of Pisa during the Etruscan-Roman transition, even though no specific elevation data are currently available. Widespread backswamp areas formed and persisted up to the beginning of the Roman period within specific portions of the Pisa plain, not affected by river migration/avulsion and surrounded by natural reliefs (Fig. 9; see also Amorosi et al., 2013a).

Thus, the development and areal extent of the lowest topographic settings were controlled by the intricate fluvial network evolving since Eneolithic times, rather than the coastline proximity.

5.2. Urban growth patterns and landscape dynamics

As attested by several historical sources (Strabo, 5.2.5; Pliny the Elder, 3.5.50; Scolio a Tolomeo, 3.1.4; Rutilio Namaziano, 1.566) the Pisa plain underwent a long history of human occupation. An interactive relationship between human settlements and alluvial environments, linked to the intense hydrodynamic activity of the two main river courses (palaeoArno and *Auser* rivers), occurred since the Etruscan period (Fig. 9A).

However, in contrast to the modern landscape, a crucial role in the early urbanization of the Pisa plain was played by the *Auser* river system, towards which all ancient human settlements gravitated. Indeed, both late Etruscan and early Roman findings are mainly concentrated in proximity of the *Auser* branches, where the main urban structures as well as manufacturing activities arose and steadily grew (Fig. 9A).

In particular, during the late Etruscan period the urban fabric extended over a narrow zone in correspondence of the Piazza Duomo relief, becoming less dense eastward along the *Auser* river course (Fig. 9A). A limited expansion of the urban tissue toward the palaeoArno River is recorded on top of the N-S relief, where sporadic archaeological findings typical of an urban context (generic structures and public buildings; see Fig. 8A) were recovered.

Despite scarcity of archaeological findings clearly related to manufacturing activities, good relationships between productive areas and water availability can be detected. Consistent with this interpretation, infrastructure remains are found close to the *Auser* river course, likely connecting the urban centre to the Pisa S. Rossore site (Benvenuti et al., 2006; Camilli and Setari 2005). Thus, the Etruscan city gravitated toward the *Auser,* which represented the main water source and the privileged marketing route for commodities from the Mediterranean Sea (Fig. 9A).

During early Roman times the urban growth patterns substantially followed the late Etruscan city's fabric (Figs. 9A, B). In this context, a marked enlargement of the urban area toward the palaeoArno River (Fig. 9B) is recorded by the high density of archaeological findings recovered in correspondence of the N-S directed relief (Figs. 8B, 9B). The *Auser* river system further strengthened its role in the history of city's development, becoming the geographic boundary between the *urbs* and an evolving *suburbium* that clearly started to differentiate (Figs. 8, 9A, B). The manufacturing sites, mainly aimed to the ceramic production (Fabiani et al., 2013b), were concentrated on the right bank of the *Auser*, confirming the importance of water availability for productive processes and trades. Their marginal position is canonical in the ancient Roman cities (Bruni, 1998; Fabiani, 2013; Menchelli, 2003).

In summary, the early phases of Pisa urbanization document the strong ability of the Etruscan and early Roman communities to adapt to a complex alluvial setting that did not favour a regular urban planning. Especially the palaeohydrography, which in turn controlled the palaeotopography, played a key role in the spatial diffusion of urban settlements and manufacturing sites, representing the main source of water supply and the major communication and supply route for products.

In this respect, the geoarchaeological analysis of Pisa landscape strongly confirmed the strict relationship existing between Mediterranean navigable rivers and past cities development and evolution (Arnaud-Fassetta et al., 2000; Bruno et al., 2013; Castaldini et al., 2009; Macklin et al., 2012; Marriner et al., 2013; Maselli and Trincardi, 2013; Mele et al., 2013; Mozzi et al., 2010; Ninfo et al., 2011; Ravazzi et al., 2013; Vannière et al., 2008).

On the contrary, the first incisive effects of extensive and intense human forcing on fluvial landscape occurred after the founding of *Colonia Opsequens Iulia Pisana*, dated back to the late 1st century BC. Around that time, the backswamp basins almost disappeared and widespread well-drained floodplain conditions developed across urban and suburban areas in response to deforestation, pasturing, agriculture and waterworks (Roman *Centuriatio*).

Thus, in the cradle of the western Mediterranean civilization the humankind started to play a primary role in transforming the Earth's surface long before the Industrial Revolution, although through extremely inhomogeneous spatial patterns. The beginning of Roman landscape disturbances and hydraulic operations represents, in fact, a crucial point in the history of Mediterranean alluvial plains evolution, marking the transition to an anthropocentric epoch.

