Quaternary Science Reviews 380 (2026) 109918

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Middle Pleistocene to Holocene glacio-eustatic sequences of the Po Basin (Italy): Towards improved geological mapping of the Quaternary period

Alessandro Amorosi [a,*], Luigi Bruno [b], Chiara D'Ambrogi [c], Donatella Magri [d], Fabrizio Michelangeli [d], Lorenzo Calabrese [e], Felicia Papasodaro [c], Paolo Severi [e], Andrea Zerboni [f], Andrea Piccin [g], Maurizio D'Orefice [h]

[a] Department of Biological, Geological and Environmental Sciences, University of Bologna, Italy
[b] Department of Chemical and Geological Sciences, University of Modena and Reggio Emilia, Italy
[c] Italian Institute for Environmental Protection and Research, Geological Survey of Italy, Rome, Italy
[d] Department of Environmental Biology, Sapienza University of Rome, Italy
[e] Regione Emilia-Romagna, Settore Difesa del Territorio, Area Geologia, Suoli e Sismica, Bologna, Italy
[f] Department of Earth Sciences "A. Desio", University of Milan, Italy
[g] Regione Lombardia, D.G. Territorio e Urbanistica, Struttura Sistema Informativo Territoriale, Milan, Italy
[h] Formerly at Italian Institute for Environmental Protection and Research, Geological Survey of Italy, Rome, Italy

A R T I C L E I N F O

Handling editor: Biagio Giaccio

Keywords:
Sequence stratigraphy
Allostratigraphy
UBSU
Synthem
Pollen
Marine isotope stage

A B S T R A C T

Unconformity-Bounded Stratigraphic Units (UBSUs) can provide an invaluable approach to the geological mapping of Quaternary successions by delineating large-scale stratigraphic patterns that reflect changes in accommodation and sedimentation mostly dictated by glacio-eustatic variations. Through the example of the Po Basin, we document that a mosaic of 115 stratigraphic units, which reflect local nomenclature from 45 official geological maps, can be grouped within a markedly simpler and unambiguous framework of few regionally mappable UBSUs using the concepts of cyclostratigraphy. Synthems that developed in response to 100-kyr, eccentricity-driven glacio-eustatic fluctuations, with characteristic transgressive-regressive facies patterns and a diagnostic pollen signature, represent the building block of the Middle Pleistocene-Holocene subsurface stratigraphy and are here suggested to serve as a primary guide to geological mapping well beyond the regional scale. Synthem boundaries correspond to transgressive surfaces and correlative fluvial abandonment surfaces: they are marked by remarkable landward facies shifts that developed at the onset of interglacial periods in response to abrupt sea-level rise. Synthems may include internal unconformities of local to regional extent that reflect transition to glacial/cold periods and that are correlated to laterally extensive fluvial channel-belt sand/gravel bodies. Synthem boundaries can be tracked with good continuity through the depocenters; in contrast, they are correlated only tentatively into uplifted fluvial terraces and glacial/fluvioglacial successions buried or cropping out discontinuously at basin margins or across buried thrust fronts. Prominent key horizons demarcate the onset of the present (MIS1), last (MIS5e), and penultimate (MIS7) interglacials. Such surfaces offer the highest potential for global correlation.

1. Introduction

Geological maps portray interpretive 3D views of rock, sediment and soil units. In modern alluvial and coastal lowlands, made up almost entirely of non-lithified Quaternary deposits, standardized procedures of interpretation and mapping may offer an essential key for predicting subsurface stratigraphic architecture and improve the scientific basis for natural resource sustainable exploitation and land-use decisions.

The Quaternary period has geologically unique characteristics and highly resolved stratigraphic successions that record the couplings of astronomical forcing, climate change, and glacial dynamics. The so-called 'Mid-Pleistocene revolution', which occurred around 900 ka (Gibbard and Lewin, 2016), denotes the marked prolongation and intensification of glacial-interglacial cycles, with the shift from 41 kyr to 100 kyr orbital rhythm (Lisiecki and Raymo, 2005). Throughout this chronologically well constrained interval of time (Martinson et al.,

* Corresponding author.
E-mail address: alessandro.amorosi@unibo.it (A. Amorosi).

https://doi.org/10.1016/j.quascirev.2026.109918
Received 11 November 2025; Received in revised form 24 February 2026; Accepted 27 February 2026
Available online 10 March 2026

1987), Earth's climate experienced high-amplitude interglacials coupled with large-scale eustatic oscillations, on the order of 100-120 m (Waelbroeck et al., 2002; Rohling et al., 2009, 2014) and glacio-eustasy acted as an important controlling factor of alluvial stratigraphy (Busschers et al., 2005; Gibling et al., 2005).

During interglacials, coastal lowlands worldwide were repeatedly affected by marine incursions, whereas during glacial periods they were subject to river incision, incised-valley formation and widespread alluvial plain development (Zaitlin et al., 1994). Within this context, typified by the rhythmic alternation of coastal/marine and continental successions, simple lithostratigraphic criteria are poorly suited for describing the Quaternary record, whereas breaks in vertical successions (stratigraphic discontinuities) appear as much more effective bounding surfaces of stratigraphic units (Miall, 1997).

Event stratigraphy, which includes sequence stratigraphy (Posamentier et al., 1988; Van Wagoner et al., 1988), UBSU stratigraphy (based on Unconformity-Bounded Stratigraphic Units, Salvador, 1994) and allostratigraphy (North American Commission on Stratigraphic Nomenclature-NACSN, 2005), places emphasis (i) on the genetic relations between sediment bodies, and (ii) on the identification as bounding surfaces of stratigraphic discontinuities that have time-stratigraphic significance.

In UBSU stratigraphy and allostratigraphy, unconformity-bounded stratigraphic units should be extended only as far as both bounding unconformities are identifiable. Sequence stratigraphy includes more flexible criteria of stratigraphic subdivision, since bounding surfaces of depositional sequences may also include 'correlative conformities': this makes the sediment routing traceable to deep waters. However, sequence stratigraphy has no standardized stratigraphic code (Catuneanu et al., 2009), and for this reason it can be used only informally. In contrast, UBSU stratigraphy and allostratigraphy can be used for geological mapping through their fundamental units: synthems and alloformations, respectively (Salvador, 1994; NACSN, 2005).

For the Quaternary record, UBSU stratigraphy and allostratigraphy have been applied to glaciogenic successions (Räsänen et al., 2009; Slomka and Eyles, 2015; Ojala et al., 2018; Hodder et al., 2024) and to aeolian deposits (Leighton et al., 2013), often in association with morphostratigraphy (Hughes, 2010). These methods have also been widely applied for studying floodplain stratigraphy: well documented examples are from the Texas Gulf coastal plain (Autin, 1992; Blum and Valastro, 1994; Blum et al., 1994; Heinrich, 2006), Arizona (Huckleberry et al., 2013), Korea (Rhee et al., 1998), France (Straffin, 2001) and Spain (Houben et al., 2011). Conversely, the application of such unconformity-related units to the subsurface geological mapping of Quaternary successions has been scarcely explored, with few exceptions from the offshore record (Rijsdijk et al., 2005).

The Po Plain (Fig. 1), one of the widest alluvial plains in Europe, preserves an almost continuous record of Middle Pleistocene-Holocene stratigraphy (Amorosi et al., 2004; Campo et al., 2020; Bruno et al., 2024), owing to high subsidence rates and stratigraphic expansion. In this region, the Quaternary stratigraphic architecture is highly sensitive to sea-level changes and glacial/interglacial shifts, thus serving as an excellent site for exploring the application of unconformity-related units to geological mapping.

The shift from lithostratigraphy to UBSU stratigraphy was proposed in Italy as the standard for the geological mapping of Quaternary deposits within the CARG project - Geological Map at 1:50,000 scale (Pasquarè et al., 1992) and used during the following decades for the production of 45 sheets of the Geological Map of Italy at 1:50,000 scale in the Po Plain area (Fig. 1). Although the incorporation of the concept of geologic time into geological maps was meant to improve their effectiveness, and the Italian geological mapping guidelines (Pasquarè et al., 1992; Germani and Angiolini, 2003; Galluzzo et al., 2009; Vita et al., 2022) provided guidance on the application of UBSUs, their representation was applied with remarkable regional variations, reflecting the different geological surveying methods in the Alpine foreland, the plain and the Apennine margin, but also a lack of obvious criteria for hierarchical classification at the basin scale. Multiple approaches of stratigraphic subdivision, stemming from the partitioning of the Italian Quaternary research community into distinct 'schools', each with specific scientific backgrounds and relying on markedly different Quaternary datasets, resulted in significantly heterogeneous and largely inconsistent classification schemes across the published Sheets of the Geological Map (Fig. 2), which were moreover produced over more than 20 years (Chiarini et al., 2008; D'Orefice, 2009). In addition, the delineation of geological map sheets did not facilitate the application of

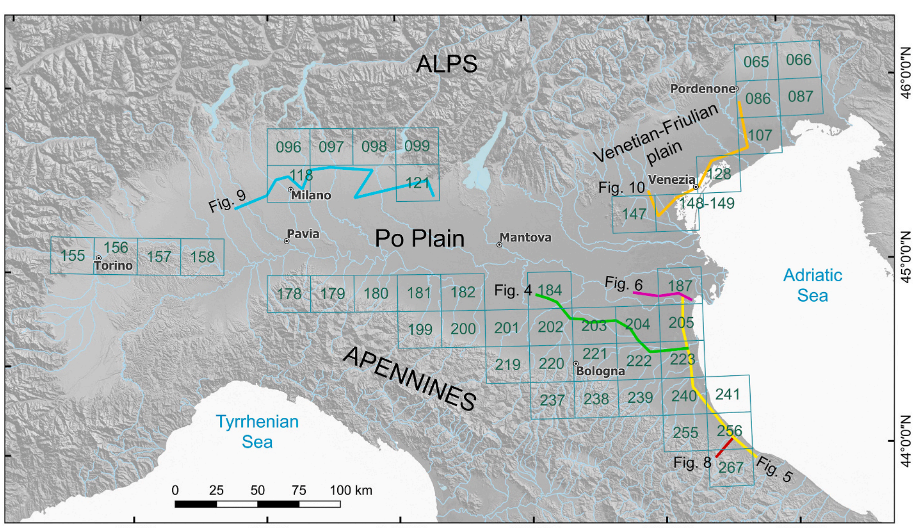

Fig. 1. Published Sheets of the Geological Map of Italy at 1:50,000 scale in the Po and Venetian-Friulian plains and section traces of Figs. 4–6 and 8–10. 65: Sheet Maniago, 66: Udine, 86: S. Vito al Tagliamento, 87: Palmanova, 96: Seregno, 97: Vimercate, 98: Bergamo, 99: Iseo, 107: Portogruaro, 118: Milano, 121: Brescia, 128: Venezia, 147: Padova Sud, 148-149: Chioggia-Malamocco, 155: Torino Ovest, 156: Torino Est, 157: Trino, 178: Voghera, 179: Ponte dell'Olio, 180: Salsomaggiore Terme, 181: Parma Nord, 182: Guastalla, 184: Mirandola, 185: Ferrara, 187: Codigoro, 194: Parma Sud, 200: Reggio nell'Emilia, 201: Modena, 202: S. Giovanni in Persiceto, 203: Poggio Renatico, 204: Portomaggiore, 205: Comacchio, 219: Sassuolo, 220: Casalecchio di Reno, 221: Bologna, 222: Lugo, 223: Ravenna, 237: Sasso Marconi, 238: Castel S. Pietro Terme, 239: Faenza, 240: Forlì, 241: Cervia, 254: Cesena, 256: Rimini, 267: San Marino. Background map: Digital Elevation Model (DEM) of Northern Italy derived from the Shuttle Radar Topographic Mission data (SRTM).

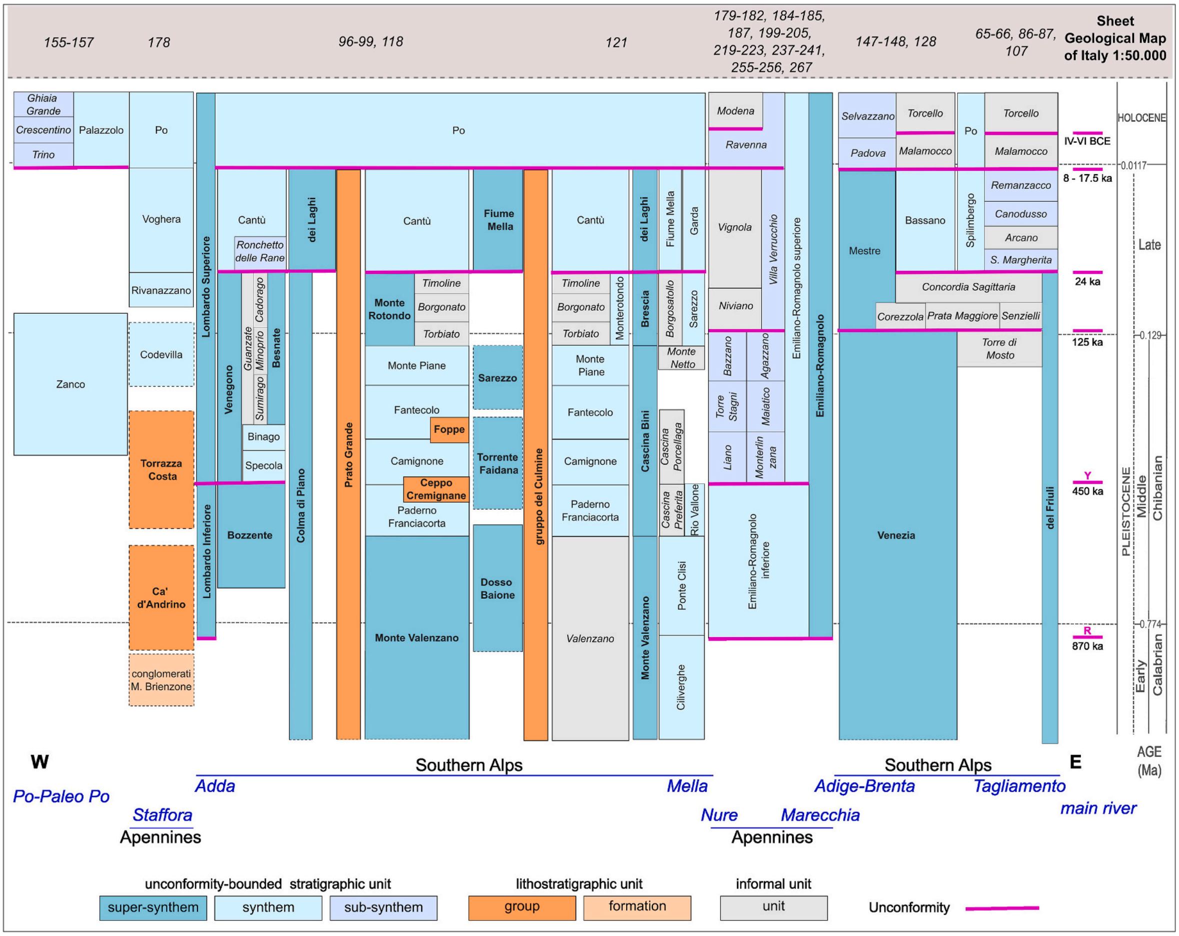

Fig. 2. Nomenclature and timing of stratigraphic units adopted in the Sheets of the Geological Map of Italy at 1:50,000 scale (Servizio Geologico d'Italia, 2002; 2003a-b; 2004; 2005a-d; 2007a-b; 2008a-c; 2009a-r; 2011a-c; 2011a-c; 2012; 2014a-f,g; 2015; 2016a-c; 2024; 2025a-c) in the study area (for location, see Fig. 1). The scheme also includes units cropping out at basin margins. Local units are not reported. Vertical and lateral stratigraphic relations are simplified. Pink lines depict stratigraphic unconformities of chronostratigraphic significance. Dashed lines highlight stratigraphic uncertainties at unit boundaries.

synthemic units, as they typically do not correspond with hydrographic basins.

