



Palaeolandscape reconstructions for the Northern Adriatic: Inundation models, depositional environments, and potential archaeological implications

Samuele Ongaro^{a,*}, Federica Donda^b, Emanuele Lodolo^b, Emiliano Gordini^b, Rachel Bynoe^a, Fraser Sturt^a

^a Archaeology Department, University of Southampton, Avenue Campus, Southampton, SO17 1BF, United Kingdom

^b Section of Geophysics, OGS – Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Borgo Grotta Gigante 42/C, Sgonico, TS, 34010, Italy

ARTICLE INFO

Handling editor: Biagio Giaccio

Keywords:

Submerged landscapes
Northern adriatic
Holocene transgression
Marine geophysics
Sea level changes
Mesolithic
Neolithic

ABSTRACT

It has become increasingly clear that submerged landscapes can help address a range of archaeological questions from topics such as human migrations, coastal settlement in prehistory, and responses to sea level change. Our ability to approach such debates, however, is limited by our knowledge of paleogeographic developments at a human scale. This is still lacking for many regions, including the Northern Adriatic Sea, one of the largest submerged landmasses in Europe and a region very sensitive to landscape changes due to its fluvially-influenced geomorphological setting. In this study, we present palaeolandscape reconstructions for the Northern Adriatic between 9000 and 4000 cal BC, based on published sedimentary core data and unpublished high-resolution geophysical data. To achieve this, different depositional environments were identified and inundation models produced to characterise the palaeolandscape both from a spatial and temporal dimension. Different generations of barrier-backbarrier complexes are identified as well as lagoon, marsh, and delta environments developing during phases of stasis in sea level rise and rapidly drowned during periods of intense inundation. Our palaeolandscape reconstructions have direct archaeological implications for both the Mesolithic and Neolithic periods. The region's ancient coastal wetlands would have been extremely attractive to forager communities, but these societies would have had to respond to environmental changes linked to sea level rise. Likewise, when farming was spreading along the Northern Adriatic coastlines, major paleogeographic developments would have been occurring. We therefore demonstrate the importance of reconstructing submerged landscapes to our understanding of several key archaeological themes.

1. Introduction

This paper presents palaeolandscape reconstructions for the Northern Adriatic based on geophysical and geological data for the period between ca. 9000 and 4000 cal BC. By drawing on published records and new data it has been possible to map the paleogeographic development of the region while also considering its potential implications for key archaeological questions relating to the Mesolithic and Neolithic.

The need for this work has become well-established. Sea level has fluctuated by as much as 120–150m over the past 2.5 million years in direct relation to glacial-interglacial cycles, radically reconfiguring land/sea boundaries (Clark et al., 2025). The latest significant changes have occurred since the Last Glacial Maximum (LGM, ca. 26–19

thousand years ago), when global eustatic sea level fell by approximately 130m (Fairbanks, 1989; Lambeck et al., 2004; Bailey and Flemming, 2008; Grant et al., 2014). The impact of these changes, especially in regions such as Europe, where submerged landscapes represent an additional 40% of today's exposed land surface (Bailey et al., 2020), can have considerable implications for our understanding of key archaeological topics. In recent decades, archaeologists have started to recognise the potential of these ancient landmasses to answer critical questions relating to patterns of human dispersal, coastal and lowland settlement, and prehistoric maritime activities (Benjamin et al., 2017; Sturt et al., 2018; Bailey et al., 2020). Thus, after more than a century of sporadic yet seminal studies (Reid, 1913; Clark, 1936; Masters and Flemming, 1983; Andersen, 1985; Fischer, 1995; Coles,

* Corresponding author.

E-mail address: S.Ongaro@soton.ac.uk (S. Ongaro).

<https://doi.org/10.1016/j.quascirev.2026.110206>

Received 28 April 2026; Received in revised form 20 July 2026; Accepted 3 August 2026

Available online 9 August 2026

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1998), the field of submerged prehistory has now been established as a key area of archaeological research (Gaffney et al., 2007, 2009; Bailey and Flemming, 2008; Benjamin et al., 2011a; Evans et al., 2014; Bailey et al. 2017, 2020; Flemming et al., 2017; Bynoe, 2018; Sturt et al., 2018; Gaffney and Fitch, 2022; Ward et al., 2022; Bailey and Cawthra, 2023; Bynoe et al., 2023; O'Shea, 2023; Walker et al., 2024; Farr, 2025).

Not all regions, however, have received the same degree of attention. Even at a European level some submerged landscapes remain poorly understood, from both a paleogeographic and archaeological point of view. This is the case with the Northern Adriatic (Fig. 1), which, at times of lowered sea level, was one of the largest exposed landmasses in Europe (Correggiari et al., 1996a; Vai et al., 2004; Miracle, 2007; Trincardi et al., 2011; Fontana and Ronchi, 2021; Peresani et al., 2021). So far, the main archaeological advances in this region have included the discovery of Late Neolithic and later submerged sites along the Croatian coastlines (Benjamin et al., 2011b; Rossi et al., 2020) and geoarchaeological investigations in reclaimed areas of the Venetian-Friulian lagoons (Fontana, 2006; Fontana et al., 2017). While these studies have focused on the coastal zone, the potential of submerged prehistory on the continental shelf has also been recognised at a theoretical level. It has been strongly noted for the Palaeolithic (Miracle, 2007; Peresani et al., 2021) but is equally critical to later periods. During the Early and Middle Holocene (9750–6250 cal BC and 6250–2250 cal BC respectively), significant paleogeographic changes would have led to the drowning of the northern part of the Adriatic basin, obscuring landscapes relevant to key questions in Mesolithic and Neolithic research, such as lowland and coastal lifeways of the last hunter-gatherers, socioecological responses to sea level rise, and the interplay of these with the spread of farming along the Adriatic coastlines (Benjamin et al., 2017; Rossi et al., 2020; Fontana and Ronchi, 2021; Ongaro et al., 2025).

The main challenge for all these periods, however, lies in understanding how, and at what rate, landscape change occurred at a regional scale. The temporal scale of these developments is particularly difficult to address, as the uncertainty of sea level curves for the basin – due to local subsidence and sediment compaction (Lambeck et al., 2004; Antonioli et al., 2009; Vacchi et al., 2016) – makes it challenging to reconstruct the inundation of the Northern Adriatic. As a result, to our knowledge, no study has attempted to produce palaeolandscape reconstructions, beyond the local scale, for the Northern Adriatic (e.g.,

Zecchin et al., 2009; Ronchi et al., 2021). More comprehensive reconstructions, however, are fundamental for addressing current archaeological questions about past lifeway, site densities, and periods' transitions. Equally, they are required to determine the edges of current knowledge and thus, also potential foci for future studies and research agendas.

This study addresses this gap through the production of palaeolandscape reconstructions for the Northern Adriatic during the Early and Middle Holocene. We focus on the period between ca. 9000 and 4000 cal BC, from when our study area (Fig. 1) started to be inundated (Fontana and Ronchi, 2021) until the maximum landward shoreline position was reached (Amorosi et al., 2008, 2017). Archaeologically, this timespan allows us to highlight the potential for exploring questions related to the study of the Early Mesolithic (ca. 9300–6800 cal BC), Late Mesolithic (ca. 6800–5600 cal BC), and Neolithic (ca. 5600–3800 cal BC) periods (Pessina and Tiné, 2022; Fontana et al., 2023; Ongaro et al., 2025). To achieve this objective, we combined a previously unpublished high-resolution geophysical dataset with published sediment cores and sea level data (SL data) (Fig. 1). The analysis of these data has allowed us to not only characterise the deposits present on the Northern Adriatic seafloor and coastal area, but also to track and quantify changes in sea level and palaeoenvironments over time. Thus, after the production of inundation models and the identification of different depositional environments, speculative palaeolandscape models are presented and used for discussion of potential archaeological implications.

2. Background and research context

2.1. Regional setting

The Northern Adriatic is the shallowest (<120m) of the three sectors of the Adriatic Sea, which represents the elongated epicontinental basin that separates the Italian peninsula from the Balkans (Fig. 1). Unlike the Southern Adriatic Sea and the Middle Adriatic Depression – the other two sectors of the basin, reaching depths of ca. –1200 and –260m respectively – the Northern Adriatic constitutes the epicontinental shelf of the basin, characterised by a very gentle longitudinal topographic gradient of ca. 0.4‰ (Correggiari et al., 1996a). Our study focuses on the Venice and Trieste Gulfs, which, although the northernmost part of the

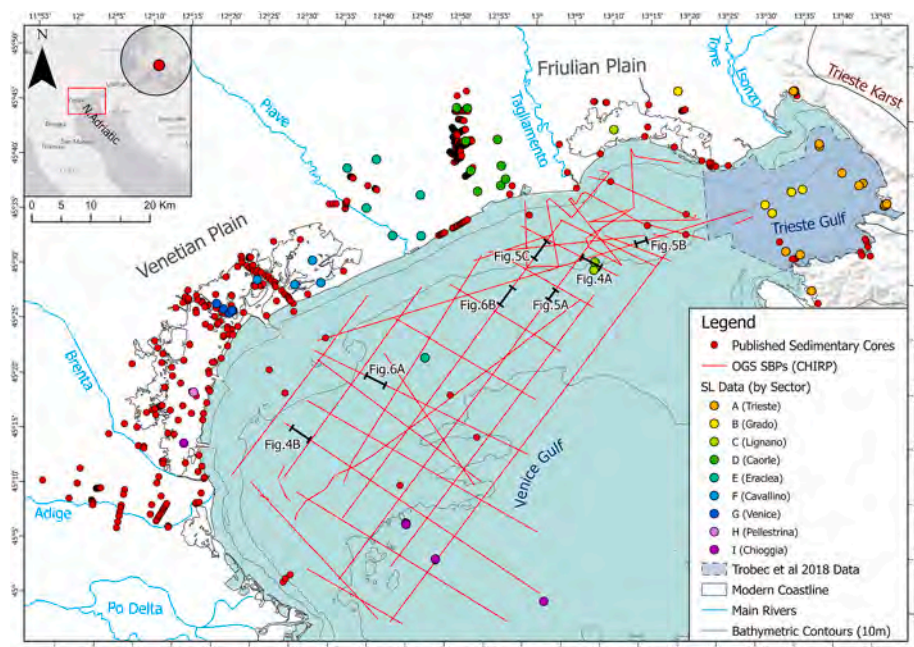


Fig. 1. Context map for the Northern Adriatic, including the study region and the data used. SL Data have been classified into sectors of different sea level trends (see main text for more details). Locations of CHIRP data shown in Figs. 4–6 have also been reported. Image created by authors 2026.

Northern Adriatic Sea, will here be referred to as 'Northern Adriatic' as they constitute the main area exposed as dryland during the Holocene.

The Northern Adriatic is one of the most sensitive Mediterranean areas to sea level fluctuations due to the very low gradient of the continental shelf and large fluvial inputs from the Alpine and Apennine catchments (Fontana and Ronchi, 2021). In fact, the Northern Adriatic continental shelf and the lowlands of Northern Italy – the Po Plain and the Venetian-Friulian Plain – constitute the sedimentary infilling of the subsiding basin formed between the Alps, Apennines, and Dinarides since the Miocene, thus making the region particularly responsive to eustatic oscillations, sediment supply, and subsidence (Amorosi et al., 2008; Zecchin et al., 2017). This geological setting has led alluvial and marine processes – linked to the aggradation of Alpine rivers and sea level fluctuations respectively – to shape the recent geomorphology of the region. As a result, the Quaternary depositional sequence alternates between marine and continental strata, with the last major alluvial deposition occurring during the LGM, when sea level dropped to around –130 m and rivers served as outwashes for the Alpine glaciers (Fontana et al., 2014; Amorosi et al., 2016). In the post-glacial period, rapid global sea level rise caused the progressive drowning of this vast alluvial plain that formerly extended across the present Northern Adriatic basin and profoundly reshaped the geomorphology of the basin, transforming a fluvial landscape into the modern lagoon–barrier–delta coastal system characteristic of the Northern Adriatic (Correggiari et al., 1996a; Amorosi et al., 2008; Trincardi et al., 2011; Fontana and Ronchi, 2021). Rates of Holocene subsidence in the Northern Adriatic coast are quite variable and tend to gradually increase on an East-West gradient (Lambeck et al., 2004). Different values have in fact been recorded, with the long-term average being less than –0.15 mm/y in the Trieste Gulf, –0.3 to –0.5 mm/y along the Friulian lagoons, –0.6 to –0.7 mm/y around the Venice lagoons, and the latter then increasing up to –1.1 mm/y moving towards the Po Delta (Lambeck et al., 2004; Amorosi et al., 2008; Antonioli et al., 2009; Vacchi et al., 2016).

In terms of sequence stratigraphy, the Lowstand System Tract (LST) in the Northern Adriatic is mainly composed of alluvial deposits and remains exposed in large areas both offshore and on the current plains (Trincardi et al., 2011; Fontana et al., 2014). The deposits formed during the inundation of the LGM plain consist instead of different generations of coastal and paralic deposits on the Northern Adriatic shelf, which form the Transgressive System Tract (TST), while fluvial sedimentation has been mainly limited to the incisions formed by Alpine rivers at the start of the deglaciation phase (Trincardi et al., 2011; Fontana et al., 2014; Ronchi et al., 2021). As the maximum landward shoreline position was being reached, the coastal and paralic deposits of the Highstand System Tract (HST) also started forming (Amorosi et al., 2008; Trincardi et al., 2011). The current Venice, Caorle, and Marano-Grado lagoons – as well as others that have recently been reclaimed (Fontana et al., 2017) – thus started developing between 6000 and 4000 cal BC (Marocco, 1991; Amorosi et al., 2008; Fontana and Ronchi, 2021). Strong progradation trends have also been recorded, especially in the southern Venice lagoon and around the current and ancient deltas of the main Alpine rivers (Amorosi et al., 2008).

The post-LGM evolution of the Northern Adriatic illustrates the complex interplay between eustatic sea level rise, fluvial sediment supply, and basin subsidence. For the study area, the transformation from a vast alluvial plain into the modern shallow marine basin occurred primarily during the Early Holocene marine transgression (Fontana and Ronchi, 2021). Subsequent slowing of sea level rise during the Middle Holocene allowed the establishment of lagoon-barrier systems and large deltaic complexes that still characterise the region today. In this respect, our study region appears as quite distinct from nearby areas. The Eastern Adriatic, characterised by a steeper gradient, deeper bathymetry, and karstic coastlines, seems to have mainly been drowned earlier, between the Late Pleistocene and beginning of the Holocene, leading to the karstic valleys and hills being transformed into the current island seascape (Dean et al., 2020; Benac et al., 2026). The evolution of the Po

Delta appears to have been more similar. Here, similar paralic environments have been recorded but a strong progradation trend has been in place since ca. 5000 cal BC, due to the much higher fluvial influence that the Po River causes compared to the Alpine rivers of the Venetian-Friulian Plain (Amorosi et al., 2008, 2017).

2.2. Palaeolandscape research in the Northern Adriatic

Recognition of the potential for submerged landscapes in the Northern Adriatic to address significant archaeological issues has not been lacking (Miracle, 2007; Broodbank, 2013; Benjamin et al., 2011b, 2017; Fozzati and Zarattini, 2018; Castagnino Berlinghieri et al., 2020; Rossi et al., 2020; Fontana and Ronchi, 2021; Peresani et al., 2021; Ongaro et al., 2025). While these studies mark a decisive step forward, they also reveal the need for further data to support regional reconstructions and their connection to the archaeology. In an ideal scenario, submerged prehistoric sites would be a fundamental part of this process, providing direct evidence for the changing interactions between people and environment. While such sites have been identified in the Eastern Adriatic, underwater evidence dating to the Mesolithic and Neolithic periods is virtually absent in the Western Adriatic (Castagnino Berlinghieri et al., 2020) and is particularly scarce in the coastal and lagoon areas of the Northern Adriatic (Auriemma and Maggi, 2013; Canal, 2015; Fontana et al., 2017).

