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Palaeoenvironmental dataset from the northern Apuo-Versilian coastal plain (NW Italy): a key tool for scientific and management applications

Abstract: Chelli A., Bini M., Brückner H., Vacchi M., Cajade-Pascual D., Pappalardo M., *Palaeoenvironmental dataset from the northern Apuo-Versilian coastal plain (NW Italy): a key tool for scientific and management applications.* (IT ISSN 0391-9838, 2026). Coastal plains represent valuable sources of palaeogeographic data, especially for the Mid and Late Holocene, revealing also important postglacial sea-level elevation and age constraints to validate glacio-hydro-isostatic (GIA) predictive models. Moreover, they provide evidence of the human-environment interaction. With this paper we present a dataset of the geomorphological and geological information collected during a long-lasting collaborative project, led by the University of Pisa, in the northern Apuo-Versilian Plain, a coastal plain located in NW Italy. The data collected are mostly unpublished, especially in their extended form. They reveal the nature of the sedimentary fill of the Apuo-Versilian Plain and its lateral changes, providing some basic chronological constraints on landscape evolution. They also represent a source of raw data to produce index and limiting points to be cross-checked with relative sea-level (RSL) change model predictions for this area since the Mid-Holocene. Such body of evidence can be used to infer information relevant to constrain the geodynamic model of the area, for assessment of ongoing subsidence of the coastal plain and for projects of flood risk management. Finally, our dataset may be a relevant source of information for ongoing and future archaeological campaigns in this area and particularly for those aimed at revealing the vestiges of the Roman city of *Luna* and its architectural evolution in the Middle Ages and beyond.

Key words: Coastal floodplain, Sedimentary fill, Coring log, Environmental evolution, Holocene, Apuo-Versilian Plain.

Riassunto: Chelli A., Bini M., Brückner H., Vacchi M., Cajade-Pascual D., Pappalardo M., *Un archivio di dati paleoambientali sulla pianura costiera Apuo-Versiliese settentrionale (Italia nord-occidentale): uno strumento chiave per applicazioni scientifiche e gestionali.* (IT ISSN 0391-9838, 2026). Le pianure costiere sono preziose fonti di dati paleogeografici, in particolare per l'Olocene medio-superiore. Esse forniscono importanti vincoli cronologici e altitudinali per la ricostruzione del livello del mare nel periodo postglaciale, utili per validare i modelli predittivi glacio-idro-isostatici, e rappresentano preziosi archivi per ricostruire i rapporti tra insediamenti umani e ambiente naturale. Lo scopo di questo lavoro è di mettere a disposizione un *dataset* di informazioni geomorfologiche e geologiche raccolte durante un progetto collaborativo pluriennale, guidato dall'Università di Pisa, nella porzione settentrionale della Pianura Apuo-Versiliese, situata lungo il tratto nord-occidentale della costa italiana. I dati raccolti nell'ambito del progetto sono per lo più inediti, soprattutto nella loro forma estesa. Essi rivelano la natura del riempimento sedimentario della Pianura Apuo-Versiliese e le sue variazioni laterali, fornendo alcuni vincoli cronologici di base per la ricostruzione dell'evoluzione del paesaggio. Rappresentano, inoltre, una fonte di dati grezzi dai quali è possibile dedurre, per quest'area, le altezze progressivamente raggiunte dal livello del mare nella sua fase di innalzamento avvenuta a partire dall'Olocene medio, che possono essere confrontate con quelle ottenute tramite modelli geofisici predittivi. Attraverso queste ricostruzioni è anche possibile quantificare le variazioni nel tempo dei tassi di subsidenza della pianura costiera, utili ai fini della mitigazione del rischio alluvionale. Infine, il nostro *dataset* può rappresentare una fonte rilevante di informazioni per le campagne archeologiche in corso e future in quest'area, finalizzate a mettere in luce le caratteristiche della città romana di *Luna* e la sua evoluzione architettonica nel Medioevo e oltre.

Termini chiave: Pianura costiera, Copertura sedimentaria, Carotaggio, Evoluzione ambientale, Olocene, Pianura Apuo-Versiliese.