Deciphering the fragmented Quaternary stratigraphic record of the Po Basin is challenging (Fig. 2). At present, there is a plethora of local terminologies (at least 115 different stratigraphic units have been used to describe Middle Pleistocene-Holocene deposits) and considerable difference exists regarding the scale and hierarchy of stratigraphic units used for geological mapping. This is clearly illustrated in Fig. 2, where it is apparent that different levels of classification (supersynthems, synthems and subsynthems) have been used interchangeably across different Sheets of the Geological Map of Italy to refer to sediment packages of the same rank that occupy substantially the same stratigraphic position. Such an inconsistent nomenclature, by reducing the clarity and comparability of the mapped information, may lead to inefficient use of the geological map, undermining both its scientific value and practical applications.

This paper summarizes and analyzes existing research on the Middle Pleistocene-Holocene stratigraphy of the Po-Venetian Basin. In this region, repeated patterns of stratigraphic architecture clearly reflect alternating phases of sea-level rise and fall that took place during the last ca. 800 kyr in response to the waxing and waning of major ice caps (Servizio Geologico d'Italia, 2002; 2005a; 2007a; b; 2008a; b; 2009a; b; 2011b; 2024; 2025a, b; Amorosi et al., 2004; Massari et al., 2004; Campo et al., 2020; Marcolla et al., 2021; Bruno et al., 2024), as well as the local tuning of sedimentation rates to the evolutionary trajectory of Pleistocene glaciers (Aghib et al., 2024; Servizio Geologico d'Italia, 2005b). Given the supra-regional significance of glacio-eustatic changes, we (i) propose a hierarchical framework of stratigraphic subdivision, based on multiple interglacial-glacial cycles, that incorporates the huge amount of local terms depicted in the official geological maps into a much simpler, consistent and robust classification scheme; and (ii) conclude that this approach can be readily applied well beyond the Po Basin, virtually to all coeval successions in which the glacio-eustatic signal is detectable.

2. Geological setting

The Po Plain and Adriatic foreland is shared by the converging South Alpine, Apennine and Dinaric chains. The Cenozoic compression reached the Southern Alps system (N-S compression) during the Middle Eocene to Miocene tectonic phases, and the Apennine system (NNE-SSW compression) from Oligocene to Pliocene and Pleistocene (Ghielmi et al., 2013). The Northern Apennines are part of an eastward migrating fold and thrust belt developed since the Late Oligocene in the context of the collision of the European plate with the Adria microplate. The development of the Apennines foredeep, in particular, has been related to the eastward rollback of the subducting Adria plate (Malinverno and Ryan, 1986; Royden et al., 1987; Doglioni, 1993). The outward migration of the Apennine fold and thrust belt gave way to a migrating set of asymmetric foredeeps (Ricci Lucchi, 1986) and associated piggy-back basins (Ori and Friend, 1984) developed on the inner margin of the thrust sheets. The Po Plain-Adriatic foredeep was affected by an active

Apennine compressional tectonics, with four major deformative phases recognized in the latest Miocene-Pleistocene interval (Ghielmi et al., 2010, 2013).

The geometry of the most external Northern Apennines thrust front consists of three main arcuate thrust systems (Monferrato, Emilia and Ferrara-Romagna-Adriatic arcs – Fig. 3A) that were not active simultaneously and reflect depocenter migration towards the foreland (Carminati and Doglioni, 2012; Amadori et al., 2018, 2019). In contrast, the Southern Alps are characterized by predominantly south-verging thrust tectonics (Fig. 3A), with the outermost thrust front buried beneath the Plio-Pleistocene sedimentary fill of the Po Basin (Toscani et al., 2014; Scardia et al., 2015). The blind geometry of buried Northern Apennines and Southern Alps thrust fronts shows few exceptions, with isolated anticline crests emerging or shallowly buried under Pleistocene sediments (Desio, 1965; Livio et al., 2009, 2014a; Perini et al., 2023).

The buried thrusts and related fault-propagation folds beneath the modern Po Plain have been investigated through interpretation of a dense network of seismic lines and well logs (Pieri and Groppi, 1981; Toscani et al., 2009; Fantoni and Franciosi, 2010; Ghielmi et al., 2013; ISPRA, 2015; Martelli et al., 2017; Livani et al., 2018; Amadori et al., 2019; D'Ambrogi et al., 2023). Anticline structures are associated with ramp overthrusts and are separated by large synclines that record much larger subsidence rates (Carminati et al., 2003; Ghielmi et al., 2010; Maesano and D'Ambrogi, 2016; Martelli et al., 2017; Servizio Geologico d'Italia, 2025b). Active seismogenic faults are present in the buried frontal portion of the compressive ramp and flat structures of the Apennines (Scrocca et al., 2007; Toscani et al., 2009; Boccaletti et al., 2010; Maesano et al., 2015; Martelli et al., 2017) and Southern Alps (Livio et al., 2014a, 2014b; Aghib et al., 2024).

The architectural style of the Po Basin fill results from the combined effect of (i) tectonic uplift/subsidence, which controlled long-term accommodation, (ii) eustasy, which took place over shorter time scales, (iii) sediment influx (Ghielmi et al., 2010), and (iv) sediment budget tuned by the Alpine glaciers expansion and shrinkage. Based on the integration of seismic imaging, well data and interpolation methods, the Pliocene to Quaternary subsurface stratigraphy of the Po Basin has been outlined by Regione Emilia-Romagna and Eni Agip (1998), Regione Lombardia and ENI Divisione Agip (2002), Ghielmi et al. (2010, 2013), ISPRA (2015), and Amadori et al. (2019), through a set of depositional sequences bounded at their base and top by regional unconformities (Fig. 3B). These studies showed that tectonic uplift and subsidence exerted a fundamental structural control on the development of stratigraphic unconformities at lower boundaries of depositional sequences.

The youngest regional unconformity, named the 'R' unconformity (Muttoni et al., 2003; Garzanti et al., 2011), separates the Middle Pleistocene-Holocene succession from underlying stratigraphic units (Fig. 3B). This unconformity, also referred to as 'Horizon U2' (Maesano et al., 2024), marks the base of sequence 'PS2' (Scardia et al., 2012; Ghielmi et al., 2013), sequence 'PS3' (Amadori et al., 2019) or Emilia-Romagna Supersynthem (Regione Emilia-Romagna and Eni Agip, 1998; Regione Lombardia and ENI Divisione Agip, 2002) and corresponds to the last phase of outward advance of the slope/basin transition

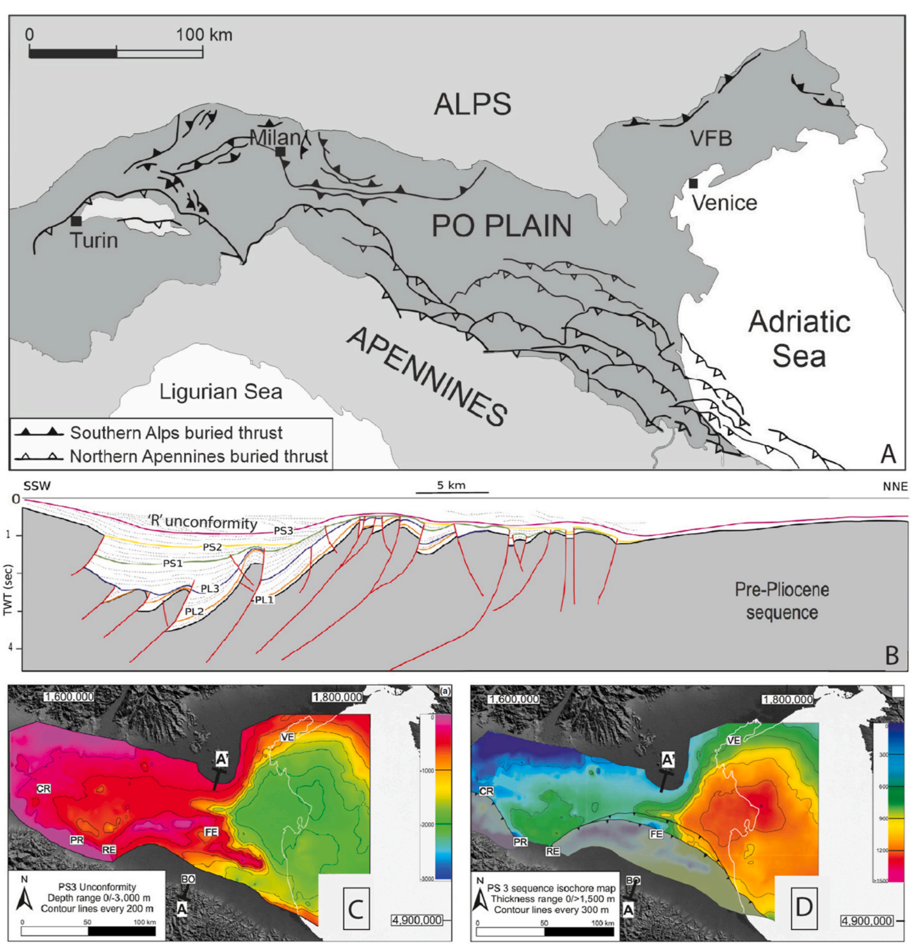

Fig. 3. A. Tectonic map of the Po Plain. B. Linedrawing of a composite seismic profile from the ENI database (approximate section trace in C and D), showing major regional unconformities within the Pliocene-Quaternary Po Basin fill. C: Isobath map of the 'R' unconformity (=PS3 in A) in the Po Basin and the northern Adriatic area. D: Isochore map of sequence PS3 north of the Ferrara (FE) Arc. Abbreviations: VFB = Venetian-Friulian Basin; CR = Cremona; PR = Parma; RE = Reggio Emilia; BO = Bologna; VE = Venice. A: slightly modified from Amadori et al. (2018); B, C and D: from Amadori et al. (2019).

toward the foreland (Ghielmi et al., 2010, 2013; Garzanti et al., 2011; Amadori et al., 2019; Zuffetti and Bersezio, 2021). The 'R' unconformity is magnetostratigraphically constrained to the first prominent Pleistocene glacio-eustatic lowstand (Marine Isotope Stage – MIS – 22) at 0.87 Ma, which correlates with the onset of major Pleistocene Alpine glaciations (Muttoni et al., 2003), though a certain diachroneity has been recorded across the basin. Because of the active structural setting, this surface is occasionally dislocated (Servizio Geologico d'Italia, 2025b) and the stratigraphic succession above the 'R' unconformity (sequence PS3 in Fig. 3B and C) shows comparatively reduced thickness (ca. 100 m) in ramp anticline zones, whereas it may exceed several hundred meters in the depocenters. Sequence PS3 reaches its maximum thickness (>1 km) in the Adriatic Sea area (Fig. 3D), where a foredeep basin with marine turbidite sedimentation was still active during the Middle Pleistocene (Amadori et al., 2019).

A general shoaling-upward trend, from dominantly marine to fully continental deposits, typifies sequence PS3 above the 'R' unconformity (Ori, 1993; Muttoni et al., 2003; Scardia et al., 2006; Ghielmi et al., 2010; Bruno et al., 2024) and reflects the ongoing deformation and progressive filling of the basin. A minor unconformity within sequence PS3, named the 'Y' unconformity (Scardia et al., 2012), separates the Lower and Upper Emilia-Romagna synthems (Regione Emilia-Romagna and Eni Agip, 1998; Regione Lombardia and ENI Divisione Agip, 2002; Scardia et al., 2012; Aghib et al., 2024; Bruno et al., 2024). This surface displays diachroneity and significantly lower correlation potential than the 'R' unconformity, especially at the Alpine margin, where it occurs within amalgamated gravel bodies (Garzanti et al., 2011; Amadori et al., 2019; Maesano et al., 2024). Its age, initially estimated around 450 ka (Regione Lombardia and ENI Divisione Agip, 2002), has recently been proved to be slightly older than 410 ka, based on IRSL dating in the central portion of the basin (Bruno et al., 2024; Servizio Geologico d'Italia, 2024).

3. Stratigraphic architecture of Middle Pleistocene-Holocene deposits in the Po-Venetian Basin

The Quaternary stratigraphy of the Po Plain is packaged into a hierarchy of large-scale and small-scale genetically related units that reflect superposed tectonic, climatic and eustatic controls. Much research over the last decades has been targeted at understanding the coupling between climate/sea-level fluctuations and the stratigraphic architecture of Middle Pleistocene-Holocene deposits (Amorosi et al., 2004, 2017a; Massari et al., 2004; Fontana et al., 2014; Bruno et al., 2017b; Campo et al., 2020; Marcolla et al., 2021), as opposed to the role played by tectonics (Amorosi et al., 2021b; Perini et al., 2023; Aghib et al., 2024; Bruno et al., 2024) or by processes internal to the sediment routing, i.e. autogenic (Stefani and Vincenzi, 2005; Bruno et al., 2018, 2021).

In general, long-term tectonic activity was punctuated by higher-frequency glacio-eustatic cycles. In terms of sequence stratigraphy, the major architectural components of the Po Basin stack to form a fourfold, cyclic hierarchy of:

(i) low-frequency depositional sequences (*sensu* Mitchum et al., 1977), 100 to 1000 m thick (Fig. 3B). These sequences span several hundreds thousand years and are separated by regional unconformities that are mainly governed by the tectonic evolution of the basin (Regione Emilia-Romagna and Eni Agip, 1998; Regione Lombardia and ENI Divisione Agip, 2002; Amadori et al., 2019);

(ii) high-frequency transgressive-regressive (T-R) sequences (Embry and Johannessen, 1992), approximately 50-100 m thick (Fig. 4), that correlate to 100 kyr (Milankovitch-scale) relative sea-level cycles superposed to regional tectonics. Given the marked asymmetry of Quaternary relative sea-level cycles, with long phases of stepped, sea-level fall followed by abrupt phases of sea-level rise, transgressive surfaces (and their landward equivalents), rather than sequence boundaries, represent effective surfaces for stratigraphic subdivisions (Amorosi et al., 2004, 2008; Bruno et al., 2024).

