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Deciphering the effects of human activity on urban areas through morphostratigraphic analysis: The case of Pisa, Northwest Italy

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Abstract

The type, thickness, and volume of anthropogenic deposits buried beneath long-settled cities are good indicators of the human impact on urban environments and topography. Pisa is a multi-layered city settled since Etruscan times in the lower Arno Plain. Stratigraphic and geomorphologic data from the urban subsurface show that Pisa today is located on a mound (*ca.* 4 m high) made up dominantly of anthropogenic deposits. Two types of anthropogenic facies are distinguished: human-modified deposits of Etruscan Age and made-ground deposits dated since the Roman Age onward. Integrating subsurface stratigraphy with ancient ground-level topography, we reconstruct the evolutionary phases of the Pisa urban landscape subject to a dominant human influence. Urbanization processes started in Etruscan times, as testified by the lower boundary of the anthropogenic succession (Pisa archaeosphere). The formation and the highest increase in elevation of the Pisa mound, which is still growing, occurred during the Roman and the Middle Ages. At the same time, the urban fabric moved southward, toward the Arno River, and a thick anthropogenic succession accumulated in the city sector where an ancient ring of walls had been hypothesized. However, the highest acceleration in the urban ground growth rate is recorded since A.D. 1950 onward, corresponding to the Anthropocene "Great Acceleration."

KEYWORDS

Anthropocene, anthropogenic deposit, geoarchaeology, Pisa, urban area

1 | INTRODUCTION

A widespread stratigraphic record of intense anthropogenic perturbations involving geochemical and sedimentary cycles and global biodiversity patterns has stimulated a serious debate about the potential formalization of the Anthropocene epoch, the characteristics and timing of its lower boundary, and its relationship with the upper part of the geosphere, also known as the "archaeosphere" (Edgeworth et al., 2015; Steffen, Grinevald, Crutzen, & Mcneill, 2011; Syvitski & Kettner, 2011; Waters et al., 2016; Waters, Zalasiewicz, Williams, Ellis, & Snelling, 2014; Zalasiewicz et al., 2011a; Zalasiewicz, Williams, Haywood, & Ellis, 2011b). In urban contexts, the contribution of geomorphology to this topic is a matter of high interest, because of the potential of a geomorphologic approach to quantify and map the spatial distribution of anthropogenic deposits and landforms (Brown et al., 2013; Ford, Price, Cooper, & Waters, 2014; Jordan, Hamilton, Lawley, & Price, 2016).

Urban areas are characterized by a shallow zone of human interaction where natural and anthropogenic processes take place (Edgeworth et al. 2015; Ford et al., 2014; Price, Ford, Cooper, & Neal, 2011). Traces of this joint human–nature activity are especially important in long-settled multilayered cities, where an enduring synergic relationship among landscape, ancient cultures, and societal evolution is commonly recorded (Bruno, Amorosi, Curina, Severi, & Bitelli, 2013; Butzer, 2008; Carver, 1987; Harris,1989; Ninfo, Ferrarese, Mozzi, & Fontana, 2011; Schuldenrein & Aiuvalasit, 2011; Stefani & Zuppiroli, 2010; Zanchetta, Bini, Cremaschi, Magny, & Sadori, 2013). In these cases, the overlap of diachronous ground levels formed artificial mounds that have become more and more recognizable in flat alluvial plains. The identification and mapping of each historical ground layer provides important information on the dynamics of the settlement and on landscape evolution, as well as ground growth rates. However, investigation of artificial grounds cannot be performed through a traditional geological mapping technique, and the differentiation of distinct construction phases based on the degree of landscape anthropogenic transformation (Ford et al., 2014) requires a comprehensive geoarchaeological approach (Amorosi et al., 2013a; Bini et al., 2012, 2013, 2015; Bruneton, Arnaud-Fassetta, Provansal, & Sistach, 2001; De Smedt et al., 2013; Ghilardi & Desruelles, 2009; Marriner, Gambin, Djamali, Morhange, & Spiteri, 2012; Parker et al., 2008; Price et al., 2011).

Based on a large amount of stratigraphic, geomorphologic and archaeological data, the multilayered city of Pisa, first settled in the Etruscan period (second half of the 7th century B.C.; Bruni, 1998), represents an ideal case study to assess the timing of human impact in the history of a typical medium-sized Italian city. In this work, we assess the type, thickness, and volume of anthropogenic deposits in the subsurface of Pisa, focusing on a city mound that stands about 4 m above the alluvial plain (Bini et al., 2015). Specifically, our objectives are as follows: (i) to quantify through a geomorphologic-geoarchaeologic approach the urban growth rates during distinct historical periods of the city settlement, (ii) to recognize the most prominent morphologic changes associated with the formation of the Pisa mound, and (iii) to investigate the anthropogenic impact in the study area in the view of the recent debate about the definition of the Anthropocene epoch.

