



Chrono-spatial modelling of deltaic progradation: timing the evolution of the Po delta Spina lobe (ca. 750 BCE–700 CE)

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ABSTRACT

Deltaic progradation, the seaward extension of deltaic landforms, is a highly complex geomorphological process shaped by interacting natural and anthropogenic drivers throughout the late Holocene. Deciphering the temporal dynamics of deltaic evolution is essential not only for reconstructing past environments but also for assessing coastal risks and predicting future responses to climate change and human pressures. Focusing on the Po Delta, this study presents a detailed chronological analysis of progradation during the first millennium BCE, a period marked by profound environmental and cultural transformations across the Mediterranean. To achieve this, we developed an innovative Chrono-Spatial Modelling (CSM) approach, which integrates high-resolution geomorphological and archaeological datasets with Bayesian age-distance modelling. This method enabled the identification of five distinct progradational systems and the precise dating of 176 beach ridges, revealing a progressive acceleration in progradation rates from the early Roman period (ca. 300 BCE–476 CE). Notably, this temporal shift aligns with escalating anthropogenic pressures, including widespread deforestation, agricultural intensification, and hydrological modifications in the Po River basin, suggesting a gradual yet decisive transition toward a human-dominated sedimentation regime, though natural factors remained influential. Beyond refining existing palaeoenvironmental hypotheses, our approach provides unprecedented spatial resolution of ancient deltaic systems and new perspectives on human-environment interactions in antiquity. Moreover, the CSM framework is readily transferable to other deltaic systems worldwide, offering a powerful tool for quantifying progradation rates and disentangling the relative contributions of natural and anthropogenic forcing over time.

1. Introduction

Deltaic progradation, the seaward expansion of deltaic landforms through sediment accumulation, has been a dominant global process over the past 8000 years following the stabilisation of post-glacial highstand sea levels (Stanley and Warne, 1994; Hori and Saito, 2007; Lambeck et al., 2014; Vacchi et al., 2016). This process occurs when fluvial sediment supply exceeds marine reworking capacity and is controlled by a complex interplay of climatic, tectonic and anthropogenic factors, with human activities increasingly amplifying sediment fluxes since the late Holocene around 1500 BCE (Maselli and Trincardi, 2013; Anthony et al., 2014, 2024; Gibling, 2018; Roberts et al., 2019). The Mediterranean basin, with its millennia-long history of human occupation, provides an ideal setting to study these interactions as shifts

in land use from Bronze Age agriculture to Roman-era deforestation have profoundly altered sediment delivery to deltas (Neboit, 1979; Walsh et al., 2019). The Po Delta in northern Italy exemplifies this dynamic with its extensive beach-ridge sequences elevated up to approximately 2 m a.s.l. and extending for tens of kilometres preserving high-resolution geochronologies of shoreline migration (Bondesan et al., 1995; Stefani and Vincenzi, 2005; Stefani, 2017). While deltaic evolution is typically examined over multi-millennial timescales, this study focuses specifically on short-term progradation rates during the first millennium BCE, a period corresponding to the active phase of the Spina deltaic system and marking a critical transition from climatically driven to anthropogenically controlled dynamics. To reconstruct this evolutionary chronology, we integrated nine high-resolution sediment cores from former river mouths with fifteen new radiocarbon dates and contextual archaeological data detailing the type, age and stratigraphic

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Abbreviation

a.s.l. =	above sea level
b.s.l. =	below sea level
ca. =	circa
c. =	century
m =	metre
r. =	reign

context of the finds, while three additional cores from a palaeochannel yielded three further radiocarbon dates. This multi-proxy dataset was analysed using a novel Chrono-Spatial Model to quantify progradation rates at unprecedented resolution.

2. Geographical context

2.1. The Po river catchment

The Po River drains a catchment area of 74,970 km² from its source at Pian del Re (2020 m a.s.l.) in the Western Alps, flowing through the west-east-oriented Po Plain foreland basin between the Alps and the Apennines (Marchetti, 2002; Castaldini et al., 2019). The Po River has a pluvio-nival hydrological regime with an average annual flow of $\approx 1500 \text{ m}^3 \text{ s}^{-1}$ (Pardé and Visentini, 1936; Nelson, 1970) and is supplied by about 141 main tributaries (Correggiari et al., 2005), with main contributions coming from the alpine rivers from the north. The Ticino ($292 \text{ m}^3 \text{ s}^{-1}$) is the most significant of these, followed by the Adda ($157 \text{ m}^3 \text{ s}^{-1}$) and the Dora Baltea ($96 \text{ m}^3 \text{ s}^{-1}$). From the south, the principal tributary is the Tanaro ($127 \text{ m}^3 \text{ s}^{-1}$). The alluvial plain is delimited by alluvial fans and megafans along the Alps (Guzzetti et al., 1997; Fontana et al., 2014) and the Apennines (Ori, 1982).

Following a 652 km course downstream from its Alpine source (Marchetti, 2008), the Po River discharges into the Adriatic Sea, a semi-enclosed basin connected to the Mediterranean through the narrow Strait of Otranto. This restricted configuration significantly limits oceanic tidal influence, creating a low-energy marine environment characterised by minimal tidal ranges and reduced wave heights (Nelson, 1970). The Po forms a major Mediterranean delta extending approximately 140 km between the Reno and Adige rivers, two former Po tributaries, creating a broad and asymmetrical band (Simeoni and Corbau, 2009; Marchetti, 2008). The present-day delta lobe is a wave-mixed-river-dominated system characterised by low-lying fine sand coasts (Trincardi et al., 2004) a feature shared by the rest of the northern Adriatic coast of Italy that extend from Rimini to the area of Trieste (Charrier, 1991). The Po River plays a central role as the primary sediment supplier, with an estimated sediment load of approximately 13 Mt/yr, more than half of which originates from the northern Apennine tributaries (Syvitski and Kettner, 2007). The prevailing winds are the Bora from the north-east, which causes the strongest storms, and the Sirocco from the south-east, which is the source of the most frequent waves and sea surges (Calderoni, 1982; Orlić et al., 1992). Erosional and depositional patterns along the coast are controlled by two main north-to-south flowing currents: the North Adriatic Dense Water (NADW) and the Western Adriatic Coastal Current (WACC). The NADW forms through winter cooling in the northern Adriatic before flowing southward into the deeper southern basins, whilst the WACC represents a westerly coastal current that transports sediments southward along the Italian coast under the combined influence of wind forcing and riverine inputs (Benincasa et al., 2019). Today, the delta faces significant vulnerability to future relative sea-level rise (Da Lio and Tosi, 2019), with heightened sensitivity to associated salinisation processes (Bellafiore et al., 2021; Gervasio et al., 2023).

2.2. Late Quaternary history of the Po Delta

Several geomorphological studies carried out over the last three decades (Bondesan et al., 1995; Amorosi et al., 2003, 2017; Campo et al., 2017) have provided valuable insights into the evolution of the Adriatic shelf of the Po during the Late Quaternary. These studies identified three main evolutionary phases:

- (1) During the Last Glacial Maximum (22,000–16,000 BCE), sea levels fell to approximately 130 m b.s.l. and the Alpine ice cover expanded by approximately 30,000 km² (Colantoni et al., 1979; Correggiari et al., 1996; Cattaneo and Trincardi, 1999; Tortora et al., 2001). At that time, the Po had a much larger catchment area (190,000 km²), almost twice its current size, and its mouth was located at the latitude of Pescara (Maselli et al., 2011; Peresani et al., 2021). During the Late Pleistocene, sedimentological and geochemical evidence indicates that the Adige River was the main source of sedimentation in the area, as highlighted by the presence of high Ba/Al ratios, an established geochemical fingerprint of Adige-derived material (Amorosi et al., 2008). The boundary between the Pleistocene and the Holocene is marked by the presence of a layer of pedogenised clay, indicating a prolonged period of sub-aerial exposure (Amorosi et al., 2008; Bruno et al., 2022).
- (2) The post-glacial eustatic sea-level rise triggered a marine transgression estimated to have extended 25–30 km inland from the current coastline (Amorosi et al., 2017). This process led to the landward position of the oldest coastal lagoon barriers, with peak flooding dated to around 4050–3550 BCE (Stefani and Vincenzi, 2005).
- (3) The first stages of the Po Delta's progradation are estimated to have occurred around 3500 BCE (Stefani and Vincenzi, 2005). As the sea-level rise trend slowed and stabilised, sea level became a secondary parameter relative to the autocyclic factors influencing the geomorphological evolution of the coastline: successive avulsions and the development and destruction of delta mouth lobes became the key elements of deltaic morphogenesis (Stefani and Vincenzi, 2005; Amorosi et al., 2017). The continental shelf of the Po Delta is relatively wide, reaching tens of kilometres in width, which promotes extensive sedimentation at depths ranging from 0 to 50 m, with a shelf slope of less than 0.5° over the first few kilometres offshore (Palinkas and Nittrouer, 2007). The Po Delta region may be divided into two main areas (Fig. 1): the "active" delta ($\approx 730 \text{ km}^2$) and the "fossil" delta ($\approx 1300 \text{ km}^2$). The former begins near Porto Viro, where the land has been shaped by a combination of wave and fluvial influences (Cencini, 1998). The latter is a mosaic of several generations of wave-dominated lobes that have been in place since the Bronze Age (Stefani and Vincenzi, 2005; Stefani, 2017). Before the northern shift following the Ficarolo avulsion in 1152 CE, the main channel of the Po Delta was located in the southern part of the delta, between Ravenna and Codigoro (Castiglioni et al., 1991; Simeoni and Corbau, 2009). The diversion of Porto Viro, carried out between 1598 and 1604 CE to prevent the silting of the Venetian lagoon, marked the beginning of the construction of the modern lobe (Visentini and Borghi, 1938), which fully formed during the Little Ice Age (ca. 1450–1850 CE) through a combination of anthropogenic modifications and climatic deterioration (Del Grande et al., 2002).

2.3. Study area: the ancient Spina lobe, Comacchio region (NE Italy)

Our selected study area is bounded to the south by the Reno Canal, to the north by the Po di Volano Canal, to the west by the Mezzano Lowland, and to the east by the Adriatic Sea (Fig. 2). The Comacchio sector is characterised by a strongly agricultural landscape, with large flat fields

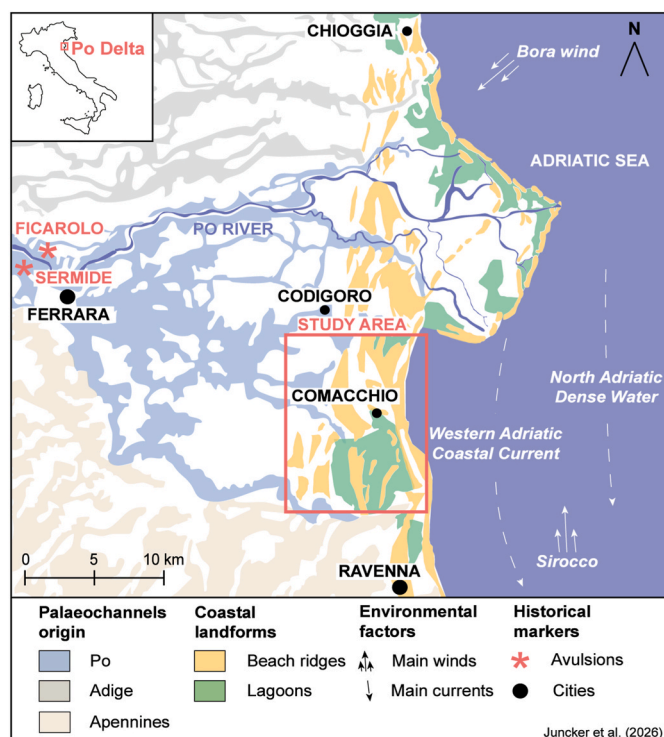


Fig. 1. Hydro-geomorphological map of the Po Delta area adapted from Stefani and Vincenzi (2005), highlighting palaeochannel networks and coastal landforms, along with some regional environmental factors (Calderoni, 1982; Orlić et al., 1992; Benincasa et al., 2019). The red rectangle delimits the study area in the Comacchio region.

divided into areas locally known as *valli*, a term referring to the ancient lagoons that existed until the 1950s–1960s (Botto, 1963). Since the 19th c. CE, extensive reclamation work has significantly reduced their extent (Valarché, 1961; Bethemont, 1974; Cencini, 1998; Le Blanc, 2002), with with approximately 65% of the ancient lagoon areas having disappeared (Da Lio and Tosi, 2019). The Comacchio Lagoon (157.42 km²) stands as a remnant of this former lagoonal system and, as the third largest lagoon in Italy after Venice (550 km²) and Goro (174.11 km²), has been recognised as a wetland of international ecological importance by the Ramsar Convention since 1971 (De Pippo and Valente, 2008). The landscape is traversed by canal banks and embankments, which, alongside roads, constitute the region's primary visible features above sea level (Bénévent, 1916). This area is highly susceptible to localised subsidence driven by water and methane extraction, as illustrated by the Mezzano Lowland (200 km²), where surface levels can reach up to 4 m b. s.l. In parallel with local subsidence, coastal erosion is a major concern along the Emilia-Romagna coast, where numerous groynes have been constructed to replenish the beaches. For instance, the area adjacent to the mouth of the Reno River experienced a retreat of 200 m between 1982 and 2006, resulting in the loss of 75 ha of land (Montanari and Marasmi, 2012). The combination of declining topographic levels and projected sea-level rise scenarios poses a threat to environments of high ecological potential, as well as to popular tourist destinations (Perini et al., 2017).