(iii) systems tracts (Posamentier et al., 1988; Hunt and Tucker, 1992; Plint and Nummedal, 2000), genetically associated stratigraphic units that were deposited during specific phases of the relative sea-level cycle. These units, developed on a dam scale, include: transgressive systems tract (TST), highstand systems tract (HST), falling-stage systems tract (FSST) and lowstand systems tract (LST)

(iv) parasequences and parasequence sets, a few meters thick, developed on millennial time scales, which typically reflect either allogenic or autogenic controls (Van Wagoner et al., 1990).

3.1. *Architectural style of interglacial-glacial (100 kyr) cycles in the Po Basin depocenter*

While natural subsidence played a fundamental role in generating accommodation in the Po Basin (Carminati et al., 2003; Teatini et al., 2011; Antonellini et al., 2019), interglacial-glacial cycles primarily

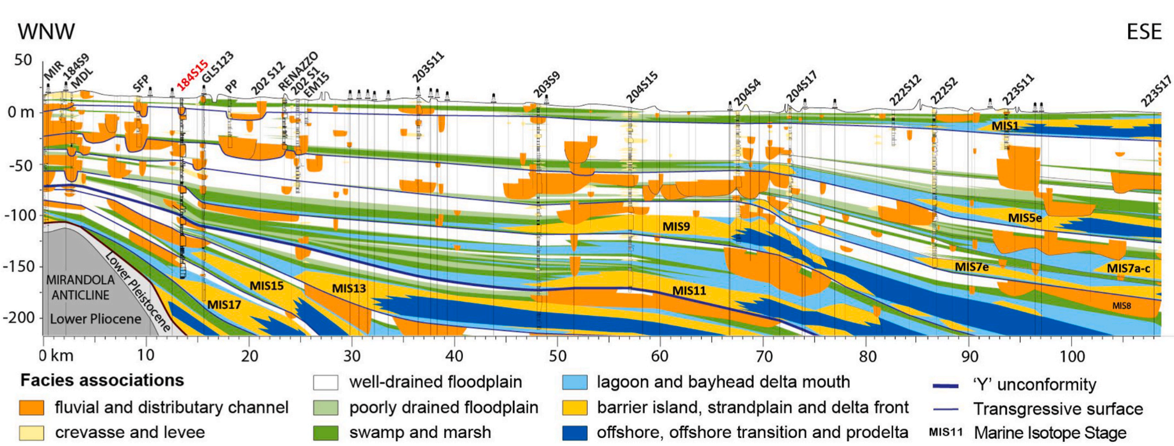

Fig. 4. Cyclic facies architecture of Middle Pleistocene-Holocene deposits in the Po Basin, from proximal (left) to distal (right) locations, showing subdivision into unconformity-bounded stratigraphic units that correlate to 100 kyr (Milankovitch-scale) transgressive-regressive (T-R) sequences. Coastal wedges (yellow and blue colors) in the lower parts of T-R cycles reflect phases of rapid landward migration of the shoreline at the onset of interglacials (odd-numbered Marine Isotope Stages-MIS). The stepped, seaward-directed shoreline trajectory results from the activity of growing tectonic structures in the west (Mirandola anticline in lower left corner). Slightly modified from Bruno et al. (2024). For section trace, see Fig. 1.

forced by changes in the Earth's orbital parameters (Maslin and Brierley, 2015) modulated the Middle Pleistocene-Holocene sedimentary record at the basin scale (Fig. 4). During interglacials, the Adriatic shoreline moved rapidly tens of km landward of its former position, and paludal, coastal, and shallow-marine environments spread onto the coastal plain (Fig. 4). Following global sea-level falls during glacial periods, the coastline shifted seawards, and former marine successions were subaerially exposed, weathered, incised, and covered with alluvial deposits (Kent et al., 2002; Amorosi et al., 2004). Subsidence continuously generated accommodation (Bruno et al., 2024), favoring the accumulation of thick successions of Quaternary deposits.

Transgressive surfaces in the Po Basin are readily identifiable features that reflect substantial breaks of extra-regional significance and constitute stratigraphic markers with greater extent and correlation potential than any other stratigraphic surface (Amorosi et al., 2004). These surfaces are characterized by marked landward facies shifts relative to underlying units and are typically overlain by coastal wedges (made up of beach-barrier, delta front, offshore and prodelta facies associations) that record marine incursions (odd-numbered Marine Isotope Stages – MIS - in Fig. 4). Coastal wedges in the lower parts of T-R sequences are stacked rhythmically in retrogradational to progradational sets bounded by chronostratigraphically significant transgressive surfaces. They commonly overlie paleosols that formed on the interfluves during previous phases of sea-level fall in response to river downcutting (Amorosi et al., 2017b).

Landward of the maximum marine ingression, transgressive coastal deposits are replaced by brackish (lagoon, marsh) and freshwater (swamp) estuarine facies associations (Fig. 4). At more internal locations, the continental equivalents of T-R sequences record widespread floodplain aggradation within organic-rich deposits and increasing frequency of channel avulsions (Campo et al., 2016). Silt-clay overbank deposits with lenticular fluvial-channel sands and a characteristic interglacial pollen signature dominate the lower parts of sequences and show upward transition to increasingly amalgamated, thick and laterally extensive fluvial-channel sand bodies that accumulated during glacial periods (Servizio Geologico d'Italia, 2005b; Amorosi et al., 2008; Bruno et al., 2024).

Periods of intense tectonic activity in the fold and thrust belt are discernible in the Middle Pleistocene-Holocene stratigraphic record of the Po Basin. For example, a recognizable pattern of deformation produced by the Apennine thrust-related anticlines is documented by the migration towards the foreland of successive coastal wedges formed in response to short-term changes in base level (Fig. 4). Changes in the trajectory of individual paleoshoreline bodies delineate an eastward shift in the loci of deposition, due to tectonic uplifting and seaward shifting by growing tectonic structures (Fig. 4).

In the distal portion of the Po Basin, beneath the modern Adriatic coastal plain, two prominent wedge-shaped coastal sand bodies of Late Pleistocene-Holocene age represent obvious stratigraphic markers that can be easily mapped due to strong (litho)facies contrasts with underlying floodplain muds (Fig. 5). These coastal wedges accumulated during the last two major transgressive pulsations (MIS 1 and MIS 5e, respectively) and are separated by a thick succession of mud-prone alluvial/paralic facies associations, deposited in a rapidly subsiding setting during the prolonged phase of sea-level fall between MIS 5d and MIS 2 (Amorosi et al., 2004). The Upper Pleistocene (MIS 5e) coastal sand body can be easily recognized beneath the modern Po Delta (core 187S1 in Fig. 5), between 100 and 130 m borehole depths (Amorosi et al., 2004; Campo et al., 2020). Moving south (towards the Apennines) and north (in the Venetian and Friulian coastal plains), the top of MIS 5e coastal sands is encountered at progressively lower depths, up to 20 m only in the area of core 268-S2 (Fig. 5), thus confirming the crucial role played by recent tectonic activity in shaping the Po Basin fill (Carminati et al., 2003; Ferranti et al., 2006).

3.2. Holocene stratigraphy

The Holocene stratigraphy of the Po Basin exhibits distinct, predictable and chronologically constrained facies patterns that denote the response of the sediment routing system to base-level change during the last 11700 years (Fig. 6). A characteristic transgressive-regressive facies pattern (Rizzini, 1974; Amorosi et al., 1999; Stefani and Vincenzi, 2005), including a set of millennial-scale parasequences (Amorosi et al., 2017a, 2019) typifies the MIS 1 coastal wedge in the subsurface of the Adriatic Sea coastal plain. In general, this facies architecture is similar to the Holocene stratigraphy outlined by several historical papers from the modern coastal and delta plains worldwide (Curray and Moore, 1964; Oomkens, 1970; Frazier, 1974; Demarest and Kraft, 1987; Stanley and Warne, 1994; Amorosi and Milli, 2001).

The low-gradient, Upper Pleistocene alluvial plain (lowstand systems tract or LST in Fig. 6) was transgressed close to the Boreal-Atlantic transition, when a wide, wave-dominated estuary formed about 9 ka BP (Bruno et al., 2017b). This resulted in a variety of landward-stepping (offshore, beach barrier, lagoon) depositional environments that migrated between 9 and 7 ka BP up to 50 km west of the modern shoreline (transgressive systems tract or TST in Fig. 6). Transgressive parasequences are stacked in a retrogradational pattern that mostly reflects stepped, early Holocene eustatic rise (Amorosi et al., 2017a).

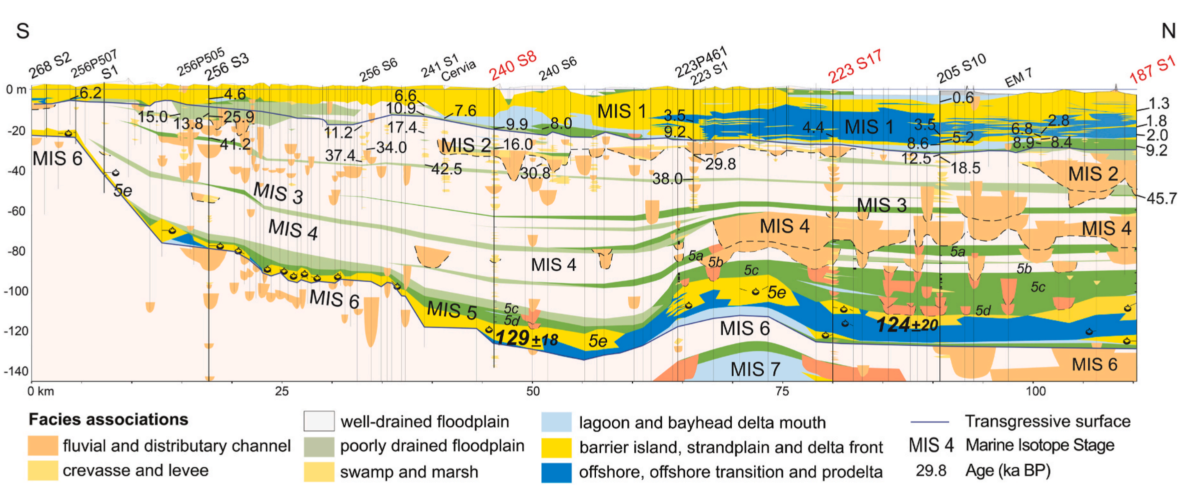

Fig. 5. Stratigraphic architecture of Upper Pleistocene-Holocene deposits beneath the Adriatic coastal plain (section trace in Fig. 1). The MIS 1 and MIS 5e coastal wedges represent two prominent stratigraphic markers that can be easily tracked in the subsurface across a significant portion of the Po Basin (from Campo et al., 2020).

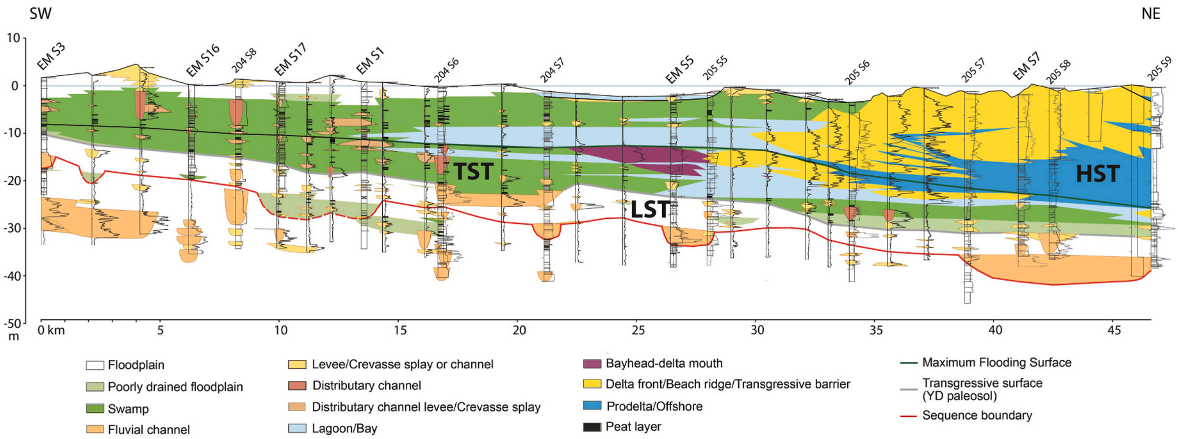

Fig. 6. Simplified depositional dip-oriented cross-section (section trace in Fig. 1) showing the transgressive (TST)-regressive (HST) stacking of Holocene swamp, lagoon, coastal and offshore facies associations above lowstand (LST) fluvial deposits. The transgressive surface (TS) is readily identifiable and more easily discriminated and mapped than the sequence boundary (SB) or the maximum flooding surface (MFS)/condensed section (CS). Modified from Amorosi et al. (2017a).

The landward migration of the shoreline was followed by the widespread progradation of wave-dominated, deltaic and strandplain depositional systems (Stefani and Vincenzi, 2005; Campo et al., 2017; Amorosi et al., 2019) that were deposited primarily from east-prograding deltas feeding the Adriatic Sea. The complex pattern of coastal progradation and delta upbuilding took place following sea-level stabilization (highstand systems tract or HST), starting at about 6 ka BP. Within HST, the major shift from dominantly aggradational (lower HST) to fully progradational (upper HST) parasequence stacking reflects evolution from wave-to river-dominated delta systems (Stefani and Vincenzi, 2005; Amorosi et al., 2019; Anthony et al., 2025).

The prominent, diachronous transgressive surface at the base of the Holocene coastal wedge delineates a sharp increase in aggradation rates (Bruno et al., 2017a) that marks increasing accommodation at the LST/TST transition (Fig. 6). Over vast portions of the Po Basin, the TS correlates with a weakly-developed paleosol formed during the short-lived, Younger Dryas cold event (Amorosi et al., 2017a): this hiatal surface, which is spatially well recognized, encompasses the Pleistocene-Holocene boundary and has high engineering-geology significance, because of remarkable differences in geotechnical properties between soft Holocene swamp clay and underlying, stiff Pleistocene alluvial mud, locally known as 'caranto' (Tosi, 1994; Mozzi et al., 2003; Donnici et al., 2011; Bruno et al., 2022; Campo et al., 2023). Where the paleosol grades laterally into an adjacent fluvial channel-belt, the TS largely coincides with the prominent facies change from a thick, Pleistocene fluvial sand body (LST) to overlying, swamp/inner estuarine muddy facies of early Holocene age (TST in Fig. 6) that onlap against the inclined Pleistocene paleosurface (Amorosi et al., 2021a). A basal peat layer and an abundance of organic clays, indicating the gradual transformation of the area in a wetland under early transgressive conditions, typically enable identification of the TS in sediment cores (Törnqvist et al., 2004; Hijma and Cohen, 2011).