2 | STUDY AREA

The multilayered city of Pisa (43°43′N;10°23′ E), famous for its Leaning Tower in Piazza Duomo, is currently located about 10 km east of the Ligurian Sea coast, in the Arno alluvial-coastal plain (NW Tuscany, Italy), a low-lying area of approximately 450 km^2. This plain, crossed from east to west by the lower reaches of the Arno River, is bounded to the north by the Serchio River, to the east by the Pisa Mountains and to the south by the Livorno and Pisa Hills (Fig. 1). In such a flat region, with a mean altitude of 2–3 m above sea level (a.s.l.), the areas close to the present-day Arno River course and the urban area of Pisa are characterized by higher elevations, about 8 and 7 m a.s.l., respectively (Fig. 2). While the former can be connected to recent fluvial dynamics (i.e., floods), it is still unclear the extent to which the Pisa mound was shaped by human activity. Natural processes include fluvial activity of the Arno and Serchio (*Auser*) paleorivers, which flowed across the alluvial plain since protohistoric times (last *ca.* 4000 years; Amorosi et al., 2013a; Bini et al., 2015; Sarti et al., 2015). During the Etruscan period, to which the foundation of the city dates (Paribeni, 2010; Pasquinucci, 1994), the Pisa urban area was characterized by extensive swamp development in a complex fluvial network. At that time, the Arno River flowed in a slightly more southern position relative to its modern course. In contrast, the ancient branch of the Serchio River (*Auser*) had a complex meandering pattern in the northern sector of the historical town (Bini et al., 2015).

A more structured urbanization developed during the Roman period (Fabiani, Ghizzani Marcìa, & Gualandi, 2013), with the emersion of the largest wetlands and the widespread development of a well-drained alluvial plain across the urban and suburban areas (Bini et al., 2015). In this period, the Arno-*Auser* rivers confluence is documented by ancient sources (Strabo, V, 2, 5, C 222) west of the city of Pisa, where a southern branch of the *Auser* flowed into the Arno River (Bini et al., 2015).

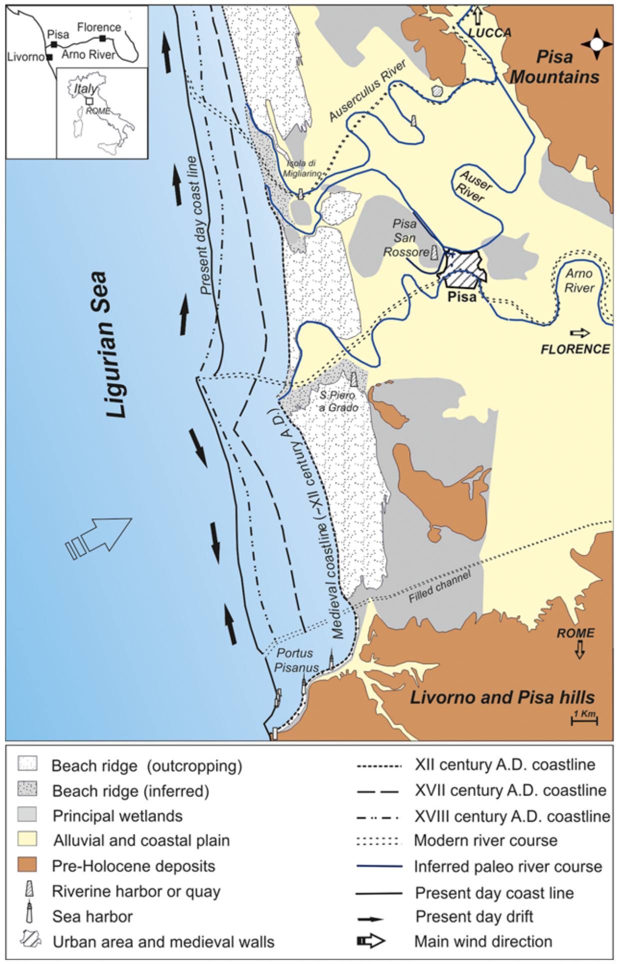

FIGURE 1 Pisa urban area in the context of the alluvial plain (modified from Bini et al., 2015); the paleo-courses of Arno and Serchio (*Auserculus* and *Auser*) rivers derive from remote sensing analyses and historical sources. [Color figure can be viewed at wileyonlinelibrary.com]

During the Middle Ages, the Arno River flowed in a similar position to the current one, while the *Auser* River flowed in proximity to the northern city walls, which started to be constructed in A.D. 1155 (Garzella, 1990). These walls are still well preserved today, while the occurrence of a smaller ring of walls (Fig. 2b) dating back to the 5th century A.D. (Redi, 1991; Tolaini, 1979) is still a matter of debate (Gelichi, 1998), and no archaeological evidence has yet been reported in the urban area.