In this area, the maximum transgression of the Early Holocene extended approximately 20 km inland from the current coastline (Amorosi et al., 2003). Prior to flowing near Ferrara, the Po River occupied its northern compartment until an avulsion shifted its course several tens of kilometres to the south-east (Corrò and Mozzi, 2017; Mozzi et al., 2020). The Spina branch is considered the oldest attested main Padanian palaeochannel in the south, whose activity is estimated to date to the beginning of the 1st millennium BCE (Veggiani, 1974)

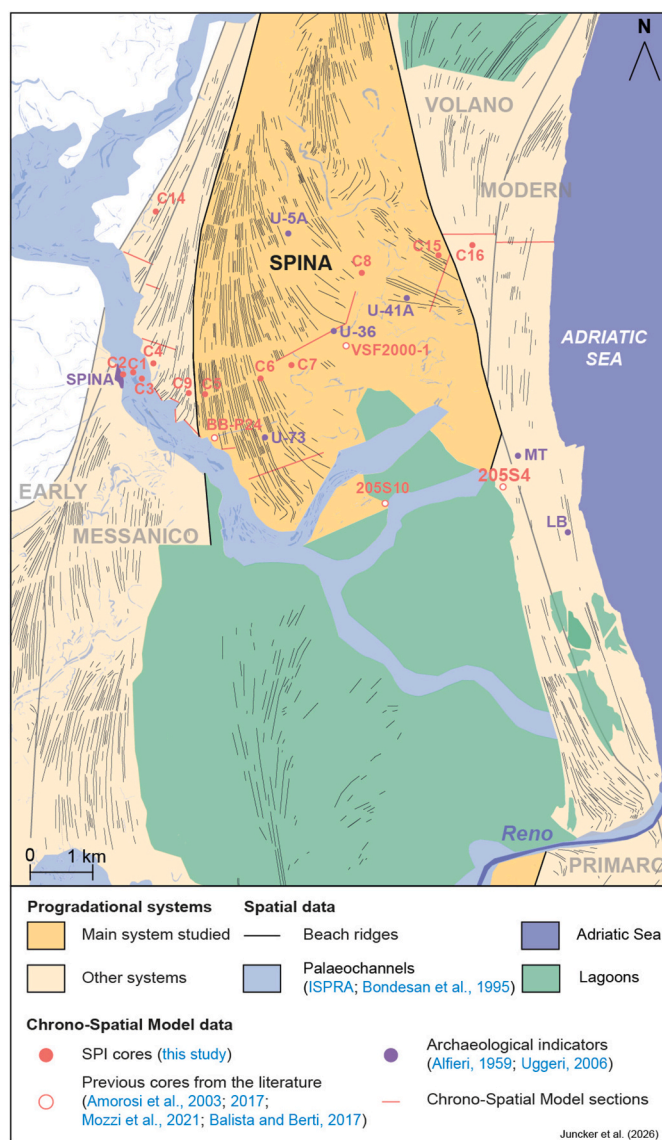


Fig. 2. Geomorphological setting of the Comacchio area showing the progradational systems and the new SPI cores collected in this study (Table 1). Previous cores from the literature (Amorosi et al., 2003, 2017; Mozzi et al., 2021; Balista and Berti, 2017) and archaeological indicators (Alfieri, 1959a; Uggeri, 2006, Table 2) are also shown.

following the Sermide avulsion (Bruno et al., 2026), whilst the Adria branch subsequently became a secondary branch, persisting through the inputs of the Mincio and the Tartaro (Balista, 2018). The hydronym derives from the Etruscan city of Spina (Baratta, 1932; Aurigemma, 1960), located on its right bank and organised around a dense grid of orthogonal canals (Izzet, 2010; Cornelio Cassai et al., 2013; Patitucci Uggeri and Uggeri, 2017; Reusser, 2017; Kay et al., 2020). Data from geomorphological and geophysical surveys have revealed that Spina was delimited to the west by the palaeochannel of the Po (Izzet, 2010; Cremaschi, 2017; Kay et al., 2020) and to the east by a deep palaeolagoon (Gaucci et al., 2025). The location of this river mouth remains uncertain, but traces are visible south-east of Comacchio. Palaeogeographical reconstructions suggest a southward migration up to the 5th c. CE (Bondesan et al., 1995), forming two main palaeochannels: the Volano and the Primaro, the southernmost historical Po branch, flowing 17 km north-east of Ravenna (Soranzo, 1964). The Primaro was later diverted through the Cavo Benedettino under Pope Benedict XIV (r. 1740–1758 CE), redirecting the Reno into this palaeochannel.

The formation of lagoons and beach ridges has been a subject of intense debate since the 19th c. CE (Lombardini, 1870), largely driven by scientific interest in land reclamation projects (Dongus, 1963, 1965; Ortolani and Alfieri, 1965; Alfieri, 1967). Identifying these morphologies remains crucial today, as they clarify the developmental stages of the Po Delta and serve as a vital stratigraphic guide for locating key ancient sites (Uggeri, 1978; Chevallier, 2000). Building on archaeological indicators, Uggeri (2006) proposed palaeo-coastlines for the Iron Age and Roman periods, while earlier interpretations by Ciabatti (1966), subsequently reassessed by Bondesan et al. (1995) and Stefani and Vincenzi (2005), have progressively refined our understanding of these coastal dynamics. Nevertheless, despite their significance in both outcropping and submerged contexts (Bonetti et al., 2022), the formation mechanisms and emergence patterns of beach ridges remain inadequately understood. Stratigraphic evidence offers a tangible record of coastal evolution and helps address these uncertainties. The study area has been extensively documented through deep drilling campaigns conducted by the University of Bologna as part of the CARG (*Cartografia Geologica e Geotematica*) project, contributing to the geological mapping of Comacchio (Sheet 205), Portomaggiore (Sheet 204), and Ravenna (Sheet 223), and providing a detailed lithological framework for the region (Calabrese et al., 2009; Cibin et al., 2009; Servizio Geologico d'Italia, 2024). Extensive radiocarbon dating along two west-east cross-sections further establishes the chronological framework discussed in this work (Amorosi et al., 2003, 2017, 2019). Geochemical provenance studies indicate that these beach ridges predominantly derive from the Padanian area, characterised by high concentrations of chromium (Cr) and nickel (Ni) (Amorosi, 2012; Amorosi and Sammartino, 2007; Amorosi et al., 2019; Curzi et al., 2006; Bianchini et al., 2012; Greggio et al., 2017). Analyses of surface samples from levelled beach ridges confirm this Padanian dominance, demonstrating both the minimal contribution of Apennine tributaries and the exclusive Alpine origin of these ridges, a crucial factor for understanding deltaic lobe chronology (Amorosi, 2012). Similar Alpine-dominated sedimentation patterns, with secondary Apennine contributions, are also evident further upstream at Ostiglia in the Ferrara sector (Demurtas et al., 2022).

3. Methodology

3.1. Beach-ridge mapping

The first methodological step in developing the CSM was to initiate a GIS project using QGIS 3.36.1 (Fig. 3). All spatial analyses were carried out in the Universal Transverse Mercator (UTM) projection system, zone 33N (EPSG:32633), with WGS 84 as the reference datum. This conformal projection preserves local angles and shapes whilst minimising areal distortion at the study area's latitude (approximately 44.7°N), ensuring reliable calculations of shoreline progradation distances and deltaic plain surfaces. As channel stabilisation and land reclamation have kept ancient landforms visible across the delta plain, digitisation drew upon a range of data sources. These include 20th c. CE

aerial photographs (RAF, 1944–1945, Volo IGM, 1931–1937, RER, 1954–1955, and RER, 1976–1978), among which the Royal Air Force reconnaissance campaign provided one of the most comprehensive visual archives available. Photographs taken in the 1950s by Valvassori using an automatic aerial camera with filters designed to accentuate aerial anomalies revealed the outline of the ancient Po River and exposed remains of the Spina settlement (Alfieri and Valvassori, 1957; Chevallier, 1964). High-accuracy historical maps were also consulted, including the *Carta storica del territorio ferrarese* from 1814 CE (Bruno et al., 2024), alongside LiDAR data from the Italian Ministry of the Environment and Energy Security and processed Sentinel-2A imagery representing bottom-of-atmosphere reflectance (Obregón et al., 2019), which eliminated the need for further atmospheric corrections. Whilst this combination of remote sensing, multi-temporal aerial surveys, and historical cartography has proved effective in analysing recent shoreline changes (Fabris, 2021), ancient landforms have undergone considerable alteration over the past centuries owing to subsidence and human-induced erosion (Supplementary material 1). Fluvial landforms, including abandoned riverbeds, river ridges, and crevasse splays, were also mapped to establish clear associations between palaeochannels and strandplains and to avoid confusion with coastal deposits. These were correlated with palaeochannel surfaces identified on geological maps produced by the *Istituto Superiore per la Protezione e la Ricerca Ambientale* (ISPRA). A reference axis running from the first digitised ridge to Lido di Pomposa, crossing multiple systems (Fig. 2), was used to measure progradation patterns. Where ridge features intersect this axis, their distance from the current shoreline was recorded as input for the ,CSM analysis.

3.2. Fieldwork

Building on the established spatial dataset, two coring campaigns were carried out in September 2022 and May 2023. A total of nine sedimentary cores (SPI) were extracted (Table 1) using an Atlas Copco Cobra TT machine coupled to a Stitz hydraulic lifter. The cores were collected along a cross-section extending from the first set of beach ridges (SPI-C14) to the first set of the Volano system (SPI-C16), covering a total distance of 19.27 km (Fig. 2).

3.3. Core description and malacofauna

Sedimentary cores were split longitudinally for stratigraphic analysis. Macroscopic examination enabled the differentiation of lithostratigraphic units based on variations in texture and colour. Shells, where encountered, were identified using published taxonomic criteria (D'Angelo and Gargiullo, 1978; Cossignani and Ardevini, 2011) and cross-referenced with the *World Register of Marine Species* to ensure consistent nomenclature. Malacological assemblages were subsequently classified by salinity tolerance into three categories (freshwater, brackish, and marine), with all taxonomic identifications at the family and species level detailed in Supplementary material 2. Malacofauna

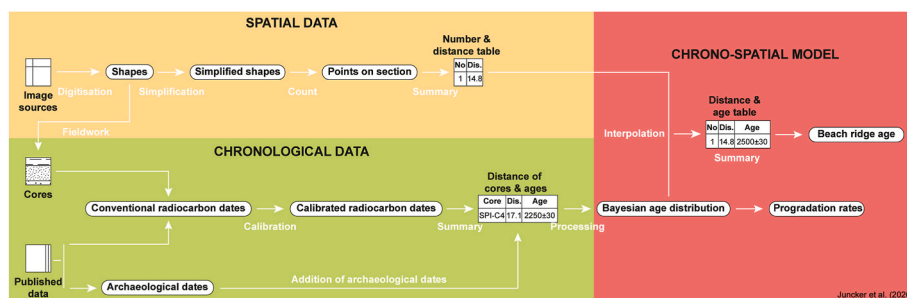


Fig. 3. Workflow of the Chrono-Spatial Model (CSM) construction, illustrating the successive methodological stages from beach-ridge digitisation and radiocarbon/archaeological dating to Bayesian age interpolation, ultimately yielding beach-ridge ages and progradation rates along the coastal transect.

from the SPI cores.

3.4. Radiocarbon dating strategy

Radiocarbon dating was preferred over OSL, as the centennial-scale resolution required by this study exceeds the typical uncertainty associated with OSL methods (5–10%). The high degree of sorting characteristic of this sedimentary context makes it particularly challenging to recover sufficient organic material. Nevertheless, proximity to the river mouth facilitates the recovery of datable terrestrial material transported from the watershed; such material displays a more homogeneous atmospheric carbon signature than marine samples, thereby providing more reliable chronological control and improving calibration of the marine reservoir effect in adjacent coastal environments (Alves et al., 2018). The selection of appropriate dating material is of paramount importance, given the potential incorporation of reworked particles into beach ridges (Scheffers et al., 2011).

A total of 18 organic samples extracted from the cores were submitted to two laboratories: the *Centre de Datation par le Radiocarbone* – CDRC (Lyon, France) and the *Centro di Fisica Applicata, Datazione e Diagnostica* – CEDAD (Lecce, Italy). Calibration was performed using OxCal 4.4 software (Ramsey and Lee, 2013) with the IntCal20 calibration curve (Reimer et al., 2020), with ages reported conventionally at 2 σ (95.4%). This recalibration was applied to previously published borehole data (Amorosi et al., 2019), trench data from archaeological projects (Mozzi et al., 2021; Balista and Berti, 2017), and the new SPI samples. Dated shells were calibrated using the Marine20 curve (Heaton et al., 2020) with $\Delta R = 0$, as no regional marine reservoir correction data are currently available for this sector of the Adriatic coast. In addition, five previously published radiocarbon dates located along the CSM transect were incorporated into the model (Table 3). Organic material suitable for dating is scarce in these coastal sediments, which accounts for the limited number of wood samples (2) and the inclusion of shell samples (3).