The almost complete lack of direct archaeological evidence from submerged contexts has hindered further investigations of palaeolandscapes from a human perspective. Yet, what is striking is the sharp contrast between the east and west of the Adriatic. The numerous submerged prehistoric sites recorded along the Dalmatian and Istrian coastline are not the result of chance discoveries, but rather the outcome of more than twenty years of systematic investigations (Benjamin and Bonsall, 2009; Benjamin et al., 2011b; Bekić et al., 2016; Rossi et al., 2020; Parica, 2022; Jerbić, 2025).

Part of the limited investigation of the Northern Adriatic stems from the assumption that archaeological evidence has either been eroded by inundation processes or remains undetectable due to the region's sedimentological conditions (Benjamin et al., 2011b; Fozzati and Zarattini, 2018). Under this view, sites are either inaccessible, if located under the very thick coastal wedge that runs along the North-Western Adriatic coastline (Antonioli et al., 2017), or destroyed, if located further offshore where strong erosive processes are at play (Trincardi et al., 2011; Gordini et al., 2023). However, the preservation and discovery of submerged sites rely not on this simple binary but on the dynamic relationship between erosion and sedimentation. While sedimentation can bury and preserve sites, often rendering them invisible, erosion can re-expose these deposits and make them accessible, albeit at a cost of increased vulnerability. Many archaeological finds from European and other Continental shelves have occurred where these opposing processes are in balance, exposing formerly buried and preserved deposits before they are destroyed or re-buried (Flemming et al., 2017; Bailey et al., 2020). Ideal conditions for the preservation of submerged prehistoric sites may therefore exist in at least localised areas of the Northern Adriatic, exposing previously buried archaeological material. Moreover, research projects in the Venetian-Friulian lagoons and coastal plain – where, similar to the offshore area, archaeology is either buried under thick deposits or exposed where postglacial sedimentation is lacking – have demonstrated that it is possible to investigate prehistoric archaeology from a geomorphological perspective (e.g., Fontana, 2006; Fontana et al., 2017). Therefore, the problem of submerged prehistoric archaeology in the Northern Adriatic Sea is one of accessibility, logistics, and funding rather than impossibility of discovery.

The vast majority of research into submerged landscapes draws on geophysical and geotechnical datasets and originates without archaeological input, with numerous studies analysing TST deposits that would have formed during the Mesolithic and Neolithic periods (Correggiari et al., 1996a; Gordini et al., 2002; Storms et al., 2008; Zecchin et al.

2008, 2009, 2015, 2024; Trincardi et al., 2011; Moscon et al., 2015; Ronchi et al., 2018, 2019, 2021). In this study we bridged this gap through uniting researchers from both communities, discerning what it is possible to achieve from a geological perspective and the questions we need to answer at an archaeological scale. To do that, our analyses were focused on providing palaeolandscape reconstructions of the Northern Adriatic at a scale and detail allowing to address archaeological questions. Our archaeological discussion is focused on how these data can move debates beyond speculation, highlighting the potential for palaeolandscape reconstructions to enhance our knowledge of key archaeological issues.

3. Materials and methods

3.1. Datasets used

To produce palaeolandscape reconstructions for the Northern Adriatic that encompass both the offshore and current coastal/lagoon areas, both published and unpublished datasets have been used, consisting of sedimentary cores and high-resolution geophysical data respectively (Fig. 1). The former were collected from all available publications in our study area, leading to the creation of a dataset of more than 600 sediment cores located mainly on the coastal and lagoon areas of the Venetian-Friulian Plain, but also on the continental shelf (see [Supplementary Material 1](#) for key information on the data used, including sources). The seismic data consists of unpublished sub-bottom CHIRP profiles collected in the frame of the OGS STENAP (Seismostratigraphic and Tectonic evolution of the Northern Adriatic in the Plio-Quaternary) and GANDI (GAs emissions in the Northern ADriatic Sea) projects between 2009 and 2014 (cf. [Donda et al., 2013](#); [Zecchin et al.,](#)

2017; [Donda et al., 2019](#); [Gordini et al., 2023](#)). The CHIRP data were collected on board the R/V OGS Explora using a hull-mounted Chirp Benthos system with 16 transducers and a sweep modulated bandwidth from 2 to 7 kHz. The ping rate was set to 0.125–0.25 s, with a vessel speed of 2 m/s – i.e., one trace per second. The data – stored in a SEG-Y format with positioning data from a GNSS system automatically incorporated – has been analysed in S&P Global Kingdom, with over 1300 km of sub-bottom profiles being employed in this study. [Fig. 2](#) describes how these datasets have been employed in the creation of the palaeolandscape reconstructions, with the main steps detailed in the following sections.

3.2. Facies identification

Analysis of CHIRP profiles included the identification and picking of the main seismic unconformities through correlation with those already identified in key studies in the Northern Adriatic (e.g., [Cattaneo and Steel, 2003](#); [Zecchin et al., 2008, 2009](#); [Trincardi et al., 2011](#); [Ronchi et al., 2019](#)), and the identification and interpretation of the different acoustic facies. In lowland settings affected by sea level rise, it is generally the case that seismic unconformities primarily reflect the transgression, where terrestrial deposits are progressively overlain by paralic and marine sediments as the shoreline migrates inland. The Transgressive Surface (TS) – also known as the maximum regressive surface – marks the onset of landward shoreline migration due to rising sea level. It is represented by a seismic reflector that separates alluvial sediments below from paralic sediments above. Its environmental significance is the beginning of marine flooding of the lowland.

This analysis led to the distinction of the LST alluvial deposits bounded by the TS, the TST back-barrier deposits bounded by the wave

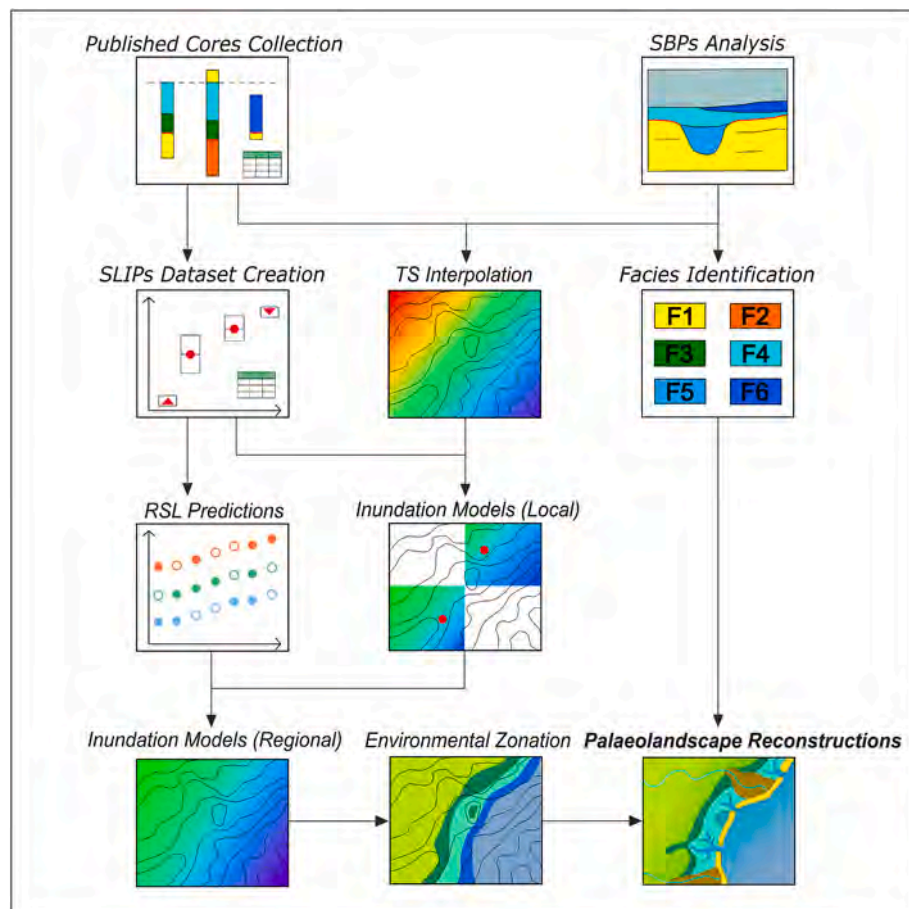


Fig. 2. Methodological flowchart illustrating the steps employed for the creation of palaeolandscape reconstructions. Image created by authors 2026.

ravinement surface (WRS), and the TST coastal and shallow marine deposits bounded by the seafloor, or by the maximum flooding surface (MFS) where HST prograding coastal and shallow marine deposits are present close to the coastline (see Figs. 4–6 for selected examples). In the Northern Adriatic, the TS corresponds to the subaerial unconformity formed due to alluvial sediment starvation in the postglacial period (Cattaneo and Steel, 2003; Trincardi et al., 2011). As noted in previous studies (Trincardi et al., 2011; Zecchin et al., 2015), the TS and WRS often correspond due to the erosion of finer back-barrier deposits caused by sea level rise. Tidal ravinement surfaces (TRS) are less common in our study area and can mainly be found in correspondence with tidal inlets or incised valleys (Zecchin et al., 2008, 2009).

We then proceeded to distinguish the different acoustic facies to detect different depositional environments. [Supplementary Material 3](#) provides a series of maps depicting each facies' extent on the CHIRP profiles. [Table 1](#) provides a summary of the facies identified and their characteristics. This was based on the seismic reflector configurations and the characteristics of the acoustic facies, as well as through comparison with detailed facies descriptions and interpretation from

previous studies (Moscon et al., 2015; Ronchi et al., 2018, 2019), and published core data for ground-truthing (Trincardi et al., 2011; Zecchin et al., 2015). To obtain more detailed information on the specific environments in which these deposits formed, and to produce an onshore-offshore correlation for our study area, facies identified in sediment cores were linked to acoustic facies ([Table 1](#)). [Table 2](#) summarises the core facies' lithological and faunal associations which were grouped together into a consistent classification after a literature review of published sediment cores data was completed (e.g., Favero and Serandrei-Barbero, 1980; Marocco, 1989a; Marocco et al., 1996; Gordini et al., 2002; Covelli et al., 2006; Tosi et al., 2007a, 2007b; Trincardi et al., 2011; Madricardo et al., 2012; Amorosi et al., 2017; Ronchi et al., 2018, 2021). The different depositional environments and their implications for palaeolandscape reconstructions in the study area are described in detail in section 4.1.

3.3. Modelling of past sea level

To reconstruct environmental changes linked to sea level rise,

Table 1

Seismic facies identified in the CHIRP data, including examples, description, and cores' facies association (see [Table 2](#) for more details on the facies identified in the cores). Table created by authors 2026.

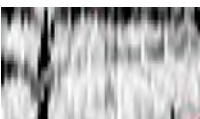
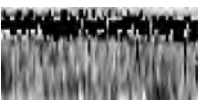
CHIRP Example	CHIRP Facies	Facies Interpretation	Description	Cores' Facies Association
	CF1	Alluvial deposits, silty-clayey layers with sand and peat intercalated	High amplitude horizontal reflectors with high lateral continuity	F1A F1B
	CF2	Fluvial deposits, sandy (or gravelly) sediments	Semi-transparent chaotic reflectors	F1C
	CF3	Backbarrier marshy deposits, thick organic rich peat	Very high amplitude reflectors	F2A F2B
	CF4	Backbarrier deltaic deposits, silty and sandy sediments	Irregular low to high amplitude reflectors with convex upwards cusped shapes	F2C-1 F2C-2
	CF5	Deltaic channel, erosive feature filled with fine-medium sand	Low amplitude lateral accreting reflectors inside channel feature	F2C-3
	CF6	Backbarrier lagoon deposits, clayey-silty and fine sand alternation	Low amplitude semi-continuous sub-horizontal reflectors	F2D-1 F2D-2
	CF7	Lagoon channel, erosive feature filled with silty/very fine sand	Low to high amplitude draping reflectors inside channel feature	F2D-3
	CF8	Backbarrier deposits, undifferentiated, silty/fine sands	Irregular low to high amplitude reflectors	F2E?
	CF9	Barrier/coastal deposits, 'wedge-shaped' sandy bodies	Transparent to semi-transparent bodies with chaotic reflectors	F3A F3B
	CF10	Inner shelf/prodelta deposits, silty-very fine sand	Low to high amplitude chaotic reflectors	F3C
	CF11	Reworked coastal deposits, sandy sub-marine dunes	Dune fields with transparent chaotic reflectors	F3D

Table 2

Facies identified after a review of published cores in the region, including lithological and faunal associations. Table created by authors 2026.

Facies ID	Description	Lithology	Fauna Association	Other Elements
F1A	Alluvial plain	Clay, silt, with fine sand and peat intercalated	Mostly barren, freshwater ostracods (e.g., <i>Candona</i> spp., <i>Ilyocypris</i> spp.) and molluscs (e.g., <i>Crenuella</i> spp., <i>Gyraulus</i> spp.) and terrestrial molluscs (e.g., <i>Vertigo pygmaea</i> , <i>Helicidae</i> sp.)	Common bioturbation, root traces, paleosols, carbonate concretions
F1B	Crevasse/levee	Sand-silt alt.	Mostly barren, freshwater ostracods (e.g., <i>Candona</i> spp., <i>Ilyocypris</i> spp.) and molluscs (e.g., <i>Bithynia tentaculata</i>)	
F1C	Fluvial channel	Medium/coarse sand	Organic rich, freshwater/brackish ostracods (e.g., <i>Candona</i> spp., <i>Pseudocandona</i> spp.) and molluscs (e.g., <i>Bithynia tentaculata</i> , <i>Succinea putris</i> , <i>Valvata macrostoma</i>)	Plant debris, wood fragments
F2A	Freshwater to brackish marsh/swamp	Clay, Peat	Organic rich, brackish foraminifera (e.g., <i>Trochammina inflata</i> , <i>Ammonia tepida</i>) and molluscs (e.g., <i>Cerastoderma glaucum</i> , <i>Hydrobia ventrosa</i> , <i>Abra segmentum</i> , <i>Loripes orbiculatum</i>)	Common bioturbation
F2B	Saltmarsh	Clay, Peat	Brackish foraminifera (e.g., <i>Cyprides torosa</i>) and molluscs (e.g., <i>Cerastoderma glaucum</i> , <i>Hydrobia ventrosa</i> , freshwater ostracods (e.g., <i>Ilyocypris</i> spp.)	
F2C-1	Delta plain	Fine/medium sand, Silt	Mostly barren, freshwater/brackish ostracods (e.g., <i>Candona</i> spp., <i>Pseudocandona</i> spp.) and molluscs (e.g., <i>Pisidium</i> spp., <i>Valvata macrostoma</i> , <i>Bithynia tentaculata</i>)	Plant debris
F2C-2	Crevasse/levee	Sand-silt alt.	Brackish foraminifera (e.g., <i>Ammonia tepida</i> , <i>Haynesina</i> spp.) and molluscs (e.g., <i>Cerastoderma</i>	
F2C-3	Distributary channel	Fine/medium sand		
F2D-1	Inner lagoon/mud flat	Clay, silt		

Table 2 (continued)