An important change in the fluvial network is documented at the beginning of the Modern Age, when the *Auser* River was forced to flow northward, to prevent flooding of the city (Bruni & Cosci, 2003). Starting from this period, the hydrography became very similar to that seen today.

3 | METHODOLOGICAL APPROACH

In order to assess the origin and spatial distribution patterns of anthropogenic sedimentation in the Pisa area and its relationship with the

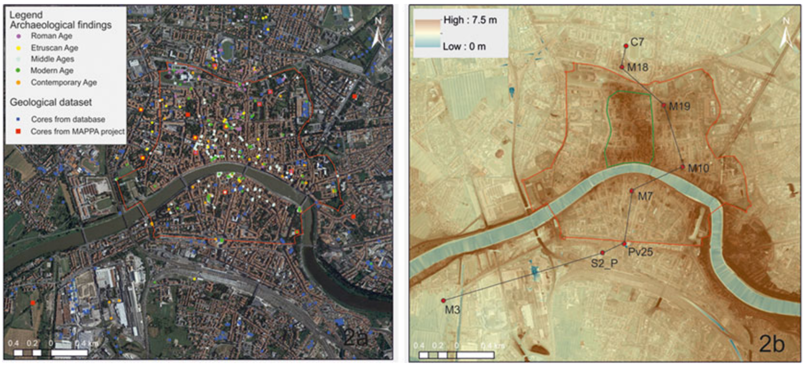

FIGURE 2 (a) The geological and archaeological dataset used in this paper; (b) digital elevation model of present-day Pisa urban area and surroundings performed by LiDAR data (2008); red line = younger city walls (still visible); green line = older city walls (dating back to early Middle Ages/Late Roman time; yet to be found); black line = stratigraphic cross-section. [Color figure can be viewed at wileyonlinelibrary.com]

current city mound, we focused on the shallow subsurface stratigraphy (5–7 m depth) of the urban–suburban zone, showing different degrees of human occupation and land use. Based on integrated ceramic dating and radiocarbon ages (Amorosi et al., 2013a; Table I), this succession dates back to the early Etruscan period (8th century B.C.) onward, and rests on alluvial deposits formed in a variety of anthropogenically undisturbed protohistoric environments (Amorosi et al., 2013a).

In this study, 10 sedimentary cores, 7–20 m long and analyzed in the context of the MAPPA project (*Metodologie Applicate alla Predittività del Potenziale Archeologico*; www.mappaproject.org), were considered as reference data (Fig. 2). Additional stratigraphic descriptions from the Arno plain dataset (Amorosi, Rossi, Sarti, & Mattei, 2013b) were used for stratigraphic correlations, especially outside the Pisa urban area (Fig. 2). Consistent with the guidelines from Zalasiewicz et al. (2011b) and Ford et al. (2014), we distinguished two main categories of anthropogenic deposits: human-modified and made-ground (Fig. 3). The first group includes deposits that record a certain degree of human-induced modification (i.e., the presence of manufactured materials—ceramic, concrete, and brick fragments, charcoal), but that preserve the sedimentary structures of their natural depositional environment. The diagnostic features of the facies associations reported in this study (swamp, poorly drained and well-drained floodplain, crevasse splay/levee, fluvial/distributary channel) are described at length by Amorosi et al. (2013a), and for this reason will not be repeated here. The reader is referred to that paper for detailed sedimentological descriptions.

In contrast, made-ground deposits show an internally complex stratigraphy, related exclusively to human activities. In this type of deposits, natural environments have been obliterated by agriculture practices and urban construction. In the latter case, made-ground deposits consist entirely or predominantly of manufactured materials and structures, such as pieces of walls, ruins, and floors, which form juxtaposed artificial layers. Distribution patterns of human-modified and made-ground deposits, and their relationships with underlying natural deposits and the present-day topography, are shown through selected stratigraphic sections that cross the city mound (Fig. 2).

Starting from the shallow subsurface stratigraphy of the Pisa area, we reconstructed the ground layer for different historical periods. Most data, including archaeological excavations and core stratigraphic descriptions, were extracted from the MAPPA Project database (Fig. 2a; www.mappaproject.org). The elevation of archaeological findings and cores was measured with a Leica GS09 differential GPS, planimetric precision ±1 cm, and altimetric precision ±2 cm. Elevation was referenced to the Italian Ordnance Datum. Data lacking accurate height information and with evidence of sediment transport (e.g., pottery from coarse-grained fluvial facies) were excluded from digital elevation model (DEM) construction. The DEMs related to the transition between the Etruscan and the Roman Ages have been shown by