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INTRODUCTION

In the subsoil of many Mediterranean coastal floodplains sedimentary bodies up to a few tens of metres thick represent the top of the Late Quaternary palaeovalleys' sedimentary fills (Blum *et al.*, 2013) that record the Holocene environmental changes. These sequences normally account for a succession of sedimentary environments that reveal a shift from a ria-type of coast or a lagoonal stage to a drained floodplain environment. In some cases, such as the one of the Pisa Plain in Central Italy (Amorosi *et al.*, 2013a), during the late phases of the Early Holocene, enhanced river discharge enabled the formation of extensive lagoons close to the foothill of the coastal mountain chain, separated from the open sea by sand barriers. In other cases, instead, the sedimentary records testify the persistence of a marine environment up to the Mid-Holocene, when a system of coastal lagoons formed (e.g. Bellotti *et al.*, 2011; Amato *et al.*, 2013) in connection with the Holocene maximum transgression around 6.5 ka BP (Lambeck *et al.* 2014; Vacchi *et al.*, 2016).

Along the Northern Tyrrhenian Sea coast (Italy) buried palaeovalley geometries have been recognised in the subsoil of the Pisa Plain (Amorosi *et al.*, 2013b) and at the southern edge of the wide coastal plain known as Versilia Plain (Rossi *et al.*, 2017; Sarti *et al.*, 2022) (fig. 1a). The global structure of the northern and central part of this

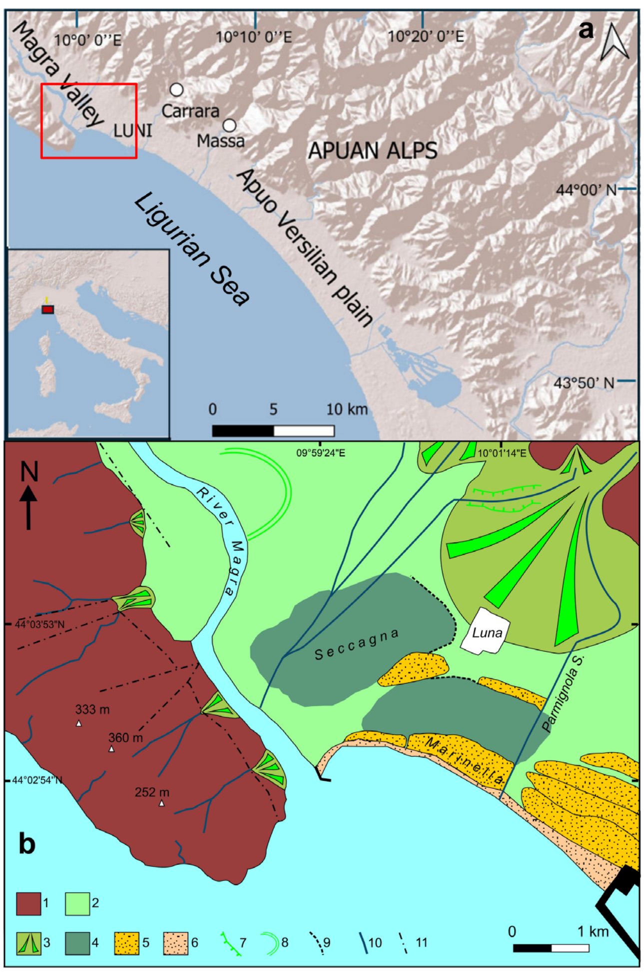

Figure 1 - a) Location map of the study area and its position within the Apuo-Versilian Plain (base map from ESRI 816 ArcMap® database); b) Geomorphological sketch map of the study area (modified after Pappalardo *et al.*, 2021). (1) bedrock, (2) floodplain, (3) alluvial fan, (4) wetland, (5) beach ridge, (6) present-day beach, (7) main stream and/or channel, (8) fault.

plain, stretching at the foothill of the Apuan Alps (and thus named "Apuo-Versilian Plain"), is instead limitedly known (Raggi, 2016). The geological model for this area accounts for a long-lasting aggradation due to an extensional regime affecting both the continental shelf and the valley of its major fluvial system, the Magra River Valley, which is geologically a graben structure (Bernini, 1991; Bernini and Papani, 2002; Molli, 2008). Nevertheless, the Apuo-Versilian coastal plain has been traditionally considered stable during the Holocene (Lambeck *et al.*, 2011), consistent with the rocky coastal tract bordering it in the north (Chelli *et al.*, 2005). The uppermost part of its sedimentary fill, built since the Mid-Holocene, has been the object of interest for many researchers. During Roman times a well famed city, *Luna* (figs 2a-d), existed close to the mouth of the Magra River, which hosted an articulated harbour system and was economically connected to the local marble quarrying district (Fabiani, 2006; Gervasini *et al.*, 2007).