3.5. Selection of archaeological indicators

Archaeological remains, alongside radiocarbon dating, provide valuable indicators in palaeocoastal reconstruction (Mason, 1993). An archaeological indicator of progradation may be defined as a remnant, structure, or artefact that can be dated using archaeological methods, provided it lies within the ridge–swale succession. It is, however, important to distinguish substantive remains from sporadic and potentially inconclusive finds, such as isolated pottery fragments. Ideally, the oldest indicator should be located as far inland as possible, whilst the most recent should be situated close to the present coastline, effectively anchoring the chronological model. Four aspects must therefore be considered for each indicator: type, age, stratigraphic context, and

Table 1

Details of the SPI cores. X–Y coordinates are given in WGS 84/UTM Zone 33N (EPSG:32,633). Elevations are expressed in metres below sea level relative to the Italian national vertical datum (Genoa, 1942 tide gauge). Depth refers to the total length of each core below the ground surface.

Core	X-Y	Elevation (m b.s.l.)	Depth (m)
SPI-C1	1,346,580 – 5,573,438	–0.52	7
SPI-C2	1,346,323 – 5,573,404	–0.13	8
SPI-C3	1,346,956 – 5,573,544	–0.63	7
SPI-C4	1,347,406 – 5,573,814	–1.55	4.5
SPI-C5	1,349,507 – 5,572,581	–1.06	7
SPI-C6	1,351,580 – 5,573,366	–1.76	7
SPI-C7	1,352,781 – 5,573,830	–1.73	7
SPI-C8	1,355,466 – 5,577,284	–2.33	6
SPI-C9	1,348,810 – 5,572,761	–1.56	5.8
SPI-C14	1,347,611 – 5,579,686	–3.02	7
SPI-C15	1,358,023 – 5,578,204	–0.92	3
SPI-C16	1,359,212 – 5,578,427	0.71	4

distance from the current coastline (Table 2).

In 1959, Rolfini documented several ceramic fragments, including two black-glazed sherds dating to the 4th–3rd c. BCE (Uggeri, 2006), alongside a variety of undecorated amphorae and jug fragments (U-73). This assemblage could constitute a relevant piece of archaeological evidence of progradation in the area, corresponding to the last phase of Spina's community (Gaucci, 2016; Reusser, 2024) and representing the oldest material record currently identified within its strandplain. Further east, a pottery fragment recovered at the Valle Cona site has been estimated to date from the same period (Balista et al., 2007). However, as this find is poorly documented, lies within the palaeochannel mobility belt, and lacks reliable sedimentary context, it will not be retained here, since its inclusion could bias the final interpretation.

North of Comacchio, the *Fortuna Maris* (U-36) is a significant Roman shipwreck discovered in 1980, renowned for its exceptional state of preservation and diverse artefact assemblage (Berti, 1990). Among its cargo, the lead bars have been the subject of extensive isotopic analysis, although their provenance remains a matter of scholarly debate. Current hypotheses suggest potential production sources in Iberia (Domergue et al., 2012), Illyria (Dušanić, 2008), or Macedonia (Bode et al., 2021). The shipwreck's sinking between 19 and 12 BCE, dated by Marcus V. Agrippa stamps (63–12 BCE) (Garcia-Bellido, 1998; Domergue et al., 2012), provides a precise chronological constraint on coastal progradation. The wreck serves as an excellent progradation indicator, as associated swash bar stratigraphies containing *Ammonia beccarii* and *Lentidium mediterraneum* (Bondesan et al., 1990) demonstrate active sediment-driven bar migration and ongoing coastal advancement. After becoming trapped in a depression near the river mouth, the wreck was rapidly covered by vegetation, preserving this key palaeoenvironmental record (Bondesan et al., 1990). Despite never being fully submerged, the cargo was abandoned, likely due to rapid sedimentation that buried or obscured the vessel beneath vegetation.

Following the discovery of structural remains and associated materials, a Roman imperial villa (U-5A) was identified at Valle Ponti during the 1950s (Uggeri, 1975).

North-east of Comacchio, late Roman finds (U-41A), recovered incidentally and of limited stratigraphic reliability, include a small handmade brick in yellowish terracotta with an irregular shallow handhold, a conical *unguentarium* base in very thin light green glass (ca. 5.5 cm in diameter), and two long thin wooden pole fragments.

In Porto Garibaldi, the Magnavacca Tower (MT), built in the 15th c. CE, is a massive, square-based watchtower that once guarded the lagoon's seaward inlet (*Ministero dei Beni Culturali e Ambientali*). This structure represents the earliest archaeological evidence of the development of the northern delta lobe following the Ficarolo avulsion and prior to the Porto Viro diversion.

Near the present shoreline, a two-masted oak boat (LS) was uncovered beneath a dune in 1959 (Alferi, 1959b; Martin, 2001). Initial archaeological analysis dated the wreck to the 15th–16th c. CE based on hull construction and associated materials (Bonino, 1978; Patitucci Uggeri, 1976), while radiocarbon dating suggested a mid-15th to mid-17th c. origin (Beltrame, 2009), though likely biased by the old-wood effect of aged Istrian oak. More decisively, the use of the metric system rather than Venetian feet places construction after the 19th c. metric adoption, dating the wreck to the late 18th or early 19th c. CE (Canalini, 2009).

3.6. Running the chrono-spatial model

Bayesian age–distance modelling was performed in R by adapting the *rbacon* package (Blaauw and Christen, 2011), originally designed for age–depth modelling, to a distance framework in which the vertical depth axis is replaced by horizontal distance from the present coastline (Fig. 3). For each core, only the most reliable and youngest dated materials were retained. A fine sedimentary slice thickness was applied to

Table 2

Details of archaeological palaeocoastal indicators integrated into the CSM. For each entry, the table provides: the ID (corresponding to the site numbering in the archaeological map of Uggeri, 2006, except for MT and LB); the nature of the find; the estimated age (BCE/CE); the X–Y coordinates (EPSG:32,633); the depth (m); and the original reference for each finding.

ID	Nature	Age (BCE/CE)	X-Y	Depth (m)	Reference
U-73U	Pottery fragments	400–200 BCE	1,351,830 – 5,570,888	–1.20 ± 0.10	Uggeri (2006)
U-36	Fortuna Maris Shipwreck	19–12 BCE	1,354,062 – 5,575,200	–3.35 ± 0.15	Berti (1990); Garcia-Bellido (1998); Domergue et al. (2012)
U-5A	Roman Villa	30 BCE–300 CE	1,352,522 – 5,578,808	0.80 ± 0.10	Uggeri (1975); Uggeri (2006)
U-41A	Roman brick, vial and wooden stakes	200–700 CE	1,357,154 – 5,576,449	–1.50 ± 0.20	Uggeri (2006)
MT	Magnavacca tower	1400–1500 CE	1,361,321 – 5,570,681	1.20 ± 0.05	Ministero per i beni culturali e ambientali
LS	Logonovo Shipwreck	1750–1850 CE	1,363,670 – 5,566,577	–2.75 ± 0.25	Alfieri (1959b); Martin (2001); Canalini (2009)

Table 3

Radiocarbon dates from sediment cores in the coastal and fluvial deposits of the Po di Spina delta (Comacchio). For each sample, the table provides: the core name and depth (m); the laboratory code (labels beginning with “LTL” for CEDAD and “Lyon” for CDRC); the dated material (plant remains, wood, charcoal, or shell); the conventional age (BP) and the calibrated age range (2σ, BCE/CE); the inferred depositional environment (e.g., active channel, channel infill, swale, upper shoreface); and the reference, distinguishing new dates (this study) from previously published data (Balista and Berti, 2017; Amorosi et al., 2019; Mozzi et al., 2021).

Core	Depth (m)	Lab. ID	Dating support	¹⁴ C age (BP)	Calendar age (BCE/CE) (2σ)	Depositional environment	Reference
SPI-C1	6.96	LTL31600	Plant mat.	1925 ± 40	8–217 CE	Channel-fill sand	This study
SPI-C2	5.93	LTL31601	Plant mat.	1542 ± 45	420–605 CE	Channel-fill sand	This study
SPI-C3	3.69	LTL31602	Plant mat.	1782 ± 45	133–404 CE	Channel-fill sand	This study
PEG-1	3.30–3.35	Beta-354,936	Charcoal	1550 ± 30	431–587 CE	Channel-fill sand	Balista and Berti (2017)
SPI-C4	1.50	Lyon-21374	Wood	2365 ± 30	540–387 BCE	Swale	This study
SPI-C4	4.35	LTL31603	Plant mat.	3392 ± 45	1872–1539 BCE	Upper shoreface	This study
SPI-C5	3.58	LTL31604	Wood	2466 ± 40	765–417 BCE	Upper shoreface	This study
SPI-C5	6.98	Lyon-21375	Plant mat.	3915 ± 30	2471–2296 BCE	Upper shoreface	This study
SPI-C6	2.81	LTL31605	Wood	1994 ± 45	107 BCE–154 CE	Upper shoreface	This study
SPI-C6	6.30	Lyon-21376	Plant mat.	6780 ± 30	5724–5631 BCE	Upper shoreface	This study
SPI-C7	1.97	Lyon-21377	Plant mat.	2155 ± 30	355–55 BCE	Swale	This study
SPI-C7	2.30	LTL31606	Charcoal	2588 ± 40	824–552 BCE	Swale	This study
SPI-C8	1.61	Lyon-21379	Plant mat.	2585 ± 30	811–592 BCE	Upper shoreface	This study
SPI-C8	5.11	LTL31607	Plant mat.	6386 ± 45	5474–5225 BCE	Upper shoreface	This study
SPI-C9	5.12	LTL31608	Plant mat.	2793 ± 40	1047–832 BCE	Upper shoreface	This study
SPI-C14	2.57	Lyon-21381	Wood	3825 ± 30	2451–2146 BCE	Upper shoreface	This study
SPI-C14	5.27	Lyon-21382	Charcoal	5255 ± 30	4229–3982 BCE	Upper shoreface	This study
SPI-C15	2.51	LTL33854	Plant mat.	2756 ± 40	1000–818 BCE	Upper shoreface	This study
SPI-C16	3.19	LTL33855	Plant mat.	2408 ± 40	750–396 BCE	Upper shoreface	This study
BB-P24	2.80	n.a.	Wood	3090 ± 130	1627–941 BCE	Upper shoreface	Balista and Berti (2017)
VSF2000-1	5.10	Beta-381,514	Wood	2270 ± 30	398–208 BCE	Upper shoreface	Mozzi et al. (2021)
205S4	9.30	KGM-OCa170055	Shell	1680 ± 40	717–1025 CE	Upper shoreface	Amorosi et al. (2019)
205S10	7.30	KGM-OCa170051	Shell	2540 ± 40	283 BCE–99 CE	Upper shoreface	Amorosi et al. (2019)
187S1	7.95	KGM-TCa180071	Shell	1910 ± 30	509–783 CE	Upper shoreface	Amorosi et al. (2019)

ensure high temporal resolution (thick = 0.1), and the probability level of age intervals was set to 99% (prob = 0.99). The distance range was defined between 0 (d.min, corresponding to the present coastline at Lido di Pomposa) and 19.27 km (d.max, west of the first beach ridge). An additional slice was appended at the base of the sequence to improve modelling of the deeper layers (add.bottom = TRUE), and a small step was applied for a fine distance interval (d.by = 0.01). Units were set to years and kilometres (depth.unit = “km”).

The shape parameter of the gamma distribution used to model sediment accumulation was set to 1.2 (acc.shape = 1.2), and a uniform mean accumulation rate of 200 yr/km (acc.mean = 200) was applied across all five progradation segments, corresponding to an average lateral progradation rate of approximately 5 m/yr. Whilst rbacon allows for segment-specific accumulation priors (Blaauw and Christen, 2011), a uniform prior was deliberately adopted owing to the limited chronological constraints available, which do not justify differentiated parameterisation at the segment scale. This value is consistent with previously published estimates of progradation rates for the Po strandplain (Bondesan et al., 1995; Stefani and Vincenzi, 2005), and provides a physically grounded prior that is subsequently updated by the Bayesian framework.

Model flexibility is ensured through the use of a low shape parameter and a weak memory component (mem.mean = 0.2, mem.strength = 0.4), allowing the posterior accumulation rates to vary significantly where required by the chronological data. This approach

enables local deviations from the prior while maintaining overall temporal coherence.

Four hiatuses were introduced (hiatus.depths = c(2.28, 4.03, 13.75, 17.88)). These correspond to major erosive discontinuities identified through geomorphological mapping, marking boundaries between successive progradational systems. Their inclusion is critical to avoid artificially continuous interpolation across phases of non-deposition or erosion, and instead allows the model to explicitly account for discontinuous coastal evolution associated with avulsion-driven shifts in sediment supply.