6. Conclusions

A large number of subsurface and surface geological and archaeological data processed through an interdisciplinary approach, including stratigraphy, geomorphology and archaeology, allowed a high-resolution reconstruction of the Pisa landscape at the late Etruscan- early Roman transition (2nd century BC- 2nd century AD). Under the strong control of a complex fluvial network, this period saw the development of the multilayered city of Pisa, a typical medium-sized urban area in the western Mediterranean civilization history.

The major outcomes of this work can be summarized as follows:

- The main palaeoenvironmental features of the Etruscan-Roman Pisa were recognised. Wide portions of the city area were characterized by poorly-drained conditions, recorded by soft grey floodplain clays and backswamp deposits. The latter were confined between the palaeoArno and *Auser* branches and represented the topographically lowest areas of Pisa at the Etruscan-Roman transition. Well-drained conditions, favoured by the Roman *Centuriatio*, were established during the 1st century AD.
- Pisa historical town was characterized by a complex palaeohydrography, including a palaeoArno river course in proximity of its present-day position and two *Auser* branches bordering the modern Piazza Duomo. This fluvial network strongly shaped the natural landscape, controlling the spatial distribution of depositional environments and topography;
- An additional *Auser* branch, flowing into the palaeoArno, was recognised through stratigraphic data along the western edge of Pisa historical city. This river course is interpreted as the one described by Strabo during the 1st century BC;
- A Digital Elevation Model of Pisa historical centre during early Roman times (around 1st century BC-2nd century AD) was elaborated using precise topographic data into a well-defined radiocarbon and ceramic-based chronological framework. This model shows a geomorphological relief reaching 3.5 m a.s.l. in correspondence of the Piazza Duomo site. A wider N-S oriented topographic high, with 2 m of elevation, is envisaged for the middle portion of the study area separating the main *Auser* to the north from the palaeoArno to the south;
- The temporal and spatial distribution of the archaeological data documents the crucial role played in the evolution of the urban context by the *Auser*, towards which gravitated ancient human settlements and manufacturing sites. The location of these sites was mainly controlled by palaeohydrography and palaeotopography, and clustered in correspondence of the topographic high close to the *Auser* river course;

- This work contributes to an estimation of the archaeological potential of Pisa subsoil and could be used as a decision-making tool in the development of the Pisa urban area.

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Figure and Table Captions

Figure 1: The study area in the context of the Pisa alluvial plain (modified from Martini et al., 2010).

Figure 2: Location map of the Pisa urban area reporting the subsurface database used for this study. Reference MAPPA continuously cored boreholes and MAPPA percussion drilling cores are shown as orange and red stars, respectively. Black dots represent stratigraphic data from the Arno coastal plain dataset. Section traces of Figure 4 (bold lines) and the Electric Resistivity Tomography (ERT) profile of Figure 5 (dotted line) are also reported. The Medieval walls and Piazza Duomo are shown.

Figure 3: Location of the archaeological findings found in the study area. In red circle the archaeological remains dating back to the late Etruscan age. In green square the archaeological findings dating back to the early Roman age.

Figure 4: Protohistoric-historic alluvial stratigraphy (sections A-C) beneath the Pisa urban area. Reference MAPPA cores are in bold. Asterisks in Figure 4B refer to radiocarbon ages obtained from mollusc shells (*Cerastoderma glaucum*) reworked from the underlying lagoonal clays. The black star in Figure 4C indicates a radiocarbon age projected from the adjacent core M6.

Figure 5: Electric Resistivity Tomography (ERT) acquired along the north Medieval city wall. The higher resistivity values (red) are interpreted to represent sandy palaeochannels (Fig. 2). In discontinuous line = area interpreted as longitudinal section of palaeochannels; Continuous line = area interpreted as transversal section of an older palaeochannel.

Figure 6: Palaeohydrography of Pisa during the Etruscan-Roman transition based upon geomorphological-stratigraphic data. The dotted blue lines represent channels inferred on the basis of exclusive stratigraphic data, recently acquired. These data that include core (black circles) and trench (white stars) stratigraphies contribute to refine previous reconstructions of the *Auser* course (Bini et al., 2013b). Palaeotraces of protohistoric and Medieval age are reported as well as those of unknown age. Section traces of Figure 4 are also reported along with core data. Reference MAPPA cores are shown as bold black circles.

Figure 7: Digital elevation model showing the approximate topography of the study area at the beginning of the Roman period compared with the current topography derived from LiDAR data.

Figure 8: Localization and relative occurrence of late Etruscan (A) and early Roman (B) archaeological findings distinguished into different typology according to the Mappa-project database.