The landward projection of the transgressive surface away from nearshore-marine deposits generally represents a challenging issue and pinpointing the landward limit of the marine influence can be highly controversial (Shanley and McCabe, 1994; Legarreta and Uliana, 1998; Milana and Tietze, 2007). Within sedimentary successions made up entirely of alluvial deposits, the TS can be placed at the base of poorly-drained floodplain deposits, reflecting the change in fluvial regime from braided to meandering river systems in response to sea-level rise (Tanabe et al., 2015, 2022).

3.3. *Pollen signature of interglacial-glacial cycles*

During the Quaternary, glacial-interglacial climate oscillations drove major biogeographical changes in the Po Plain, deeply affecting biological communities and causing biome shifts. In addition, the repeated landward and seaward migrations of depositional systems driven by T-R cycles resulted in recurrent re-arrangement of ecosystems. These processes left clear imprints on the palaeoecological record, revealing distinctive spatio-temporal patterns in vegetation structure, trends, and composition across the Po Plain.

The cross-comparison of five pollen records along a land–sea transect (Fig. 7) provides evidence of vegetation dynamics, climatic oscillations, and palaeogeographic changes in the Po Plain area, offering a foundation for basin-wide chronostratigraphic correlation and refined characterization of facies tracts. The 175 m-long pollen sequence of core 184S15, by revealing a succession of eight forest phases that reflect interglacial climatic conditions (assigned to MISs 17, 15, 13, 11, 9, 7, 5, and 1), is a benchmark for deciphering the cyclic depositional signature preserved in the stratigraphic record of the Po Basin (Bruno et al., 2024). In this pollen sequence, forest expansions within 'transgressive' deposits alternate with stacked fluvial-channel sand bodies and paleosols that typically lack pollen or contain only *Pinus,* indicating enhanced fluvial activity during glacial periods. A similar pattern of alternating forested and sterile phases is recorded in all the other selected pollen records (204S4, 240S13, 223S17, 240S8 - Fig. 7).

In the Italian Peninsula, glacial periods were characterized by steppe vegetation (Follieri et al., 1988; Magri and Sadori, 1999; Massari et al., 2004; Pini et al., 2009; Magri et al., 2017), which is poorly represented in the pollen records from the Po Plain due to unsuitable taphonomic conditions in sandy deposits and fluvial erosion. Nevertheless, interglacial records are generally sufficiently detailed to allow stratigraphic correlation between pollen sequences. Based on ecologically-consistent pollen groups, namely mesophilous mixed oak forest, montane forest (*Abies*, *Fagus,* and *Picea*), and riparian trees (*Alnus, Salix,* and *Populus*), regional vegetation dynamics were traced across the depositional systems.

The upper sections of all pollen records display high abundance of mixed oak forest taxa, consistent with Holocene warm conditions and supported by AMS ^{14}C dates. Slight differences in vegetation trends likely reflect site-specific sedimentary dynamics. In the most proximal site (184S15), a few pollen samples show a peak in mixed oak forest, reflecting the establishment of mature forested landscapes. A similar expansion of mesophilous forest, with abundant riparian taxa, occurs in the 223S17 record. The Holocene forest expansion in cores 204S4, 240S13, and 240S8 is preceded by an abrupt drop in the mesophilous vegetation, reflecting the short-lived climate reversal of the Younger Dryas (YD). Below Holocene and lateglacial deposits, limited palynological evidence is available for the Last Glacial Maximum (LGM), with

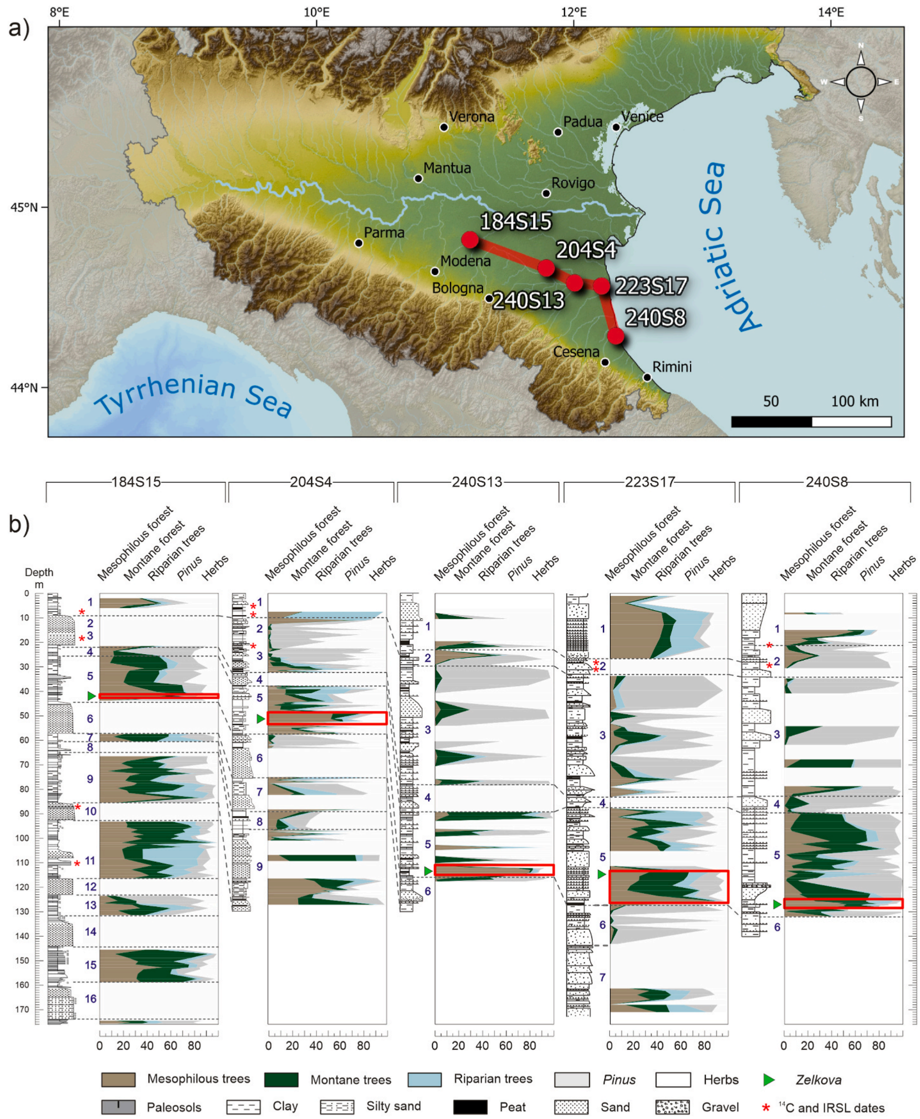

Fig. 7. Comparison of pollen records from the Po Basin. a) Map of the Po Plain showing the pollen records arranged along a land–sea transect. b) Synthetic pollen diagrams including mixed oak forest (brown), montane trees (dark green), riparian trees (light blue), Pinus (grey), and herbs (white). Numbers refer to Marine Isotope Stages (MISs). Red rectangles mark intervals with the last occurrence of Zelkova (green triangles); this biostratigraphic marker, assigned to MIS 5e, facilitates correlation to other cores.

few samples showing sparse tree cover in pollen records 204S4, 240S13, and 240S8.

A peak in mixed oak forest in the 184S15 record provides evidence of relatively warm climatic conditions, attributed to an early phase of MIS 3. Towards the coast, MIS 3 is better resolved, spanning thicker stratigraphic intervals in cores 204S4, 240S13, 223S17, and 240S8, where appreciable values of mixed oak forest are accompanied by moderate percentages of montane taxa. These vegetation features indicate the persistence of semi-forested landscapes and suggest relatively mild climatic conditions, consistent with other MIS 3 archives from Northern Italy (Pini et al., 2010; Guido et al., 2020; Marcolla et al., 2021) and Central Italy (Follieri et al., 1988; Magri, 1999; Magri and Sadori, 1999), and more generally from the Mediterranean region (Fletcher and Sánchez Goñi, 2008; Badino et al., 2020; Carrión et al., 2024). Below this forest interval, open vegetation is observed in the coastal 240S8 pollen record, indicating fully glacial cool/arid climatic conditions, corresponding to MIS 4.

Comparison of all pollen profiles reveals a regionally coherent phase of forest expansions reflecting interglacial climatic conditions during MIS 5. Fluctuations in the relative abundance of mixed-oak forest, montane tree taxa, and *Pinus* highlight an adaptive vegetation response to climate variability, capturing the paleoclimatic signature of warmer and cooler sub-stages. At the base of MIS 5, a rapid forest expansion marks the highest values of mixed-oak mesophilous forest within each pollen profile, reflecting remarkably warm and humid climatic conditions. This prominent signal of rapid forest development defines a sharp interglacial onset, which is consistent with the vegetation dynamics recorded for MIS 5e in several pollen records from S Europe (Follieri et al., 1988; Brauer et al., 2007; Tzedakis, 2007; Pini et al., 2010; Donders et al., 2021; Novellino et al., 2025; Roberts et al., 2025). Evidence for *Zelkova*, a regionally extinct tree genus, further validates the inferred chronology for this forest expansion. This taxon is not recorded after MIS 5e in the Po Plain and, more broadly, in Northern Italy (Amorosi et al., 2004; Marcolla et al., 2021; Bruno et al., 2024). *Zelkova* is found in high percentages (5-15%) during MIS 5e in Central Italy (Follieri et al., 1986; Roberts et al., 2025), where it locally persisted until MIS 3 (Follieri et al., 1988; Magri, 1999; Magri and Sadori, 1999; Giardini, 2007). It is recorded in Holocene pollen records from Sicily (Michelangeli et al., 2022a, b), where it is still living in the Hyblaean Mountains. The last occurrence of *Zelkova* in the pollen records from the

Po Basin (red rectangles in Fig. 7) offers a valuable biostratigraphic constraint for MIS 5e, being detected throughout the transect at increasing depths towards the Adriatic coast. The MIS 6-5 transition is marked by open vegetational landscapes with *Pinus* in the 223S17 and 204S4 pollen records, reflecting the extreme climate conditions of the penultimate glacial period (Roucoux et al., 2011; Hughes et al., 2020).

Below MIS 6 deposits, a forested phase with a double-peaked expansion of mesophilous broadleaved taxa and moderate percentages of montane and riparian trees is documented in cores 223S17, 204S4, and 184S15. This phase is recorded within highstand coastal deposits (Amorosi et al., 1999). Based on vegetation dynamics and pollen composition, this highstand phase can be correlated to the Roma I and II forested phases (pollen zones VdC 3 and 5) detected in Central Italy (Follieri et al., 1988), attributed to MIS 7. Below the MIS 7 interglacial, a thin stratigraphic interval with low arboreal pollen percentages is detected in the 204S4 pollen record, reflecting the open vegetation landscapes of MIS 8.

The interglacial phase that preceded MIS 8 is documented exclusively in inland sequences (cores 184S15 and 204S4). In the 184S15 pollen record, two peaks in mixed oak forest are consistent with the vegetation patterns observed at Ioannina (Katara and Pamvotis), Tenaghi Philippon (Kavala and Litochori), Boiano (zones 3a and 3b) and Bouchet/Praclaux (Amargiers and Landos phases), corresponding to the MIS 9a and MIS 9e substages, respectively (Tzedakis, 1994; Tzedakis et al., 2001; Reille et al., 1998, 2000; Fletcher et al., 2013; Orain et al., 2013). This interpretation is supported by an IRSL age of 369,900 ± 41,300 BP (= MIS 10) from underlying fluvial sands (Bruno et al., 2024). A similar pattern is observed in the 204S4 pollen record, where two peaks in mixed oak forest, marking the onset and the end of a forested interval interrupted by sterile sandy layers, support the attribution of this phase to MIS 9.

Earlier interglacial periods are recorded exclusively in the 184S15 pollen record. Based on the IRSL date of 411,900 ± 49,500 BP, the forest phase between ca. 115 and 94 m is attributed to MIS 11. Further down the sequence, two additional forested intervals have been tentatively ascribed to MIS 13 and MIS 15, respectively (Bruno et al., 2024).

Overall, the palynological and stratigraphic data converge in documenting recurrent T-R cycles across the Po Plain. Pollen records, in particular, through the identification of glacial-interglacial transitions, provide chronostratigraphic constraints that can assist in tracing transgressive surfaces into more proximal (inland) areas, where these surfaces may lack a clear sedimentological expression.

3.4. Tracing bounding unconformities to the Apennine basin margin

Predicting the stratigraphic response of the basin margins to changes in the forcing variables that govern stratigraphic architecture (eustasy, tectonics, and climate) is a difficult task. Landward of the maximum marine/paralic influence, within entirely alluvial deposits, and far away from the thick depocenters, the effects of sea-level fluctuations are difficult to decipher, and identification of sequence bounding unconformities may be increasingly affected by uncertainties (van Balen et al., 2010). In addition, periods of incision and aggradation may generate discontinuity-bounded sequences (aggradational–degradational rhythms) on timescales as short as 10^3 to 10^4 years (Gibling et al., 2011). Consequently, the classification and hierarchy of stratigraphic units may fail to provide internal consistency.

Tectonic and climatic processes are the primary drivers of alluvial fan evolution (Mack and Leeder, 1999; Blair and McPherson, 2009). Climate by influencing temperature, precipitation, and vegetation, may affect erosion and sediment dynamics, impacting all stages of the sedimentary cycle, from catchment erosion to alluvial fan deposition (Feng et al., 2025).

At the southern margin of the Po Basin, shallowly buried alluvial-fan and fan-delta systems are genetically related to patchily exposed fluvial terraces of the feeding Apennine river valleys (Fig. 8) that are discontinuously covered by wind-blown silt (Cremaschi et al., 2015; Zerboni et al., 2015). Distal alluvial fan deposits exhibit a distinct response to interglacial-glacial cycles, being typified by the repeated alternation of (interglacial) floodplain muds, locally marked at the base by peat-bearing deposits, with thick, fluvial gravel bodies, mostly deposited during glacial periods (Amorosi et al., 1996; Servizio Geologico d'Italia, 2005b - Fig. 8).