In the last decades of the 20th century, the coastal plain's geo-bio-archives have been extensively explored in order to unravel the spatio-temporal evolution of the landscape and reveal the location of the anchorage facilities used especially for marble trading (Delano Smith, 1986; Fazzini and Maffei, 2000; Bini *et al.*, 2006 and references therein). Starting from 2005, in the framework of a collaborative research between the Universities of Pisa, Parma and Cologne (Bini *et al.*, 2006; Bini *et al.* 2009a; Mancusi *et al.*, 2023) under the auspices of the archaeological authority in charge for the archaeological remains of the ancient city of *Luna* (Soprintendenza per i Beni Archeologici della Liguria), 24 sediment cores from the archaeological area and its surroundings were retrieved and analysed. Sedimentological evidence from cores, complemented by microfaunal analyses, and chronologically constrained by archaeological evidence and radiocarbon (AMS-^{14}C) dates, provided insight into the environmental evolution of the area and explored indicators for relative palaeo-sea-level change retrieved from the sediment cores (Bini *et al.*, 2009b). Based on these data, new evidence for the Holocene shoreline changes, especially its location during Roman times near the city of Luna, were obtained (Bini *et al.*, 2010). Finally the palaeoenvironmental evolution of the area was reconstructed in detail (Bini *et al.*, 2012; Pappalardo *et al.*, 2015; Pappalardo and Chelli, 2015), with a particular focus on the palaeogeographic scenario during Roman times (Bini *et al.*, 2013). Moreover, Chelli *et al.* (2017) using the Holocene relative sea-level estimates from sedimentological index points corrected for the effect of sediment compaction, calculated for the basin a tectonic subsidence rate of 0.5 mm/yr during the last 6 millennia. Finally, Based on the analysis of a 9-m-long sediment core, Pappalardo et al. (2021) studied sediment compaction; they demonstrated that this effect has largely been underestimated in clastic sediments of Mediterranean coastal plains.

Figure 2 - a) The city of Luna in its environmental setting: in the foreground the Magra River mouth, in the background the Apuan Alps, the approximate position of the city vestiges is indicated by the arrow; b) pavement of the main street (*decumano maximus*); c) view of the amphitheater from one of its gates; d) unearthed floor mosaic from one of the excavated Roman houses (*domus di Oceano*).

Part of the data collected during the collaborative project are unpublished, especially in their extended form, and some of them were published in Italian and/or in books and journals with limited access for the wider scientific community. Therefore, the aim of this paper is to create an open-access dataset of all the project data, useful for geoscientists working in the Apuo-Versilian area and beyond. Although the dataset essentially contains the description of sedimentary records, it was planned and implemented with the main purpose to detect the stratigraphy of landforms previously identified through remote sensing and field mapping (fig. 1b) in order to reconstruct their spatio-temporal evolution. In this sense, our work represents an example of how a typical geomorphological research subject can be addressed using atypical research tools for the discipline. In fact, in coastal plains landforms are quickly formed, sheltered and buried, often leaving only weak morphological traces for the reconstruction of landscape evolution. In these cases, stratigraphic analysis is essential to detect past landforms and infer their evolution. Based on the experience of previous work, potential fruitful applications of the dataset are outlined in the end.

CONTENT AND STRUCTURE OF THE DATASET

The dataset contains the description of 24 sediment cores, drilled in the study area in the years 2006-2016 as well as associated 16 radiocarbon ages, obtained from datable materials retrieved from the cores sediments, together with all necessary metadata.