Figure 9: Reconstructed alluvial landscape of Pisa during the Etruscan-Roman transition (2^{nd} century BC-2^{nd} century AD). The contour lines refer to the Pisa ground level at the beginning of the Roman period. Spatial distribution of late Etruscan (A) and early Roman (B) findings are reported.

Table 1: List of radiocarbon dates discussed in this paper.

Table 2: Elevation range of palaeotopography reconstructed for the beginning of Roman time compared with the current topography derived from LiDAR data.

Table1
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Core sample depth (m)	Dating materials	Conventional age (yr BP)	Calibrated age (2_sigma cal yr BC)
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%)
M9_5.35	wood fragments	2456±41	669-411 BC (75.3%)
M26_4.60	wood fragments	2563±75	863-479 BC (94.8%)

Table2

Range of elevation at the beginning of Roman times	Percentage area
H>2.5 a.s.l.	8 % ca.
0<H>2.5 a.s.l.	61 % ca.
H<0 a.s.l.	31% ca.
Range of elevation today	Percentage area
H<2 a.s.l.	18 % ca.
2<H>5 a.s.l.	66.5 % ca.
H>5 a.s.l.	15.5% ca.

Figure1

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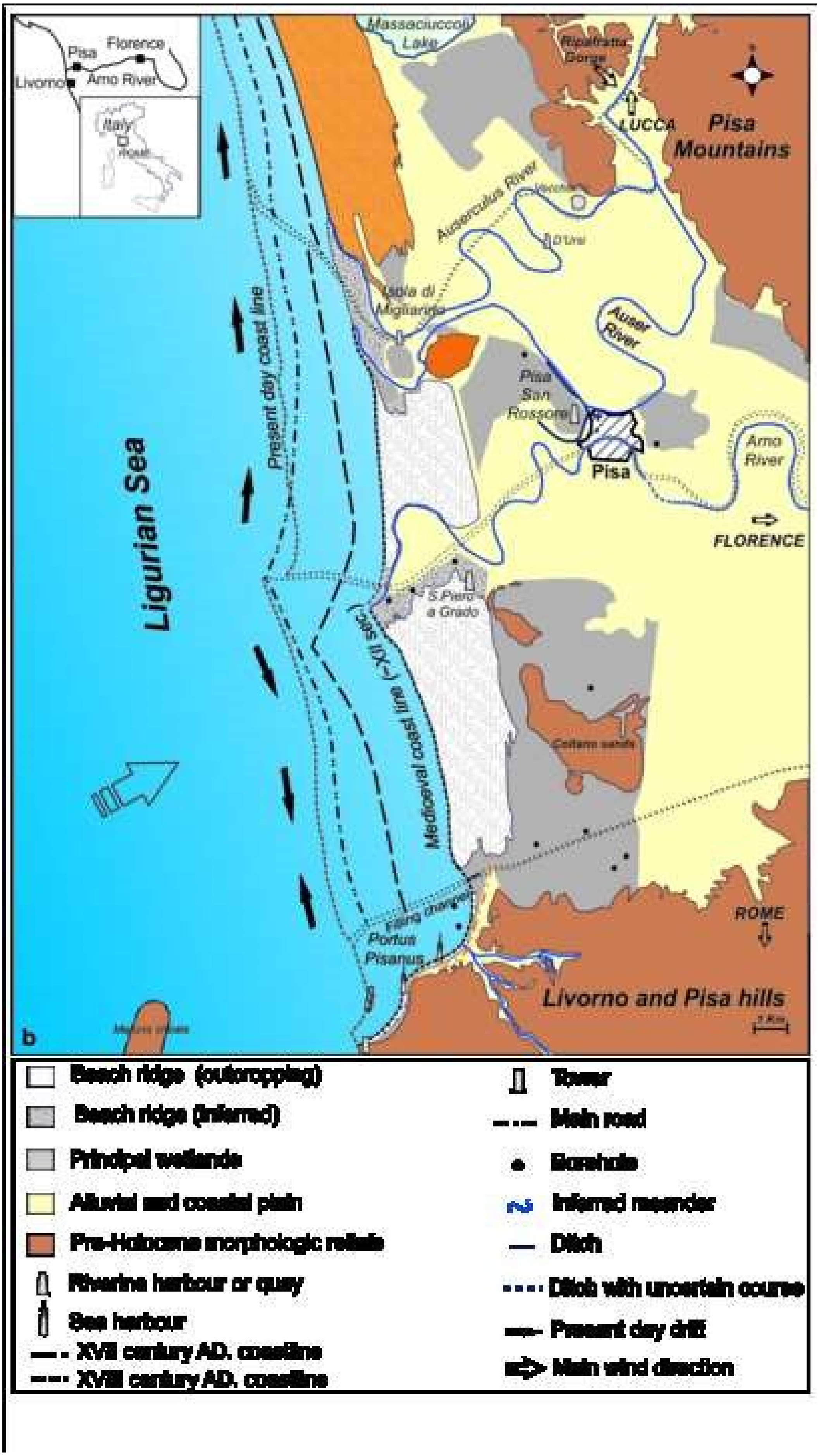