In proximal alluvial fan systems, where the rate of creation of

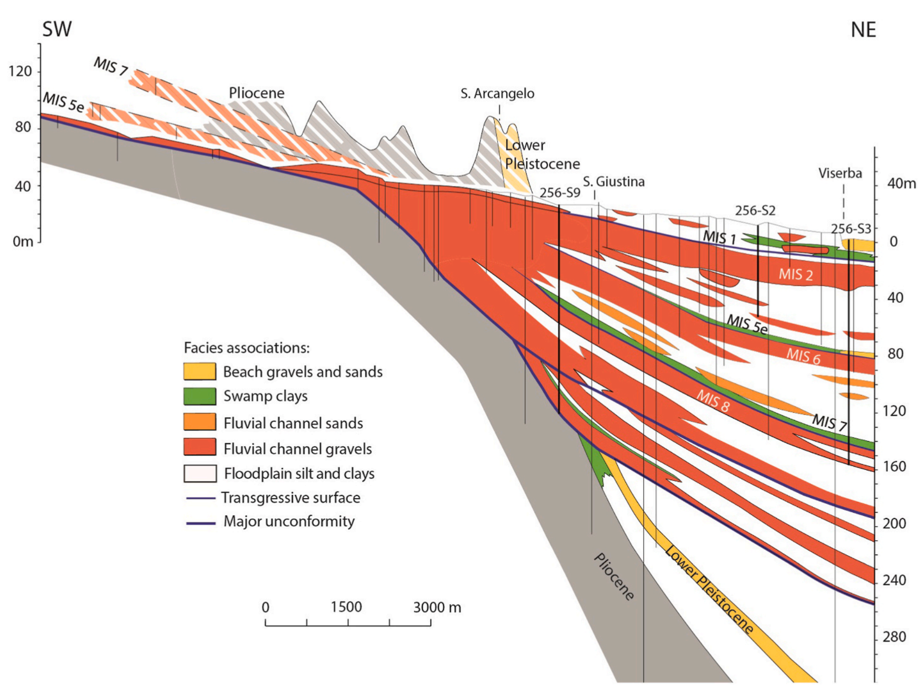

Fig. 8. Cyclic facies architecture in fan-delta and terraced fluvial successions at the southern margin of the Po Basin (section trace in Fig. 1 – modified from Servizio Geologico d'Italia, 2005b). The sharp facies change from laterally extensive gravel bodies to overlying floodplain deposits is correlative at distal locations with the lower boundary of swamp clays and coastal sands, and marks the base of a transgressive-regressive (interglacial-glacial) cycle.

accommodation space is low, fluvial gravel bodies become increasingly amalgamated, floodplain deposits have limited preservation, and individual cycles are difficult to resolve (Amorosi et al., 1996; Scardia et al., 2012). In general, the Po Basin fill thins and wedges out toward the northern and southern basin margins, and unconformities younger than the 'R unconformity' become too close together in these areas to be confidently traced by seismic lines and deep wells alone in the subsurface (Garzanti et al., 2011; Maesano et al., 2024).

Inherent complexity, small-scale lithologic/petrographic variations, tectonically generated topography, and problematic chronologic attributions are just some of the factors that limit stratigraphic correlation at the Apennine margin. Furthermore, significant autogenic control may overwhelm the effect of climate change. Although numerous attempts have been made in upland areas to correlate Quaternary stratigraphy with the repeated pattern of glacial cycles recognized downstream (Amorosi et al., 1996; Picotti and Pazzaglia, 2008; Gunderson et al., 2014; Zuffetti and Bersezio, 2021 – see Fig. 8), stratigraphic correlation far away from the marine shorelines and from their laterally equivalent deposits remains difficult and highly controversial.

In upland settings, Quaternary deposits include terraced fluvial and marine successions that can be examined essentially through morphostratigraphic criteria (Macklin et al., 2002; Woodward et al., 2008) and with the aid of luminescence dating (Lamothe, 2016). Numerous researchers have explored the relationship between fluvial terrace evolution and orbital-scale climatic oscillations (Vandenberghe, 1995, 2015; Rittenour et al., 2007; Bridgland and Westaway, 2008; Counts et al., 2015; Yu et al., 2024). The characteristic step-like profile results from alternating phases of aggradation (during interglacials) and river incision (during glacial periods) (Wang et al., 2015). At the Apennine foothills, differences in elevation, associated with pedostratigraphic, petrographic and archaeological characterization of terraced surfaces may facilitate the delimitation of unconformity-bounded stratigraphic units and tentative correlation with events recorded in the marine isotope record (Cremaschi, 1987; Picotti and Pazzaglia, 2008; Wegmann and Pazzaglia, 2009; Wilson et al., 2009; Zuffetti et al., 2018a; Zuffetti and Bersezio, 2021; Scarciglia et al., 2023 – Fig. 8). A high-resolution stratigraphic age model used to unravel tectonic and climatic (glacial/interglacial) controls on stratigraphy has been carried out along the exceptionally exposed Enza River section (Gunderson et al., 2014).

3.5. *Tracing bounding unconformities to the Alpine basin margin*

The Alpine basin margin hosts a sparse and fragmentary outcrop record of Quaternary stratigraphy that cannot be easily resolved and correlated even across adjacent river valleys. Along the Alpine foothills, uncertainties in regional stratigraphic correlation due to a lack of robust chronologic constraints have resulted in the use of separate sets of stratigraphic units for substantially equivalent deposits (Bini, 1997 – Fig. 2). Within glaciogenic (glacial, fluvioglacial, and lacustrine) depositional systems cropping out at the Alpine margin of the Po Basin, the UBSU stratigraphic approach is complicated by multiple glacial scouring that typically generates a wide range of unconformities (Bini, 1997). In these areas, the definition and hierarchical ranking of erosional bounding surfaces (bedding planes, scours, erosion surfaces, and unconformities – Miall, 1985) can hardly be established on an objective and descriptive basis, and identification of major unconformities necessarily includes significant interpretation.

By focusing, with a local perspective only, on the geological mapping of individual valleys and related glacial amphitheaters, early stratigraphic investigations of Quaternary successions in the Alpine region have led to an increasing number of stratigraphic units. Recently, a substantial change in the geological surveying methods (Servizio Geologico d'Italia, 2025b), based primarily on the identification of key stratigraphic surfaces in lowland areas and on their tracing into upstream regions, has largely simplified the stratigraphic framework of the Middle and Upper Pleistocene successions, increasing effectively their correlation potential across wider areas, such as the Adda–Mella transect (Fig. 2).

At the Alps foothills, tectonic deformation has brought to the surface a significant portion of the Middle Pleistocene sedimentary succession. In this area, Holocene and even Upper Pleistocene deposits may be lacking (Servizio Geologico d'Italia, 2025b) and stratigraphic analysis of Middle-Upper Pleistocene sediment bodies that accumulated in glacial outwash braid-plain settings can be carried out at relatively low resolution only. From proximal to distal locations, Middle Pleistocene glaciogenic (glacial and fluvioglacial) deposits transition into fully fluvial sequences, characterized by a typical downstream fining trend. In vertical sections, these units are differentiated based on their grain size, which reflects the upward transition from distal (sand-dominated) to proximal (gravel-dominated) fluvial settings (Fig. 9). Within these commonly amalgamated coarse-grained successions, there is no clear evidence of internal, 100 kyr orbital-scale cyclicity; as a result, stratigraphic correlation with transitional (lagoon and swamp) deposits identified in the depocenter is not obvious. In the northernmost part of the basin, where glacial influence on sedimentation was strongest and glacial material was repeatedly reworked, juxtaposed gravel bodies can only occasionally be distinguished on a petrographic basis, thus making their chronologic resolution difficult (Aghib et al., 2024).

Small outcrops at the Alps foothills can be investigated through a morphostratigraphic approach combined with detailed soil characterization, though polygenic landforms cannot be easily correlated to specific glacial cycles (Hughes, 2010). Relatively objective UBSUs clearly depict the Last Glacial Maximum (LGM) expansion (Bini et al., 2004; Monegato et al., 2017a, 2017b), as opposed to older deposits, based upon a combination of morphologic, geometric, weathering and elevation data. For LGM deposits, ample availability of AMS^{14}C dating enables a reliable chronologic attribution to MIS 2 (Bini et al., 2015; Servizio Geologico d'Italia, 2025b).

Additional, recurrent features can be used as correlation tools and for reliable age assignments at the northern margin of the Po Plain. Loess cover and loess/paleosol sequences (Muhs and Bettis, 2003) generally overlie fluvial or fluvioglacial deposits and are dated between about 75 and 16 ka (Cremaschi, 1987, 2004; Cremaschi et al., 2015; Zerboni et al., 2015; Zuffetti et al., 2018b; Lehmkuhl et al., 2021). Sedimentary traps for loess aggradation are glacial sediments (moraines), fluvio-glacial terraces, and tectonic hills in the Prealps, but also fluvial terraces at the Apennine foothills (Zerboni et al., 2018; Lehmkuhl et al., 2021). These wind-blown sediments, dated through OSL, can be used within an UBSU stratigraphic approach as stratigraphic markers of MISs 4 and 2. Intercalated peat layers that accumulated within the range of radiocarbon dating represent nearly isochronous stratigraphic markers that may largely improve the chronologic framework (Servizio Geologico d'Italia, 2025b). Pedogenetic horizons should be used cautiously, as in many cases these actually represent secondary soil accumulations (geologic pedorelicts *sensu* Cremaschi and Rodolfi, 1991) reworked by fluvial or glacial processes (Aghib et al., 2024).

3.6. *Correlation with the Venetian-Friulian plain*

The influence of glacio-eustatic fluctuations on Middle Pleistocene-Holocene stratigraphy has also been demonstrated outside the Po Plain, in the coastal areas of the adjacent Venetian plain (Fig. 1). In this area, the rhythmic alternation of continental and marine facies associations, spanning MIS 8 to MIS 1, was first recognized in the Venezia-1 core (Kent et al., 2002; Massari et al., 2004). Facies characteristics and pollen data indicate a consistent pattern: continental sediment packages correspond to glacial conditions, whereas maximum flooding intervals align with interglacial phases. Accordingly, the Venice area was repeatedly submerged during glacio-eustatic highstands and became emergent during subsequent major lowstands (Massari et al., 2004).

The same cyclic pattern of alternating marine and continental facies

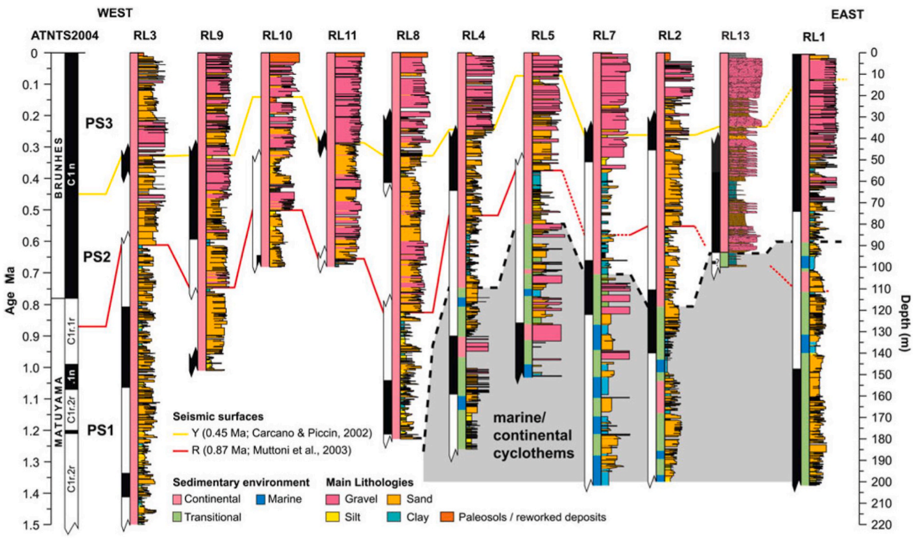

Fig. 9. Stratigraphic correlation of the 'R' (red) unconformity (assigned at 0.87 Ma) across the western Po Plain (from Scardia et al., 2012; Aghib et al., 2024). Note the upward transition from distal (sand-domianted with silt and clay) PS2 to proximal (gravel or gravel/sand) PS3 outwash braid-plain Middle-Upper Pleistocene deposits.

illustrated in Fig. 5 has been recognized in the Friulian plain (Servizio Geologico d'Italia, 2008a; 2011b), where transgressive, coastal and shallow-marine deposits of MIS 1 and MIS 5e age, respectively (Fontana et al., 2010) unconformably overlie stratigraphic discontinuities typically marked by immature paleosols (Servizio Geologico d'Italia, 2011b).

In a recent study from the Venetian lowlands (Marcolla et al., 2021), a stratigraphic unconformity dated to MIS 7 delineates a laterally continuous stratigraphic marker at the base of a well developed transgressive-regressive sequence that can be tracked for about 70 km into the Friulian Plain (Fig. 10 – Servizio Geologico d'Italia, 2008a; Pini et al., 2009). Transgressive deposits assigned to the MIS 7 interglacial exhibit the same stratigraphic architecture described for the Holocene facies tract in the Po Plain (Fig. 6), with marine deposits gradually replaced upstream by restricted marine (bay), brackish (lagoon) and freshwater (swamp) facies associations (Marcolla et al., 2021).

In more proximal areas, the transition from paralic to continental deposits is more difficult to decipher due to the complex, sedimentary response to glacial cycles. Large sectors of the present surface of the Venetian-Friulian plain consist of fluvioglacial deposits accumulated during the LGM in fan-shaped alluvial features, commonly referred to as fluvial megafans. These megafans were mainly constructed from meltwater and sediment discharges related to the demise of the Last Glacial Maximum and were subsequently incised under Holocene climate conditions (Fontana et al., 2008, 2014).

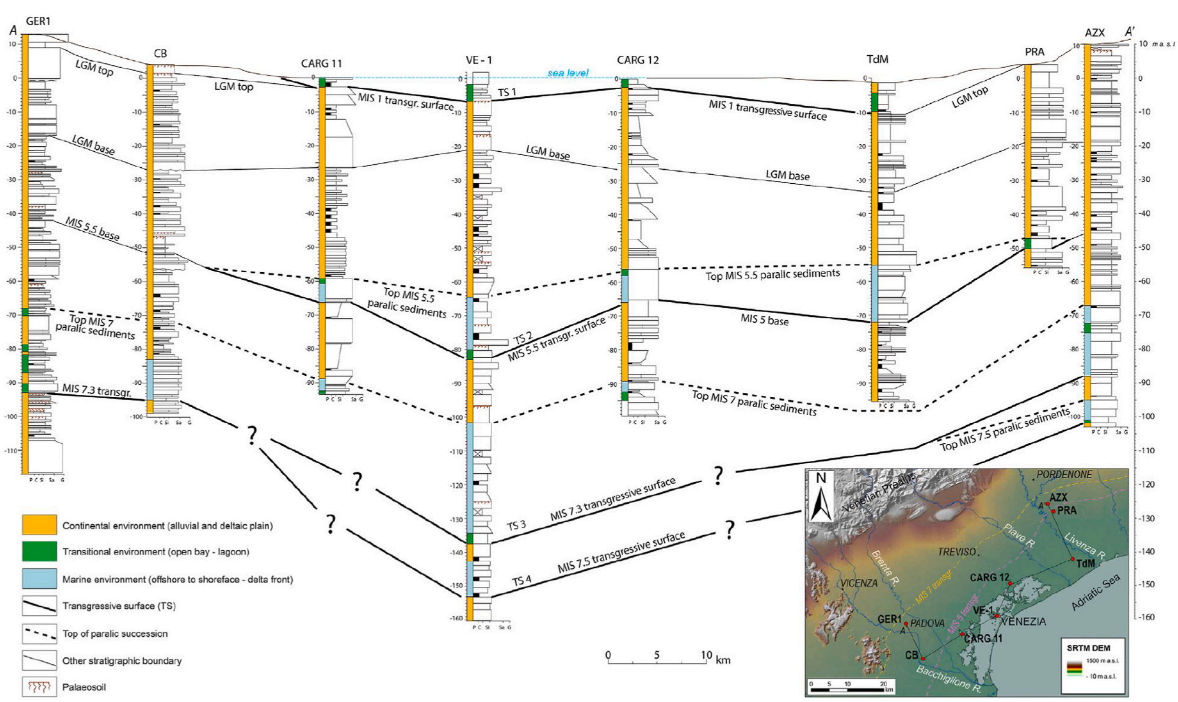

Fig. 10. Cyclic stratigraphic architecture of the Venetian and Friulian coastal plains (from Marcolla et al., 2021). Note the alternation of marine/paralic and continental deposits and its correlation with interglacial/glacial cycles. MIS: Marine Isotope Stage.