Facies ID	Description	Lithology	Fauna Association	Other Elements
F2D-2	Outer lagoon/shallow bay	Clay-sand alt.	<i>glaucum</i> , <i>Hydrobia ventrosa</i> , <i>Abra segmentum</i> , <i>Loripes orbiculatum</i>) Brackish foraminifera (e.g., <i>Ammonia tepida</i> , <i>Cyprides torosa</i>) and molluscs (e.g., <i>Cerastoderma glaucum</i> , <i>Lentidium mediterraneum</i> , <i>Tellina lactea</i>), marine foraminifera (e.g., <i>Leptocythere</i> spp.)	Common bioturbation
F2D-3	Tidal Inlet/lagoon channel	Very fine sand-silt alt.	Brackish foraminifera (e.g., <i>Ammonia tepida</i> , <i>Elphidium</i> spp., <i>Haynesina</i> spp.) and molluscs (e.g., <i>Cerastoderma glaucum</i> , <i>Hydrobia ventrosa</i>)	Plant debris
F2E	Overflood deposits	Sand-clay/silt alt.	Mostly barren, possibly brackish/shallow marine molluscs (e.g., <i>Cerastoderma glaucum</i> , <i>Tritia neritea</i> , <i>Lentidium mediterranea</i>)	Plant debris
F3A	Barrier Island	Fine/medium sand, Silt	Brackish/shallow marine foraminifera (e.g., <i>Cyprides torosa</i> , <i>Ammonia tepida</i>) and molluscs (e.g., <i>Tritia neritea</i> , <i>Lentidium mediterranea</i> , <i>Donax semistriatus</i>)	/
F3B	Delta Front	Fine/medium sand, Silt	Brackish/shallow marine foraminifera (e.g., <i>Cyprides torosa</i> , <i>Ammonia tepida</i>) and molluscs (e.g., <i>Tritia neritea</i> , <i>Lentidium mediterranea</i> , <i>Donax semistriatus</i>)	Plant debris
F3C	Prodelta/Inner shelf	Very fine/fine sand, Silt	Shallow/Open marine foraminifera (e.g., <i>Miliolids</i> spp., <i>Elphidium</i> spp., <i>Textularia</i> spp.) and molluscs (e.g., <i>Lembulus pella</i> , <i>Corbula gibba</i> , <i>Bittium submamillatum</i>)	Common bioturbation
F3D	Offshore (reworked deposits)	Fine/medium sand, Silt	Open marine foraminifera (e.g., <i>Miliolids</i> spp., <i>Elphidium</i> spp., <i>Textularia</i> spp.) and molluscs (e.g., <i>Lembulus pella</i> , <i>Corbula gibba</i> , <i>Bittium submamillatum</i>)	/

detailed knowledge of the sea level history of the area and its effects on the ancient land surface were required. However, as mentioned above, although different sea level curves for the Northern Adriatic Sea have been produced (Lambeck et al., 2004; Antonioli et al., 2007, 2009; Vacchi et al., 2016), these still contain a considerable degree of uncertainty. In our study region the global and time-dependent eustatic sea level interplays not only with an isostatic component, but also with local subsidence (Lambeck et al., 2004). While the former are more regular and predictable, and thus relatively easy to calculate, local subsidence is more complex and is mainly controlled by both tectonics and sediment compaction caused by the consolidation of recent compressible deposits (Teatini et al., 2011). For the Northern Adriatic, Glacial Isostatic Adjustment (GIA) models alone (e.g., Linsalata et al., 2023) have already been shown to be insufficient for reconstructing relative sea-level curves. They capture the regional isostatic component well, but in low-lying sedimentary environments such as the study area, tectonic deformation and especially subsidence can significantly modify the local sea-level record, sometimes by amounts comparable to or exceeding the GIA signal over Holocene timescales. For relatively stable rocky coasts (such as parts of the Trieste and Istrian regions), GIA-based reconstructions tend to be much more reliable, although site-specific evaluation of vertical land motion remains advisable. Because of this, sea level curves for the Northern Adriatic Sea tend not to work at a local scale and recorded sea level data can exhibit significant spatial variability (Vacchi et al., 2016; Fontana et al., 2017; Amorosi et al., 2017).

With the aim of producing palaeolandscape maps at a spatial and temporal scale sufficient to address archaeological questions, we took a more localised approach. To achieve this, we collected all available SL data for our study area spanning the period between ca. 9000 and 4000 cal BC, predominantly sea level index points (SLIPs) but also including limiting points (see [Supplementary Material 2](#) for a list of SL data used, including rejected data, and related calculations). These have been derived from dated, published cores but also from studies that provide enough information to produce SL data (e.g. Kaniewski et al., 2024). All data and calculations reported here have been expressed relative to mean sea level (MSL).

Relative Sea Level (RSL) and final error (e) were calculated for each SL datum (i) following equations by Shennan and Horton (2002) and Vacchi et al. (2016):

$$RSL_i = A_i - RWL_i$$

$$e_i = \sqrt{e_{IR}^2 + e_l^2 + e_s^2 + e_t^2 + e_{env}^2}$$

Where A_i is the sample altitude and RWL_i is the reference water level (RWL) of the SL datum. The RWL is subtracted to the sample altitude to obtain the RSL value, based on the assumption that each sample would

have sat at a specific elevation relative to RSL based on the type of SL datum (Table 3). This elevation, however, is not a specific point, but rather corresponds to a possible range at which the sample would have sat, known as the indicative range (IR). The RWL is thus taken at the midpoint of the IR, while the IR is used to calculate vertical error expressed in $\pm m$ – i.e., divided by two – which corresponds to the e_{IR} (Shennan and Horton, 2002). The final error e_i is calculated by adding in quadratic errors, including the error associated with the IR (e_{IR}), but also errors related to levelling (e_l) and sampling (e_s), tidal errors (e_t), and environmental errors (e_{env}). Of these, levelling, sampling, and tidal errors are based on defaults by Shennan and Horton (2002) and Vacchi et al. (2016), while the environmental error corresponds to an additional 0.5m uncertainty that was added in when the depositional environment was not completely certain, following the procedure outlined by Vacchi et al. (2016) and Fontana et al. (2017).

Using the best suited IR for each SL datum is therefore fundamental for producing accurate RSL calculations – this value varies for each type of SL datum under consideration. Table 3 reports the rules for each type of SL datum as well as the associated IR and derived values, based on Vacchi et al. (2016) and Fontana et al. (2017). The values reported are based on local tidal datums, with MSL corresponding to 0m, highest astronomical tide (HAT) to 0.6m, and mean lowest water (MLW) to -0.45m (Fontana et al., 2017). In order to classify each SL datum into a specific type of SLIP or limiting point, we had to convert our core facies (Table 2) to a type of SL datum with a specific IR (Table 3). Most core facies correspond to a specific type of SL datum (e.g., saltmarshes, inner lagoon, outer lagoon) while others need to be classified more carefully. Barrier island and delta front deposits could be both terrestrial or marine limiting points depending on whether the sample was acquired above or below past sea level, and thus only data including sufficient environmental information to make a distinction between beach and shoreface deposits has been used (Vacchi et al., 2016). Samples taken in marsh contexts were classified as terrestrial limiting points if clearly deposited in a freshwater environment. If not, they were grouped as SLIPs under the undifferentiated brackish label (Vacchi et al., 2016), similar to delta plain deposits, so that their IR would span the entirety of the tidal zone. Unlike other lagoon facies, samples taken in lagoon channels were classified as marine limiting points, as these features can deepen several metres below past sea level and are also filled during drowning in a transgressive context (Ronchi et al., 2018). Samples taken in fluvial channels were rejected due to rivers being incised several metres during the postglacial period in the study area, flowing at an uncertain position relative to past sea level. Samples taken in alluvial plain deposits were classified as terrestrial limiting points, even if the RSL value they report can be misleading as it could elevate several metres above sea level.

The final step involved in the production of SL data was to calculate the horizontal error associated with each datum. This is obtained by

Table 3

Types of SL data used for this study and association with depositional environments identified in the cores (see Table 2 for more details on the cores' facies); Rules for each SL datum type and specific IR values are based on local values by Vacchi et al. (2016) and Fontana et al. (2017). The RWL corresponds to the IR midpoint, while the IR $\pm$ error corresponds to the IR/2. Abbreviations: Mean Sea Level (MSL), Highest Astronomical Tide (HAT), Mean Lowest Water (MLW). Table created by authors 2026.

SL Data Type		Theoretical IR (m MSL)	RWL value (m)	IR error value ($\pm m$)	Cores' Facies Associated
Lagoon Index Points	Undifferentiated brackish	HAT to MLW (0.6 to -0.45)	0.075	1.05/2 = 0.525	F2A (brackish) F2C-1
	Saltmarsh	HAT to MSL (0.6 to 0)	0.3	0.6/2 = 0.3	F2B
	Inner lagoon	MSL -1 (0 to -1)	-0.5	1/2 = 0.5	F2D-1
	Outer lagoon	MSL -2 (0 to -2)	-1	2/2 = 1	F2D-2
Limiting Points	Marine limiting point	Below MSL (<0)	0	0	F2D-3 F3A (shoreface) F3B (shoreface) F3C
	Terrestrial limiting point	Above MSL (>0)	0	0	F1A F2A (freshwater) F3A (beach) F3B (beach)

calibrating the radiocarbon age of the sample to cal BC in OxCal 4.4, using the IntCal20 calibration curve (Reimer et al., 2020). The age error therefore corresponds to the 2σ confidence level expressed in $\pm$ years. Samples taken on marine shells were corrected for the marine reservoir effect using values by Siani et al. (2000).

Fig. 3 displays the SL data used in this study. SL data of the same date can vary by up to 10m if taken at opposite sides of the basin, although always showing an east-west gradient. We therefore assigned each SL datum to one of nine sectors, A to I, moving from east to west (Fig. 1) and representing sub-divisions in our study area that correspond to changes in subsidence rates (Table 4). To highlight differences in RSL across our study area, we present localised inundation models (Figs. 7–10), but for practical reasons we display the sea level trends in four sub-regions, based on sectors A-I. These four sub-regions group together adjacent sectors of similar sea level trends where differences in RSL at the same age are in the order of magnitude of the average final error of the SL data (Fig. 3). Thus, the inundation models in Figs. 7–10 showcase RSL in four different sub-regions: the Trieste Gulf and eastern Friulian Plain, the central and western Friulian Plain, the eastern and central Venetian Plain, and the western Venetian Plain and Adige coastal plain (see section 4.2 below).

To produce the inundation models, the SL data were plotted on a Digital Terrain Model (DTM) (Figs. 7–10). This was obtained through the interpolation of the TS derived from its identification in the geophysical data for the offshore area and in the sediment cores for the coastal area (See Supplementary Material 3 for a map of the TS DTM). In the sediment cores this surface is easily identifiable due to a clear change in sedimentary facies. In the CHIRP data the TS is clearly recognisable as a medium to high amplitude reflector, at highly variable depth below the present-day sea floor, that can also locally crop out particularly further offshore than the current coastal wedge. Trincardi et al.'s (2011) regional map of the TS has also been used as an approximate guideline.

For the DTM generated using data points from the seismic dataset, a TWT-depth conversion was applied, using a sound velocity value of 1530 m/s (after Trobec et al., 2018). The data points of the depth of the TS from both datasets were thus interpolated in ArcGIS Pro using Natural Neighbour as the interpolation method, with a cell size of 375m, as best determined by the toolbox. This toolbox allows the production of overall smooth surfaces except at sample location, thus reducing the risk of generating an over-interpolated model (ESRI, 2026). Finally, since our geophysical data does not cover the Gulf of Trieste (Fig. 1), we integrated the DTM for the base of Holocene deposits created by Trobec et al. (2018) for this area, as the TS and this surface theoretically coincide in the Northern Adriatic (see above). This was added as an existing interpolation based on a very similar dataset of CHIRP and Boomer profiles, although we resampled the original cell size of 50m to our DTM resolution.

3.4. Palaeolandscape modelling

Palaeolandscape models were produced by combining sea level data with evidence for depositional environments formed at different stages through time. The main challenge was producing regional reconstructions, with SL data displaying contrasting RSL trends between different sectors (Fig. 3). Ideally, a high number of SL data evenly distributed across space and time would allow each sector's sea level history to be considered first on its own and then when combined with all data at a regional scale. Yet, as Table 4 shows, SL data across the Northern Adriatic do not present an even distribution across different sectors and they only allow the reconstruction of RSL at different moments in time for specific subregions. In order to fill the gaps in the SL data record, we decided to produce a series of sea level reconstructions for our study area based on the available SLIPs and limiting points, integrating the subsidence rates reported in the literature. The trend we

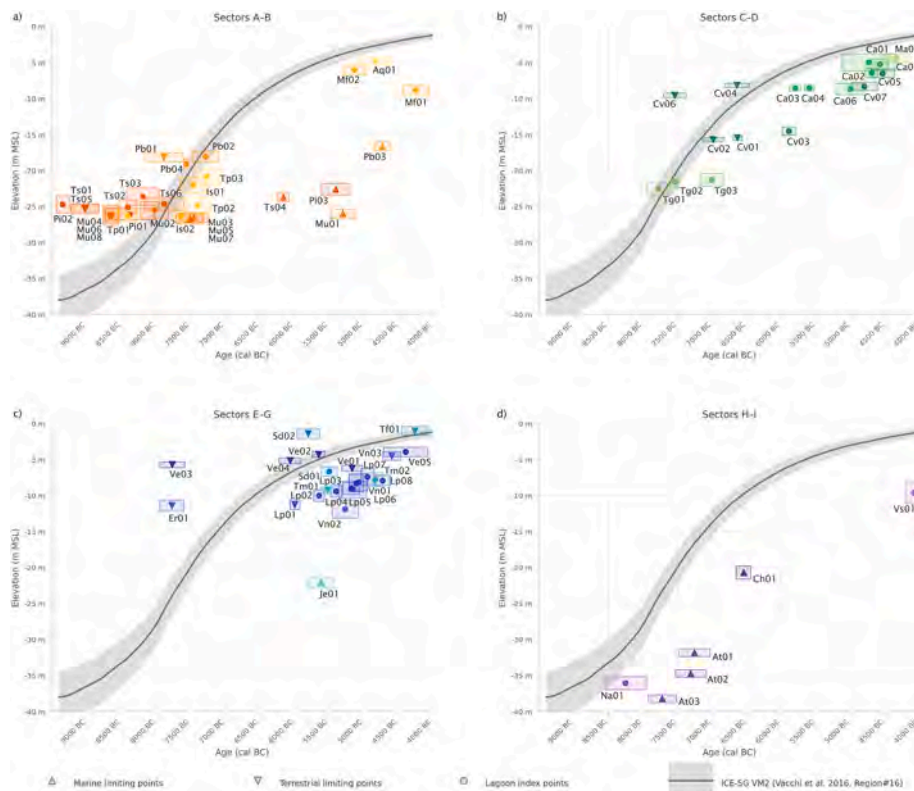


Fig. 3. Plot graph of the SL Data used to produce the inundation models, classified by sectors and grouped into four sub-regions (see Fig. 1 and main text for more details). Vacchi et al. (2016) GIA curve for the Northern Adriatic (region #16) has been plotted for comparison. See Supplementary Material 2 for more details on each specific SL Datum. Image created by authors 2026.

Table 4

Subsidence rates and SL data availability for different regions; note: the time period covered are based on horizontal errors of the SLIPs and limiting points, meaning that coverage does not equate to accurate sea level data availability – for more details see Fig. 3 and Supplement 2. Table created by authors 2026.

Sector	Subsidence Rates (mm/y) and Reference		SL data count	Approximate Time Periods Covered (Cal BC)
A (Trieste)	0.1	Lambeck et al., (2004); Antonioli et al., (2009)	23	9400-7200, 6200-6100, 5400-4800, 4400-4100
B (Grado)	0.3	Lambeck et al. (2004)	6	8500-8300, 7800-7100, 5000-4600
C (Lignano)	0.4	Lambeck et al., (2004); Vacchi et al., (2016)	4	7900-6800, 4500-4100
D (Caorle)	0.5	Lambeck et al., (2004); Vacchi et al., (2016)	13	7700-7300, 7100-6500, 6000-5500, 5200-4400
E (Eraclea)	0.6	Amorosi et al., (2008); Vacchi et al., (2016)	7	7900-7600, 5900-5400, 4900-4700, 4400-4000
F (Cavallino)	0.7	Lambeck et al., (2004); Vacchi et al., (2016)	11	6000-5900, 5700-4400
G (Venice)	0.8	Antonioli et al. (2009)	5	7900-7600, 6200-5900, 5700-5000, 4700-4000
H (Pellestrina)	0.9	Antonioli et al. (2009)	1	4200-4000
I (Chioggia)	1	Amorosi et al., (2008); Vacchi et al., (2016)	5	8600-7000, 6700-6400

detected of an east-west decrease in altitude (section 3.3) correlates well with the increasing gradient in subsidence rates from the Trieste Gulf in the east to the Po Delta in the west (section 2.1). We thus assigned an increasingly higher subsidence value – always consistent with the long-term average ones recorded in the literature – for each sector (Table 4). We then used the following formula to calculate RSL in sectors missing SL data:

$$\begin{cases} RSL_{th} = RSL_x - \frac{tR_x}{1000} \\ RSL_{th} = RSL_y - \frac{tR_y}{1000} \end{cases}$$

Where RSL_{th} stands for a theoretical RSL value (in metres) not affected by any subsidence, RSL_x and RSL_y stand for the RSL in different sectors x and y, affected by different subsidence rates R_x and R_y respectively (in millimetre/year), and t stands for the time (in years) since the RSL values were recorded. Multiplying t and R thus allows us to estimate the contribution of subsidence to RSL in a given sector (divided by 1000 to convert from mm to m). The contribution of subsidence can then be removed from the RSL value to obtain the RSL_{th} , but it can also be added to the RSL_{th} to obtain the RSL where this is not known because of the lack of SL data.