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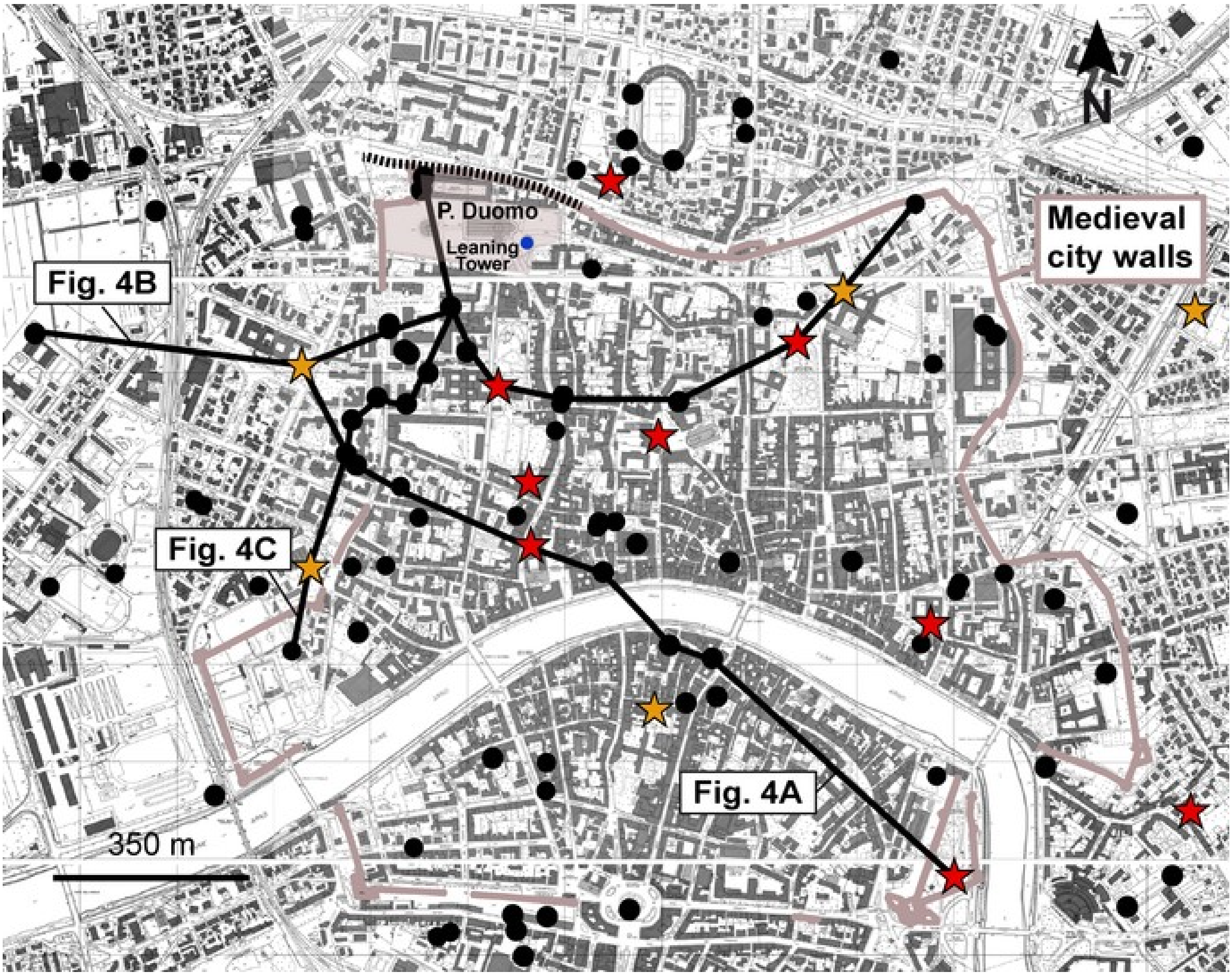