All the data are provided in the Supplementary Material for this article which contains:

i) Supplementary material 1: image with drilling point locations LUN_1-20 and LUN_22-23, projected on Bing Satellite basemap (WMS service, accessed 09/2025) via Quantum GIS software;
ii) Supplementary material 2: stratigraphic logs of the sediment cores;
iii) Supplementary material 3: photographs of the sediment cores;
iv) Supplementary material 4: metadata associated to the logs;

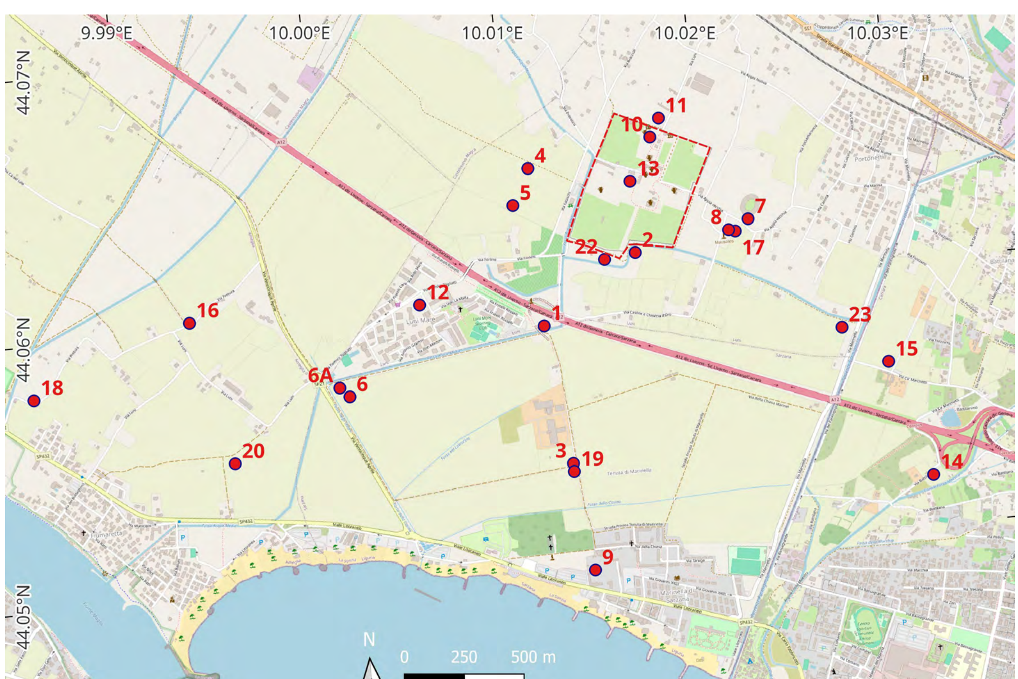

Figure 3 - Location of LUN_1-20 and LUN_22-23 drilling points. The base map is © OpenStreetMap contributors, available under the Open Database License (ODbL), accessed via Quantum GIS 2025.

v) Supplementary tab. 1: topographic position of the drilling points;
vi) Supplementary tab. 2: radiocarbon data sheet (including uncalibrated and newly calibrated ages).

METHODOLOGY OF DATA ACQUIREMENT AND PROCESSING

Selection of drilling points

The position of drilling points (fig. 3, suppl. mat. 1) was based on a preliminary detection of landforms (Bini *et al.*, 2006, fig. 1b), performed through the analysis of multiple remote sensing products (aerial and satellite images) as well as historical and modern maps. The list of analysed documents is reported in Bisson and Bini (2011), who used the same material to detect palaeotraces of different nature.

A valuable support for landform detection was the granulometric analysis of subsurface deposits sampled with an Edelman hand auger (at 50 cm from ground level) from the features identified through remote sensing. This method proved effective to overcome the mixing effects on sediments of different grain size produced on the surface by human activities and particularly by ploughing.

In addition, all of the stratigraphic data available for the area – from surveys as well as core sampling carried out for the construction of public works and private buildings – were collected, georeferenced and analysed (Bini *et al.*, 2006) to predict, where possible, the broad geological features of the sedimentary sequence in each drilling point.