This formula can therefore be used to calculate RSL in a sector without SL data based on RSL from a sector for which SLIPs or limiting points are available by solving the equation as following:

$$RSL_y = RSL_x - \frac{tR_x}{1000} + \frac{tR_y}{1000}$$

This was carried out for all sectors for the periods for which SL data were available (see Supplementary Material 2 for further details). We selected time periods of 200 years as this resolution accounts best for the horizontal errors of most SL data. When more than one sector presented RSL data for a specific time period, multiple SLIPs and limiting points were used to corroborate the sea level reconstructions and identify the most suitable value to use as the RSL_{th} . This of course implies a degree of interpretation and adjustment of the RSL values reported by the SL data, in line with their horizontal and vertical errors. Moreover, since different SL data even inside the same sector over the same period can display different RSL values, the RSL_x used was selected based on the value consistent with the most SL data, meaning that some SLIPs or limiting points have not been used for the sea level reconstructions.

The sea level predictions were also used to calculate rates of sea level rise using the following formula:

$$r = \frac{\Delta RSL_x}{\Delta t} 1000$$

Where r is the rate of sea level rise (in millimetre/year – hence the multiplication by 1000 to convert from m in the RSL to mm). The Δt was kept constant at 200 years for consistency with the sea level predictions. The values obtained are discussed in section 4.3 below and are also used to highlight impacts of changes in the palaeolandscape on human

societies in the Early and Middle Holocene (see Supplementary Material 2 for further details).

The sea level reconstructions were finally used to generate inundation models at a regional scale (Fig. 2). Period-specific environmental zonation models were then produced, showing possible environments developing in a specific time window in different sectors (Fig. 2). These were based on the assumption that different paralic environments would develop at different elevations relative to past sea level, with zonation values being based on the indicative distribution of these environments in the Northern Adriatic at present (Marocco, 1989b; Fontana, 2006; Trincardi et al., 2011; Fontana et al., 2017), i.e., marshes being present between 1 and 0m above sea level, lagoons being present between 0 and 2m below sea level, and the upper shoreface being present between 0 and 4m below sea level; at the extremes of this zone a forested plain and marine environment were predicted at >1m above sea level and <4m below sea level respectively. To corroborate these predictions, we looked at the depositional environments recorded in the sediment core and geophysical data at depths associated with each specific zonation to see whether the specific environments were actually detectable, and, if possible, to characterise them more accurately (e.g., saltmarsh vs inner lagoon, delta plain vs outer lagoon, etc.). This finally led to the production of several palaeolandscape maps providing a summary of the main evolutionary moments for the Northern Adriatic during the Holocene transgression between ca. 9000 and 4000 cal BC (see section 4.3 below). These are then used to address archaeological issues and highlight the importance of these paleogeographic developments to the study of human societies in the Early and Middle Holocene.

4. Results

4.1. Depositional environments

This section describes the different depositional environments identified in our study area through the association, and interpretation of the acoustic and sediment cores' facies. At a general level these can be grouped into alluvial, marsh, lagoon, deltaic, and coastal facies, although different sub-facies corresponding to specific environments and distinct geomorphological features have also been identified. Undifferentiated and reworked facies will be discussed separately.

4.1.1. Alluvial and fluvial facies (F1A, F1B, F1C)

Facies associated with alluvial and fluvial depositional phases are the most common and can be detected in all CHIRP data (Figs. 4–6). These are predominantly alluvial plain deposits, internally characterised by high amplitude, continuous horizontal reflectors (CF1). They can be correlated with the intercalation of clay, silt, and fine sand of core facies F1A, which is associated with freshwater and terrestrial ostracods and molluscs (Tables 1 and 2). F1A could potentially be subdivided into different sub-facies (e.g., proximal vs distal plain), due to the occurrence of very high amplitude reflectors possibly representing peat layers and palaeosols (Figs. 4–6). The former are likely to represent freshwater marshes formed during the LGM in areas away from fluvial deposition

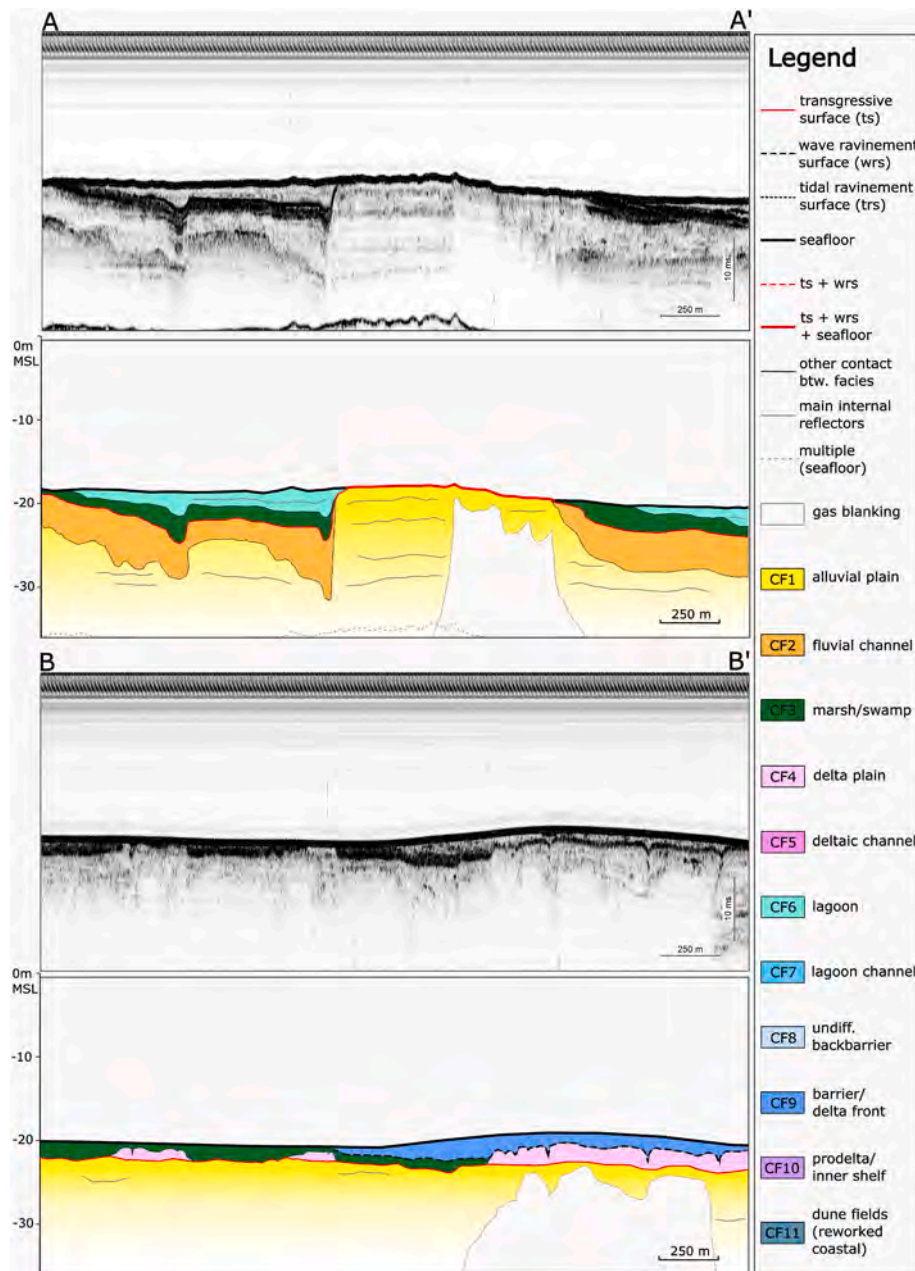


Fig. 4. Example of CHIRP data and interpretation following the seismic facies presented in Table 1, showing different seismic unconformities, depositional environments, and acoustic artifacts (locations of the profiles has been reported in Fig. 1). Focus on alluvial and backbarrier deposits. Image created by authors 2026.

(Miola et al., 2006; Gordini et al. 2002, 2023; Donda et al., 2019), while the latter are associated with sediment starvation in the postglacial period and the formation of the so-called ‘caranto’. The caranto is an over consolidated, clay-rich paleosol, a few centimeters to a few meters thick, which acts as the key Pleistocene-Holocene stratigraphic boundary in the area (Mozzi et al., 2003; Bondesan et al., 2008; Donda et al., 2008; Donnici et al., 2011). Other alluvial facies include fluvial channel deposits and crevasse-levees. The channel deposits are associated with semi-transparent chaotic reflectors in the CHIRP data (CF2) and the barren sandy-gravelly sediments of F1C (Tables 1 and 2), while the crevasse-levees are more easily identifiable in the sediment cores, appearing as the barren sand-silt alternation of core facies F1B. These can occasionally be distinguished in the CHIRP data (Fig. 6a) but are mostly grouped under CF1.

Overall, alluvial facies are ubiquitous below the TS across the entirety of our study area being mostly associated with the LST, and thus

with the major alluvial depositional phase that characterised the Northern Adriatic during the LGM. This phase led to the sedimentation of ca. 20-30m of alluvial plain and fluvial channel deposits in the Venetian-Friulian Plain (Fontana et al., 2014). Alluvial facies are also identified at the top of the sediment cores located on the coastal area. Here they represent the HST deposits linked to the Middle to Late Holocene aggradation of Alpine rivers on the paralic environments formed at the maximum flooding in the Northern Adriatic (Bondesan et al., 2008; Fontana, 2024). For the Early Holocene, these facies are less common and are mostly fluvial incision fill deposits detected in sediment cores inside postglacial incised valleys, with the best studied example being the Concordia Incised Valley formed by the Tagliamento river (Fontana, 2006; Fontana et al., 2012; Ronchi et al., 2021). Only in the Trieste Gulf are alluvial plain deposits dated to this period commonly identified in the sediment cores (Covelli et al., 2006; Trincardi et al., 2011; Zecchin et al., 2024). These seem to be associated with a

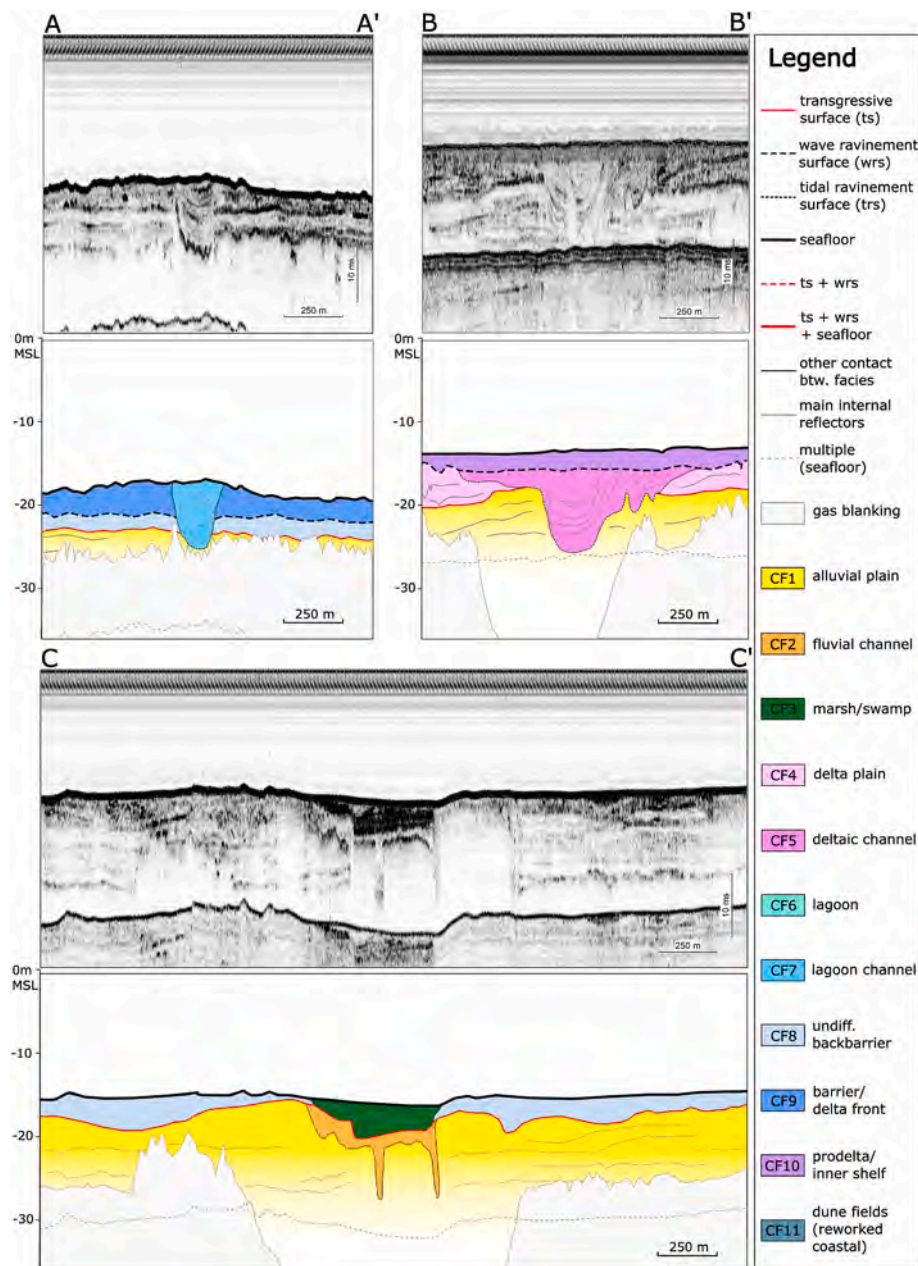


Fig. 5. Example of CHIRP data and interpretation following the seismic facies presented in Table 1, showing different seismic unconformities, depositional environments, and acoustic artifacts (locations of the profiles has been reported in Fig. 1). Focus on alluvial, backbarrier, and coastal deposits. Image created by authors 2026.

depositional phase of the Isonzo river between ca. 15000 and 8000 cal BC, for which a large paleochannel has been mapped (Novak et al., 2020; Ronchi et al., 2023). No other clear fluvial paleochannels can be distinguished in our data, except for previously identified incised valleys in onshore areas (Bondesan et al., 2008; Marocco, 2010; Fontana et al., 2012; Mozzi et al., 2013). This is likely to be because the alluvial facies in our CHIRP data are often blanked by either gas and/or other sandy deposits, typically represented by an overall semi-transparent facies. Exceptions include the occasional channelised features detected off the western Friulian Plain (Fig. 4a and 5c), which could tentatively be interpreted as the offshore continuations of the incised valleys dug by the Tagliamento river (Fontana et al., 2012). Furthermore, the crevasse-levee systems that we occasionally detected are probably associated with fluvial ridges formed in the late glacial period (Fontana, 2006).

These data therefore support the existence of a sediment-starved alluvial plain before the transgression in the Northern Adriatic. Based on pollen data (Bondesan et al., 2003; Canali et al., 2007; Miola et al., 2010; Kaniewski et al., 2024), we can characterise this area as a forested plain dominated at first by mixed oak forest and then by a warm woodland, while fen trees and wet meadow components have also been recognised, probably in correspondence with depressed and water-logged areas and riparian environments. This plain would have been crossed by both active and inactive fluvial incisions, with the former being occupied by Alpine rivers and the latter by smaller streams and freshwater marshes (cf. Ronchi et al., 2021). Topographic highs associated with fluvial ridges would also have been present. The position of both these features is, however, hard to map with accuracy, meaning that reconstructing the course of rivers on the palaeolandscape is particularly challenging.