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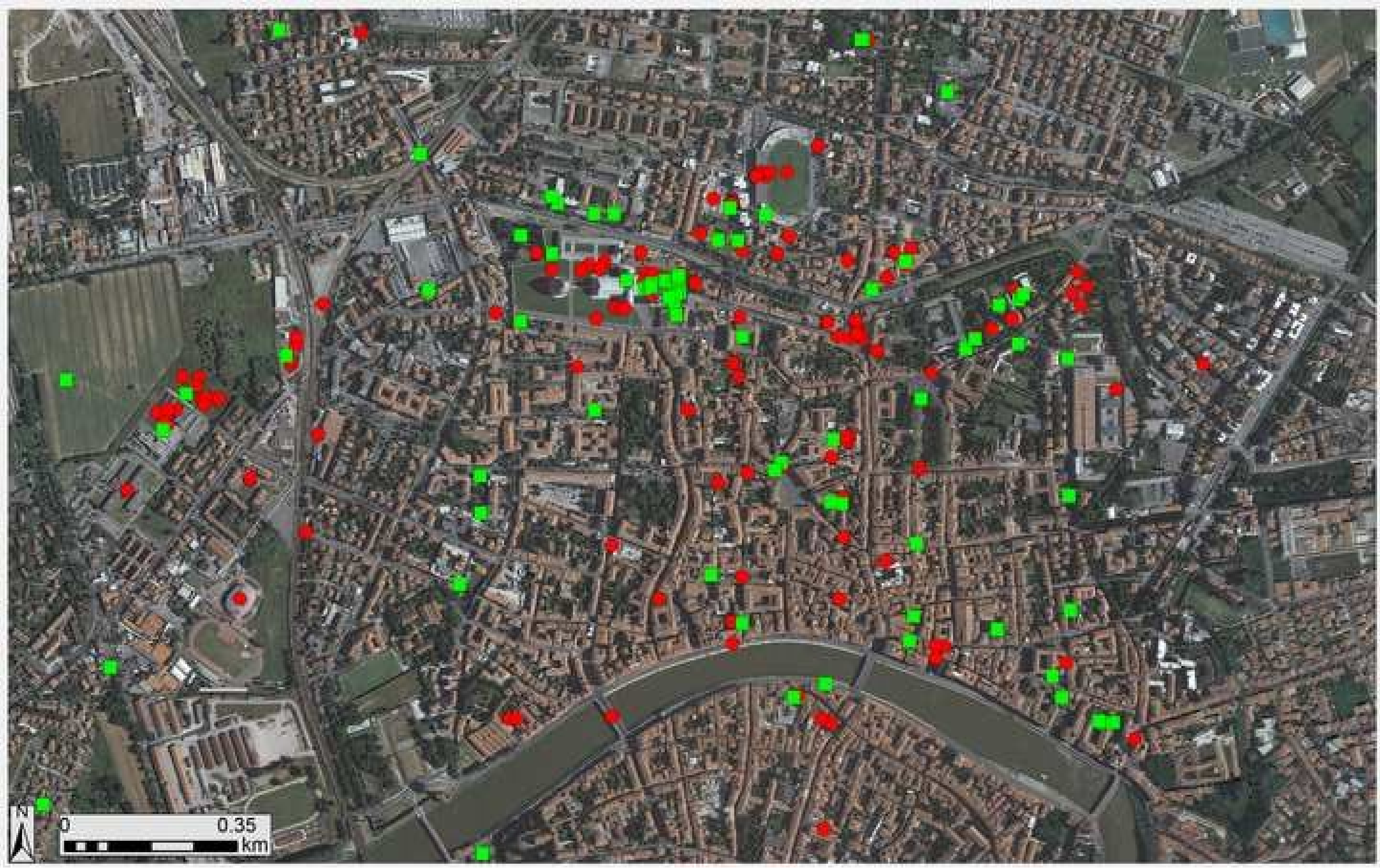