Topographic positioning of drilling points

The position of the drilling points (suppl. tab. 1) was determined using a 'Leica GS09' differential GPS. Coordinates were recorded in the WGS84 reference system. High accuracy (< 0.05 m on average) was secured through differential correction provided by Leica Geosystems RTK network correction service (Italpos). They are reported as ellipsoidal elevations, for future referencing against whatever datum. Orthometric altitudes of the ground surface at drilling points were measured through ground levelling with reference to the closest point of the official Italian geodetic network. The elevations in this network are consistent with the official geoid model ITALGEO2005, which is referenced against the master tide gauge of Genoa (datum Genova42). Significant discrepancies may originate from the difference between the orthometric zero elevation and mean sea level obtained from modern tide gauge data (Pappalardo *et al.*, 2019), although in our case-study such discrepancy is probably negligible.

Drilling technique

The cores were collected (fig. 4a) with a gasoline powered, hand-operated vibracorer (Cobra TT of Atlas Copco Co.), equipped with a drilling set, including percussion gouges, shaped in the form of half-open one meter long auger heads, connected to extension rods. These, screwed together using a coupling sleeve, could be combined for drilling to a depth up to 15 m. In order to pull the auger head from the subsurface a hydraulic extractor was used (figs 4b-c). The diameter of the auger heads was 6/5 cm for 0 to 5 m below surface, and 5/3.8 cm for 5 to 15 m b.s., respectively. To optimize the use of the percussion drilling set, minor modifications to the augers were performed in the workshop of the Department of Earth Sciences of the University of Pisa. These proved very useful to retain the sediment within the auger head, particularly in sandy terrain. The system was operated keeping the hammer perpendicular to the ground surface, in order to avoid the gouge to go into the ground diagonally. After the drilling was completed, the augers filled with the sediment cores were cleaned and aligned in the sunshine to be documented photographically (figs 4d-e). Finally, the core was subdivided into stratigraphic layers, described from top to bottom and sampled for laboratory analyses (fig. 4f).

The coring progress of this vibracoring with each augerhead being one metre long, is metre by metre. Therefore, with every new metre sediments from the walls of the borehole may accumulate at its bottom. This happens especially when poorly consolidated strata are drilled. The collapsed material is incorporated in the uppermost part of the following auger head; thus, it pushes downwards the depth of the layer boundaries and the position of the samples within the stratigraphy. This fact must be taken into account. Based on our experience with the vibracoring with the Cobra TT hammer of Atlas Copco, starting from the second metre we generally corrected the depth for an error of +10 cm. The top 10 cm of each core metre were discarded from the stratigraphic description.

Sediment analysis and facies interpretation

The description of the stratigraphic logs reported in suppl. mat. 2 is the result of the analysis performed in the field according to standard methodologies (Nelson, 2015). The features described in the field are: i) grain size; ii) colour (according to to Munsell Soil Color Chart); iii) content of calcium carbonate (test with HCl, 10%); iv) faunal and floral macroremains (mollusk shells, gastropods, organic matter); v) artefacts (fragments from ceramics, tiles etc.).

The qualitative detection of grain size was confirmed by granulometric analyses performed on part of the samples at the University of Cologne (Noß, 2012). On the most significant samples different types of geochemical and micropal-

Table 1 - Main features of the 23 cores.

Core code	Length (m)	Chronological constraints n° (suppl tab. 2)	Facies types (M = marine; Te = terrestrial; Tr = transitional)	Tested presence of Microfauna (+ = yes; - = no)
LUN_1	12	2	Te, Tr	+
LUN_2	6	-	Te	-
LUN_3	10	2	Te, Tr	+
LUN_4	3	1	Te, Tr	-
LUN_5	8.5	3	Te, Tr	+
LUN_6	13	2	Te, Tr, M	+
LUN_6A	9	2	Te, Tr	+
LUN_7	6	-	Te	-
LUN_8		-	Te, Tr	+
LUN_9	8	-	Te, M	+
LUN_10		-	Te	-
LUN_11	5	-	Te	-
LUN_12	7	-	Te, Tr, M	+
LUN_13		-	Te	-
LUN_14	12	-	Te, M	-
LUN_15		-	Te, M	-
LUN_16		3	Te, Tr	+
LUN_17		-	Te	-
LUN_18		-	Te, Tr, M	+
LUN_19		-	Te, Tr	+
LUN_20		-	Te, Tr, M	+
LUN_21		-	Te	-
LUN_22		1	Te, Tr, M	+
LUN_23		-	Te, Tr	-

aeontological analyses were conducted, the results of which have been published (Bini *et al.* 2012; Chelli *et al.*, 2017; Pappalardo *et al.*, 2021); they were used for sedimentary facies interpretation (tab. 2).