Finally, the chronology was expressed in BCE/CE format instead of the default BP scale (BCAD = TRUE).

This iterative approach enables the calculation of age estimates for each ridge identified from the spatial data, as well as inter-ridge time intervals from which fine-scale progradation rates can be derived. Ages were calculated at 10 m intervals along the entire transect, with summary statistics comprising the mean, median, minimum, maximum, 95% confidence interval, and the 2.5th and 97.5th percentiles.

Mean progradation rates for each deltaic system were calculated using the following expression:

$$R_{\text{mean}} = \frac{(d_{\text{max}} - d_{\text{min}}) \times 1000}{\text{age}_{\text{min}} - \text{age}_{\text{max}}} \text{ (m yr}^{-1}\text{)} \quad (1)$$

where dmin and dmax represent the spatial boundaries of a given system, with corresponding ages extracted from the median age estimates

of the Bacon model. To achieve a finer temporal resolution, rates were also computed over successive 25-year intervals. For each target age, the associated distance was obtained via linear interpolation within the model. The rate for each interval was subsequently calculated as:

$$R_{int} = \frac{[d(t - 25) - d(t)] \times 1000}{25} \text{ (m yr}^{-1}\text{)} \quad (2)$$

Each interval was then attributed to a specific deltaic system based on its median spatial position, ensuring consistency between temporal segmentation and geomorphological boundaries.

4. Results

4.1. Spatial data

The manual digitisation of 11,752 beach ridge polygons enabled the identification of 176 individual ridges distributed across five progradational systems, separated by four major erosive discontinuities (Fig. 2). These systems were named after the river mouths that historically supplied sediment to the ridge complexes (Veggi and Roncuzzi, 1968; Bondesan et al., 1995; Cencini, 1998). The Spina system, the central focus of this study, comprises the largest assemblage with 93 ridges, preceded by two older systems (the Early, 7 ridges, and the Messanico, 39 ridges) and followed by two younger systems (the Volano, 18 ridges, and the Modern, 19 ridges). The analysis of 4,354 mapped fluvial landforms further revealed a dense palaeodrainage network, comprising geofoms associated with the Spina palaeochannel and several secondary channels.

4.2. Sedimentary data

Cores SPI-C1, SPI-C2 and SPI-C3 record similar stratigraphic successions reflecting the progressive abandonment of the ancient Po di Spina channel (Fig. 4). The basal units of each core are characterised by fine- to medium-grained sand deposits without any malacofauna, interpreted as the product of active bedload and mixed-load fluvial transport under relatively high-energy hydrodynamic conditions (A1). These sediments are consistent with in-channel sedimentation during a phase of sustained discharge, when the Po di Spina still functioned as a

principal distributary of the delta system. Moving upward through the stratigraphic succession, these sandy deposits are progressively overlain by clayey to silty channel-fill layers, indicative of a marked reduction in flow competence and discharge capacity (A2). This fining-upward trend is characteristic of channel abandonment sequences, wherein decreasing hydraulic energy promotes the settling of fine suspended sediment within the relict channel. Such deposits are typically associated with the gradual infilling of a distributary following avulsion or flow diversion, ultimately leading to the transformation of the active channel into a shallow, low-energy or stagnant waterbody prior to its complete burial (A3). The uppermost unit (A4) consists of mixed brown silty sand, interpreted as anthropogenic backfill deposited during the excavation of drainage canals as part of the land reclamation works carried out in the last century. In SPI-C2, a shell-rich lagoonal horizon is intercalated within the upper part of the succession (L2), suggesting an episode of marine or brackish water influence during the final stages of channel infilling, possibly reflecting a transgressive incursion into the abandoned distributary system. The mixed malacofauna recovered from this unit, combining marine, brackish, and freshwater elements, is consistent with a confined, low-salinity environment subject to episodic marine influence, corroborating the lagoonal interpretation inferred from sedimentological evidence.

Coastal transect cores revealed clear ridge-swale stratigraphic alternations (Fig. 5). The base of all cores is characterised by grey fine- to medium-grained sand, corresponding to the upper shoreface deposits described by Amorosi et al. (2003). Three principal units were nonetheless distinguished on the basis of sedimentological variations: grey fine- to medium-grained sand with shell hash (B1), grey fine- to medium-grained sand with organic layers (B2), and grey fine- to medium-grained sand (B3). All three units yield a consistently marine malacofauna dominated by infralittoral and mediolittoral taxa. This faunal assemblage is fully consistent with active shoreface deposition under open-marine conditions. In several cores, a brown fine-grained sand unit was identified at the top of the sequences, interpreted as a pedogenically altered backshore facies developed on beach-ridge crests (B4), consistent with soil formation on prograded beach deposits (Tamura, 2012). The transition between upper shoreface and foreshore deposits could not always be clearly distinguished in the cores. This limitation does not, however, affect the chronological interpretation, as

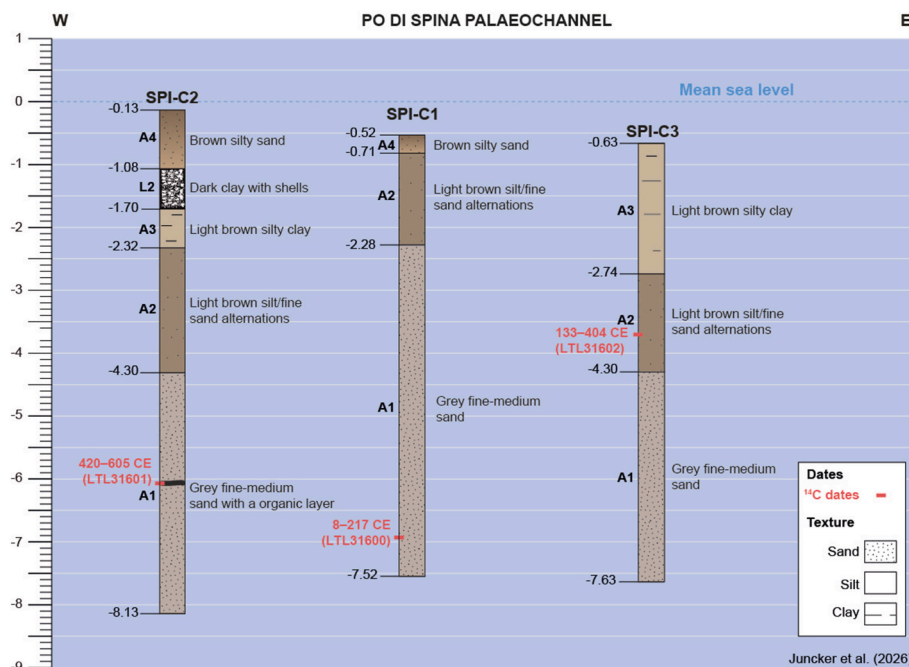


Fig. 4. Sedimentary cores (SPI-C1, C2 and C3) collected in the Po di Spina palaeochannel.

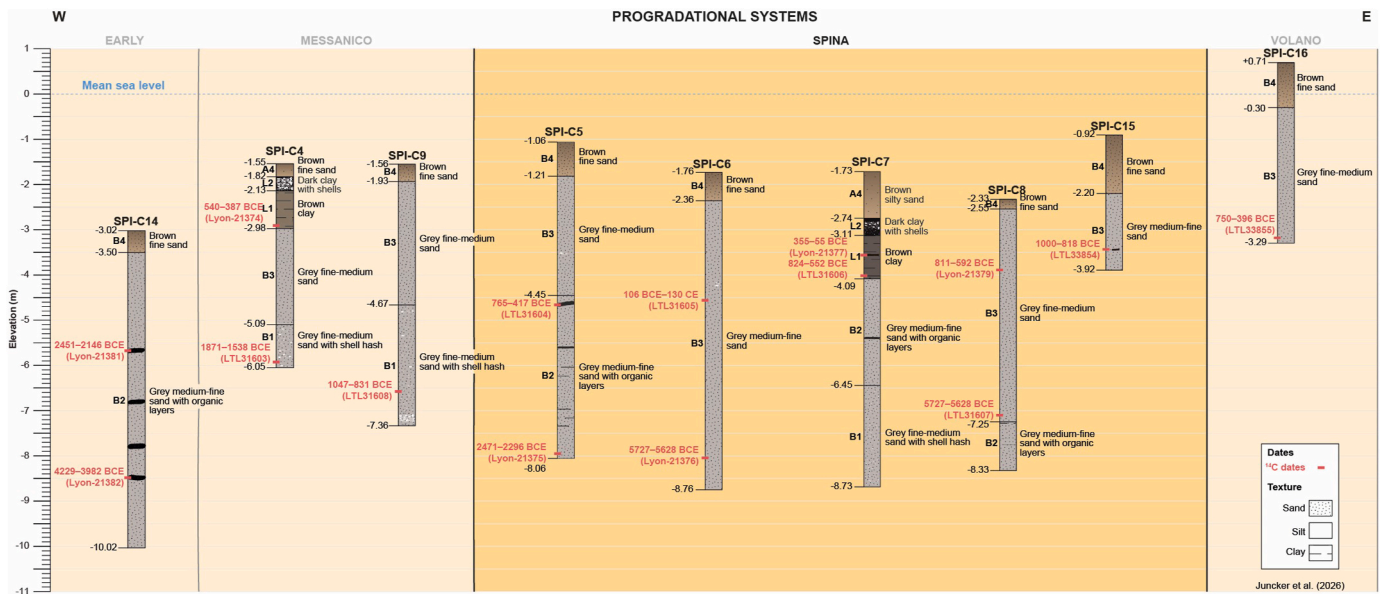


Fig. 5. Sedimentary cores collected across the progradational systems: Early system (SPI-C14), Messanico (SPI-C4 and C9), Spina (SPI-C5, C6, C7, C8 and C15), and Volano (SPI-C16).

radiocarbon samples were systematically collected from organic material and marine malacofauna within stratigraphically well-defined units whose depositional context was unambiguously determined prior to sampling. The stratigraphic successions remain broadly homogeneous and consistent across the transect, supporting the reliability of the radiocarbon dating framework and permitting the reconstruction of the progradational dynamics of the beach-ridge system through time. Two cores (SPI-C4 and SPI-C7) record fine-grained deposits exceeding 1 m in thickness, containing mixed and reworked malacofauna of fluvial, brackish, and marine affinity, interpreted as swale facies. The sands at the top of these two cores likely reflect aeolian input and/or anthropogenic backfill associated with land reclamation works carried out during the last century. Within the swale succession, a basal clayey unit (L1) is overlain by a dark, shell-rich deposit (L2), the latter also identified in SPI-C2, possibly representing the lagoonal environment that preceded drainage and reclamation. The malacofauna of L2 supports this interpretation, comprising a mixed assemblage of marine, brackish, and freshwater taxa, indicative of a low-energy, confined waterbody subject to fluctuating salinity. These swale depressions were subsequently infilled by silty sand deposits (A4), whose reworked and taxonomically mixed fauna reflects a disturbed depositional context with no coherent environmental signal.

4.3. Radiocarbon dates

The dated material comprises three samples from fluvial sequences and fifteen from coastal sequences (Table 3). These latter include non-woody plant remains, such as stems (9), as well as wood fragments (4) and charcoal (2). In terms of terminology, 'plant mat.' refers exclusively to non-woody herbaceous remains, 'wood' designates uncharred lignified material and wood fragments, and 'charcoal' refers to charred wood.

4.4. Chrono-Spatial Model

The first CSM developed corresponds to the Bayesian age probability curve without interpolation (Fig. 6). Samples collected from swales provide an upper chronological limit because the lagoonal environment of swales is characterised by predominantly vertical aggradation rather than progradational deposition, in contrast to the underlying shoreface deposits. From the total dataset with the calibrated dates from the

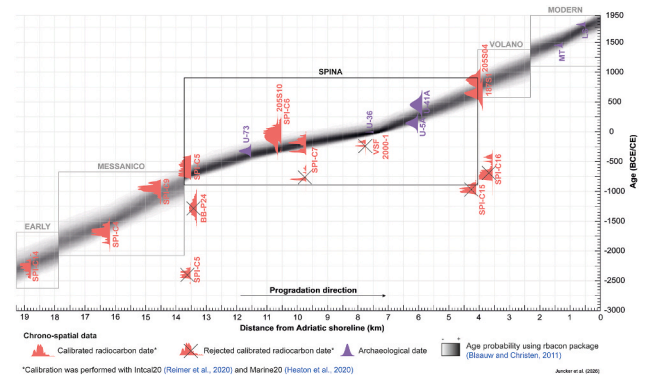


Fig. 6. Chrono-Spatial Model (CSM) of the Po Delta progradational history. The grey shaded envelope represents the age probability (95% confidence interval) generated using the rbacon Bayesian software package (Blaauw and Christen, 2011). The model is constrained by calibrated radiocarbon dates (red distributions) and archaeological markers (purple distributions). Radiocarbon calibrations were performed using IntCal20 (Reimer et al., 2020) and Marine20 (Heaton et al., 2020) curves. The crosses indicate rejected radiocarbon dates identified as outliers. The horizontal axis represents the distance from the modern Adriatic shoreline (km) and the vertical axis displays the chronological framework in years BCE/CE. Among the progradational phases identified; the Spina system is highlighted in a black box, while the secondary systems (Early, Messanico, Volano, and Modern) are represented in grey.

literature, fifteen fit into the age–distance models, whereas eight were excluded due to age reversals attributed to reworking. Among the retained dates, six provide key chronological constraints on the progradation history.