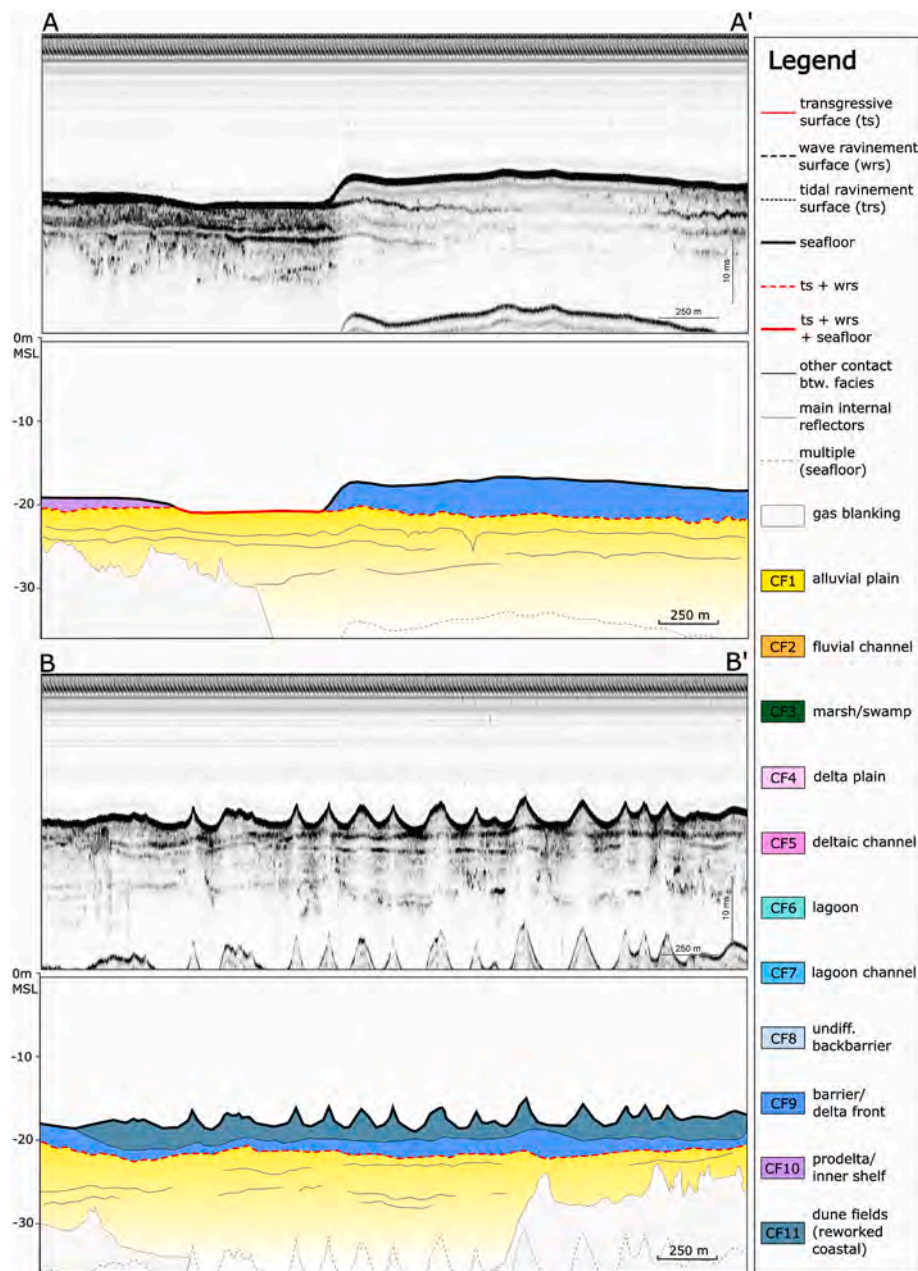


Fig. 6. Example of CHIRP data and interpretation following the seismic facies presented in Table 1, showing different seismic unconformities, depositional environments, and acoustic artifacts (locations of the profiles has been reported in Fig. 1). Focus on alluvial and coastal deposits. Image created by authors 2026.

4.1.2. Brackish marsh/Swamp and saltmarsh facies (F2A, F2B)

Facies associated with brackish marshes, swamps, and saltmarshes have only been detected occasionally (Figs. 4 and 5c). Nevertheless, these can easily be identified in our CHIRP data where they appear as very high amplitude reflectors (CF3) indicative of organic rich clay and peat layers associated with facies F2A and F2B (Table 1). The distinction between the two is not simple, however, as it requires specific associations with freshwater to brackish ostracods and molluscs for the former, and halophytic vegetation pollen, brackish molluscs and foraminifera – particularly *Trochammina inflata*, which is a clear saltmarsh indicator in the Northern Adriatic lagoons (Favero and Serandrei Barbero, 1980, 1981) – for the latter (Table 2). Thus, in both the sediment cores and CHIRP data we leaned towards a more generic CF3-F2A correlation to characterise these paralic facies unless clear saltmarsh indicators were present.

Overall, F2A can mainly be identified in correlation with, or just

above, the TS, at the start of the transgressive sequence mostly in the sediment cores but occasionally also in the geophysical data. For the latter, this facies tends to be detectable inside depressed areas in thick sequences, which are often associated with possible fluvial incisions (Fig. 4a and 5c). This pattern seems to be consistent with that previously identified in sediment cores from the Concordia Incised Valley. Here the peat and even gyttja sediments indicate the formation of palustrine, and possibly lacustrine, environments at the time sea level started to have an influence on the area (Ronchi et al., 2021). F2A can also be identified occasionally in sediment cores on top of other paralic deposits, especially when lagoon areas are being silted up as part of aggradation processes (Bondesan et al., 2008; Ronchi et al., 2021). F2B is instead mainly identified within lagoon sequences or on top of them (the latter being modern saltmarsh deposits of the Northern Adriatic lagoons) but only in the coastal sediment cores, suggesting that saltmarsh communities only started developing after ca. 6000 cal BC (Kaniowski et al.,

2024). While this might be due to conditions conducive to their formation only being met when sea level rise was gentle enough (Ronchi et al., 2019), in periods of stasis during the Early Holocene these conditions could have been met and we simply do not have enough sediment core data to distinguish brackish marshes identified in the CHIRP data from saltmarshes. This is especially the case when these develop in correlation with deltaic environments (Fig. 4b).

These data therefore indicate that brackish marshes and swamps would have developed at the start of the inundation phase in the Northern Adriatic. These would have been present not only at the margin of the lagoons, but also inside fluvial incisions and other depressions in the TS, where they formed thick organic-rich sequences before the incised valleys would be occupied by liman-lagoon environments (see below). Saltmarshes would instead develop inside the lagoons formed towards the end of the transgressive phase – or possibly earlier, although evidence is lacking – probably in association with areas receiving more sediment input close to deltaic sources (see below).

4.1.3. Lagoon facies (F2D-1, F2D-2, F2D-3)

One of the most common paralic environments in the Northern Adriatic are coastal lagoons, yet these are not particularly evident in our CHIRP data where they are only detected in very localised areas (Fig. 4a), usually through association with nearby sediment cores. In the CHIRP profiles, lagoon facies appear as low amplitude, semi-continuous reflectors inside deposits that are usually only a few metres thick (CF6), which makes them hard to identify (Table 1). In the sediment cores, however, facies F2D-1 and F2D-2 are particularly frequent and distinguishable due to the association with brackish, lagoon, and marine foraminifera (e.g., *Ammonia tepida*) and molluscs (e.g., *Cerastoderma glaucum*) (Table 2). Increased marine species and coarser sediments (i.e., sandier rather than just silt and clay) allow us to easily distinguish F2D-2 from F2D-1, and thus an outer rather than inner lagoon environment. On the other hand, lagoon channels and tidal inlets are not just common in the sediment cores – where they are associated with facies F2D-3, characterised by an alternation of fine sand and silt and similar fauna to F2D-2 (Table 2) – but have also been identified in great numbers on the Adriatic seafloor (Ronchi et al., 2018). In the CHIRP data (Fig. 5a), these erosional features (CF7) are particularly distinguishable due to their channel geometry and their fill, which is made up of an alternation of low and high amplitude draping reflectors (Table 1).

Similar to marshy facies, lagoon facies are also uncommon on the Adriatic seafloor, although they are frequent in sediment cores from the coastal area. This is due to current lagoons being more long-lived than those associated with the TST, which were comparatively short-lived. As a result, lagoons associated with the TST are less likely to have deposited thick sedimentary sequences, making them more vulnerable to erosion following the transgression (Ronchi et al., 2018, 2019). Like marshes, however, lagoons would have developed inside fluvial incisions following the transgression (Ronchi et al., 2021) and this is seen in our CHIRP data, where they can be identified inside depressions in the TS (Fig. 4a). They have also been detected under thick coastal deposits, associated with the ancient Po Delta to the south-west or the current coastal wedge (Trincardi et al., 2011). Moreover, sediment core data shows that outer lagoon deposits are quite common in the Trieste Gulf, where high rates of sedimentation have better preserved the TST paralic deposits compared to the rest of the Northern Adriatic (Trincardi et al., 2011). Due to the anticlockwise current circulation in the Northern Adriatic, in periods when the Isonzo would have flowed further west these lagoon areas would have probably been more like shallow bay environments, not protected by barrier islands seen further west (Zecchin et al., 2024). In the remainder of our study area, while mudflat deposits have not been preserved, the very common tidal inlets – and barrier complexes (see below) – indicate the presence of several generations of lagoons (Ronchi et al., 2018). Unfortunately, because of the lack of preservation of other lagoon facies in the offshore area, it is hard to characterise the precise morphology of these lagoons.

Our data therefore support the existence of several generations of coastal lagoons in the Northern Adriatic. These would have developed during different phases of sea level rise, in association with barrier complexes and other paralic environments (see below). Lagoons would have also infiltrated fluvial incisions, creating liman environments, as data from the Concordia Incised Valley suggests (Ronchi et al., 2021). In the current coastal area, lagoon deposits seem to have been present since at least ca. 6000 cal BC (Miola et al., 2006; Zecchin et al., 2009; Ronchi et al., 2021), where they have persisted until present day unless silted up by fluvial activity or reclaimed by humans (Fontana et al., 2017).

4.1.4. Deltaic facies (F2C-1, F2C-2, F2C-3)

The last clearly identifiable type of paralic environments in our study area are deltaic deposits. These are generally characterised as back-barrier deposits that include both freshwater and brackish elements. They contain coarser sediments than other paralic environments due to increased proximity to the sediments source, meaning that they are quite distinguishable in the sediment cores (Table 2). Even in the CHIRP data deltaic deposits present distinctive acoustic and geomorphological elements. The first consists of convex upwards cusped geometries (Fig. 4b) that can be associated with crevasse/levee features (CF4). These are elements that, while associated with alluvial facies, can also be found in deltaic environments (Ronchi et al., 2019). Thus, when these elements have been found above the TS, they have been associated with core facies F2C-2 (Tables 1 and 2). The second element consists of erosional features (CF5), which in the CHIRP data appear distinct to tidal inlets, as they consist of a larger channel geometry and are filled with low-amplitude lateral accreting reflectors (Fig. 5b) suggesting a more fluvially-influenced nature for these features. In particular, the coarser sediments associated with the low-amplitude reflectors indicate a sandy fill, meaning these channel features were associated with core facies F2C-3, which indicates a distributary channel (Tables 1 and 2). Facies F2C-1 can mainly be identified in sediment cores, which represents delta plain deposits associated with silt and fine sand and brackish and freshwater fauna (Table 2). In the CHIRP data the irregular low to high amplitude reflectors located in lateral continuity with both the crevasse-levee and channel features (CF4) were associated with facies F2C-1 (Table 1).

Deltaic environments have mostly been identified around the Po Delta and the deposits associated with its ancient respective course offshore (Moscon et al., 2015; Amorosi et al., 2017; Ronchi et al., 2019). Nevertheless, both acoustic facies and core facies in our study area can be associated by morphology, reflectors, lithology, and fauna with the deltaic deposits of the Po Delta. This suggests that smaller deltaic environments would also have been present in the Gulf of Venice in association with river mouths. From evidence of coarse sand and gravels inside incisions even in the coastal plain (Bondesan et al., 2008; Fontana et al., 2012; Ronchi et al., 2021), we hypothesise that rivers had a high sedimentary load in the Early and Middle Holocene that was funnelled inside postglacial incisions and would have been able to create small delta plains crossed by crevasse/levees channels and a larger river channel, silting up limited areas of the lagoons during periods of slower sea level rise. In fact, deltaic facies are found intercalated with lagoon facies in the coastal sediment cores, where a long-lived backbarrier complex is present, while they are capped by coastal deposits in the offshore area (Fig. 4b and 5b), indicating a rapid drowning. In the CHIRP data, deltaic facies can often be laterally associated with marsh facies (Fig. 4b), suggesting these more fluvially-influenced deposits were not particularly extensive.

Our data therefore demonstrates the existence of several generations of more fluvially-influenced backbarrier deposits amidst the more marine-influenced coastal lagoons. These have been characterised as small deltaic complexes, formed in correspondence with river mouths during periods when accommodation rates were outbalanced by accretion rates, and thus indicative of slower sea level rise. They would have not been particularly extensive or long-lived, however, as they are both

laterally and vertically associated with marsh, lagoon, and coastal deposits.

4.1.5. Undifferentiated backbarrier facies (F2E?)

While the previous sections have described distinguishable paralic facies, most of the backbarrier deposits in our study area are undiagnostic (CF8) and have thus been grouped under the label of undifferentiated backbarrier facies (Table 1). This is likely due to a combination of factors, but primarily strong erosional forces often reworking or truncating deposits and making the acoustic facies affected harder to discern. For this reason, where sediment core data was available we used that to characterise undiagnostic deposits. In the CHIRP data, these deposits are often internally characterized by irregular, low amplitude reflectors with no distinguishable internal geometry (Fig. 5).

Different interpretations for these facies could be suggested: these could be lagoon and/or deltaic deposits truncated by the transgression and subsequently reworked by marine processes. However, there are also similarities with deposits identified under the Venice Lagoon, at the base of the Holocene sequence and above the aforementioned caranto, interpreted as overflow deposits linked to rapid transgression periods (Tosi et al., 2007a, 2007b). This interpretation relies on the facies' regular appearance at the start of the TST sequence indicating a correlation with core facies F2E, also characterised by chaotic sand-silt/clay alternations (Table 2) and linking to these overflow deposits. Thus, we hypothesise that these deposits would have formed in the offshore area as well, where they would be more common due to repeated periods of fast sea level rise in the Early Holocene compared to the period in which the current lagoons would have formed (see section 4.2).

Therefore, while it is difficult to precisely characterise these facies, we suggest that they could represent initial deposition at different stages of the transgression. This would be occurring before periods of slower sea level rise would have allowed the formation of a more significant, resilient backbarrier complex, thus associating these CHIRP facies with core facies F2E. More sediment core data is nevertheless needed to more precisely characterise these deposits.

4.1.6. Coastal and shallow marine facies (F3A, F3B, F3C, F3D)

The remaining facies in our study area consist of coastal and shallow marine deposits. These are particularly frequent in the CHIRP data (CF9), where they appear as transparent to semi-transparent 'wedge' bodies with chaotic reflectors (Figs. 4–6). These can be associated with the sandy deposits of core facies F3A and F3B, which both present shallow marine foraminifera and molluscs (Table 2). As such, the distinction between the two is not straightforward; for the sediment cores it has been based on the interpretation reported in the literature, while for the geophysical data this was more challenging. We associated most coastal deposits with barrier island deposits (F3A), unless core data or associated deltaic facies proved an association with a delta front environment (F3B). Fine-grained coastal facies interpreted as prodelta or nearshore coastal deposits (CF10) are also present in the CHIRP data (Fig. 5b), and they can be correlated with the fine sand and silt of core facies F3C, which are associated with a shallow to open marine fauna (Table 2). Finally, reworked coastal deposits are easily identifiable in the CHIRP data (CF11), which appear as transparent chaotic bodies arranged in large submarine sandy dune fields (Fig. 6b). We associated these deposits with core facies F3D (Table 2).