TABLE I List of radiocarbon dates reported in this paper

Core Sample, Depth (m)	Material	Conventional Age (^{14}C yr B.P.)	Calibrated Age (2 sigma)	References
M3, 6.65	Wood fragments	4155 ± 64	2890–2575 B.C.	This study
M3, 5.75	Wood fragments	3496 ± 27	1890–1745 B.C.	Sarti et al. (2015)
M7, 11.40	Wood fragments	2843 ± 23	1056–921 B.C.	Sarti et al. (2015)
M7, 8.77	Wood fragments	2777 ± 23	998–890 B.C.	Sarti et al. (2015)
M7, 7.10	Wood fragments	2559 ± 28	802–748 B.C.	Sarti et al. (2015)
M7, 3.40	Wood fragments	905 ± 23	A.D. 1040–1113	This study
M10, 5.30	Wood fragments	2465 ± 27	670–483 B.C.	Sarti et al. (2015)
M18, 3.65	Organic clay	2785 ± 34	1011–840 B.C.	This study

Conventional ages were calibrated using CALIB5 software and the calibration curves of Reimer et al. (2009).

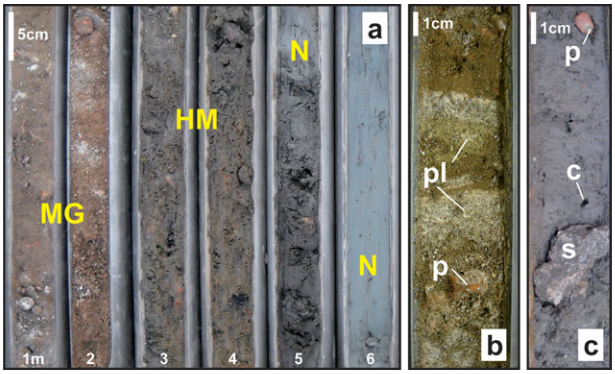

FIGURE 3 Representative photographs of Core M19, showing facies associations in the Pisa subsurface; (a) N-natural deposits (poorly-drained floodplain clays) overlain by Etruscan human-modified (HM) deposits, formed in a backswamp, and made-ground (MG) deposits dating from the Roman Age onward; (b) close view of MG deposits showing the juxtaposition of plaster layers (pl) and the presence of potsherds (p); (c) close view of HM deposits, with diffuse presence of anthropogenic materials, such as potsherds (p), stones (s) and charcoal (c). [Color figure can be viewed at wileyonlinelibrary.com]

Bini et al. (2015), to which we refer for a more detailed description of the methodology. We reconsidered these data here to provide a continuum of anthropogenic deposit growth starting from the Etruscan Age.

All points acquired were processed by statistical validation methods, with detection and elimination of the outliers. The final dataset consists of a minimum of 49 points (Etruscan topography), up to a maximum of 207 points (Medieval topography), with data density between 32/km^2 and 103 /km^2. In order to minimize interpolation errors, DEM boundaries were delimited taking into account the point distribution, and were digitized internally to the distal elements of the dataset. According to the availability of input points, we reconstructed the paleotopography of the area inside the Medieval city walls for the Medieval, Modern, and Contemporary Ages. We also reconstructed the paleotopography of a smaller area, north of the Arno River, for the Etruscan and Roman times.

The DEMs were built 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 elevation accuracy after quantitative comparison, based on reiterative cross-validation techniques with other "general purpose" methods (i.e., Spline, IDW).

The ground elevations represented by DEMs are not necessarily the exact elevations of the quoted periods, but represent their preserved expression in the Pisa subsurface, in relation to the present-day sea-level datum.

Local human reworking may locally influence the mean topographic values of DEM reconstructions. Similarly, subsidence in the Pisa plain due to tectonics plus sediment compaction, may result in an underestimation of the elevations quoted at the time of their formation. However, this did not significantly affect our reconstructions of ground-level growth rates over the last 3000 years. The mean growth in elevation for each period was in fact calculated by subtracting the DEMs of successive historical periods, analyzing the histogram. Finally, we estimated the mean volume growth using subtraction DEMs between two historical periods. The mean volume growth was calculated by dividing the sum of volumes of prisms subtended by each individual cell by the total number of interested cells.

4 | RESULTS

4.1 | Stratigraphy of anthropogenic deposits

High-resolution stratigraphic correlations of reference cores, combined with additional stratigraphic data from outside the present-day Pisa city mound (Fig. 2), reveal the stratigraphy of the anthropogenic deposits in the study area. The section through the city mound shows variable thickness, composition, and chronology of the anthropogenic deposits above the Mid–Late Holocene coastal-alluvial succession. This latter shows a progradational tendency, which is reflected by the vertical superposition of lagoon, swamp, and alluvial facies (Fig. 4; Sarti et al., 2015).

Inside and close to the borders of the Middle Ages walls, the thickness of the anthropogenic succession varies between about 2.5 and 6 m, with the highest values north to the modern Arno River course (cores M19, M10 in Fig. 4). This succession includes both human-modified and overlying made-ground deposits and shows an irregular, diachronous lower boundary, that ranges in depth between 1 m below sea level (b.s.l.) and 1 m a.s.l. (dotted line in Fig. 4). In contrast, made-ground deposits, associated with recent urban growth phases or agricultural activities, are very thin outside the historical city area at depths <1 m (Figs. 2 and 4).