A second CSM was also developed to obtain the interpolated age distribution of each of the 176 observed beach ridges (Fig. 7), presenting their chrono-spatial distribution across the five progradational systems of the Po delta plain and plotting their rbacon-modelled ages (BCE/CE) accordingly. Ridge ages increase monotonically with distance from the coast, tracing a continuous seaward progradation over approximately four millennia, from ca. 2200 BCE in the most inland systems to ca. 1865 CE near the modern shoreline. The sampling strategy focused coring efforts on the Spina lobe, the main system studied, which accounts for 93

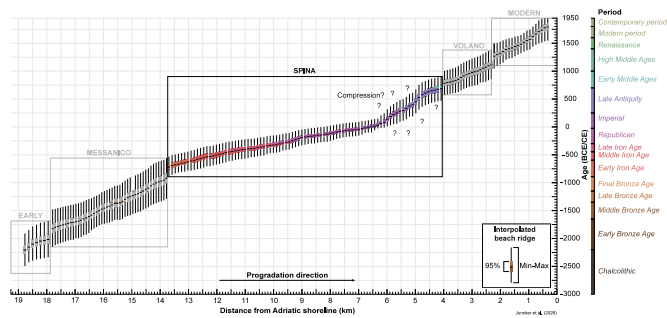


Fig. 7. Age distribution of the digitised beach ridges of the Spina strandplain, grouped according to the chronological cultural periods established for Emilia-Romagna (*Patrimonio culturale – Emilia Romagna*; Zamboni, 2021).

of the 176 dated ridges. Two transitions merit particular attention. The first is the Messanico-to-Spina boundary, located approximately 13.75 km from the shoreline and dated to around 750 BCE. The second is the Spina-to-Volano boundary, located 4.03 km from the shoreline and dated to around 700 CE. Chronological precision is greatest in the Spina system (ca. 750 BCE–700 CE), with 95% confidence intervals consistently below 300 years and reaching a minimum of around 227 years at the BCE/CE transition.

The innermost beach ridges, which are predominantly located to the south-east of the Mezzano Lowland (Bondesan and Bucci, 1971), can be categorised into two progradational systems based on their orientation. The Early system (19.27–17.89 km) comprises seven beach ridges over an area of 100 km². It forms a narrow band in the north and a wider strandplain with a succession of coastal spits to the south. The temporal amplitude of the Early system spans approximately 1297 years based on the minimum–maximum envelope, whilst the 95% credible range provides a more constrained estimate of approximately 535 years, corresponding broadly to the interval ca. 2500–1700 BCE. This is broadly consistent with the chronological framework proposed by Stefani and Vincenzi (2005), although the apparent discontinuity within this phase is likely attributable to an erosion surface that separates the two sub-systems.

The second system (17.88–13.75 km), associated in the literature with the Messanico branch mentioned by Pliny the Elder (*Nat. Hist.*, III, 20, 119–121; Veggi and Roncuzzi, 1968), comprises 39 beach ridges covering an area of approximately 170 km². This system spans a greater temporal range than the previous system, at nearly 1000 years, the modelled ages obtained partially overlap. In SPI-C4, plant material recovered from the upper shoreface was dated to 1871–1539 BCE, providing a calibration point for the CSM at the onset of this system. Further east, plant material from core SPI-C9, sampled from the terminal beach ridge and dated to 1047–831 BCE, corroborates the arrival of the Po di Spina system in this area, estimated after the 8th c. BCE (Veggi, 1974; Balista, 2018). These results are consistent with the chronological framework established by Bondesan et al. (1995), who attributed these formations to the mid-Subboreal to early Subatlantic period.

Stretching from 13.75 km to 4.03 km from the shoreline, the Spina system is the principal strandplain in this region, comprising 93 beach ridges (Fig. 7) and covering a minimum surface area of 282 km². It displays an exceptional temporal span, with a maximal amplitude of ≈1914 years based on the absolute minimum–maximum range (966 BCE–948 CE), whilst the 95% confidence interval indicates a lifespan of ≈1671 years (843 BCE–829 CE). Flatter age distribution values indicate an acceleration in progradation velocity towards the 3rd c. BCE, which is further reflected in the increasingly wider spacing of beach ridges as the delta opens seaward. Paradoxically, the most recent phases of the Spina lobe are the least well documented (Fig. 7). This gap is nonetheless offset by the Roman villa and artefacts uncovered in the eastern part of the system (Uggeri, 1975, 2006), helping to constrain the progradational curve over the final centuries of the system's activity. For the most

recently digitised beach ridge, the model places its formation between 499 and 818 CE (95% confidence interval). Beyond the Spina lobe itself, another Padanian river mouth further north, the Sagis, named after the *Sagis ad Padum* travel station (*Peutinger map*; Cremonini, 2021), was likely active around the 3rd–4th c. CE (Patitucci Uggeri, 1989). In core EMS7, located east of this configuration, a deltaic front shell dated to 74–445 CE (Amorosi et al., 2017) represents the last dated sample and defines the maximum seaward extent of the delta front prior to its subsequent erosion.

The Volano system presents a shorter section spanning 2.29–4.03 km and comprising 18 beach ridges, although only its distal portion is captured here, necessitating further detailed investigation. Age distributions for this system are less well-constrained than those of the preceding systems, with 95% confidence ranges averaging approximately 365 years, compared to a total temporal amplitude of approximately 973 years estimated from the absolute minimum–maximum envelope; this discrepancy suggests that the credible intervals may underestimate true age uncertainty. The core SPI-C16, collected beyond the erosive discontinuity, could not be successfully dated, as plant material yielding an age of 750–396 BCE was rejected by the model (Fig. 6). Two shells recovered from cores 205S04 and 187S1, dated to 717–1025 CE and 509–784 CE respectively, indicate that beach ridge formation on the left bank of the Volano commenced during the Late Antiquity–Early Middle Ages transition (Amorosi et al., 2019; Cremonini, 2021).

Taken together with the Spina chronology, these dates suggest a rapid transition from the dismantling of the Spina lobe to the initiation of the Volano system, likely facilitated by the short distance between the avulsion point near Ferrara and the site of deltaic deposition (Figs. 2 and 8). Plant material dated to 420–605 CE from the uppermost fluvial unit of core SPI-C2, alongside charcoal dated to 431–587 CE from PEG-1 (Balista and Berti, 2017), provides the most recent dates within the infilling sequence, indicating that the Spina palaeochannel was entering its final infilling phase by the late 6th or early 7th c. CE (Fig. 8). These fluvial ages overlap with the formation of the earliest Volano beach ridges, suggesting a transitional period during which both distributary systems were likely active simultaneously. This timing is consistent with Cremonini's (2021) suggestion that the Po of Spina ceased to function between the early 5th and mid-6th c. CE, as further supported by the CSM (Fig. 7). The medieval emergence of the hydronym *Padus Vetus*, meaning 'old Po', lends additional support to the hypothesis of channel abandonment during this period (Rucco, 2015). Further south, delta-front deposits are interpreted as the product of activity from the Primaro branch, which developed contemporaneously with the Volano (Ciabatti et al., 2006; Curzi et al., 2006).

The most recent beach ridges formed after the Po River migrated northward. The modern system, spanning 2.28–0 km and comprising 22 ridges, developed around the river mouth established after 1152 CE, reflecting the distal deposits of the modern lobe accumulated over roughly eight centuries. However, the youngest ridges have been considerably altered by coastal management interventions, including beach nourishment and mechanical cleaning (Montanari and Marasmi, 2012).

5. Discussion

5.1. Deltaic morphological changes over time

Prior to the development of the Spina lobe, the Mezzano Lowland functioned as a tidally influenced estuarine drainage system from ca. 4000 BCE onward, shaped by local embayment morphology and high-stand sea levels (Giacomelli et al., 2018). The north–south-oriented strip closing the Mezzano Lowland to the east formed the earliest progradational system (Balista, 2018), which is partly eroded (Fig. 9). This discontinuity is clearly visible just north of Spina, where seven beach ridges separate SPI-C14 from the hiatus marking the end of this system.

The Messanico branch crossed these beach ridges to form a far more

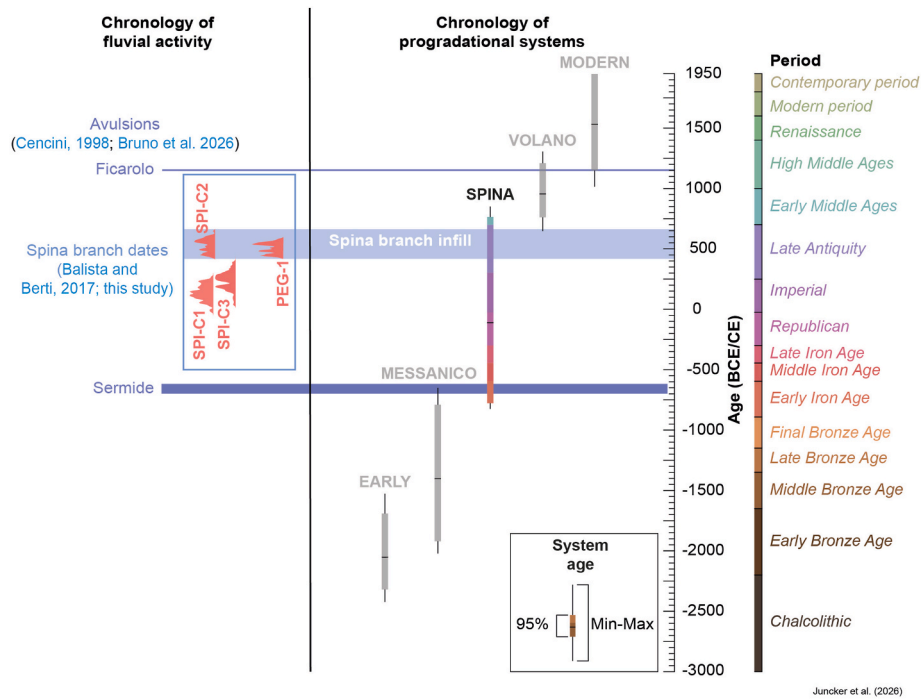


Fig. 8. Chronological boundaries of the beach-ridge systems along the studied cross section estimated with the CSM and calibrated by the palaeo-fluvial data, including radiocarbon dates (Balista and Berti, 2017; this study) as well as the recorded historical avulsions (Cencini, 1998; Bruno et al., 2026).

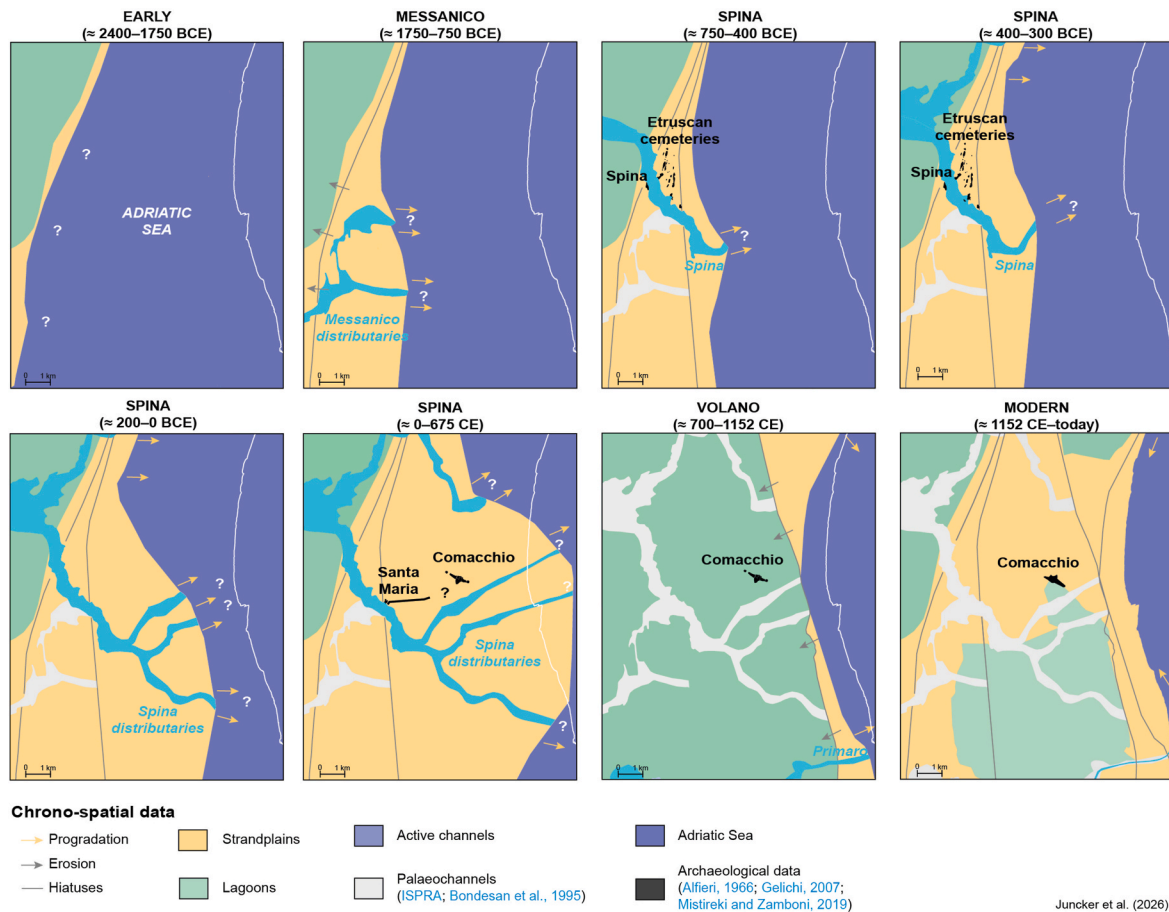


Fig. 9. Reconstruction of the successive coastal progradational systems near Comacchio, from the Bronze Age to the present, highlighting the development and spatial extent of the Spina deltaic system.