Overall, coastal deposits are almost ubiquitous in our study area – they appear in great number offshore and are often present more inland than the current coastline in the coastal area. The former have long been known and associated with different palaeocoastlines, as they represent the barrier complex of ancient barrier lagoon systems (Trincardi et al., 2011; Fontana and Ronchi, 2021). The latter indicate similar environments, while also suggesting relatively strong progradation tendencies in many areas of the Northern Adriatic (Amorosi et al., 2008). Delta front deposits can be identified locally in the coastal sediment cores in correspondence with deltas of Alpine rivers, while they are harder to

identify offshore. The main delta front environment identified in the literature is the Trezza Grande palaeodeltaic complex off the current Tagliamento delta (Gordini et al., 2002; Zecchin et al., 2015), which forms a thick depositional body composed of both paralic and coastal facies (Fig. 5b). The only area where coastal deposits associated with core facies F3A and F3B are scarcer is the Trieste Gulf, where they only appear occasionally in sediment cores. While this could be due to our lack of coverage in the area, previous studies have also failed to identify major barrier complexes in the Trieste Gulf (Trincardi et al., 2011). This is probably because, due to the current circulation in the Northern Adriatic, barrier islands would have only formed West of the Isonzo. Instead, the Trieste Gulf is covered by shallow marine deposits that can be more closely associated with prodelta facies and can reach several metres of thickness (Covelli et al., 2006; Trincardi et al., 2011; Zecchin et al., 2024). In contrast, prodelta deposits are less common to the West, where they are mainly associated with the current coastal wedge or the Trezza Grande palaeodelta, probably due to the strong erosional trends of the Adriatic seafloor. Because of these same processes, coastal deposits on the Northern Adriatic seafloor are often reworked into dune fields, which were likely formed soon after the transgression (Correggiari et al., 1996b).

Our data therefore confirms the existence of several drowned barrier complexes. When exposed on the seafloor, these are often reworked or partially eroded, while under the current coastal area they can be covered by both paralic and coastal deposits, indicating strong progradation in some parts of the Northern Adriatic. These deposits are particularly significant for reconstructing ancient palaeoshorelines in our study area but can also indicate the presence of deltaic complexes.

4.2. Inundation models

This section presents the results obtained from the inundation models created for different sub-regions, highlighting different periods of stasis, slow and rapid sea level rise. The distribution of the SL data over time and space is not consistent, meaning that each sub-region illustrates a RSL scenario not only specific to that distinct sub-region, but also to distinct time periods. All altitude values are reported at mean sea level (MSL).

4.2.1. Trieste Gulf and eastern Friulian Plain (sectors A-B)

This sub-region presents the highest number of internally consistent SL data, making the reconstructions particularly reliable (Fig. 7). However, 22 out of the 29 SLIPs and limiting points here concentrate on the period between ca. 9000–7000 cal BC (Fig. 3a), which poses a challenge when analysing the sea level history of this sub-region in the following centuries. Moreover, the SL data values here are particularly shallow, as they almost display an uplift tendency even compared to a GIA curve (Fig. 3a). In particular, a very early phase of inundation is recorded as early as ca. 9400–9200 cal BC in an open lagoon environment formed at the entrance of the Trieste Gulf (Pi02, Novak et al., 2020). Three SLIPs and two terrestrial limiting points record RSL at -26 ± 1 m MSL between ca. 9000–8600 cal BC (Fig. 7a), indicating a more stable phase of sea level rise. Following a rise of ca. 2 m between 8600 and 8200 cal BC, another phase of stability can be detected between ca. 8200–7800 cal BC, when different SLIPs record RSL at -24 ± 1 m MSL (Fig. 7b). An even more pronounced period of strong sea level rise can be detected after ca. 7800 cal BC, when SL data indicates an increase of ca. 4 m in about 400 years (Fig. 3a). After this point, SLIPs indicate RSL at -20 ± 2 m MSL between ca. 7600–7200 cal BC (Fig. 7c). Finally, the only later period when sea level data is available for this sub-region is around ca. 5000–4800 cal BC, when SLIPs from reclaimed areas of the eastern Friulian Plain record RSL at -5 ± 1 m MSL (Fig. 7d).

4.2.2. Central and Western Friulian Plain (sectors C-D)

This sub-region also presents enough SL data to allow relatively reliable reconstructions to be made (Fig. 8). Unlike the previous sub-

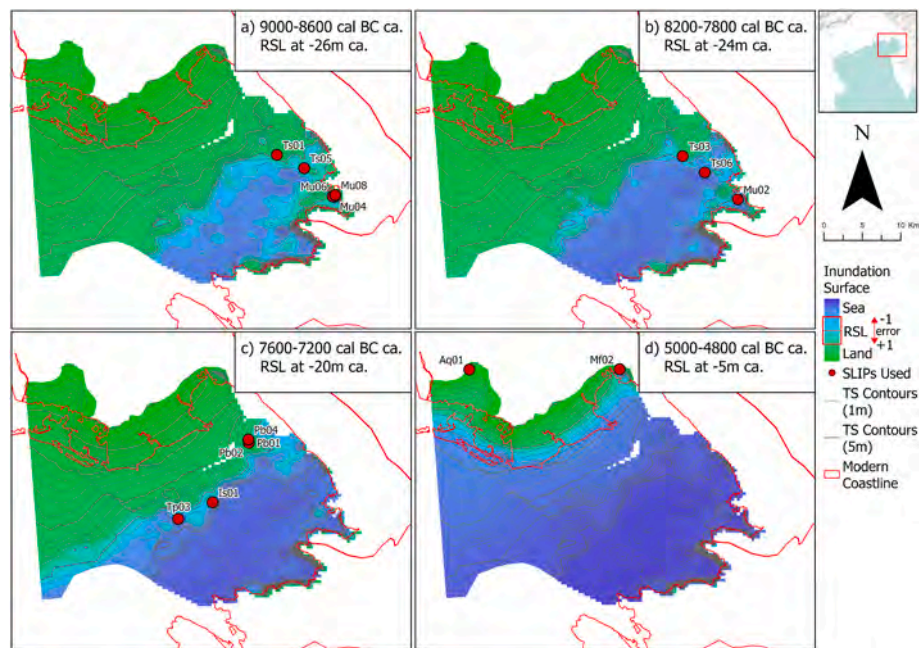


Fig. 7. Inundation Models for the Trieste Gulf and eastern Friulian Plain (Sectors A-B), including SL Data used. Image created by authors 2026.

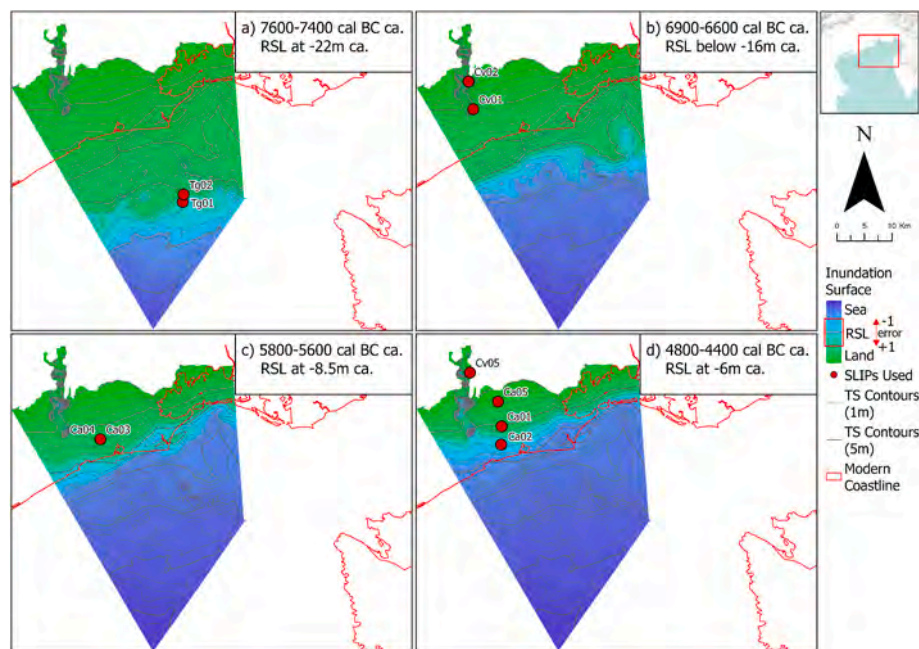


Fig. 8. Inundation Models for the central and western Friulian Plain (Sectors C-D), including SL Data used. Image created by authors 2026.

region, SLIPs and limiting points here are distributed more evenly through time (Fig. 3b), providing a good overview of the sea level history of the whole study area for the Early and Middle Holocene. This, however, does not include the period before ca. 7700-7400 cal BC, as the first SLIPs from offshore brackish deposits are only recorded in this period, indicating RSL at -22 ± 1 m MSL (Fig. 8a). This probably suggests that this sub-region started to be inundated before or around this period. Although the magnitude of sea level rise in this drowning phase is uncertain in this sub-region, a strong phase of sea level rise can be more confidently recorded later between ca. 7000-6800 cal BC. This is from terrestrial limiting points from marshes inside the Concordia Incised Valley that suggest RSL below -16 ± 0.5 m MSL between ca. 6900-6600 cal BC (Fig. 8b). Although this is only based on limiting points, we

can still assume a rise of up to 5 m in 400 years (Fig. 3b). Subsequently, a gap in SL data is present up to ca. 6000-5800 cal BC, when one SLIP indicates the first lagoon influence in the Concordia Incised Valley at a depth of -14.5 ± 0.5 m MSL (Cv03, Ronchi et al., 2021). Another very rapid phase of sea level rise could be detected from SLIPs in the Caorle lagoon, which indicate RSL at -8.5 ± 0.5 m MSL between ca. 5800-5600 cal BC (Fig. 8c). Although SLIPs for the rest of the 6th millennium cal BC are lacking for this sub-region, this next period seems relatively stable with only a limited rise in sea level (Fig. 3b). The next series of lagoon SLIPs record a phase of relatively more marked inundation between ca. 5000-4800 cal BC, as they indicate a RSL of -6 ± 1 m MSL between ca. 4800-4400 cal BC (Fig. 8d).

4.2.3. Eastern and central Venetian Plain (sectors E-G)

This sub-region presents enough SL data to produce accurate reconstructions (Fig. 9), but concentrated between ca. 6000 and 4500 cal BC, and so they only provide a detailed picture for the 6th and part of the 5th millennium cal BC (Fig. 3c). The first datum is a terrestrial limiting point dated to ca. 6100-5900 cal BC and likely indicates RSL below -12m MSL (Fig. 9a). More secure data is then present for the period between ca. 5700-5300 cal BC, when SLIPs from the oldest lagoon deposits under the northern Venice lagoon indicate RSL at $-10\pm 1\text{m}$ MSL (Fig. 9b). A stable phase in sea level rise is thus recorded in this period, until a rise of 1m between 5300 and 5200 cal BC (Fig. 3c). In the period between ca. 5200-5000 cal BC, an increased marine influence in the northern Venice lagoon shows in SLIPs recording RSL at $-9\pm 1\text{m}$ MSL (Fig. 9c). Finally, another phase of more substantial sea level rise is recorded between ca. 5000-4900 cal BC, as SLIPs from the period between ca. 4900-4600 cal BC indicate RSL at $-7.5\pm 1\text{m}$ MSL (Fig. 9d).

4.2.4. Western Venetian Plain and Adige Coastal Plain (sectors H-I)

This sub-region lacks SL data (Fig. 10), which are few and are temporally patchy (Fig. 3d). While this makes local reconstructions particularly challenging, we can still identify some key evolutionary moments in its sea level history. Moreover, due to the proximity to the Po Delta – and thus higher subsidence rates – sea level values here are some of the deepest recorded and can be quite discordant with those recorded in previously discussed sub-regions. The first SLIP records RSL at $-36\pm 1\text{m}$ MSL around ca. 8600-8000 cal BC (Fig. 10a), showing that the earliest marine influence and formation of brackish environments in the west happened later than in the east. The next SL data have all been obtained from the fills of tidal inlets, which therefore only provide marine limiting points. These show the drowning of lagoon systems at ca. 7900-7500 cal BC and 7500-7000 cal BC under sea level rise conditions (At01-03, Ronchi et al., 2018). For the latter period, a RSL above $-31.5 \pm 0.5\text{m}$ MSL has been estimated (Fig. 10b). Another marine limiting point records RSL above $-20\pm 1\text{m}$ MSL around ca. 6700-6500 cal BC (Fig. 10c), showing again a strong rise in sea level between ca. 7000-6700 cal BC. Finally, a SLIP from the southern Venice lagoon dated around ca. 4200-4000 cal BC records RSL at $-9.5 \pm 1.5\text{m}$ MSL (Fig. 10d).

4.3. Palaeolandscape reconstructions

The inundation models discussed above have revealed different trends in the sea level history of the Northern Adriatic region, which can vary from one sub-region to another. Through our sea level reconstructions (see section 3.4) we were able to not only match these trends, but also to calculate rates of sea level rise. This has allowed us to identify different phases of stability or very slow sea level rise, alternating with periods of rapid drowning. Moreover, different generations of depositional environments identified above can be associated with each of these phases, allowing us to produce palaeolandscape reconstructions for our whole study area. Key moments in the paleogeographic history of the region have thus been displayed in Figs. 11 and 12 and will be discussed in more detail below. Note that the position of rivers is indicative and based on information provided in the literature.

The first reliable evidence for the start of the marine influence in the Northern Adriatic is dated between 9000 and 8600 cal BC, when the Trieste Gulf started being inundated, while some paralic environments seem to have formed also further west (Fig. 11a). This period seems to be characterised by a relative stability in sea level rise, with rates $<1\text{ mm/y}$ (Supplementary Material 2) leading to the formation of both lagoons and deltaic systems. The latter have been detected in our CHIRP data both at the southernmost point of our study area, where delta plain facies possibly linked to the Adige-Po palaeodelta are visible, and further up where we can see a similar depositional environment possibly linked to the Brenta river (Supplementary Material 3), whose incision seems to have flowed in this directory of its megafan (Zecchin et al., 2009; Mozzi et al., 2010). Between these more fluviially-influenced environments, the sea level reconstructions suggest that initial marine influence might have also led to the formation of marshes and lagoons, although deposits confirming this are lacking (Supplementary Material 3). More certainly, sediment cores in the Trieste Gulf (Supplementary Material 1) record brackish marshes and open lagoon environments similar to shallow bays, while alluvial facies also suggest the uncertain presence of the Isonzo river delta.