Beneath the historical city area, the first record of human-modified deposits dates back to the 8th–5th centuries B.C., that is, the early Etruscan period. North of the modern Arno River course (cores M19 and M10 in Figs. 2–4), it occurs around 1 m b.s.l, across swamp and poorly drained floodplain facies (Fig. 4). In this area, the stratigraphy of the anthropogenic unit suggests an almost continuous human occupation of the Pisa plain, up at least to the early Roman Age, as testified by an uninterrupted (4 m-thick) succession of human-modified deposits. These deposits, which contain charcoal, pieces of brick and concrete, and a vertical succession of early Etruscan to early Roman ceramic fragments, are separated from the overlying (2 m-thick) late Roman to Medieval made-ground unit by an erosional truncation.

Within the historical city south of the Arno River (core M7; Fig. 2) and along the northern and southern borders of the Medieval walls (cores M18 and PV2S; Fig. 2), human-modified deposits are about 2–2.5 m-thick, with a lower boundary around sea level (Fig. 4), and are overlain by 1- to 2-m-thick made-ground deposits of Modern to Contemporary Age. Radiocarbon and archaeological data suggest a continuous late Etruscan–early Roman occupation of the northern limit, since at least the 2nd century B.C., whereas a more discontinuous, Medieval occupation of the southern part of the city is attested (Fig. 4).

Close to the southern limit of the Medieval walls (core S2_P; Fig. 2), the thickness of the anthropogenic unit further decreases (*ca.* 2.5 m in

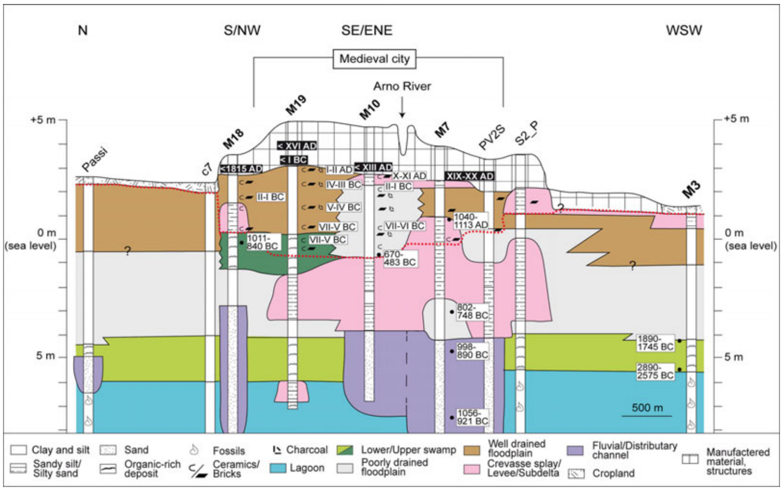

FIGURE 4 Subsurface stratigraphy of Pisa urban and suburban areas, showing distribution patterns of anthropogenic deposits above the coastal-alluvial succession of Mid–Late Holocene age; the lower boundary of the anthropogenic succession is shown as a red dotted line; the cross-section crosses the Pisa city mound (see Fig. 2b, for location); reference cores are in bold; black circles indicate radiocarbon ages (reported as calibrated ages); ages extrapolated from ceramic materials are reported as century B.C./A.D. [Color figure can be viewed at wileyonlinelibrary.com]

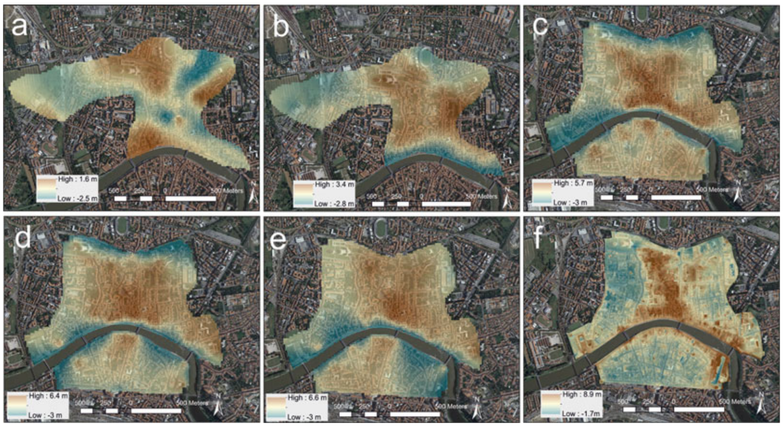

FIGURE 5 Digital elevation models of the Pisa historical town for five distinct historical periods: (a) Etruscan time; (b) Roman time; (c) Middle Ages; (d) Modern Age; (e) Contemporary Age; (f) Present day. [Color figure can be viewed at wileyonlinelibrary.com]

Fig. 3), with a lower boundary around 1 m a.s.l. (dotted line in Fig. 4). The lower half of this unit is made up of overbank silt–sand deposits containing manufactured materials (human-modified deposit) of undefined age, while the upper half consists of artificial layers.