developed wave-dominated delta, with 39 beach ridges prograding into the present-day Comacchio lagoons (Cremonini, 1993, 2007; Bruni, 2020), suggesting that, as an important southern tributary of the Po, it carried a significant sediment supply. This branch probably diverged into two distributaries, one trending southwards and one northwards (Fig. 9). This bifurcation is reflected in the morphology of the associated ridges, which exhibit a distinctive convex geometry near Spina, unlike the straight or concave profiles typically observed in other strandplains. Such geometry arises from the interaction between wave energy and approach angles: as incoming waves shift direction relative to the deltaic shoreline, the ridges progressively narrow towards each mouth, broadly consistent with wave-driven sediment transport mechanisms (Ashton and Giosan, 2011). The left bank furthermore underwent a long-term morphological transition, evolving from an initial convex configuration through a straight profile to a pronounced concave shape, reflecting the progressive reorganisation of the system around these two outlets. The southern mouth was probably eroded prior to the establishment of the Spina system, which marked a significant reorientation of the shoreline. In the Comacchio lagoons, the earliest coastal ridges associated with the Po di Spina trend north–south, occupying precisely the position of the former Messanico terminus (Fig. 9).

For the Spina system, five main chronological intervals have been identified (Fig. 10):

The Spina system initiated under slow progradation rates (5.7 m/yr), reflecting steady but moderate sediment input across 1.99 km. The Sermide avulsion marks a pivotal transition in the evolution of the Po Delta, decoupling the southern plain from sustained sediment supply and shifting the locus of deltaic progradation eastward (Fig. 1). The sedimentary record of this avulsion node (U3) reveals a weakly sinuous, anastomosing river pattern, typical of avulsion-controlled systems and characterised by the deposition of medium to coarse sands (Bruno et al., 2026). The age obtained from the CSM is consistent with these chronological bounds (Fig. 8).

As can be seen on the Messanico strandplain, the beach ridges here are concave, which is typical of a wave-dominated delta. Although the river initially flows southwards, a strong coastal drift forces it to re-direct northwards, creating an asymmetrical delta. This is likely due to the Sirocco wind, which plays a key role in the longshore drift process in the northern Adriatic by controlling the direction of the swell and guiding the drift currents. This helps to redistribute sediments preferentially in a north-west direction. In the direction of Comacchio, core 205S10, which was obtained from the right bank of the Po di Spina branch, shows no evidence of river mouth or fluvial facies (Amorosi et al., 2003). The absence of facies S3 and the described lagoonal facies could be consistent with a swale morphology where a shell was discovered and dated to 328 BCE–69 CE (Amorosi et al., 2019). Since the Middle Ages (ca. 700–1400 CE), substantial subsidence has largely obscured the right bank of the strandplain. Nevertheless, the Boscoforte

peninsula remains a prominent geomorphological feature within the Comacchio lagoon and a remnant of the system that was established during the 1st millennium BCE (Fig. 2). This relief forms a series of positive elevations ranging from 0.5 to 2.6 m a.s.l. and cannot be attributed to recent land development, as the peninsula is already depicted on early cartographic documents, including *Romagna olim Flaminia* by G. A. Magini (1598 CE). However, the origin of this ridge's elevated position relative to neighbouring ridges has not been studied, and further north, a high-elevation ridge appears to be continuous (Ciabatti, 1966).

The relation is clearer for the timeframe between the end of the 5th c. BCE and the end of the 1st c. BCE. A linear relation is observed between the progradation distances and the rates. This indicates the gradual growth and expansion of the delta. As the amount of sedimentary material accumulates, the lobe advances at an accelerated rate (Fig. 10). The supply of a greater volume of sediment also results in an increase in the amount and diversity of organic matter, which makes the precise dating of these recent forms challenging. This is evidenced by the high variability in the ^{14}C ages rejected by the model (Fig. 6). For example, SPI-C7 yielded ancient plant material dated to 821–563 BCE, a result substantiated in SPI-C8 and in VSF2000-1 (Mozzi et al., 2021). Similarly, SPI-C15, collected in the last beach-ridge before the erosion zone, contained plant material dated to 1000–818 BCE. The presence of reworked materials reflects erosive activity in the upper Po plain, resulting from the river's division into three distributaries east of the main deltaic system and marking the onset of a southward channel migration (Balista and Berti, 2017, Fig. 2). Although prodelta deposits found to the south suggest activity of late distributary branches draining into adjacent valleys (Ciabatti et al., 2006), this fluvial migration remains poorly documented. Nonetheless, it is broadly consistent with the Roman Republican period, as suggested by the CSM (Fig. 6). Although most reconstruction scenarios rely on Pliny the Elder's account of the seven Po mouths (*Nat. Hist.*, III, 119–121), translating this text into geographical reality remains challenging (Calzolari, 2007). Pliny the Elder notably mentions that Emperor Claudius (r. 41–54 CE) sailed this section of the Po during the celebrations following his triumph in Britain in 44 CE (Roncaglia, 2019), suggesting that the channel was active during the Roman Imperial Period.

The CSM clearly underestimates progradation during this period as a result of coastal erosion (Fig. 9). This methodological limitation is significant for the period 0–675 CE (Fig. 10), where progradation rates decrease drastically despite a greater distance covered by the model. Based on spatial reconstruction, progradation rates were most likely greater than 12 m/yr. A progradation rate of 12 m/yr represents an exceptional degree of fluvio-coastal mobility, resulting in a shoreline displacement of 120 m per decade and 1200 m per century. On the other hand, the widening gap between increasingly arched ridges indicates significant progradation rates and delta transformation as river influence and longshore drift intensified. This deltaic advance likely led to the formation of three distributary branches, which reflect an anastomosing fluvial pattern characterised by frequent avulsions, slow channel abandonment and the contemporaneous maintenance of active branches across the floodplain (Makaske, 2001). In such systems, the distribution of discharge across multiple channels reduces stream power per channel, thereby enhancing lateral stability while dispersing sediment deposition rather than concentrating it. This subdivision reduces the energy of the mouth plume, favouring the lateral and proximal dispersion of sediment (Syvitski et al., 2005), which promotes the enlargement of swales. Ancient writers documented the presence of these vast lagoons and their regional significance (Herodian, *Hist. Rom. Emp.*, VIII, 7; Pliny the Elder, *Nat. Hist.*, III, 119; Pomponius Mela, *De Chorographia*, II, 62). These processes ultimately transformed the previous cusped mouth into a lobate, bird's-foot delta, covering a surface area of approximately 380 km², comparable to the modern delta, and likely extending beyond the current coastline (Fig. 9). Meanwhile, the northern sector was characterised by significantly lower littoral mobility. The Adige

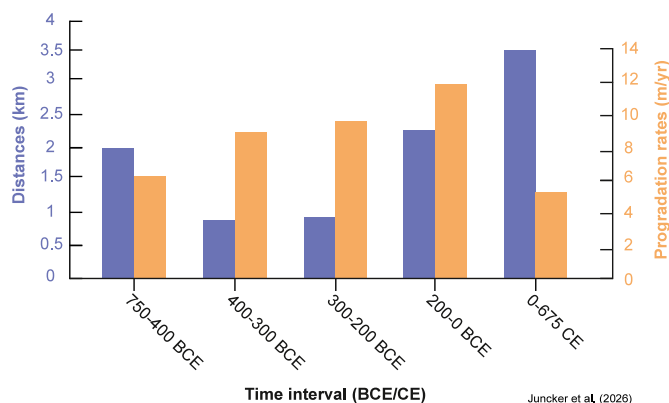


Fig. 10. Progradation distances (km) versus progradation rates (m/yr) of the Spina coastal system during the main phases of its evolution.

preserved its mouth position from the early 1st millennium BCE through to the Roman Empire, forming a smaller delta to the south of the Venice Lagoon (Piovan et al., 2012). The extensive Spina delta underwent severe erosion, leaving a remnant visible as a broad elongated ridge (0.5–1.7 m elevation) beneath the modern coastal road, contrasting sharply with the surrounding reclaimed valleys. The eastward emergence of a new distributary branch, the Volano, signalled a significant shift in ridge orientation, establishing the subsequent deltaic system (Fig. 9).

5.2. Strengths, limitations and transferability of the CSM

The CSM developed in this study represents a multi-proxy integrative approach that overcomes the limitations of conventional linear progradation estimates. By synthesising high-resolution geomorphological mapping, archaeological archives, and new geochronological data, the CSM treats coastal progradation as a dynamic and non-linear process. The strength of this framework lies in its ability to convert diverse spatial indicators into a continuous chronological sequence. In this architecture, the rbacon framework acts as the computational engine, dividing the stratigraphic sequence into contiguous sections with independent accumulation rates drawn from a gamma distribution. In contrast to uniform interpolations, this integrated methodology accounts for local fluctuations in sedimentation and progradation, helping to identify specific pulses of deltaic growth or phases of relative stability. Therefore, the resulting age-distance curve is not merely a statistical output but also a probabilistic envelope based on the physical reality of the Po Delta's evolution. This envelope is influenced by prior geomorphological assumptions and empirical radiocarbon evidence.

Although the CSM offers a robust and innovative framework, its full potential is best appreciated when considered alongside certain methodological and conceptual factors. A fundamental constraint stems from the radiocarbon calibration curve, particularly during plateaux such as the Hallstatt (ca. 740–445 BCE) and later (ca. 350–200 BCE) intervals, where stable atmospheric ^{14}C concentrations produce multimodal probability distributions severely limiting chronological resolution (Reimer et al., 2020). While rbacon mitigates these uncertainties through stratigraphic ordering and accumulation rate priors, it cannot fully eliminate plateau-related ambiguities. Additional challenges emerge from depositional environment variability, as the model does not formally incorporate facies changes into its Bayesian framework. The integration of archaeological markers presents further complications. Essential for chronological control, these may introduce circular reasoning when typological dating conflicts with radiometric evidence. The Logonovo shipwreck exemplifies this issue, initially dated to the 15th–16th c. CE based on typology but later reinterpreted as late 18th–early 19th c. after accounting for the old-wood effect (Canalini, 2009). Moreover, Bacon's treatment of archaeological date ranges as Gaussian distributions, despite them typically being expressed as uniform intervals, may distort chronological uncertainty by implying unimodal probability densities centred on interval midpoints.

The CSM demonstrates considerable potential for application across other well-documented deltaic systems, such as the Tiber (Salomon et al., 2018; Salomon, 2020), Rhône (Vella et al., 2005), and Nile deltas systems (Stanley et al., 1996; Marriner et al., 2012). However, its reliability in such settings depends on a targeted coring strategy that is aligned with the specific geometry of the delta or mouth lobes. Its particular strength lies in reconstructing shoreline trajectories in systems with abundant sediment supply and clear geomorphological or archaeological evidence of progradation.

To enhance its accuracy and temporal resolution, several improvement avenues exist. Multi-proxy approaches could provide independent chronological constraints, with OSL dating offering direct sediment deposition ages (albeit with 5–10% precision) and dendrochronology providing near-annual resolution when wooden remains are available. The integration of fluvial dynamics data, including historical avulsions

(e.g., Ficarolo in 1152 CE) and hydraulic works (e.g., canal excavations), would particularly benefit distal progradation front chronologies.

Crucially, the model's flexibility allows for continuous enrichment through historical data, including archival records of coastal engineering projects, land reclamation efforts, storm events, and navigation patterns, which can provide independent validation of progradational chronologies. This historical dimension proves particularly valuable for recent centuries where documentary evidence becomes abundant. Furthermore, interdisciplinary collaboration remains essential, requiring critical evaluation of evidence across geomorphology, archaeology, and historical philology to avoid forcing interpretations into preconceived narratives (Arnaud, 2000; Leveau and Troussset, 2000). Adopting a reflexive, multi-method approach that considers inherent uncertainties and incorporates various data streams can transform the CSM from a heuristic tool into a robust framework for reconstructing past deltaic changes in many deltas worldwide.

5.3. Drivers of delta growth

Having estimated progradation rates and geomorphological changes, we now turn to the potential drivers of these deltaic transformations. We shall examine both climatic and anthropogenic forcing at global and regional scales, although these interpretations should be approached with caution, as Lespez (2025) warns that the statistical sophistication of Bayesian models can create an illusion of precision while potentially reinforcing existing interpretative frameworks.