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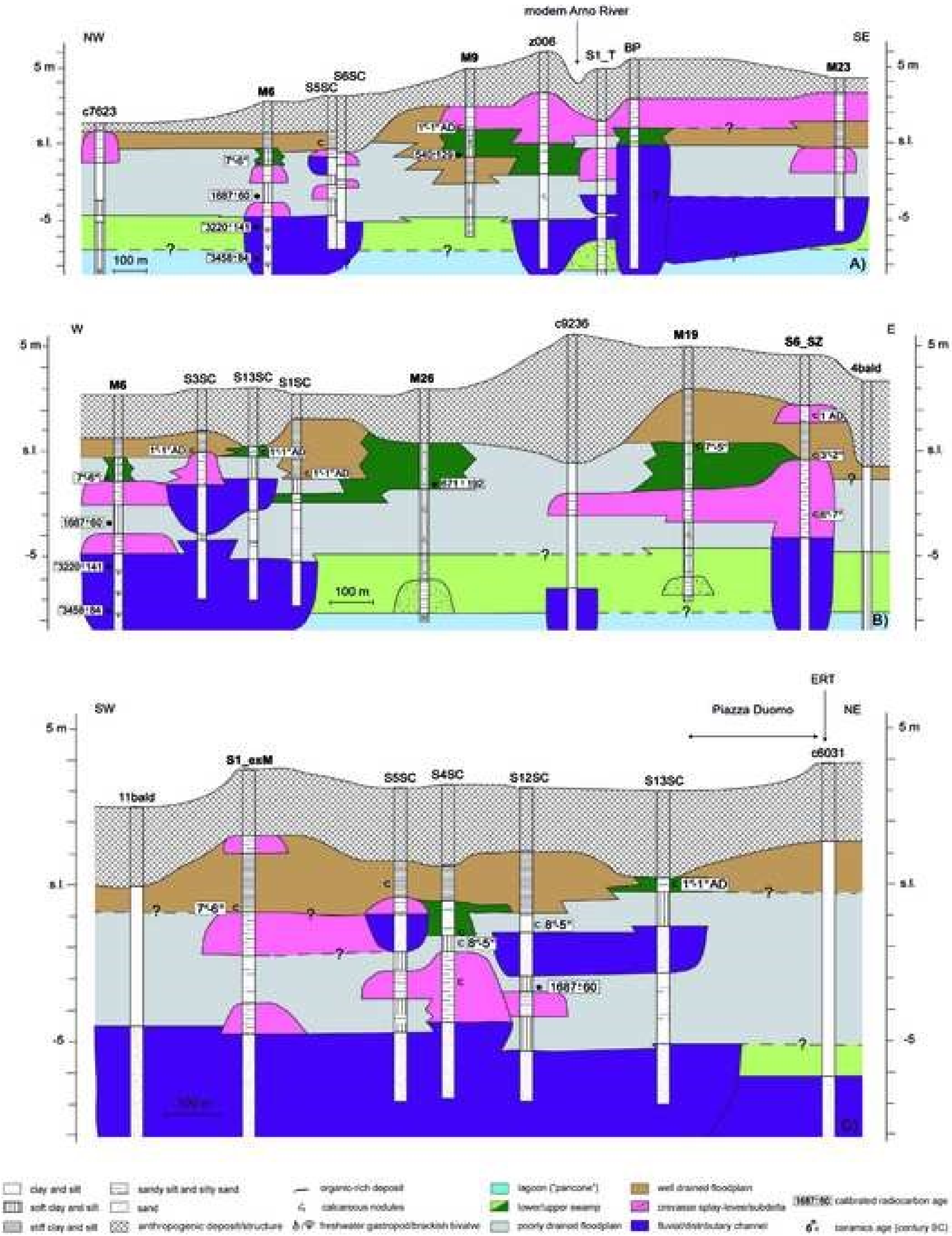

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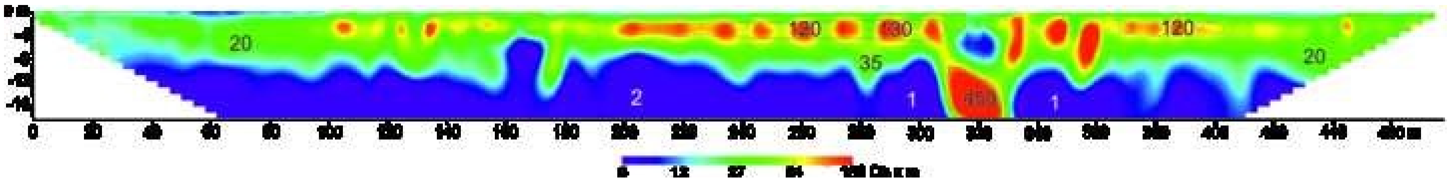