4.2 | Ground-level topography

Based upon stratigraphic, chronological, and topographic data, we reconstructed the DEMs of the Pisa historical town for five distinct historical periods (Fig. 5): Etruscan (8th–2nd centuries B.C.); Roman (1st century B.C.–5th century A.D.); Middle Ages (6th–15th centuries A.D.); Modern Age (16th–18th centuries A.D.); Contemporary Age (19th century A.D.–A.D. 1950). Finally, we discuss the present-day urban topography obtained through LiDAR in A.D. 2008 (Bini et al., 2015).

4.2.1 | Etruscan Age

The DEM for the Etruscan period has a density of 32 points/km^2 and exhibits a mean elevation of 0 m, with minimum and maximum values of −2.5 m and 1.5 m a.s.l, respectively. The highest elevation is in the northern sector of the study area. Here, a large relief, 0.5 km^2 wide and with its apex a few meters east of Piazza Duomo, is dissected by a well-defined, N–S oriented depression. A lower relief area is observed in the SW part of the study area, close to the present Arno river course. This relief, along with the northern one, forms an almost continuous, N–S oriented incipient ridge (Fig. 5a).

4.2.2 | Roman Age

The DEM related to the Roman period, with a density of 42 points/km^2, exhibits a mean elevation value of 1 m a.s.l., with minimum and maximum values of −2.8 m and *ca.* 3.5 m a.s.l., respectively (Fig. 5b). A topographic rise, with average height of 2 m a.s.l. and areal extent of 1 km^2, characterized the central part of the study area. The highest elevation coincides with the NW edge of the Pisa historical city center, and strictly corresponds to the small area of Piazza Duomo (Fig. 5b). In contrast, the topographically lowest areas, approximately 0 and 1 m b.s.l., are recorded at the southern and western margins of the study area, respectively.

TABLE II Volumetric growth of anthropogenic deposits for each historical period

	Volume (m^3)	Area (m^2)	m^3/m^2
LiDAR–Contemporary Age	2,772,371	1,900,920	1,458,436
Contemporary Age–Modern Age	1,404,364	1,900,920	738,781
Modern Age–Middle Ages	1,286,655	1,900,920	676,859
Middle Ages–Roman Age	806,013	1,000,562	805,560
Roman Age–Etruscan Age	143,5081	1,455,648	985,871

Data were normalized taking into account the investigated areas.

4.2.3 | Middle Ages

This DEM has a density of 104 points/km^2 and shows a homogeneous relief in the central part of the city, inside the walls (Fig. 5c). The mean ground elevation is 1.2 m a.s.l., while the highest value (5.7 m a.s.l.) is recorded in the central part of the city, between the Arno and *Auser* rivers (the latter flowing along the northern walls).

4.2.4 | Modern Age

This DEM, with a density of 45 points/km^2, has similar characteristics to the previous historical periods (Fig. 5d). The central relief, however, was higher (up to 6.5 m a.s.l.) and wider. The mean value of the ground level is 1.8 m a.s.l.

4.2.5 | Contemporary Age

This DEM has a density of 52 points/km^2 (Fig. 5e). During this period, the central relief maintained its elevation (maximum value 6.6 m a.s.l.), but was further enlarged. The mean ground elevation is about 2.2 m a.s.l.

4.2.6 | Present day

Morphometric elaborations on a LiDAR-based DEM (vertical and horizontal accuracies of $\pm$15 and $\pm$30 cm, respectively) document a further growth of the central relief (up to *ca*. 7 m a.s.l.). Moreover, a new marked relief is attested in the SE sector of the study area and along the Arno river banks (Fig. 5f). The mean elevation is about 3.5 m a.s.l.

The Raster differences between DEMs from successive historical periods (Fig. 6) highlight the topographic changes that have occurred in the study area since the Etruscan age. Statistical data of each subtraction, reported in Table II, furnish an estimation of urban ground growth through the centuries.

During the Roman Age, ground elevation increased to about 3–4 m in the central part of the study area (Fig. 6a). A marked increase in elevation (up to *ca*. 8 m) occurred during the Middle Ages in the southern part, close to the Arno River banks (Fig. 6b). During the Modern Age, the ground level raised up to about 5 m, mostly close to the eastern and western boundaries (Fig. 6c). Finally, the Contemporary Age increase in elevation (*ca*.10 m) was recorded especially along the northern and southern boundaries of the city walls (Fig. 6d). Since A.D.1950, the maximum increase in ground-level elevation occurred in proximity to the Arno River and at the SE edge of the study area (Fig. 6e).