Before the emergence of the Spina system, regional pollen records indicate a drier, warmer Subboreal period (2750–950 BCE), characterised by the prevalence of Mediterranean broadleaved species such as holly oak (*Quercus ilex*) and evidence of significant deforestation (Accorsi et al., 1996; Mercuri and Sadori, 2014). Evidence from the Adriatic RF93-30 core (Oldfield et al., 2003) and the EM2 core near Ferrara (Cacciari et al., 2018, 2020) confirms widespread deforestation and human expansion around 1650–1700 BCE, favouring the expansion of pastoral taxa. Within the Po Plain, climatic stress acted as a co-factor in the collapse of the Terramare culture, compounded by intensive agropastoral activities, deforestation, and resource depletion. Together, these pressures led to widespread site abandonment and the abrupt disappearance of the Terramare in the 12th c. BCE (Cremaschi, 1997; Cremaschi et al., 2006; Cremaschi et al., 2016; Mercuri et al., 2006). Paradoxically, upstream Po basin lakes maintained high water levels and flood frequency despite a regional aridification trend, suggesting localised humid conditions (Magny et al., 2013).

The erosive discontinuity separating the Spina and Messanico systems has been identified along the delta (Stefani and Vincenzi, 2005; Balista, 2018) and was originally attributed to the cold, windy Göschenen I oscillation (Zoller et al., 1966; Burga et al., 2001). However, recent glaciological reassessments question the occurrence of a significant glacier advance during this phase and suggest that Göschenen I should not be regarded as a distinct glacial stage (Boxleitner et al., 2019). This period of climatic instability broadly overlaps with the Homeric minimum (770–580 BCE), a period of reduced solar activity associated with cooling and increased atmospheric instability (Martin-Puertas et al., 2012). Rather than reflecting a direct glacial forcing, this climatic instability may have intensified fluvial activity across the Po catchment. As demonstrated by Glur et al. (2013), cold phases promote shifts or intensification of storm tracks over Central Europe, increasing the frequency of extreme precipitation events in the Alps and amplifying flood regimes at the catchment scale. The erosive discontinuity recorded in the Spina system may therefore reflect a hydroclimatic response to large-scale atmospheric forcing rather than a purely local geomorphological signal.

Between 750 and 400 BCE, minimum progradation rates remained stable at ≥ 6 m/yr during the initiation of the wave-dominated delta (Fig. 11). The appearance of this lobe took place against a backdrop of sustained hydrological intensification, characterised by elevated water

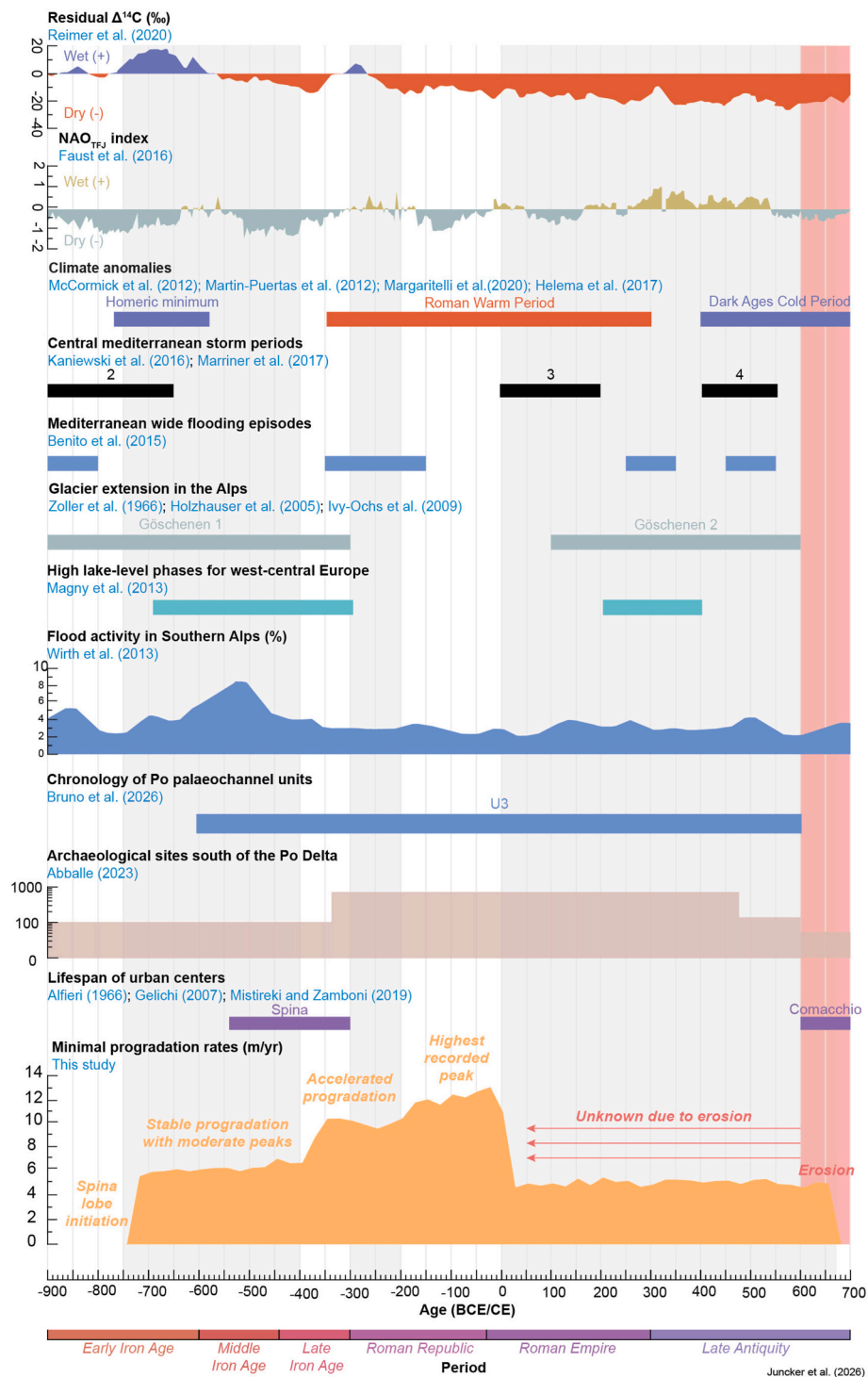


Fig. 11. Comparison of measured deltaic progradation rates for the Spina system with reconstructed global and regional climatic and anthropogenic proxies. Residual $\Delta^{14}\text{C}$ (Reimer et al., 2020) acts as a global proxy for natural solar forcing fluctuations. The North Atlantic Oscillation (NAO) index (Wanner et al., 2001; Faust et al., 2016) reflects the pressure difference between the Azores High and the Icelandic Low, directly influencing Mediterranean climate; positive NAO phases correlate with drier conditions, whilst negative phases correlate with wetter periods (Pociask-Karteczka, 2006). Late Holocene warm and cold periods (McCormick et al., 2012; Helama et al., 2017; Martin-Puertas et al., 2012; Margaritelli et al., 2020) serve as indicators of thermal forcing in climate variability, encompassing events such as the Roman Warm Period and the Little Ice Age. Mediterranean storm periods, identified from stratigraphic archives (Kaniewski et al., 2016; Marriner et al., 2017), denote high-energy coastal events linked to phases of climate deterioration in the Mediterranean and North Atlantic. Mediterranean-wide flooding episodes (Benito et al., 2015) provide evidence of large-scale hydrological extremes. Glacial advances in Alpine valleys (Zoller et al., 1966; Holzhauser et al., 2005; Ivy-Ochs et al., 2009) function as proxies for past climate conditions, influencing water flow in the Po River's tributaries (Cremaschi et al., 2016; Balista, 2018). High-lake-level phases (Magny et al., 2013) reflect wetter climatic conditions, whilst flood activity in the Southern Alps (Wirth et al., 2013) records periods of heightened precipitation and river discharge. The multiproxy chronostratigraphic scheme for the Po River (Bruno et al., 2026) establishes the temporal framework for late Holocene channel activity and avulsion phases. The number of archaeological sites south of the Delta (Abballe, 2023) and the lifespan of the main sites (Alfieri, 1966; Gelichi, 2007; Mistireki and Zamboni, 2019) act as regional indicators of anthropogenic pressure. The grey background denotes the main chronological intervals derived from the CSM.

levels across Western Europe, the Alps, and central Italy (Magny et al., 2013), conditions that are well documented throughout the region during the Iron Age, as illustrated by the lower Mincio valley (Ravazzi et al., 2013). These enhanced precipitation patterns probably ensured a sustained supply of water and sediment discharge for the Po River, which could have provided the consistent sediment supply needed to maintain steady rates of deltaic progradation. This could explain the relatively uniform progradational dynamics observed during the formation of the Spina lobe in its early centuries. During the mid-6th c. BCE, the Po Plain underwent significant territorial reorganisation, characterised by substantial population growth and the development of urban centres, including Spina, which was founded around 530–520 BCE (Quirino, 2017; Mistireki and Zamboni, 2019; Zamboni, 2021). During this time, archaeological sites south of the Po Delta increased in number (Abballe, 2023), while forest cover started to show a slight decrease in Europe (Kaplan et al., 2009). Although climatic forces still dominated overall erosive trends during the Subboreal–Subatlantic transition, the evolution of catchments into complex anthroposystems characterised by incipient farming practices meant that spatial erosion patterns increasingly reflected human activity (Allée and Lespez, 2006). This early anthropogenic shift probably caused an increase in sediment yields, as land clearance and cultivation started to alter natural erosion processes across the Po catchment. However, human influence remained secondary to the prevailing wet phase, which continued to drive sustained progradation through enhanced natural delivery.

The progradation rates of the Spina lobe increased significantly during the interval from 400 to 200 BCE, reaching values of at least 9 m/yr (Fig. 11). However, this phase of accelerated coastal advance, which partially overlapped with the Early Roman Warm Period (ca. 250 BCE–400 CE), exhibited slight deceleration or stabilisation between 300 and 200 BCE. This climatic phenomenon was regionally variable rather than globally synchronous (Bianchi and McCave, 1999; Neukom et al., 2019; Shi et al., 2022), and disparities in regional sea surface temperatures suggest that warming trends were not uniform during this generally stable period (Margaritelli et al., 2020). The progradational pulse also coincided with a marked intensification of anthropogenic pressure from the mid-4th c. BCE onwards, as evidenced by the rise in recorded settlement sites south of the palaeodelta (Abballe, 2023), reflecting a rapid expansion of human occupation and land use across Northern Italy. Environmental transformation during Roman expansion resulted from the complex interplay of institutional, technological, and socio-economic factors beyond simple demographic pressure, with Romanisation intensifying land use through agricultural specialisation and the systematic settlement of high-quality lands (Mather and Needle, 2000; Lo Cascio, 2004; Zerbini, 2007).

The highest progradation peak is estimated between 200 and 0 BCE, when the coastal shoreline model reaches ca. 12 m/yr (Fig. 11). In a broader geomorphological context, such sustained rates highlight the extraordinary level of deltaic expansion, implying a shoreline displacement of over a kilometre within a single secular interval. This exceptional progradation was likely driven by the convergence of rapid urbanisation, road network expansion, and systematic land division through centuriation along the *Via Aemilia* (Chevallier, 1961; Franceschelli, 2008; Bertrand, 2021). These cumulative pressures drove large-scale land clearance for agriculture and urban development across the Po plain, contributing to the sharp decline in forest cover documented across Europe during this period (Kaplan et al., 2009) and likely amplifying erosional fluxes towards the delta. The combination of optimal climatic conditions, intensive land use, and hydraulic infrastructure thus maximised sediment supply through enhanced erosion and runoff, sustaining exceptional progradation rates in the Spina lobe well into the early imperial period.

The progradation increased significantly during and after the 1st c. CE until the 6th–7th c. CE (Fig. 11). Although the values measured here remain below 4 m/yr, the actual rates were in all likelihood substantially higher, probably exceeding 12 m/yr, given that a significant proportion

of coastal archives has been lost by erosion, leaving centuries of progradation unquantified and systematically underrepresented. By the end of the 3rd c. CE, anthropogenic pressures had caused severe environmental deterioration in the Po plain, characterised by accelerated erosion that, according to Marchetti (2002), probably led to rapid delta progradation. This dynamic is broadly consistent with the pattern identified by Maselli and Trincardi (2013), who demonstrate that the major southern European deltas (Ebro, Rhône, Po and Danube) grew in synchrony during the Roman Empire and the Little Ice Age. While the progradational phases identified here align with this synchrony, the rates reported by Maselli and Trincardi (2013), reaching 20–40 m/yr for the Po, considerably exceed the values reconstructed in the present study, a discrepancy that likely reflects both the erosional loss of coastal archives and differences in spatial and temporal averaging between datasets. This period of sustained progradation progressively gave way to significant environmental deterioration during the 5th–6th c. CE, marked by numerous avulsion events (Cremonini et al., 2013; Brogiolo, 2015), reflecting a long-term pattern of riverbed aggradation and landscape instability driven primarily by the collapse of Roman land management systems. This fluvial instability manifested locally through the formation of numerous crevasse splays (Mozzi and Rucco, 2023). Furthermore, the avulsions of the Primaro and Volano rivers are attributed to this same transitional phase, which occurred amid a sharp demographic decline and a decrease in the number of archaeological sites (Abballe, 2023) during the era of invasions (300–600 CE).