After an increase in sea level rise at 8600-8200 cal BC, with rates between 5.3 ± 0.5 and $5.7 \pm 0.5\text{ mm/y}$, a renewed phase of stasis with rates again $<1\text{ mm/y}$ occurred (Supplementary Material 2). This led to the formation of another generation of paralic environments probably in

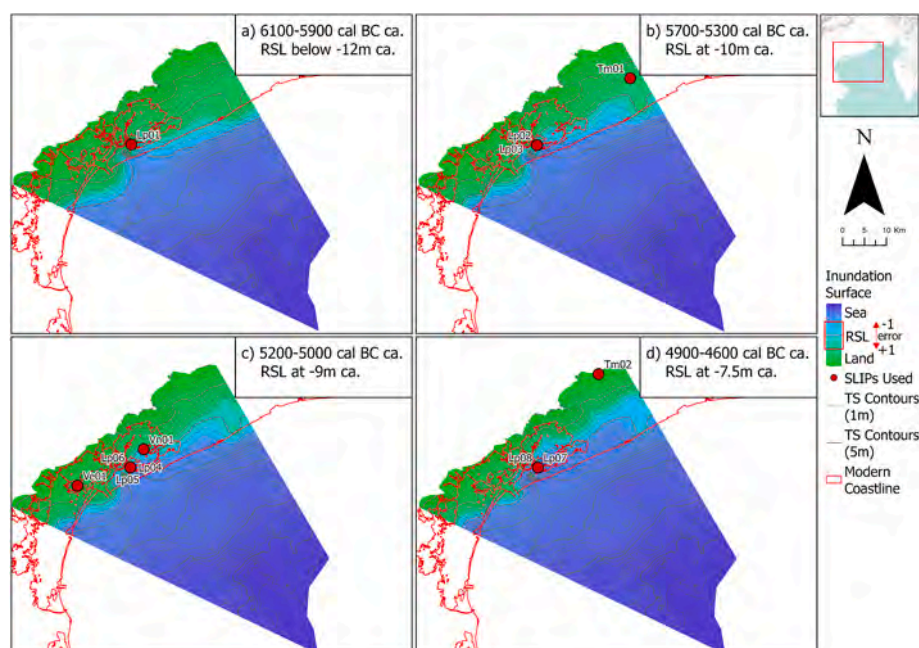


Fig. 9. Inundation Models for the eastern and central Venetian Plain (Sectors E-G), including SL Data used. Image created by authors 2026.

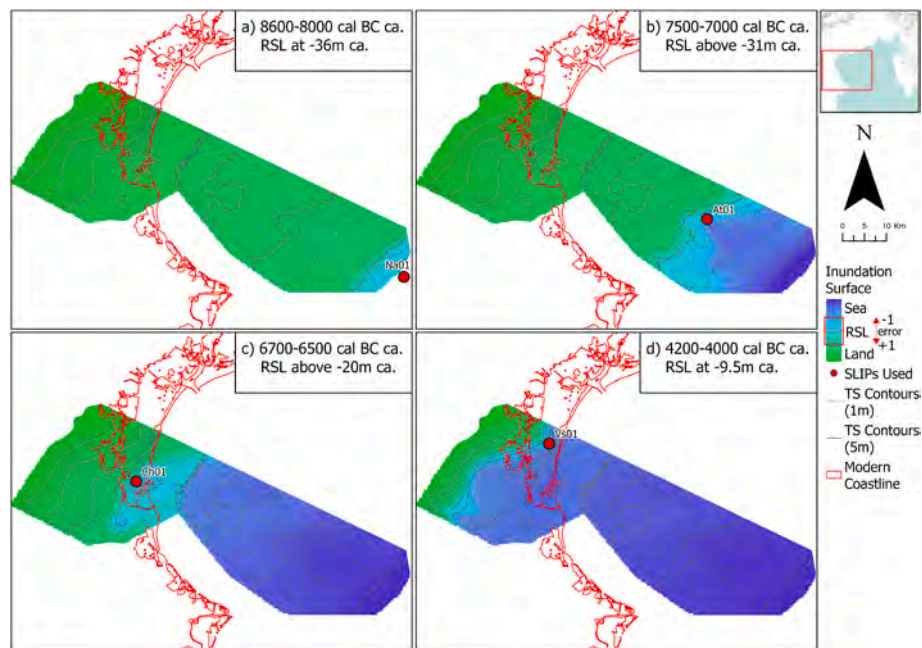


Fig. 10. Inundation Models for the western Venetian Plain and Adige Coastal Plain (Sectors H-I), including SL Data used. Image created by authors 2026.

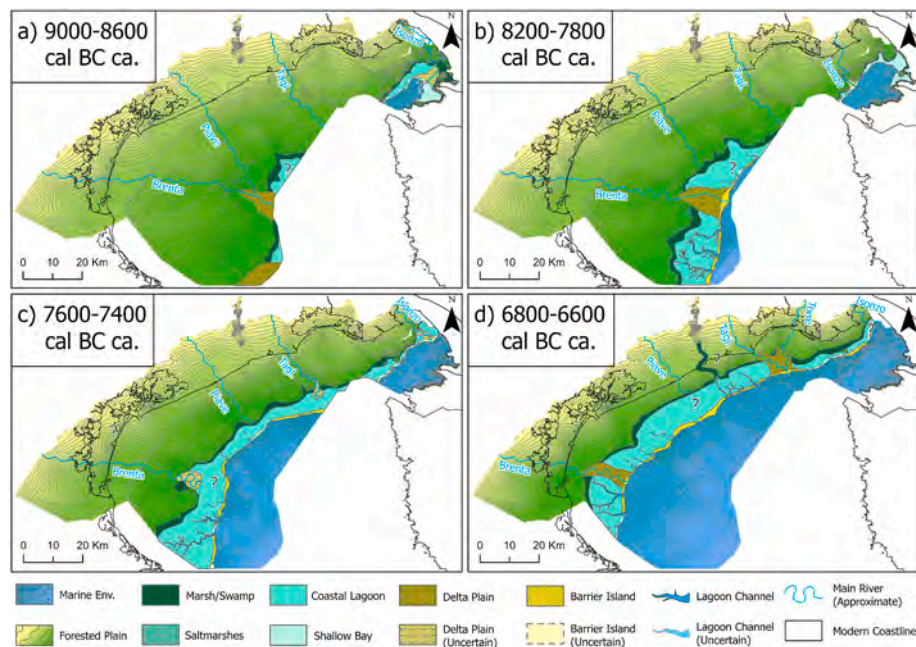


Fig. 11. Hypothetical palaeolandscape reconstructions for the Northern Adriatic (9000 to 6600 cal BC ca.). Question marks indicate areas of particular uncertainty. Major Alpine rivers' palaeocourses have also been traced (Tagl. is short for Tagliamento) but note that the rivers' position is approximate and based on the literature (e.g., Fontana, 2006; Bondesan et al., 2008; Marocco, 2010; Mozzi et al., 2013; Fontana, 2024). Image created by authors 2026.

place until ca. 7800 cal BC (Fig. 11b). The presence of lagoons in the western sectors is now quite certain, as the CHIRP data shows partially preserved lagoon deposits, tidal inlet systems, and the first evidence of a barrier complex (Supplementary Material 3). The delta of the Brenta river appears to be in a similar position to the earlier phase, although relocated further inland (Supplementary Material 3). Based on the sea level reconstructions, the central sectors instead seem to have still been almost fully emerged. In the Trieste Gulf, sediment core data suggests the inland expansion of shallow bay brackish environments, drowning almost all the previously established marshes, while alluvial facies seem to indicate a westward migration of the Isonzo river delta

(Supplementary Material 1).

A very intense phase of sea level rise seems to have followed, as between 7800 and 7600 cal BC we record rates of sea level rise of 20.8 ± 0.5 mm/y, leading to an increase in RSL of 4m (Supplementary Material 2). Between 7600 and 7000 cal BC, sea level rise seems to have slowed down with rates between 2.6 ± 0.5 and 3.9 ± 0.5 mm/y (Supplementary Material 2). Although with the available SL data it is unclear whether this period was characterised by a steady rise in sea level or an alternation of brief phases of drowning and stability, the latter possibility might be confirmed by different barrier complexes matching the age-depth association of this period being recognisable in

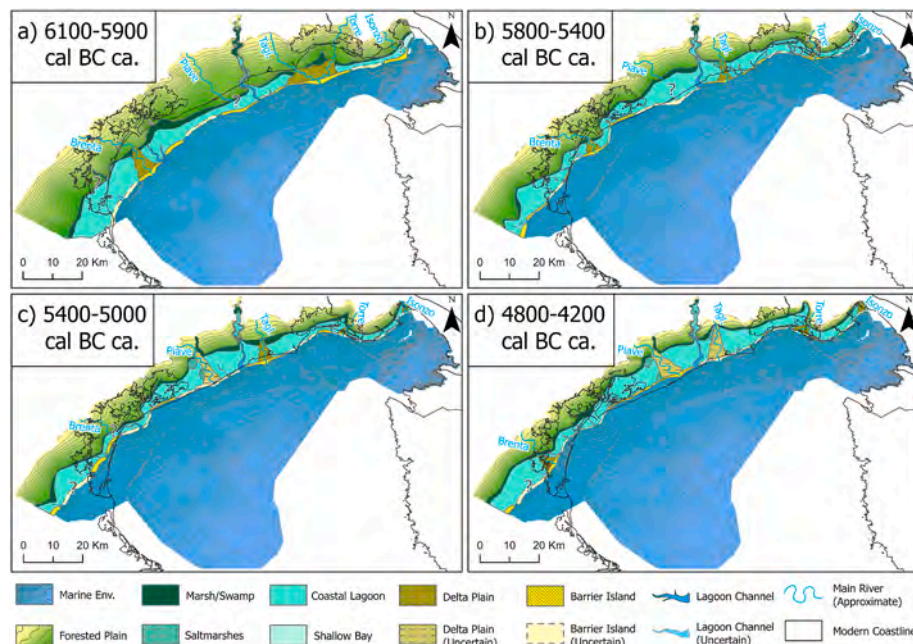


Fig. 12. Hypothetical palaeolandscape reconstructions for the Northern Adriatic (6000 to 4200 cal BC ca.). Question marks indicate areas of particular uncertainty. Major Alpine rivers' palaeocourses have also been traced (Tagl. is short for Tagliamento) but note that the rivers' position is approximate and based on the literature (e.g., Fontana, 2006; Bondesan et al., 2008; Marocco, 2010; Mozzi et al., 2013; Fontana, 2024). Image created by authors 2026.

the CHIRP data (Supplementary Material 3). In fact, short-lived lagoon systems might have still formed, for instance around 7600-7400 cal BC (Fig. 11c). In the CHIRP data barrier lagoons with large tidal inlets can be identified in the western sectors (Supplementary Material 3). In the central sectors, depressed areas start to be occupied by marshes (Fig. 4a), although we cannot precisely map incised valleys in our data, so their full extension inland is uncertain (Supplementary Material 3). The sea level reconstructions suggest the Trieste Gulf being now under a high degree of marine influence, with core data indicating lagoon environments forming offshore the Eastern Friulian Plain (Supplementary Material 1). Although some deltaic deposits can be identified (Supplementary Material 3), the presence and position of deltas in this period is uncertain, which could be explained by the inability of rivers to form deltaic systems under conditions of more intense sea level rise.

Another major rise in sea level is suggested by rates of 22.5 ± 0.5 mm/y between 7000 and 6800 cal BC (Supplementary Material 2), although sea level data for the 7th millennium is scarce (Fig. 3). While this makes it particularly challenging to reconstruct the palaeolandscape in this period, one of our maps shows a possible scenario between 6800 and 6600 cal BC, when the most data are available (Fig. 11d). Due to the intense drowning amounting to a rise of 10m since 7800 cal BC, sea level reconstructions indicate the coastline of this period being located much closer to the current one. An extensive system of lagoons has been detected, as tidal inlets and barrier islands detected in the CHIRP data indicate (Fig. 5a and 6). Core data suggests that marshes seem to have also started developing inside the Concordia Incised Valley in this period (Supplementary Material 1), which could link to similar deposits that we identified offshore the Western Friulian Plain (Fig. 5c). Two major deltaic systems can also be identified in the CHIRP data (Fig. 4b and 5b), one aligned with the same position of the Brenta river as in previous periods, and the other associated with the Trezza Grande palaeodelta. The latter has been suggested to have been linked to the Tagliamento river (Zecchin et al., 2015), which would match with the dates of activation of this course onshore (Fontana, 2006). Yet, since we identify two main deltaic channels in the CHIRP data (Supplementary Material 3), and since one seems to originate more to the east, away from the Tagliamento megafan, we suspect the influence of another river in this deltaic system – perhaps the Torre river,

whose avulsion history is still uncertain (Fontana, 2024).

Because of a lack of SL data between 6500 and 6000 cal BC, no sea level reconstruction could be produced for this period, and thus also no rates of sea level rise. Our next map instead reports the palaeolandscape around 6000 cal BC (Fig. 12a), when another generation of paralic environments seem to have formed, based on the identification of lagoon and barrier island deposits in the CHIRP data (Supplementary Material 3). Marshes can only be detected in some of the cores, especially in the Adige Coastal Plain and in the Western Friulian Plain (Supplementary Material 1). In these areas, lagoon deposits can also be detected in the cores (Supplementary Material 1), most likely associated with the lagoons of the Po palaeodelta for the former (Amorosi et al., 2017) and the Concordia Incised Valley liman for the latter (Ronchi et al., 2021). Two very similar deltaic systems to the ones detected in the previous phase can also be identified in the CHIRP data (Supplementary Material 3). The one associated with the Brenta river seems to be related to a new course of it (Zecchin et al., 2008; Mozzi et al., 2010), while the Trezza Grande delta seems instead to be still in place, although retreated slightly more inland, before its final drowning.

Another rapid increase in sea level is recorded between 6000 and 5800 cal BC, with rates of 25.5 ± 0.5 mm/y (Supplementary Material 2). While these rates are the highest recorded, causing an increase in sea level of ca. 5m, it is still based on a limited number of SL data (Fig. 3). Nevertheless, sea level predictions for the period between 5800 and 5400 seem to reliably point out to a stable phase, with sea level rise rates between 0.5 ± 0.5 and 2 ± 0.5 mm/y (Supplementary Material 2). This is consistent with a slowdown in sea level rise as the highstand is reached (Amorosi et al., 2008, 2017; Fontana and Ronchi, 2021), leading to the coastline being located almost in its present-day position (Fig. 12b). In the western sectors, paralic environments exist much more inland than today, as indicated by lagoon deposits identified in cores, while in the central and eastern sectors palaeolagoons underneath the existing and reclaimed modern ones can be detected (Supplementary Material 1). The first evidence of saltmarshes is also recorded from cores in this period (Supplementary Material 1), which might be linked to a new palaeodelta of the Tagliamento river that seems to have moved further westward in correspondence with the most likely fluvial course of this period (Fontana, 2006). The Brenta river delta seems to instead be

following the same course as previously (Zecchin et al., 2008), while a possible delta of the Torre or Isonzo rivers could be present to the east as recorded in cores (Supplementary Material 1).

After 5400 cal BC, sea level rise rates remain generally low – no more than 2 ± 0.5 mm/y – until 5000 cal BC (Supplementary Material 2). Because of the low rates of sea level rise, the paralic environments of the period between 5400 and 5000 cal BC are thus located in a very similar position to the previous phase (Fig. 12c). Lagoon and marsh environments are nevertheless expanding further inland, especially around depressions in the pre-existing plain as suggested by cores (Supplementary Material 1). Deltaic systems seem instead to have changed more, as the Brenta river delta cannot be detected in cores in this period, and new deltas can be identified in cores under the Grado lagoon and on the edge with the Karst hills (Supplementary Material 1), perhaps linked to the Torre and Isonzo river respectively. Moreover, saltmarshes can also be detected in the Piave river coastal plain (Supplementary Material 1), also very likely associated with its delta previously identified in this area (Bondesan et al., 2008).

Between 5000 and 4800 cal BC, rates of sea level rise increased again to 7 ± 0.5 mm/y but then decrease at an average of 1.5 ± 1 mm/y (Supplementary Material 2). Thus, between 4800 and 4200 cal BC, the maximum landward migration of the coastline in most of the study area is reached (Fig. 12d). The only sector where this does not seem to be the case is the central Venice lagoon, which, according to our sea level reconstructions, seems to only start being inundated in this period. Similar to the previous phase, this period sees the persistence of the pre-existing lagoon systems and their expansion further inland, as supported by core data (Supplementary Material 1). Most of the previous deltaic systems seem to survive, although now a possible delta of the Brenta river could be identified under the southern Venice lagoon (Supplementary Material 1). Saltmarshes also seem particularly rich in this period, as they can be identified in several areas between the Tagliamento and northern Venice lagoon (Supplementary Material 1).