5 | DISCUSSION

5.1 | Pisa urban topography: Evolutionary phases and controlling factors

Based on the integration of subsurface stratigraphy with ground level topography, we reconstructed the origin and evolution of the present-day Pisa urban landscape. This is characterized by a central mound rising up to about 4 m above the surrounding landscape (Fig. 5f).

According to historical sources (Fabiani et al., 2013), the urbanization process started during Etruscan times in proximity of the current north city walls, as testified by the record of human-modified deposits and by the higher ground elevations (Figs. 4 and 5a). This is the area where the *Auser* River flowed, attracting both manufacturing and settlement structures (Bini et al., 2015). It was only with the Roman Age that a marked relief started to develop in the very central sector of the historical town, in conjunction with a slow southward migration of the urbanization (Figs. 4 and 5b). The uninterrupted growth of this relief led to the formation of the present-day mound, as documented by its internal stratigraphy which shows a vertical succession of artificial layers from the 1st century B.C.–1st century A.D. onward (Fig. 4). These made-ground deposits, which are almost absent in the cores recovered outside the Pisa mound, record successive phases of habitation, built on the remains of earlier developments.

The highest increase in elevation occurred during the Middle Ages, when the energy of the *Auser* River began to weaken (Bini et al., 2015), and the urban fabric developed toward the Arno River (Figs. 4 and 5c). As a result, a marked ground level growth took place in the same position where the first ring of walls in the Late Roman/Early Middle Ages had been hypothesized (Redi, 1991; Tolaini, 1979). The existence of this first, and smaller, ring of walls is still unclear. According to Medieval topographic data, the well-defined relief in the central sectors is consistent with a possible wall perimeter (Figs. 2b and 5c). In the Modern Age, the Arno was the only river that flowed through Pisa (Bini et al., 2015; Bruni & Cosci, 2003). In this period, as well as during the following Contemporary Age, the topographic relief extended into a larger space protected by the walls built in the Middle Ages, and still visible today (Fig. 2). Made-ground deposits filled in the intramural gaps, leading to a generalized lateral expansion, rather than an increase in elevation.

In summary, the present-day morphology of Pisa historical town is the result of a continuous and predominant anthropogenic action, mostly worked during the Roman and the Middle Ages when made-ground deposits started to form and concentrate in the central sector. However, the city growth patterns were also influenced by the historical evolution of the fluvial drainage, which documents a gradual decline of the *Auser* River through time (Fig. 1; Bini et al., 2015).

5.2 | Tracking human influence in a long-settled city

Human impact on the environment in the Pisa urban area marks three major milestones:

1. The first systematic evidence of human activity, dating back to the beginning of Etruscan times (*ca*. 8th century B.C.; Figs. 4

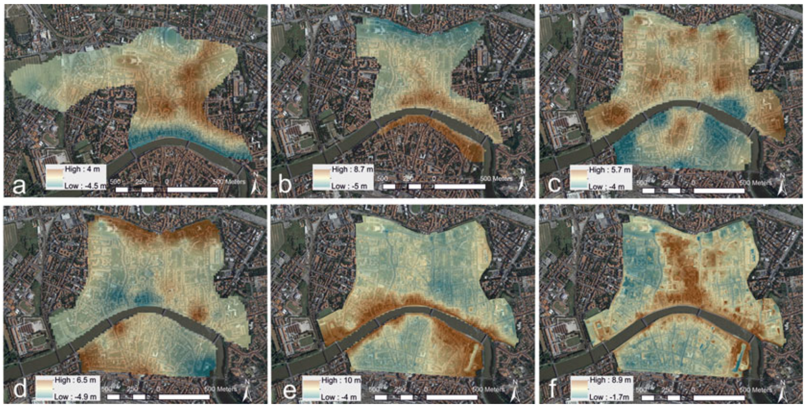

FIGURE 6 Subtraction between Raster digital elevation models (DEMs) of successive historical periods: (a) Roman Age DEM–Etruscan Age DEM; (b) Middle Ages DEM–Roman Age DEM; (c) Modern Age DEM–Middle Ages DEM; (d) Contemporary Age DEM–Modern Age DEM; (e) present-day DEM–Contemporary Age DEM; (f) present-day DEM, representing the final result of ground layers accretion since Etruscan times. [Color figure can be viewed at wileyonlinelibrary.com]

and 6), and interpreted as the local lower boundary of the "archaeosphere" (Boundary A of Edgeworth, 2014). This human-modified deposit could be taken as a direct indicator of the beginning of human impact on the environment. It is reasonably hypothesized that humans also indirectly affected the study area before Etruscan times, increasing sedimentation rates through deforestation (Amorosi et al., 2013a; Pranzini, 2001; Sarti et al., 2015). However, these activities left no clear traces in the stratigraphic record of the Pisa subsurface (Fig. 4).