The 7th c. CE erosion of the delta lobe (Fig. 7) occurred during the Dark Ages Cold Period (410–775 CE), a climatic phase characterised by reduced solar irradiance, lower temperatures, and recurring drought episodes (Helama et al., 2017). Decreased solar activity is known to intensify the frequency and severity of coastal flooding events (Kaniewski et al., 2016), an effect further compounded by the prolonged negative NAO index that characterised this period, bringing harsh winters and persistently wet conditions across the Mediterranean (Pociask-Karteczka, 2006). In the Western Mediterranean, this climatic instability is evidenced by lagoonal storm deposits, identified by coarse grain size and strontium enrichment, which reveal a resurgence of high-energy storm events between 400 and 800 CE, with a peak from 600 to 750 CE during periods SP6 and SP5 (Degeai et al., 2015). These sedimentary archives coincide with proxies from Core AQ III in Aquileia, where records indicate that cold and wet phases also occurred during the Late Antique Little Ice Age (ca. 535–660 CE), a sub-period triggered by several major volcanic eruptions (Kaniewski et al., 2022; Büntgen et al., 2016). This cooling, confirmed by dendroclimatological data across Eurasia, is thought to have contributed to famines, the Plague of Justinian, mass migrations, and political upheavals (McCormick et al., 2012; Zonneveld et al., 2024). Together, these climatic and demographic disruptions significantly curtailed sediment delivery to the delta mouth, inducing a systemic deltaic disequilibrium in which marine processes prevailed over weakened fluvial inputs. Such observations corroborate the estimates of Maselli and Trincardi (2013), highlighting a generalised retrogradation of North Mediterranean deltas following the fall of the Western Roman Empire (395–476 CE). This morphological retreat thus primarily reflects the drastic reduction in anthropogenic pressure that accompanied the collapse of Roman-era land use: population decline, reforestation, and the abandonment of intensive agriculture reduced soil erosion and sediment yield, reinforcing this shift towards morphodynamic equilibrium. This contrasts sharply with the previous period, when combined anthropo-climatic forcing drove accelerated progradation and a river-dominated, lobate morphology.

5.4. Consequences of deltaic progradation on settlement dynamics

Little is known about the earliest settlements in the area. The Podere Boccagrande and Podere Alberti sites in the Mezzano Lowland are the oldest documented settlements, dating to the Final Bronze Age–Early Iron Age (Saronio, 1987, 1993; Bermond Montanari, 1993; Cattani and

Boccuccia, 2018). As outlined in previous sections, the first major settlement in this region was Spina, founded in the second half of the 6th c. BCE (Reusser, 2021). The city was established on the left bank of the Messanico strandplain, adjacent to a Po palaeochannel, within a complex hydrological network in which the Padanian tributaries lacked the energy to breach the coastal ridges, including the Santerno River, which descends from the Apennines and joins the Vaternus branch, reusing the Messanico palaeochannel (Bucci, 2023). Etruscan necropolises developed parallel to the reconstructed protohistoric coastline to the east of Spina and provide valuable palaeotopographical data. However, most of the Valle Pega burials remain unstudied, as do the dynamics of the area's occupation (Gaucci and Mancuso, 2016; Mancuso and Zampieri, 2023). The necropolises of Valle Trebba and Valle Pega together form a single, spatially continuous funerary complex, distributed across a series of sandy ridges known as *Dossi*. The southern sector, Valle Pega, comprises funerary areas located on these ridges, with the core of SPI-C9 corresponding to the easternmost *Dosso A* and containing 734 documented tombs (Desantis, 2017). The orientation of these ridges, broadly parallel to the reconstructed protohistoric shoreline, provides independent palaeotopographical constraints on the coastal configuration during the city's occupation. The CSM results are consistent with this picture, indicating that the strandplain deposits beneath Spina were formed around 1500 BCE, approximately one millennium before the city's foundation, in agreement with the 2500–1500 BCE interval proposed by Stefani and Vincenzi (2005).

A rectilinear fluvial anomaly approximately 2 km in length runs through the strandplain in the vicinity, corresponding to the course of the Motta della Giratta Canal (Fig. 9). This structure, approximately 30 m wide, has been dated to the post-Roman period (Balista et al., 2007; Balista and Berti, 2017; Rucco, 2015), rendering any direct attribution to the Etruscan inhabitants of Spina untenable (Alfieri, 1959a). Nevertheless, in light of the CSM results, the hypothesis that the Etruscans sought to maintain coastal access by excavating a passage through the prograding beach ridges of the 1st millennium BCE remains plausible, with a more likely location identified further north, between Valle Pega and Valle Trebba (Govi and Gaucci, 2024). Recent archaeological studies have further revealed evidence of a river connection to the early medieval settlement of Comacchio (Rucco, 2015; Beltrame et al., 2021). By this period, the delta had already reached an advanced stage, covering approximately a third of its future maximum surface area and obstructing access to the city, which was situated some 6 km from the river mouth by the 3rd c. BCE.

The city of Spina faced steady delta progradation along its seaward margin until approximately the end of the 4th c. BCE. The *Periplus of Pseudo-Scylax*, now considered to describe a situation dated to the first half of the 4th c. BCE (Pseudo-Scylax; Brillante, 2020), provides crucial evidence for reconstructing the progradation of the Spina system: the Greek navigator estimated the distance between the city and the mouth of the Po at 20 stadia (ca. 3.5 km), suggesting that Spina was still relatively close to the shoreline at that time (Counillon, 2004; Patitucci Uggeri and Uggeri, 2017). This period also corresponds to a significant decline in Athenian ceramic imports, though the region adapted by establishing new trading networks (Gaucci, 2015; Gaucci et al., 2024). The latest archaeological activity in the excavated urban area corresponds to the extraction of salt using briquetage techniques dated to around 300 BCE (Reusser, 2024). This shift in function from residential to artisanal use reflects a profound transformation of the city's urban fabric during its final phase (Mistireki and Zamboni, 2019; Reusser, 2021). However, funerary and epigraphic records suggest that the site remained occupied until at least the mid-3rd c. BCE, before a gradual decline whose chronology remains debated and is commonly attributed to a combination of geopolitical pressures and environmental deterioration (Gaucci, 2016; Mistireki and Zamboni, 2019). By the 1st c. BCE, when the coastline had shifted considerably, (Strabo, *Geographica*, V, I, 7) recorded a distance of 90 stadia (ca. 16.6 km) between Spina and the sea (Patitucci Uggeri and Uggeri, 2017), implying a net progradation of

approximately 13 km over three centuries. The CSM provides a quantitative reassessment of this progradation, estimating that the delta advanced by approximately 2 km between the 4th and 1st centuries BCE. This offers, for the first time, a model-based calculation of the rate at which deltaic expansion encroached upon Spina during the period of its decline and eventual abandonment. The delta had already prograded by around 2 km between 750 and 400 BCE, bringing the total advance to roughly 4 km by the time Spina ceased to exist. Although geopolitical pressures and shifting trade networks played a well-documented role in Spina's decline, the CSM results suggest that deltaic progradation was nonetheless a significant contributing factor. The progressive seaward displacement of the shoreline would have imposed increasing constraints on navigability and the potential burial of harbour infrastructures under prograding sediments. Such conditions would have progressively undermined the city's capacity to maintain the maritime and fluvial connectivity on which its economic prosperity depended, a dynamic well documented in comparable deltaic harbour contexts across the ancient Mediterranean (Giaime et al., 2019).

Over the following centuries, the deltaic landscape was transformed into an anthropo-hydro-lagoonal system (Rousse, 2007), shaped by major hydraulic works, including canals running parallel to the shoreline. The *Fossa Augusta*, considered to have been constructed under Augustus (r. 27 BCE–14 CE), is the best documented one (Pliny the Elder, *Nat. Hist.*, III, 119–120; Sidonius Apollinaris, *Let.*, I, 5; Jordanes, *Get.*, XXIX, 150; Rousse, 2005). This canal probably ran through the study area, partially following the course of the Vaternus palaeochannel (Bucci, 2023), as suggested by the presence of nearby lighthouse remains (Marrocchino et al., 2022). Notably, the *Fossa Augusta* was an important infrastructural link connecting the port of Classis to Ravenna, a major Roman settlement which had no direct connection to the Po waterway (Augenti and Cirelli, 2012; Abballe et al., 2022). Subsequently, the *Fossae Clodia* and *Flavia* were also excavated (Pliny the Elder, *Nat. Hist.*, III, 119–120). This engineered landscape supported dispersed rural settlements (*villae*, *vici*, *fossae*) sustaining water-based economies of *saltus* management, fish farming, and salt production (Peutinger Map; Uggeri, 1978, 2020; Rousse, 2016; Salomon and Rousse, 2022; Page, 2024; Patitucci Uggeri, 2015). Archaeological evidence includes the *Agosta*, *Salto del Lupo*, *Baro degli Ortazzi* and *Lagosanto* villas and the *Bocca Delle Menate* factory, which transitioned to a villa (Uggeri, 2006, 2020; Patitucci Uggeri, 2015; Rizzo et al., 2023). In this context, the CSM contributes to identifying the palaeoenvironmental setting of key archaeological sites and offers a spatial framework conducive to future research on human-environment trajectories across this vast deltaic region. It should nonetheless be regarded as a heuristic tool rather than a substitute for site-specific palaeoenvironmental analysis, which remains essential for interpreting the local stratigraphic and ecological contexts of individual sites.

The Paleo-Christian Church of Santa Maria in Padovetere was founded during the maximum deltaic expansion in the Late Antiquity period, between 519 and 521 CE, at the intersection of the Po and the beach ridges (Alfieri, 1966). A cemetery and the remains of a harbour development have been discovered, along with a 5th-c. river barge. A detailed study of the barge confirmed fluvial activity during this period (Beltrame et al., 2021; Costa and Beltrame, 2021), which aligns well with our CSM-based estimation.

Later, Comacchio was founded in the 7th–8th c. CE following the estimated erosion period of the Spina system (Fig. 9; 10). The town was built on a distinctive ridge-and-swale terrain formed between 250 and 50 BCE, and its urban layout closely follows a northwest-to-southeast orientation adapted to this morphology. Underlying beach ridges confirm the persistence of this substrate (Gasparini, 2005; Veronese, 2006), even though these coastal formations were subsequently eroded by meandering channels. The chronological alignment between Comacchio's foundation and the erosional truncation of the Spina system suggests a causal link between coastal instability and urban relocation. In this framework, the CSM implies that geomorphological

degradation of the Roman-era strandplain drove a regional settlement reorganisation towards more resilient lagoonal nucleation points. Bounded by lagoons to the east and by the sea to the west, where the Volano lobe progradation was underway, and accessible only via a single land route until 1840 CE (Maestri, 2013), Comacchio nonetheless emerged as a major trade hub in the northern Adriatic (Gelichi, 2007), mirroring Spina's earlier role and reflecting a broader pattern of urbanisation shaped by shifting deltaic formations.

6. Conclusion

This study presents a Chrono-Spatial Model (CSM) that, for the first time, reconstructs the trajectory of the main Po lobe over a pluricentennial scale from the 8th c. BCE to the 7th c. CE. By synthesising geomorphological and archaeological data within a Bayesian framework, this methodology represents a significant advance in quantifying deltaic processes, generating detailed interpolated age distributions for individual beach ridges and enabling precise progradation rate measurements. A key finding is the documented intensification of erosional processes during the Roman period, providing clear evidence of anthropogenic impact on coastal dynamics and contributing new data to broader debates on human-environment interactions in Mediterranean deltaic systems. Beyond these regional insights, the CSM demonstrates considerable potential for application in other well-documented deltaic environments worldwide, as its ability to integrate heterogeneous proxy data into a probabilistic chronological framework is not specific to the Po Delta context. Future research expanding the core dataset and incorporating additional archaeologically dated materials will not only refine model accuracy but also enable a more nuanced reconstruction of the Po Delta history, further consolidating the CSM as a robust tool for reconstructing past coastal changes.

Sample CRediT author statement

Joé Juncker: Conceptualization, Methodology, Investigation, Writing - Original Draft, Visualization. Ferréol Salomon: Conceptualization, Methodology, Investigation, Resources, Writing - Original Draft, Supervision, Funding acquisition. Andrea Gaucci: Investigation, Resources, Writing - Original Draft, Supervision, Project administration, Funding acquisition. Paolo Mozzi: Investigation, Writing - Review & Editing. Enrico Zampieri: Investigation, Writing - Review & Editing. Samuel Ladouce: Investigation. Laurent Schmitt: Supervision, Writing - Review & Editing.

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None. The author(s) did not use generative AI or AI-assisted technologies when writing this text.

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Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.quascirev.2026.110057>.

Data availability

A link to the data and/or code is provided as part of this submission.

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