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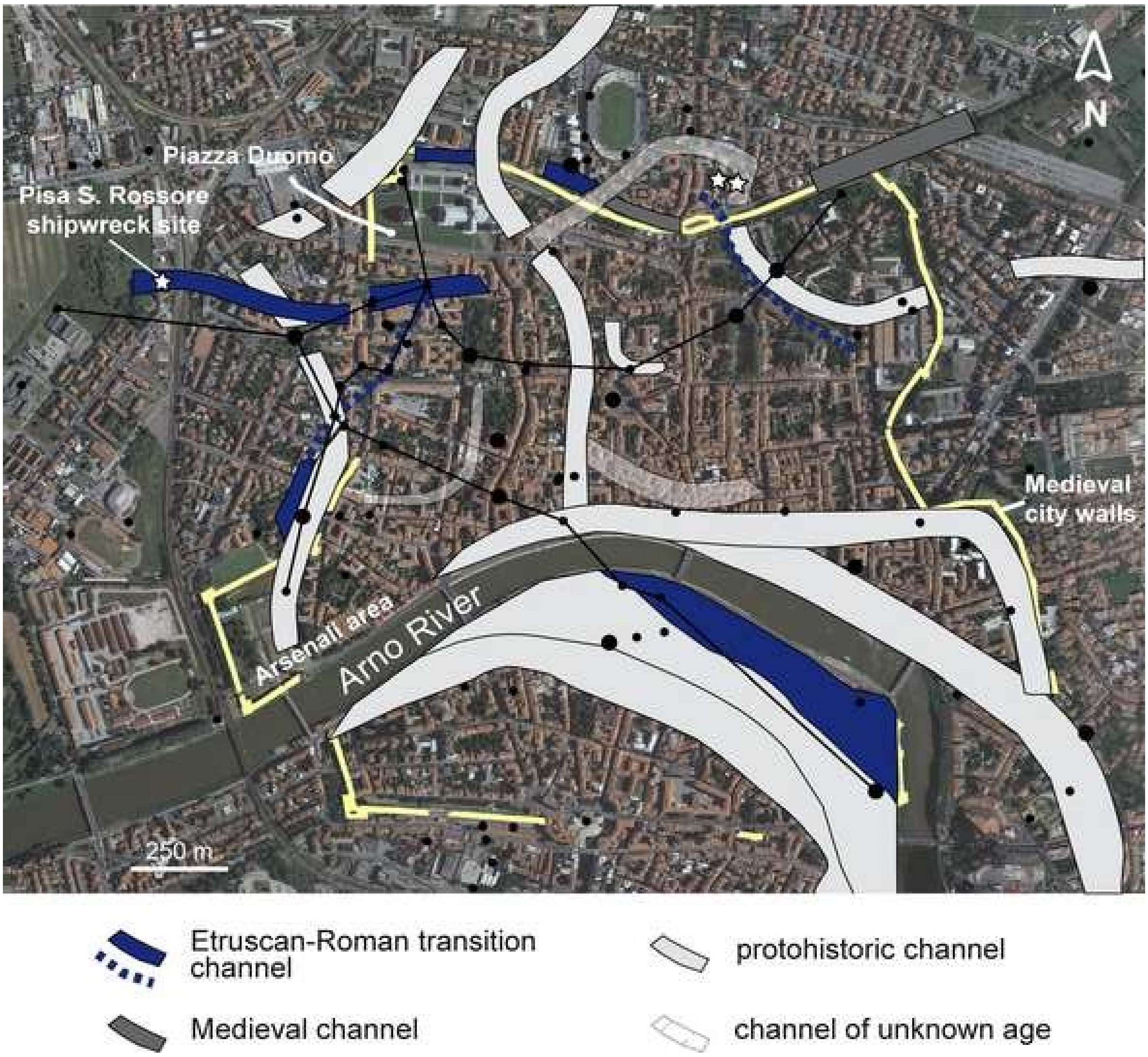

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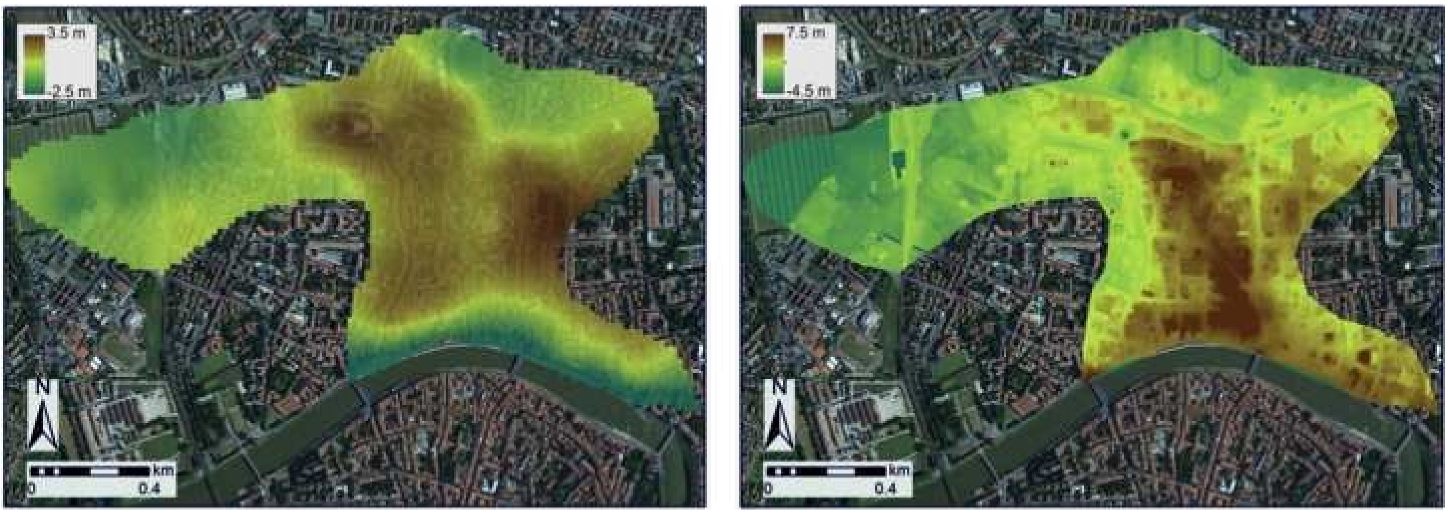