5. Discussion

5.1. Palaeolandscape evolution

The results presented above allow us to distinguish several phases in the palaeolandscape evolution of the Northern Adriatic region. Comparisons with nearby areas are only possible with the Po Delta, which witnesses relatively similar developments (Amorosi et al., 2017), but unfortunately these are more challenging with the Eastern Adriatic due to the very different karstic setting, deeper bathymetry, and the lack of local SL data for the period in question for the Istrian, Kvarner, and Dalmatian coastlines (Dean et al., 2020; Benac et al., 2026). Our data supports the idea of an in-place drowning mechanism for the Northern Adriatic shelf, with the stepped nature of sea level rise resulting in barrier-backbarrier complexes, developed during periods of stasis, being rapidly transgressed (Storms et al., 2008; Zecchin et al., 2015).

This stepped trend seems to predominate up to ca. 6000 cal BC, with distinct generations of paralic systems separated by pulses of sea level rise detected (Fig. 11). We identified three main phases of strong sea level rise, with rates between ca. 20–25 mm/y, around 7800–7600, 7000–6800, and 6000–5800 cal BC. These phases roughly match those identified for the Po Delta around ca. 7200 and 5700 cal BC (Amorosi et al., 2017). Because of the shallow gradient of the basin, these punctuations in sea level rise caused major changes in the palaeolandscape, with barrier-backbarrier complexes being displaced several kilometres inland. Nevertheless, the stable phases in-between seem to have continued to support the formation of barrier lagoons and swamps separated by small deltaic complexes. These lagoons would have been crossed by a large network of tidal inlets and channels and sheltered by barrier islands (Trincardi et al., 2011; Ronchi et al., 2018). The only exceptions to these seem to have been the brackish shallow bays of the Trieste Gulf, which would have been more open than the ones further

west (Zecchin et al., 2024). Our data also allows us to characterise the palaeodeltas of this region, which would have been crossed by sub-aerially exposed ridges separated by marshy pockets and possibly wet meadows. These deltas are not, however, comparable to the large marshy coastal plain and inner estuary of the Po palaeodelta, although similarities can be found in the barrier-backbarrier complexes separated by deltaic systems (Amorosi et al., 2017). Instead, in our study area incised valleys would have allowed the formation of at first marshes and then liman environments further inland than the rest of the palaeolagoons, although the Concordia one is the only example for which enough data was available to allow detailed reconstructions (Ronchi et al., 2021). During phases of rapid sea level rise, overflood deposits might have also formed, which likely represent flooded areas of the pre-existing plain, leading to the establishment of short-lived lagoons and marshes protected by more ephemeral barrier complexes.

The subsequent highstand period after 5800 cal BC is characterised by much slower rates of sea level rise, except for the period between 5000 and 4800 cal BC, which led to the stabilisation of the barrier-backbarrier complex around the current lagoons (Fig. 12). This is consistent with data by Amorosi et al. (2017), which indicate the maximum shoreline migration of the Po Delta being reached in the 6th millennium. The embryo of the modern lagoons (including the ones now reclaimed) thus started forming around 5800–5400 cal BC – even though the southern Venice lagoon might have already been in its formation stages by 6000 cal BC, while its central sector only started being inundated around 4500 cal BC. The progradation trends already seen in the Po Delta shortly after 5000 cal BC (Amorosi et al., 2017) are not particularly evident in our study area, where the paralic environments continued to expand further inland while the shoreline seemed relatively stable, especially around palaeodeltas. After 4000 cal BC, marshes and lagoons would continue their expansion further inland until reaching their maximum extent before their reclamation (Fontana et al., 2017). Given the stability of sea level rise after 5800 cal BC, paleogeographic changes were mostly related to local retrogradation and progradation trends driven by fluvial activity (Amorosi et al., 2008). Nevertheless, similar environments to the lagoons, marshes, and deltas of the stable phases before 6000 cal BC would have formed. A notable difference is the more solid evidence for saltmarshes being present, which seem to have developed especially around deltas – although more offshore core data might confirm their existence even during periods of stasis in the Early Holocene. Throughout all these periods, however, the environments that would have formed, and thus the local palaeolandscape picture, would have been highly variable through time and space. Compounding this variability, although difficult to detect at our current data resolution, coastal lagoons are dynamic and sensitive environments, and smaller scale changes are likely to have been occurring at even smaller timescales.

5.2. Archaeological potential

Although no archaeological evidence has been recovered from these offshore palaeolandscapes, key aspects relating to Mesolithic and Neolithic lifeways and communities can be addressed by considering the palaeolandscape reconstructions produced in this study. This section will therefore stress the relevance of the landscape changes described above to selected archaeological themes, highlighting the potential of submerged landscape archaeology in the study area. The themes that will be discussed are the occupation of the Northern Adriatic lowlands by Mesolithic groups, the effects of sea level changes on prehistoric communities, and the implications of a different landscape setting in the context of the spread of farming in the area.

Palaeolandscape reconstructions are particularly relevant for the study of Mesolithic foragers in the Northern Adriatic, with wetland development suggesting extensive highly productive paralic environments forming at different stages of the transgression. These environments would have been very attractive to Mesolithic populations, which

are generally thought to have been drawn to coastal wetlands for fishing, shellfish gathering, and hunting of birds and larger game, as both ethnographic and archaeological evidence shows (Nicholas, 2007). This means that it is very likely that Mesolithic foragers exploited and settled the Northern Adriatic palaeolandscape. In fact, archaeological evidence in the region suggests that these societies had an interest in coastal and aquatic resources, as evidenced by faunal remains, harpoons and other fishing implements, and ornamental perforated shells (Voytek, 2024; Dean et al., 2020; Kačar, 2020; Fontana et al., 2023). Yet, lowland sites in the region are mainly constituted by surface scatters of flint tools, often composed of a limited number of artifacts (Fontana and Visentin, 2016; Fontana et al., 2023). Thus, very little direct evidence of the exploitation of lowland and coastal environments by Mesolithic communities remains. This problem is exacerbated by the contrasting wealth of knowledge on the highland occupation in the Mesolithic (Visentin, 2017; Fontana et al., 2020, 2023), which pinpoints the Northern Adriatic as a region where several hunter-gatherer groups lived in the Early Holocene. Therefore, the submerged landscapes identified here may be of key relevance to fill this knowledge gap, as the barrier lagoons, marshy incised valleys, and deltaic complexes would have all provided excellent environments for Mesolithic communities to thrive in. Underwater archaeological investigation of these deposits will be a necessary step to advance our knowledge of communities living away from the highlands, which might open new windows into our understanding of the Mesolithic in the Northern Adriatic. Where these deposits survive there is the potential for excellent preservation resulting from waterlogged fine deposits (Flemming et al., 2017), further stressing the archaeological potential of our study area.

As our sea level reconstructions have shown, periods of strong sea level rise would have occurred, rapidly drowning extensive areas of the palaeolandscape. While phases of stasis or slow rise would have allowed the development of stable paralic environments that Mesolithic societies could exploit and even settle in, periods of rapid drowning would have forced foraging communities to cope with environmental changes caused by sea level rise. Significantly, periods of rapid inundation would have had an impact on the availability of coastal resources and could have inundated areas suitable for settlement, especially in low-lying environments particularly vulnerable to sea level changes (Benjamin et al., 2017). The shallow gradient of our study area and the coastal wetlands we identified would have been particularly affected by these changes, especially for those periods in which rates of sea level rise exceeded the 20 mm/y, leading to the displacement of the barrier-backbarrier complex several kilometres inland in just a couple centuries. Even if changes in sea level were not perceived at an individual scale, the ecological consequences would still have had an impact on Mesolithic communities at a generational scale. This raises the question of how foragers in the region would have adapted to these changes and if those adaptations could be detectable. Evidence from the submerged landscapes of the Southern Baltic Sea suggests it could be, as relocation and increased exploitation of aquatic resources has been noted to occur as sea level increased (Harff and Lüth, 2007, 2011). In this respect, it could be argued that the gradually increasing exploitation of aquatic resources from the Early to the Late Mesolithic in the Northern Adriatic (Fontana et al., 2023) could reflect some of these patterns. However, whether this represents a gradual adaptation to an increasingly wet landscape or a biased picture constrained by earlier evidence for coastal exploitation being submerged remains unknown. Nevertheless, because of phases of pronounced drowning and the overall vulnerability of the palaeolandscape to sea level change, our study area could constitute an ideal location to investigate responses to sea level rise. This issue would have to be approached through the identification of underwater prehistoric sites, stressing again the relevance of submerged landscapes to archaeological debates in the Northern Adriatic.

While Mesolithic communities in the Northern Adriatic would have had to cope with environmental changes, social transformations would have also been unfolding during the 6th millennium with the Neolithic

transition. Starting from ca. 7000 cal BC, the technology of farming would have been spreading from Anatolia to the coastlines of the Mediterranean (Guilaine, 2013; Shennan, 2018; Binder et al., 2022), leading to the shift from foraging to food production and thus major societal changes such as new economic strategies, increased sedentism, and larger populations (Robb, 2013; Palmisano et al., 2021; Leppard, 2022). While demic diffusion lay at the root of these changes, the role of foragers in this process has always been hypothesised, although still debated for some areas of Europe (Zvelebil, 2001; Robb, 2013; Perrin and Manen, 2021). By 6000 cal BC, farming would have reached the Adriatic shorelines, at first in the East and South (Forenbaher and Miracle, 2005, 2014; Kačar, 2021) and then in the North around 5500 cal BC (Ferrari et al., 2018; Starnini et al., 2018; Ongaro et al., 2025). As our reconstructions have shown, significant landscape changes would have kept occurring well into the period in which farming was spreading along the Adriatic coastlines. This means that the palaeolandscape setting needs to be considered when discussing the transition to farming in the area, as the environmental context inevitably affects the settlement and movements of people. This is especially pertinent when considering the different ecological needs of farmers compared to foragers. The data we produced here indicates the presence of coastal wetlands into the Neolithic period in the Northern Adriatic, which would have supported a Mesolithic presence in the area. This might explain some patterns of piecemeal adoption of farming by hunter-gatherers in the region (Binder et al., 2022), as the pre-existing socio-ecological conditions would have not been so favourable to the demic dispersal of farmers in the area, meaning that the adoption of farming could have been mediated by local populations (Ongaro et al., 2025). However, many Neolithic sites in the area show no evidence of continuity with the previous Mesolithic tradition, especially in terms of a fully developed farming economy (Ferrari et al., 2018), thus making it challenging to understand the exact dynamics of the spread of farming in the area. It is very likely that crucial archaeological evidence of the diffusion of farmers or farming products among forager communities lies on the palaeolandscapes identified in this study, as farming would have spread along the coastline now submerged (Benjamin et al., 2011b; Rossi et al., 2020; Ongaro et al., 2025). Therefore, not only should the different paleoenvironmental settings be analysed when discussing the spread of farming in the Northern Adriatic, but the palaeolandscape is likely to be of great significance for uncovering evidence to inform this archaeological debate.

Overall, all these themes demonstrate how important the study of submerged landscapes is for the understanding of Early and Middle Holocene prehistoric societies in the Northern Adriatic. This discussion has only focused on the potential that this field of study has in the area, and any further analysis is beyond the scope of this paper. In fact, it would be challenging to move beyond a theoretical discussion without solid evidence from the palaeolandscape. Therefore, we believe that future investigations should focus on modelling the paleoenvironmental data we produced here into an analysis of landscape use by Mesolithic and Neolithic societies (e.g., site location prediction, movement patterns, interaction with resources), while also considering the possibility of identifying archaeological evidence on the palaeolandscape. For the latter, accessibility of deposits, potential preservation of material, and predictive models should all be considered to construct a targeted approach for optimising archaeological investigation.

6. Conclusion

The combination of new and published data allowed us to identify different depositional environments and produce inundation models for the Northern Adriatic between 9000 and 4000 cal BC. Through our palaeolandscape reconstructions, we offered an interpretation of how the distribution of these environments would have made the palaeolandscape appear in several periods at a century scale. The temporal and spatial palaeolandscape characterisation led us to distinguish

different phases of paleogeographic evolution:

1. The first reliable evidence for the start of the marine influence in our study region is dated between 9000 and 8600 cal BC, when stable rates of sea level rise led to the formation of brackish marshes, open lagoons, and deltaic systems.
2. After a rapid sea level rise of a few meters around 8400 cal BC, a renewed phase of stasis occurred between 8200 and 7800 cal BC, leading to the formation of further paralic environments; in the west of the study area, the first evidence of a barrier-backbarrier complex is evidenced, with large lagoons crossed by tidal channels and deltaic systems.
3. Between 7800 and 7600 cal BC, a sea level rise of ca. 4m occurred; this peak is followed by a period in which more gentle rates of sea level rise led to the formation of short-lived lagoon systems, with repeated backstepping until 7000 cal BC.
4. After another rise of more than 4m in a few centuries, stasis seems to have occurred between 6800 and 6600 cal BC; although the repeated drowning phases displaced the barrier-backbarrier complex of the 8th millennium several kilometres inland, lagoons, deltaic systems, and marshes infiltrating depressions in the landscape formed.
5. While data is lacking for most of the 7th millennium, a similar situation to the above seems to have been present before 6000 cal BC, which was followed by a major rise in sea level of up to 5m. This led to the barrier-backbarrier complex being backstepped again.
6. From 5800 cal BC the barrier-backbarrier system seems to have stabilised along the current one; the lagoons of this period were the embryos of the modern ones, as rates of sea level rise remained relatively low during the following centuries. several areas nevertheless experienced progradation trends and thus lagoons are witnessed further inland than today (especially after reclamation), especially in the west and inside incised valleys, which formed liman-like landforms.
7. Apart from a brief phase of more punctuated sea level rise between 5000 and 4800 cal BC, landscape changes in the highstand seem to mainly be controlled by fluvial avulsions and the slow expansion of lagoons further inland, which led to the formation of barrier lagoons as well as deltaic systems and saltmarshes; the maximum landward migration of most of our study area took place during the 5th millennium.

The variety of paralic and coastal environments, including barrier lagoons, deltaic complexes, brackish marshes and swamps, liman-like landforms, and saltmarshes would have created attractive landscapes for foragers due to the high productivity of coastal wetlands in terms of resources for hunting, fishing, and shellfish gathering. While lowland and coastal occupation by Mesolithic groups was therefore very likely on these palaeolandscapes, these communities would have also had to respond to environmental changes induced by sea level rise, exacerbated by the region's flat morphology which was prone to significant land loss. While these issues make the Northern Adriatic a pivotal area for a better understanding of the local Mesolithic, landscape changes would have occurred as farming would have spread in the region. This raises questions of how different paleoenvironments would have been targeted by foragers and farmers respectively and how this would have influenced dynamics of interaction and thus of Neolithization, which are still poorly understood in the area. It is likely that the Northern Adriatic palaeolandscapes contain deposits that preserve archaeological evidence of crucial significance to the debates mentioned above. These results therefore allow us to consider the archaeological implications of palaeolandscape changes in the Northern Adriatic, including the Mesolithic exploitation of coastal wetlands, responses to environmental changes driven by sea level rise, and the palaeoecological implications to the spread of farming in the area.

It should nevertheless be stressed that additional work is required, both to precisely map landforms and accurately characterise sea level

change in areas and periods suffering from a lack of data, but also in archaeological terms, as our discussion of relevant themes remains one of potential. However, the outcomes of this study are twofold: 1) they provide the necessary contextual information to build a solid research framework for submerged landscape archaeology in the Northern Adriatic; 2) they can guide the next research steps, facilitating the effective recovery of archaeological evidence through future investigations.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests. Samuele Ongaro reports financial support was provided by The Leverhulme Trust. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The research presented here has been conducted as part of Samuele Ongaro's PhD at the University of Southampton, under the Intelligent Oceans doctoral programme. We would like to thank the Southampton Marine and Maritime Institute and the Leverhulme Trust for funding this project. We acknowledge S&P Global for providing an academic license of Kingdom™ Geoscience Software. Finally, we would also like to thank the editors and the anonymous reviewers for their insightful feedback, which decisively improved the content and quality of this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.quascirev.2026.110206>.

Data availability

Most of the data has been shared (see Supplementary Material 1-3) with the exception of the original .sgy CHIRP data, which would be unpractical to attach as a supplement. Please email the authors for any enquiry about the data.

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