Radiocarbon dating

Radiocarbon age determinations, necessary to provide the chronologic framework, were mainly conducted on vegetal materials (peat, poorly decomposed organic matter and vegetal macroremains); rarely, however, on marine or freshwater shell fragments, in order to avoid reservoir correction. In this paper new ^{14}C ages are presented. They are reported in suppl. tab 2 together with those already published in previous papers. All of the ^{14}C ages were calibrated or recalibrated with the latest calibration curves (Reimer *et al.*, 2020; Heaton *et al.*, 2020).

THE DATA

The main features of the 24 cores retrieved are summarised in tab. 1, including length, number of radiocarbon ages, microfaunal content and determined facies. In the research working documents and in publications the cores have been labelled in different formats: LUNn°, LUN_n°*,* LUNIn°*, LUNI n°.* In this article the labelling LUN_n° is adopted for all of the 24 cores. This number is the unique identifier for each core. The microfauna awas only analysed in a limited number of layers and not in all cores (see in particular: Bini *et al.*, 2009a; Bini *et al.*, 2012; Chelli *et al.*, 2017; Pappalardo *et al.*, 2021).

In the retrieved sedimentary sequences five different types of sedimentary facies can be recognised, the main features of which, partly described in published papers (particularly in Bini *et al.*, 2009a; 2012; Chelli *et al.*, 2017; Pappalardo *et al.*, 2021), are summarised in tab. 2.

The synopsis of the collected data reveals the the geological structure of the coastal plain's sedimentary body. The modern and recent alluvial plain deposits overlap a sedimentary unit typical of a freshwater swamp. In the area closest to the foothills of the mountains the marsh deposits directly overlap the alluvial fan created by the Parmignola Stream, a minor collector of surface waters from the reliefs backing the coastal plain (fig. 1b). In the seaward part of the coastal plain, conversely, the freshwater marsh sediments rest on a lagoonal unit, a few metres thick, representing an ancient deltaic mouth of the Magra River. In some of the cores, this surmounts littoral sediments of the Mid-Holocene transgression. Still located close to the foothills of the Apuan Alps ca. 6.5 ka BP, the coastline has since then shifted seaward due to the formation of the coastal plain fed by the prograding Magra delta and sediment accretion due to longshore drift. This included lagoons and salt marsh basins; the latter progressively evolved into coastal freshwater swamps. The delta system also contained sand ridges, mainly parallel to the coastline and therefore linked to the littoral dynamics (coastal erosion and longshore drift), but also transversal ones, produced by fluvial dynamics (levees).

Table 2 - Main sedimentological features of the sedimentary environment types detectable in the database cores.

Sedimentary environment	General sedimentological features
Alluvial fan	Rounded to sub-rounded pebbles in a silty sand matrix. Presence of terrestrial gastropods fragments
Floodplain (encompassing channel to levee facies)	Alternating clay and sandy silt layers
Distributary channel	Silty fine to medium sand with interdigitated layers of organic clay and subordinately rounded pebbles. Scattered shell fragments of transitional and marine environment (dominant *Cerastoderma glaucum* and *Turritella* spp.) and foraminifera (*Ammonia batava*)
Swamp	Clayey silt barren of ostracods and foraminifera, with abundant organic matter mostly in the form of plant remains and peat lenses
Lagoon	Clayey silt with high organic content in the form of decomposed plant remains and subordinately wood fragments, seeds, charcoals; frequent shell fragments of transitional and marine environment (*Cerastoderma glaucum* and *Turritella* spp.) and foraminifera (*Trochammina inflata*)
Littoral	Medium to fine sand with gravels, marine gastropods and bivalve fragments and saltwater foraminifera
Open marine bay	Silty fine sand with marine gastropods and bivalve fragments and saltwater foraminifera

Figure 4 - Fieldwork activities during the campaigns of the years 2008 to 2010.

POTENTIAL APPLICATIONS

The dataset presented here can be of interest for applications in the framework of projects of regional land management and for scientific research of broader relevance. These mainly concern the contribution to palaeo-sea-level databases and the quantification of subsidence rates in coastal plains.