4. Implications for subsurface geological mapping: Moving from a local to the global scale

Disentangling the complex dynamics that underpin rhythmic sedimentation patterns in the geological record is not straightforward and there have been many attempts in the geological literature to discern allogenic controls on stratigraphic architecture. The subdivision of the stratigraphy into packages of sedimentary rocks separated by extra-regional unconformities was first introduced by Krumbein and Sloss (1951) and later elaborated by Sloss (1963). However, the detailed examination of the relationship between depositional-system stacking patterns and relative sea-level cycles was undertaken only decades later by Posamentier et al. (1988). Below the hierarchical level of the depositional sequence, the stratigraphic architecture of parasequences was subsequently explored by Van Wagoner et al. (1990).

The subdivision of successions recording alternating glacial and nonglacial climatic conditions into unconformity-bounded stratigraphic units has been investigated across multiple geological periods in the history of the Earth, including Paleozoic successions (Fielding et al., 2008), and 100 kyr-scale cyclic stratigraphic architectures have been recognized as a common tract of alluvial depositional systems (Busschers et al., 2005, 2007; Peeters et al., 2016).

The Quaternary is characterized by a much higher chronologic resolution than earlier geological periods (Gibbard and Lewin, 2016). Cyclic changes in the volume of water in the oceans during the Middle Pleistocene-Holocene were due to alternating glaciations and deglaciations, which were responsible for high-amplitude sea-level variations (Martinson et al., 1987; Waelbroeck et al., 2002). Climate change also affected continental sedimentary systems (Fjeldskaar and Amantov, 2018), principally through cyclic changes in vegetation, weathering conditions, erosion, and sediment transport. Sea-level and climate fluctuations, thus, may provide an interpretation template for Quaternary successions, and stratigraphic subdivisions can be effectively guided by the well-constrained oxygen-isotope chronology. Despite this potential, however, application of cyclostratigraphic concepts to the geological mapping of unconformity-bounded stratigraphic units of Quaternary age has never been satisfactorily undertaken in the literature.

The fundamental units of formal UBSUs are synthems (Chang, 1975): these are coherent packages of strata that are genetically related, traceable for considerable distances across a basin, and bounded by "significant and demonstratable unconformities" (Salvador, 1994). In the Po Basin, the Middle Pleistocene-Holocene stratigraphic framework outlined above reflects glacially forced sea-level changes and relies on the global correlation of potentially synchronous stratigraphic boundaries. In the depocenter, where stratigraphic patterns of highstand and lowstand deposits are best preserved, ten transgressive-regressive sequences driven by orbital mechanisms in the Milankovitch (100-kyr) band form the building block of the Middle Pleistocene-Holocene stratigraphy (Fig. 4). For this reason, these sequences are here suggested to serve as synthems for time-unit partitioning and geological mapping purposes (Fig. 11).

In this view, synthems represent prominent, regionally mappable depositional units (T-R sequences) that formed during 100 kyr interglacial-glacial cycles (Fig. 11). Lower-rank units (subsynthems) mark the boundaries between interstadials and stadials (e.g. MIS 5-4 or MIS 3-2 transitions) or vice versa. Subsynthems can be organized into lithostratigraphic units (Lucchi, 2019): these latter represent genetically related depositional systems and facies associations that developed in response to short-lived climate and eustatic oscillations. We suggest using the term Supersynthem to refer to the sediment package formed over the last ca 870 ka, at the shift from 41 kyr to 100 kyr orbital cyclicity (Fig. 11), which in the southern Po Basin incidentally corresponds to a tectonically-originated unconformity ('R' unconformity in Fig. 3).

Unlike classic sequence-stratigraphic models (Vail et al., 1977; Posamentier and Vail, 1988), in asymmetric Quaternary cycles, sequence boundaries formed during prolonged sea-level falls are less chronostratigraphically significant than transgressive surfaces formed during rapid rises (Bhattacharya, 2011). Accordingly, Quaternary synthems in the Po Basin are best recognized in cores and logs not by their erosional sequence boundary, but by the development of transgressive surfaces that coincide with periods of great inundation of the basin margin (Amorosi et al., 2004; Campo et al., 2020; Bruno et al., 2024), as

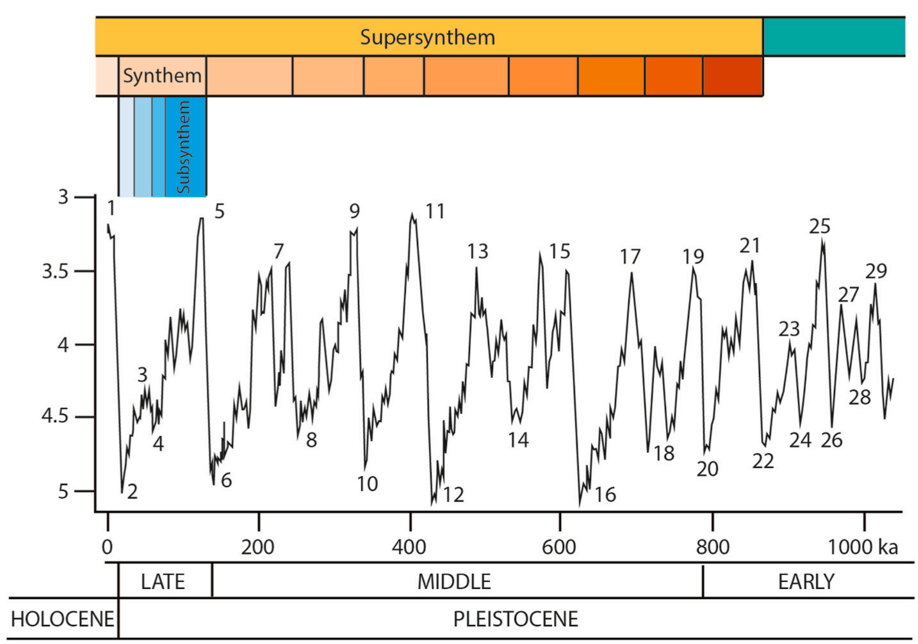

Fig. 11. Hierarchical subdivision of Middle Pleistocene-Holocene deposits into unconformity-bounded stratigraphic units (supersynthems, synthems, and subsynthems) based on the oxygen-isotope chronology of Lisiecki and Raymo (2005): odd numbers: interglacials, even numbers: glacials. Synthems correlate with transgressive-regressive cycles that start and end at the onset of interglacials. Subsynthems are interpreted to have been deposited during stadials or interstadials (minor peaks in the diagram). The lower boundary of the supersynthem demarcates the shift to the 100 kyr orbital rhythm.

in the pioneer allostratigraphic approach of Bhattacharya and Walker (1991). At synthem boundaries, depositional systems commonly backstep onto the basin margin, producing characteristic onlap geometries. Substantial landward shifts of facies, i.e. 'non-Waltherian' facies dislocations, translate into abrupt contacts between transgressive paralic and coastal facies and underlying lowstand alluvial deposits (Figs. 4 and 12). At the local scale, these diachronous transgressive (or maximum regressive) surfaces typically correspond to regional unconformities, which may locally be represented by paleosols or ravinement surfaces (Mancini and Puckett, 2002).

At more inland locations, synthem boundaries may separate amalgamated (LST) channel belts from overlying, more aggradational and isolated (TST) channels, marking an abrupt change in the fluvial regime (Shanley and McCabe, 1993; Plink-Björklund, 2005; Labourdette and Jones, 2007; Blum et al., 2013; Tanabe et al., 2022). Regardless of their facies expression, synthem boundaries bear a diagnostic palynological signature (Fig. 7) associated with the abrupt expansion of thermophilous vegetation, which reflects the onset of warm-temperate (interglacial) climate conditions (Fig. 12).

During relative sea-level fall and lowstand, the continental shelf (and the coeval alluvial plain upstream) became exposed and incised by the river drainage network. Pedogenized horizons that formed during this phase of prolonged subaerial exposure correlate laterally with amalgamated fluvial channel belt bodies at the base of 'incised-valley systems' (Zaitlin et al., 1994): these latter are interpreted as deposits of braided- and low-sinuosity rivers that developed during glacial periods in response to increased sediment supply and low accommodation (Fig. 12). Correlation of interfluve paleosols with valley bases (Gibling et al., 2011) becomes increasingly difficult at inland locations, moving from the coastal-plain to alluvial paleovalleys (Blum et al., 2013).

Although transgressive (or maximum regressive) surfaces represent robust stratigraphic markers that can be tracked continuously across most of the basin to delineate individual synthems (Figs. 4–7 and 12), flexibility needs to be retained when mapping synthem boundaries close to the basin margins. Indeed, several factors concur in tuning sedimentary and erosional processes at the southern and especially northern margins of the Po Plain. (i) Tectonic activity or autogenic processes at mountain foothills can locally overwhelm the effects of climate and sea-level change, especially where glacial/interglacial cycles made available large amounts of sediment. (ii) Patchily exposed sedimentary units or amalgamated gravel bodies may not be unequivocally assigned to a particular synthem. (iii) Stratigraphic boundaries can be strongly diachronous on a local scale due to the factors listed above (iv) Depending on the depositional system (e.g., glacial and fluvioglacial deposits). and the types of data available, stratigraphic surfaces can be cryptic and hardly distinguishable. (v) Finally, a reliable chronologic framework can be missing, as a lack of suited material can prevent accurate numerical dating.

We deliberately leave the Middle Pleistocene-Holocene stratigraphic units of Fig. 11 unnamed, because the formal revision of classification of

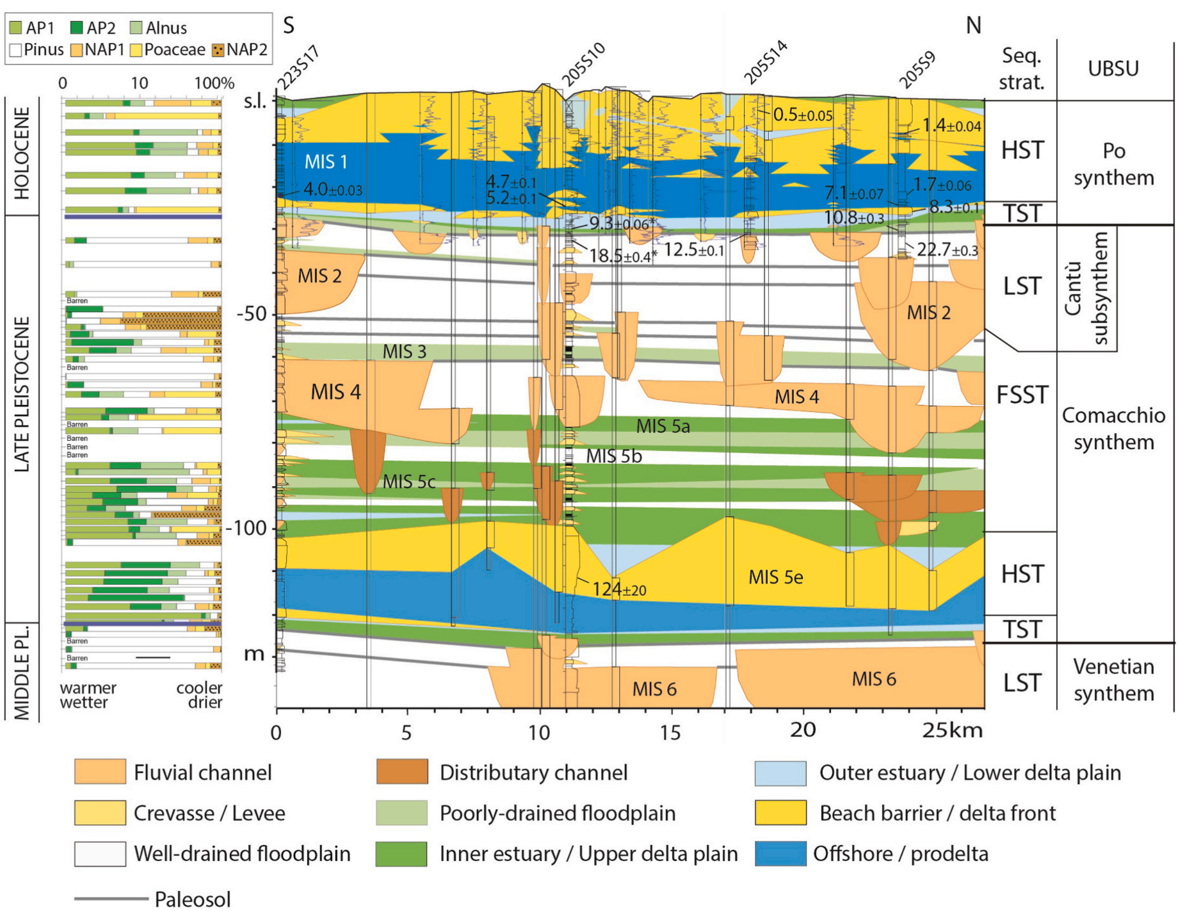

Fig. 12. Chronostratigraphy, palynostratigraphy, stratigraphic architecture, sequence stratigraphy, and proposed UBSU stratigraphy of the Middle Pleistocene-Holocene succession of the Po-Venetian Basin (based largely on Amorosi et al., 2004), depicting a markedly simple subdivision into unconformity-bounded stratigraphic units (synthems) that correlate to distinct 100 kyr Milankovitch cycles. Synthems reveal distinctive transgressive-regressive facies patterns that correlate with interglacial/glacial cycles. Synthems lower boundaries (MIS 1 and 5e) record abrupt marine incursions and are paralleled by distinct peaks in arboreal pollen percentages, marked by prominent increases in mixed oak forest (AP1). Paleosols and related fluvial channel belts characterize, instead, glacial intervals (MIS 2, 4 and 6). MIS: Marine Isotope Stage, FSST: Falling-Stage Systens Tract, LST: Lowstand Systems Tract, TST: Transgressive Systems Tract, HST: Highstand Systems Tract. AP1+AP2: arboreal pollen, NAP: non-arboreal pollen.