2. A strong increase in human impact on the urban landscape, marked by artificial ground constructions (made-ground deposits; Figs. 3, 4, and 7) dated to Roman Age. Around the 1st century B.C.–1st century A.D., the shift from human-modified to ground-made deposits marks an important and clearly recognizable stratigraphic surface within the Pisa archaeosphere (Fig. 7). Moreover, during Roman times urbanization processes induced the development of a still visible feature in the present Pisa topography ("the central mound"; Figs. 5b and 7).
3. The extremely rapid increase in city growth rates, since A.D. 1950 onward (Figs. 6e and 7; Table II). This marked acceleration in urban ground accretion, outside the range of variation documented in pre-existing epochs, marks a surface detectable only through a quantitative morphological approach.

In the view of the ongoing debate on the Anthropocene as a new epoch with a synchronous onset, stratigraphically distinct from the Holocene (Waters et al., 2016; Zalasiewicz et al., 2015), the mid-20th century acceleration in Pisa ground accretion is consistent with the global signal of Earth system changes called the Great Acceleration, and recently proposed as the most appropriate boundary for the Anthropocene (Waters et al., 2016, and references herein). In contrast, the other two surfaces (points 1 and 2 above) provide an important, but local indication of human influence on urban landscape evolution, showing its importance for a better comprehension of how different cultural developments have shaped long-settled city areas (Edgeworth, 2014; Edgeworth et al., 2015).

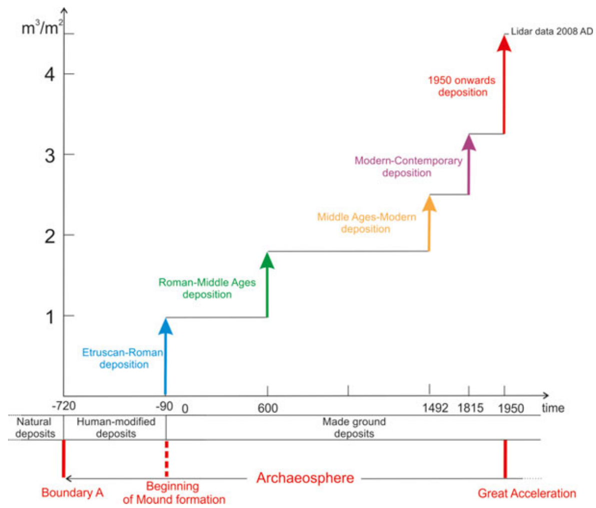

FIGURE 7 Growth rates of anthropogenic deposits in the Pisa urban area; data are normalized per unit of area and reported for each historical period of the settlement; note three key events/surfaces (in red) related to human influence in the Pisa area: (i) Boundary A (Edgeworth, 2014), that is, the lower limit of the archaeosphere (Etruscan Age); (ii) boundary between human-modified deposits and made-ground deposits (Roman Age), marking the development of the Pisa mound; (iii) marked increase in the rate of anthropogenic deposits accretion (A.D. 1950 onward); this latter surface correlates with the Great Acceleration testified by several global proxies, and proposed as the most appropriate lower limit of the Anthropocene. [Color figure can be viewed at wileyonlinelibrary.com]

6 | CONCLUSIONS

The integration of stratigraphic, geomorphologic, and archaeological data allowed us to reconstruct the origin and accretionary phases of the mound that shapes the present-day Pisa topography, and investigate the human influence on the Pisa urban landscape during the last 3000 years or so.

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

1. The present-day Pisa mound is formed by anthropogenic deposits that we classified into two groups: human-modified deposits (with

evidence of human activity in a natural environmental context) and made-ground deposits (entirely due to human activity).

2. Humanly modified deposits date back to the early Etruscan times (8th–5th centuries B.C.), consistent with Pisa foundation, while the made-ground deposits are chronologically constrained to the 1st century B.C. onward (Roman Age–Present day).
3. Pisa urbanization, reconstructed comparing DEMs of different historical periods, started to develop in the northern sector during Etruscan times. The urban fabric moved southward in the Roman Period, and finally expanded in an E–W direction during the Modern and Contemporary Ages. Our data about Middle Ages topography also support the hypothesis of an older (early Medieval/late Roman) ring of walls in the central part of the urban area.
4. Three key events, recorded in the subsurface of the historical town, influenced the present-day Pisa landscape. The oldest one, chronologically constrained to the Etruscan Age, marks the early human influence on the study area and corresponds to the lower boundary of the anthropogenic succession (Boundary A by Edgeworth, 2014). The second one, early Roman in age, marks a strong increase of human capability to shape the urban landscape through the accretion of made-ground deposits and the formation of a city mound still visible today. The youngest event, post mid-20th century A.D. in age, corresponds to a marked increase in the urban ground growth rate. This acceleration is consistent with several global environmental changes of the Earth system that are considered the proof of the beginning of a new Epoch (Anthropocene) stratigraphically distinct from the Holocene.

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