In palaeo-sea-level reconstructions sediment cores taken from coastal plains have been a traditional source of data (Nelson, 2015): they record changes in depositional environments (marine to transitional to terrestrial) that can provide quantitative evidence of past sea-level position relative to present-day. This evidence is mainly represented by sea-level index points (SLIPs) and, subordinately, by terrestrial or marine limiting points which represent an upper or lower boundary of the paleo-sea-level position, respectively (Vacchi *et al.*, 2016). Each sea-level evidence must be provided with the following four attributes: i) coordinates, so that it can be georeferenced against a global coordinate system; ii) known elevation referenced against a tidal datum or relative to its modern analogue; iii) distance between the midpoint of the indicative range (IR, which is the elevation range once covered by the feature) and its contemporary tidal datum; iv) age of the feature, which for Holocene features is generally represented by a radiocarbon age, preferably performed on terrestrial material (e.g. peat) in order to overcome correction for the reservoir effect.

SLIPs with these attributes can be incorporated in standardised palaeo-sea-level databases with global coverage such as, for the Holocene, the one initiated by the HOLSEA project (Khan *et al.*, 2019).

Land subsidence is a significant issue in the Apuo-Versilian plain, like in many coastal plains in Italy and worldwide (Giosan *et al.*, 2014; Bruno *et al.*, 2020). In order to disentangle the effects of regional tectonic subsidence, sediment compaction and groundwater overexploitation, the approach based on comparing the position of basal peats formed above an uncompressible bottom layer to that of coeval peat layers in the mid-late Holocene sedimentary sequence (base-to basal method *sensu* Van Assselen, 2011) can be adopted (Brain, 2015; Nienhius *et al.*, 2023). In the Apuo-Versilian coastal plain, this method was successfully adopted in the pilot paper by Chelli *et al.* (2017). The new stratigraphic information from this dataset may address future research aimed at refining, using this approach, the subsidence pattern in the study area and investigate the relationship between sediment compaction and landform evolution (Xotta *et al.*, 2022).

The effects of ongoing global climate warming are particularly evident in the Apuo-Versilia plain due to its pluviometric, hydrographic, and morphological characteristics (Baroni *et al.*, 2015; Luppichini *et al.*, 2025), which trigger severe and destructive flood events. Under these conditions, land management projects and remediation strategies for regional flood mitigation need to be addressed in the study area to support sustainable planning and to optimise land management policies (Luppichini *et al.*, 2024). The data provided by this article offer a valuable basis to reconstruct palaeo-hydrology, identify areas historically prone to flooding, and plan remediation strategies for regional flood mitigation. Such an approach is particularly relevant for the Magra River basin and the smaller Apuan watercourses, where flood events triggered by negative NAO oscillations have been recurrent in the last centuries (Coletti *et al.*, 2025) and the amount of sediment discharged has been remarkable (Pappalardo *et al.*, 2021). The sediment input, that in the past century had been interrupted by dredging in the river bedload, has recently been restored causing an enlargement of the submerged river delta (Pratellesi *et al.*, 2018). Sedimentary evidence disclosed in the coastal plain can effectively compliment instrumental measurements in order to compare short- and long-term trends of river activity.

The dataset presented here is also intended as a support to ongoing and future archaeological projects in the area. Based on the results of a limited number of archaeological excavations performed in the past decades, it is evident that much of the archaeological heritage in the area is still to be disclosed. Excavations and research projects are currently underway, with the aim of continuing investigations into the ancient Roman city of Luna to improve our knowledge of both the Roman settlement (Ribolini, 2020; Menchelli *et al.*, 2024 and references therein) and of the changes that the site has undergone during the Middle Ages and later (DEMEL, Discovering Early Medieval Luni Project; Cagnana *et al.*, 2021). Furthermore, enhancing the attractiveness of the existing archaeological heritage is a major goal of the Italian national archaeological authorities. In fact, the site has recently undergone a major restoring project that has led to the inauguration of a new National Archaeological Museum. In the framework of the new exhibition strategies this dataset might provide a general geomorphological and stratigraphic framework, useful to contextualise this important archaeological heritage.

SUPPLEMENTARY MATERIAL

Supplementary material associated to this article can be found in the online version at https://doi.org/10.4454/rtcva423

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