Quaternary strata in the Po Basin is largely beyond the scope of this paper and a larger discussion is ongoing. However, as cleaning up nomenclature will require the abandonment of tens of stratigraphic units while revising or naming new ones, we tentatively propose names for the three youngest (and best resolved) synthems, as follows (Fig. 12):

- Po Synthem (MIS 1), since the detailed stratigraphic architecture of the Holocene transgressive-regressive cycle, first investigated by Amorosi et al. (1999) and Servizio Geologico d'Italia (2002), has been widely recognized throughout the Po River Plain.
- Comacchio Synthem (MIS 5e-MIS 2), since numerical (Electron Spin Resonance) dating (Ferranti et al., 2006) of the coastal wedge assigned to the Eemian or MIS 5e (Amorosi et al., 2004) was first performed in Sheet 205-Comacchio (core 205S10 in Fig. 12 - Servizio Geologico d'Italia, 2009b). Within this unit, MIS 2 deposits display a high correlation potential, from the depocenter to the basin margins (where they also have clear morphologic expression), and are incorporated into a lower-rank unit assigned to the Last Glacial Maximum (Cantù Subsynthem; Bini, 1987, Bini et al., 1992; Servizio Geologico d'Italia, 2008d).
- Venetian synthem (MIS 7-MIS 6), since wide documentation of the MIS 7 transgression derives from integrated analysis of core Venezia-1 (Kent et al., 2002; Massari et al., 2004) and its stratigraphic correlation across the Venetian coastal plain (Marcolla et al., 2021).

Measured sections, well logs, maps and a striking amount of data accompany the description of these synthems in the geological maps of the Po, Venetian, and Friulian plains. In addition, these units offer high potential for correlation also at the basin margins (Fig. 9), especially where the MIS 7-MIS 1 succession is represented by a chronologically well constrained set of fluvial deposits (Picotti and Pazzaglia, 2008; Gunderson et al., 2014; Zuffetti and Bersezio, 2021) or end moraine systems (Monegato et al., 2023).

Simple lithostratigraphic maps no longer provide the level of information needed in modern land-use planning, and society would greatly benefit from the existence of practical stratigraphic classification systems and formal stratigraphic frameworks interconnected with international geological databases (Räsänen et al., 2009). The use of a limited number of synthems to characterize the subsurface stratigraphic architecture of modern alluvial and coastal plains (Fig. 12) can be used to support extra-regional correlations much more effectively than through the present, indecipherable plethora of stratigraphic units (Fig. 2). In addition, understanding a control on accommodation and sedimentation dictated by glacio-eustatic variations can make it possible to use facies modeling and basin analysis outside the data points as a powerful predictive tool for geometry, extent, thickness and properties of shallowly buried sediment bodies.

5. Conclusions

Society can greatly benefit from the production of basin-scale, nationally consistent geological maps *in lieu* of complex schemes of named material reflecting a local stratigraphic nomenclature only. In the Po-Venetian basin, a total of 115 Middle Pleistocene-Holocene stratigraphic units depicted in 45 official geological maps reflect the complexity of buried alluvial, coastal, and shallow-marine depositional systems, and of their coeval terrace deposits and glaciogenic successions cropping out discontinuously at basin margins. The information derived from these geological maps has made it possible to outline the hierarchical framework proposed in this study, which is not intended as a prescriptive standard, but rather as a consistent interpretive framework for stratigraphic architecture that can facilitate correlation and comparison beyond local scales.

In this study, we demonstrate the high sensitivity of shallow-marine and alluvial realms to Quaternary, high-amplitude interglacial-glacial fluctuations. Relatively conformable stratigraphic packages formed in a variety of depositional environments and reflecting potentially external controls can be grouped within a simple hierarchy of regionally mappable unconformity-bounded stratigraphic units that may have relevance for applied mapping. Stratigraphic architectural patterns recognized across a range of spatial and temporal scales throughout the Po-Venetian Basin emphasize the concept of geologic time archived in the stratigraphic record and can be summarized as follows:

1) Synthems developed in response to 100-kyr, Milankovitch-scale glacio-eustatic oscillations represent readily mappable units that provide a comprehensive, three-dimensional view of facies architecture across much of the Po-Venetian Basin, forming the building block of Middle Pleistocene-Holocene stratigraphy. These synthems exhibit distinct, predictable and chronologically constrained facies patterns, as well as diagnostic climatic signatures that can be traced throughout the basin.
2) Key stratigraphic discontinuities at synthem boundaries are linked to prominent transitions from glacial to interglacial periods that may be globally representative. They record abrupt landward shifts in depositional settings that locally contravene Walther's law and correspond to initial flooding (or maximum regressive) surfaces of large geographic extent that developed in response to abrupt sea-level rise at the onset of interglacials. In interfluvial areas, synthem boundaries coincide with erosional or hiatal surfaces marked by stiff, pedogenically modified horizons that represent wide exposure and significant breaks in the stratigraphic record. Genetically-related channel-belt sand or gravel bodies typically cluster in the upper parts of synthems.
3) Ten 100 kyr-scale synthems, spanning interglacial-glacial cycles dated approximately to the last 870 kyr, have a diagnostic pollen signature in the Po Basin and are the major architectural components of the supersynthem of Middle Pleistocene-Holocene age, a stratigraphic unit that is clearly imaged on seismic profiles and that marks the abrupt shift from relatively low amplitude cycles to increasing amplitude cycles (i.e., the onset of Pleistocene glaciations in the Alps).
4) At a finer scale, subsynthems emphasize the relations between global sea-level trends, climate change and facies patterns at the transition from interstadial to stadial conditions (and vice versa) or even at a higher temporal resolution. Within the MIS 5-2 synthem, laterally extensive fluvial channel-belt sand bodies can be correlated to the onset of LGM (MIS 2) and MIS 4.
5) In upland regions, close to basin margins, tectonic, glacial or autogenic processes may increasingly account for diverging stratigraphic architectural patterns, fragmentary stratigraphic record, and local amalgamation of thick gravel bodies, which can locally prevent synthem identification. In these cases, mapping should be carried out assigning units at the supersynthem level.
6) Establishing a basinwide stratigraphic synthesis for the Middle Pleistocene-Holocene succession of the Po Basin depends on the resolution of chronological data, which decreases with depth and age. Prominent synthem boundaries that demarcate the onset of the present (MIS 1), last (MIS 5e), and penultimate (MIS 7) interglacials can be tracked upstream, from the rapidly subsiding coastal plain into the moraine systems and uplifted fluvial terraces. Such synthems have a (relatively) isochronous base, offering the potential for correlation on a global scale.

Changes occurring simultaneously and reflecting major Earth system transitions (marine isotope record, global climate shifts, paleomagnetic reversals) affect both the marine and terrestrial record and can be deciphered within Middle Pleistocene-Holocene successions. Reading astronomical climate forcing from Quaternary successions through a cyclostratigraphic approach may help interpret stratigraphic patterns in response to climatic and eustatic fluctuations, therefore providing a comprehensive understanding of onshore and offshore stratigraphic architecture largely beyond the local scale.

Author contribution

Alessandro Amorosi: Conceptualization, Methodology, Investigation, Writing – Original Draft, Supervision, Funding acquisition. Luigi Bruno: Methodology, Investigation, Writing – Original Draft. Chiara D'Ambrogi: Methodology, Investigation, Writing – Original Draft. Donatella Magri: Investigation, Writing – Original Draft. Fabrizio Michelangeli: Investigation, Writing – Original Draft. Lorenzo Calabrese: Investigation, Writing – Review & Editing. Felicia Papasodaro: Formal analysis, Investigation, Writing – Review & Editing. Paolo Severi: Investigation, Writing – Original Draft. Andrea Zerboni: Investigation, Writing – Original Draft. Andrea Piccin: Writing – Review & Editing. Maurizio D'Orefice: Conceptualization, Formal analysis, Investigation, Writing – Review & Editing.

Declaration of competing interest

All authors declare that they have no financial and personal relationships with other people or organizations that could inappropriately influence or bias their work.

Acknowledgments

This study was supported by the PRIN project 2022PMEN2K "*Refining the sequence stratigraphic model through high-resolution onshore-offshore correlation (ON/OFF): The late Quaternary succession of the Po-Adriatic system*" funded by the Ministero dell'Università e della Ricerca, Italy. The research was also supported by funds from the CARG Project - Geological Map of Italy 1:50.000. We gratefully acknowledge Salvatore Milli and an anonymous reviewer for their insightful and invaluable reviews.

Data availability

All data and/or code is contained within the submission.

References

Aghib, F.S., Muttoni, G., Norini, G., Mariani, G.S., Zerboni, A., de Franco, R., Di Capua, A., Tira, M.A., Brusamolino, A., Menici, S., Caielli, G., Groppelli, G., Piccin, A., 2024. The Pleistocene tectono-stratigraphic evolution of the northern Po Plain (Italy) around the Castenedolo and Ciliverghe hillocks. Quat. Res. 117, 170–182.
Amadori, C., Garcia-Castellanos, D., Toscani, G., Sternai, P., Fantoni, R., Ghielmi, M., Di Giulio, A., 2018. Restored topography of the Po Plain-Northern adriatic region during the Messinian base-level drop—Implications for the physiography and compartmentalization of the palaeo-Mediterranean basin. Basin Res. 30, 1247–1263.
Amadori, C., Toscani, G., Di Giulio, A., Maesano, F.E., D'Ambrogi, C., Ghielmi, M., Fantoni, R., 2019. From cylindrical to non-cylindrical foreland basin: Pliocene-Pleistocene evolution of the Po Plain-Northern Adriatic basin (Italy). Basin Res. 31, 991–1015.
Amorosi, A., Milli, S., 2001. Late Quaternary depositional architecture of Po and Tevere river deltas (Italy) and worldwide comparison with coeval deltaic successions. Sediment. Geol. 144, 357–375.
Amorosi, A., Farina, M., Severi, P., Preti, D., Caporale, L., Di Dio, G., 1996. Genetically related alluvial deposits across active fault zones: an example of alluvial fan-terrace correlation from the upper Quaternary of the southern Po Basin, Italy. Sediment. Geol. 102, 275–295.
Amorosi, A., Colalongo, M.L., Pasini, G., Preti, D., 1999. Sedimentary response to late Quaternary sea-level changes in the Romagna coastal plain (northern Italy). Sedimentology 46, 99–121. https://doi.org/10.1046/j.1365-3091.1999.00205.x.
Amorosi, A., Colalongo, M.L., Fiorini, F., Fusco, F., Pasini, G., Vaiani, S.C., Sarti, G., 2004. Palaeogeographic and palaeoclimatic evolution of the Po Plain from 150-ky core records. Global Planet. Change 40, 55–78.
Amorosi, A., Pavesi, M., Ricci Lucchi, M., Sarti, G., Piccin, A., 2008. Climatic signature of cyclic fluvial architecture from the Quaternary of the central Po Plain, Italy. Sediment. Geol. 209, 58–68.
Amorosi, A., Bruno, L., Campo, B., Rossi, V., Scarponi, D., Hong, W., Bohacs, K.M., Drexler, T.M., 2017a. Global sea-level control on local parasequence architecture from the Holocene record of the Po Plain, Italy. Marine and Petroleum Geology 87, 99–111.
Amorosi, A., Bruno, L., Cleveland, D.M., Morelli, A., Hong, W., 2017b. Paleosols and associated channel-belt sand bodies from a continuously subsiding late Quaternary system (Po Basin, Italy): new insights into continental sequence stratigraphy. Geol. Soc. Am. Bull. 129, 449–463.
Amorosi, A., Barbieri, G., Bruno, L., Campo, B., Drexler, T.M., Hong, W., Rossi, V., Sammartino, I., Scarponi, D., Vaiani, S.C., Bohacs, K.M., 2019. Three-fold nature of coastal progradation during the Holocene eustatic highstand, Po Plain, Italy—Close correspondence of stratal character with distribution patterns. Sedimentology 66, 3029–3052.
Amorosi, A., Bruno, L., Cacciari, M., Campo, B., Rossi, V., 2021a. Tracing marine flooding surface equivalents across freshwater peats and other wetland deposits by integrated sedimentological and pollen data. Int. J. Coal Geol. 246. https://doi.org/10.1016/j.coal.2021.103830.
Amorosi, A., Bruno, L., Campo, B., Costagli, B., Hong, W., Picotti, V., Vaiani, S.C., 2021b. Deformation patterns of upper Quaternary strata and their relation to active tectonics, Po Basin, Italy. Sedimentology 68, 402–424. https://doi.org/10.1111/sed.12784.
Anthony, E., Syvitski, J., Cohen, K., Saito, Y., Zainescu, F., Vespremeanu-Stroe, A., Nicholls, R., Marriner, N., Amorosi, A., Maselli, V., Minderhoud, P., Tamura, T., Day, J., Woodroffe, C., Preoteasa, L., Tatui, F., Sabatier, F., Morhange, C., Besset, M., Kemp, P., Chen, Z., 2025. A 7000-year record of human influence on Global River Deltas: geomorphology, stratigraphy, the Anthropocene overprint and future. Earth Sci. Rev. 271, 105302.
Antonellini, M., Giambastiani, B.M.S., Greggio, N., Bonzi, L., Calabrese, L., Luciani, P., Perini, L., Severi, P., 2019. Processes governing natural land subsidence in the shallow coastal aquifer of the Ravenna coast, Italy. Catena 172, 76–86.
Autin, W.J., 1992. Use of alloformations for definition of Holocene meander belts in the middle Amite River, southeastern Louisiana. Geol. Soc. Am. Bull. 104, 233–241.
Badino, F., Pini, R., Ravazzi, C., Margaritora, D., Arrighi, S., Bortolini, E., Figus, C., Giaccio, B., Lugli, F., Marciani, G., Monegato, G., Moroni, A., Negrino, F., Oxilia, G., Peresani, M., Romandini, M., Ronchitelli, A., Spinapolice, E.E., Zerboni, A., Benazzi, S., 2020. An overview of Alpine and Mediterranean palaeogeography, terrestrial ecosystems and climate history during MIS 3 with focus on the Middle to Upper Palaeolithic transition. Quat. Int. 551, 7–28. https://doi.org/10.1016/j.quaint.2019.09.024.
Bhattacharya, J.P., 2011. Practical problems in the application of the sequence stratigraphic method and key surfaces: integrating observations from ancient fluvial–deltaic wedges with Quaternary and modelling studies. Sedimentology 58, 120–169.
Bhattacharya, J.P., Walker, R.G., 1991. Allostratigraphic subdivision of the Upper Cretaceous Dunvegan, Shaftesbury, and Kaskapau formations in the northwestern Alberta subsurface. Bull. Can. Petrol. Geol. 39, 145–164.
Bini, A., 1987. L'Apparato Glaciale Würmiano di Como. Università degli Studi di Milano, Milano. Ph.D. thesis.
Bini, A., 1997. Problems and methodologies in the study of quaternary deposits of the southern side of the Alps. Southern Alps Quaternary Geology. Geol. Insubrica 2, 11–20.
Bini, A., Bosi, C., Carraro, F., Castiglioni, G.B., 1992. Cartografia geologica del Quaternario continentale. In: Pasquarè, G., Abbate, E., Castiglioni, G.B., Merenda, L., Mutti, E., Ortolani, F., Parotto, M., Pignone, R., Polino, R., Sassi, F.P. (Eds.), Guida Al Rilevamento Della Carta geologica D'Italia Alla Scala 1:50.000. ISPRA, pp. 63–83.
Bini, A., Zuccoli, L., Bussolini, C., Da Rold, O., Corbari, D., Ferliga, C., Rossi, S., Viviani, C., 2004. Glacial history of the southern side of the central Alps, Italy. Dev. Quat. Sci. 2, 195–200.
Bini, A., Baio, M., Pavia, F., 2015. Analisi di una sezione geologica tracciata tra Adda e Mella, al margine tra alta e bassa pianura. Geol. Insubrica 11, 3–16.
Blair, T.C., McPherson, J.G., 2009. In: Parsons, A.J., Abrahams, A.D. (Eds.), Geomorphology of Desert Environments. Springer, Netherlands, Dordrecht, pp. 413–467.
Blum, M.D., Valastro, Jr.S., 1994. Late Quaternary sedimentation, lower Colorado River, Gulf Coastal Plain of Texas. Geol. Soc. Am. Bull. 106, 1002–1016.
Blum, M.D., Toomey III, R.S., Valastro Jr, S., 1994. Fluvial response to Late Quaternary climatic and environmental change, Edwards Plateau, Texas. Palaeogeogr. Palaeoclimatol. Palaeoecol. 108, 1–21.
Blum, M.D., Martin, J., Milliken, K., Garvin, M., 2013. Paleovalley systems: insights from Quaternary analogs and experiments. Earth Sci. Rev. 116, 128–169.
Boccaletti, M., Corti, G., Martelli, L., 2010. Recent and active tectonics of the external zone of the Northern Apennines (Italy). Int. J. Earth Sci. 99, 1591–1618.
Brauer, A., Allen, J.R.M., Mingram, J., Dulski, P., Wulf, S., Huntley, B., 2007. Evidence for last interglacial chronology and environmental change from Southern Europe. Proc. Natl. Acad. Sci. USA 104, 450–455. https://doi.org/10.1073/pnas.0603321104.
Bridgland, D., Westaway, R., 2008. Climatically controlled river terrace staircases: a worldwide Quaternary phenomenon. Geomorphology 98, 285–315.
Bruno, L., Amorosi, A., Severi, P., Costagli, B., 2017a. Late Quaternary aggradation rates and stratigraphic architecture of the southern Po Plain, Italy. Basin Res. 29, 234–248.
Bruno, L., Bohacs, K.M., Campo, B., Drexler, T.M., Rossi, V., Sammartino, I., Scarponi, D., Hong, W., Amorosi, A., 2017b. Early Holocene transgressive palaeogeography in the Po coastal plain (Northern Italy). Sedimentology 64, 1792–1816.
Bruno, L., Piccin, A., Sammartino, I., Amorosi, A., 2018. Decoupled geomorphic and sedimentary response of Po River and its Alpine tributaries during the last glacial/post-glacial episode. Geomorphology 317, 184–198.
Bruno, L., Amorosi, A., Lugli, S., Sammartino, I., Fontana, D., 2021. Trunk river and tributaries interactions recorded in the Pleistocene-Holocene stratigraphy of the Po Plain (northern Italy). Sedimentology 68, 2918–2943.