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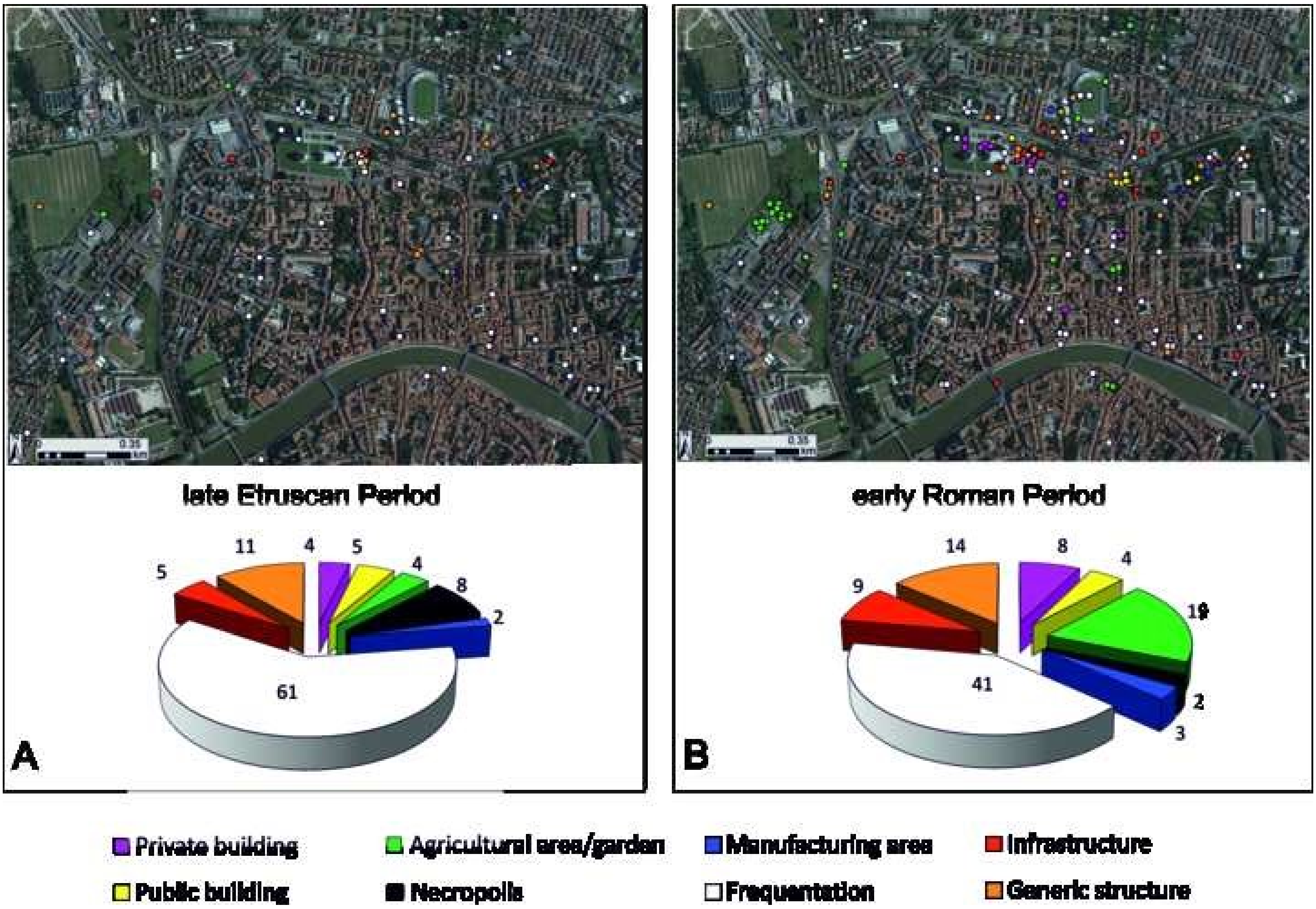

Figure9

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