Bruno, L., Campo, B., Hajdas, I., Hong, W., Amorosi, A., 2022. Timing and mechanisms of sediment accumulation and pedogenesis. Insights from the Po Plain (Northern Italy). Palaeogeogr. Palaeoclimatol. Palaeoecol. 591. https://doi.org/10.1016/j.palaeo.2022.110881.

Bruno, L., Demurtas, L., Magri, D., Michelangeli, F., Rittenour, T., Hong, W., Rossi, V., Vaiani, S.C., Vecchi, A., Amorosi, A., 2024. Sedimentary response of the Po Basin to Mid-Late Pleistocene glacio-eustatic oscillations. Quat. Sci. Rev. 344, 109005. https://doi.org/10.1016/j.quascirev.2024.109005.

Busschers, F.S., Weerts, H.J.T., Wallinga, J., Cleveringa, P., Kasse, C., de Wolf, H., Cohen, K.M., 2005. Sedimentary architecture and optical dating of middle and late Pleistocene Rhine-Meuse deposits—Fluvial response to climate change, sea-level fluctuation and glaciation. Neth. J. Geosci. 84, 25–41.

Busschers, F.S., Kasse, C., van Balen, R.T., Vandenberghe, J., Cohen, K.M., Weerts, H.J.T., Wallinga, J., Johns, C., Cleveringa, P., Bunnik, F.P.M., 2007. Late Pleistocene evolution of the Rhine-Meuse system in the southern North Sea basin: imprints of climate change, sea-level oscillation and glacio-isostacy. Quat. Sci. Rev. 26, 3216–3248.

Campo, B., Amorosi, A., Bruno, L., 2016. Contrasting alluvial architecture of Late Pleistocene and Holocene deposits along a 120-km transect from the central Po Plain (northern Italy). Sediment. Geol. 341, 265–275.

Campo, B., Amorosi, A., Vaiani, S.C., 2017. Sequence stratigraphy and late Quaternary paleoenvironmental evolution of the Northern Adriatic coastal plain (Italy). Palaeogeogr. Palaeoclimatol. Palaeoecol. 466, 265–278.

Campo, B., Bruno, L., Amorosi, A., 2020. Basin-scale stratigraphic correlation of Late Pleistocene-Holocene (MIS 5e-MIS 1) strata across the rapidly subsiding Po Basin (northern Italy). Quat. Sci. Rev. 237. https://doi.org/10.1016/j.quascirev.2020.106300.

Campo, B., Bruno, L., Amorosi, A., 2023. Sedimentary facies characterization through CPTU profiles: an effective tool for subsurface investigation of modern alluvial and coastal plains. Sedimentology 70, 1302–1327. https://doi.org/10.1111/sed.13079.

Carminati, E., Doglioni, C., 2012. Alps vs. Apennines: the paradigm of a tectonically asymmetric Earth. Earth Sci. Rev. 112, 67–96. https://doi.org/10.1016/j.earscirev.2012.02.004.

Carminati, E., Doglioni, C., Scrocca, D., 2003. Apennines subduction-related subsidence of Venice (Italy). Geophys. Res. Lett. 30, 50–51.

Carrión, J.S., Ochando, J., Michelangeli, F., Jiménez-Espejo, F., Ojeda, F., Amorós, G., Munuera, M., Marín-Arroyo, A.B., González-Sampériz, P., Rodríguez-Vidal, J., Di Rita, F., Magri, D., 2024. Tracing 40,000 years of vegetation change in the Baetic-Rifan biodiversity hotspot. Rev. Palaeobot. Palynol., 105202 https://doi.org/10.1016/j.revpalbo.2024.105202.

Catuneanu, O., Abreu, V., Bhattacharya, J.P., Blum, M.D., Dalrymple, R.W., Eriksson, P.G., Fielding, C.R., Fisher, W.L., Galloway, W.E., Gibling, M.R., Giles, K.A., Holbrook, J.M., Jordan, R., Kendall, C.G.St.C., Macurda, B., Martinsen, O.J., Miall, A.D., Neal, J.E., Nummedal, D., Pomar, L., Posamentier, H.W., Pratt, B.R., Sarg, J.F., Shanley, K.W., Steel, R.J., Strasser, A., Tucker, M.E., Winker, C., 2009. Towards the standardization of sequence stratigraphy. Earth Sci. Rev. 92, 1–33.

Chang, K.H., 1975. Unconformity-bounded stratigraphic units. Geol. Soc. Am. Bull. 86, 1544–1552.

Chiarini, E., D'Orefice, M., Graciotti, R., 2008. Le unità stratigrafiche di riferimento nella rappresentazione cartografica dei depositi plio-quaternari continentali nel Progetto CARG – Esempi: Arco Alpino, Pianura Padana e Sardegna. Il Quat. 21, 51–56.

Counts, R.C., Murari, M.K., Owen, L.A., Mahan, S.A., Greenan, M., 2015. Late Quaternary chronostratigraphic framework of terraces and alluvium along the lower Ohio River, southwestern Indiana and western Kentucky, USA. Quat. Sci. Rev. 110, 72–91.

Cremaschi, M., 1987. Paleosols and Vetusols in the Central Po Plain (Northern Italy): a Study in Quaternary Geology and Soil Development, 28. Unicopli.

Cremaschi, M., 2004. Late Pleistocene loess. In: Explanatory Notes of the Litho-Palaeoenvironmental Maps of Italy During the Last Two Climatic Extremes, 15. Museo Capellini, Bologna, pp. 361–368.

Cremaschi, M., Rodolfi, G., 1991. Il Suolo – Pedologia Nelle Scienze della Terra e Nella Valutazione del Territorio. La Nuova Italia Scientifica, Roma.

Cremaschi, M., Zerboni, A., Nicosia, C., Negrino, F., Rodnight, H., Spötl, C., 2015. Age, soil-forming processes, and archaeology of the loess deposits at the Apennine margin of the Po plain (northern Italy): new insights from the Ghiardo area. Quat. Int. 376, 173–188.

Curray, J.R., Moore, D.G., 1964. Pleistocene deltaic progradation of continental terrace, Costa de Nayarit, Mexico. In: Van Straaten, L.M.J.U. (Ed.), Deltaic and Shallow Marine Deposits. Elsevier, Amsterdam, pp. 193–215.

D'Ambrogi, C., Maesano, F.E., Marino, M., Congi, M.P., Morrone, S., 2023. Geological 3D model of the Po Basin. https://doi.org/10.15161/OAR.IT/76873.

Demarest, J.M., Kraft, J.C., 1987. Stratigraphic record of Quaternary sea levels: implications for more ancient strata. In: Nummedal, D., Piikey, O.H., Howard, J.D. (Eds.), Sea-Level Fluctuations and Coastal Evolution, 41. SEPM Special Publication, pp. 223–239.

Desio, A., 1965. I rilievi isolati della Pianura Lombarda ed i movimenti tettonici del Quaternario. Rend. Ist. Lomb. Acc. Sci. Lett., Sez. A 99, 881–894.

Doglioni, C., 1993. Some remarks on the origin of foredeeps. Tectonophysics 228, 1–20.

Donders, T., Panagiotopoulos, K., Koutsodendris, A., Bertini, A., Mercuri, A.M., Masi, A., Combourieu-Nebout, N., Joannin, S., Kouli, K., Kousis, I., Peyron, O., Torri, P., Florenzano, A., Francke, A., Wagner, B., Sadori, L., 2021. 1.36 million years of Mediterranean forest refugium dynamics in response to glacial–interglacial cycle strength. Proc. Natl. Acad. Sci. USA 118, e2026111118. https://doi.org/10.1073/pnas.2026111118.

Donnici, S., Serandrei-Barbero, R., Bini, C., Bonardi, M., Lezziero, A., 2011. The caranto paleosol and its role in the early urbanization of Venice. Geoarchaeology 26, 514–543.

D'Orefice, M., 2009. Gli Elementi Innovativi nell'ambito Della Cartografia Geologica del Quaternario (Progetto CARG), 88. Memorie Descrittive della Carta Geologica d'Italia, pp. 89–94.

Embry, A.F., Johannessen, E.P., 1992. T-R sequence stratigraphy, facies analysis and reservoir distribution in the uppermost Triassic-Lower Jurassic succession, western Sverdrup Basin, Arctic Canada. In: Vorren, T.O., et al. (Eds.), Arctic Geology and Petroleum Potential. Proceedings of the Norwegian Petroleum Society Conference, 2. Norwegian Petroleum Society. Special Publication, Trondheim, pp. 121–146.

Fantoni, R., Franciosi, R., 2010. Tectono-sedimentary setting of the Po Plain and Adriatic foreland. Rendiconti Lincei 21, 197–209.

Feng, S., Tan, C., Plink-Björklund, P., Shan, X., Li, S., Li, S., Yu, X., Chen, L., Ji, H., 2025. Sedimentary response to glacial-interglacial cycles in an alluvial fan at the marginal East Asian monsoon zone, northern China. Sedimentology 72, 1375–1401.

Ferranti, L., Antonioli, F., Mauz, B., Amorosi, A., Dai Prà, G., Mastronuzzi, G., Monaco, C., Orrù, P., Pappalardo, M., Radtke, U., Renda, P., Romano, P., Sansò, P., Verrubbi, V., 2006. Markers of the last interglacial sea-level high stand along the coast of Italy: tectonic implications. Quat. Int. 145–146, 30–54.

Fielding, C.R., Frank, T.D., Birgenheier, L.P., Rygel, M.C., Jones, A.T., Roberts, J., 2008. Stratigraphic imprint of the Late Palaeozoic Ice Age in eastern Australia: a record of alternating glacial and nonglacial climate regime. J. Geol. Soc. 165, 129–140.

Fjeldskaar, W., Amantov, A., 2018. Effects of glaciations on sedimentary basins. J. Geodyn. 118, 66–81.

Fletcher, W.J., Sánchez Goñi, M.F., 2008. Orbital- and sub-orbital-scale climate impacts on vegetation of the western Mediterranean basin over the last 48,000 yr. Quat. Res. 70, 451–464. https://doi.org/10.1016/j.yqres.2008.07.002.

Fletcher, W.J., Müller, U.C., Koutsodendris, A., Christanis, K., Pross, J., 2013. A centennial-scale record of vegetation and climate variability from 312 to 240 ka (Marine Isotope Stages 9c–a, 8 and 7e) from Tenaghi Philippon, NE Greece. Quat. Sci. Rev. 78, 108–125. https://doi.org/10.1016/j.quascirev.2013.08.005.

Follieri, M., Magri, D., Sadori, L., 1986. Late Pleistocene zelkova extinction in central Italy. New Phytol. 103, 269–273.

Follieri, M., Magri, D., Sadori, L., 1988. A 250 000-years pollen record from Valle di Castiglione (Roma). Pollen Spores 30, 329–356.

Fontana, A., Mozzi, P., Bondesan, A., 2008. Alluvial megafans in the Venetian-Friulian Plain (north-eastern Italy): evidence of sedimentary and erosive phases during Late Pleistocene and Holocene. Quat. Int. 189, 71–90.

Fontana, A., Mozzi, P., Marchetti, M., 2014. Alluvial fans and megafans along the southern side of the Alps. Sediment. Geol. 301, 150–171.

Frazier, D.E., 1974. Depositional-Episodes: Their Relationship to the Quaternary Stratigraphic Framework in the Northwestern Portion of the Gulf Basin, 74. University of Texas Austin Bureau of Economic Geology Geological Circular, pp. 1–28.

Galluzzo, F., Cacciuni, A., Chiarini, E., D'Orefice, M., Falcetti, S., Graciotti, R., La Posta, E., Papasodaro, F., Ricci, V., Vita, L., 2009. Carta geologica d'Italia–1:50.000 - Progetto Carg: Modifiche Ed Integrazioni Al Quaderno n. 1/1992, 12. Quaderni del Servizio Geologico d'Italia ser. III, pp. 1–54.

Garzanti, E., Vezzoli, G., Andò, S., 2011. Paleogeographic and paleodrainage changes during Pleistocene glaciations (Po Plain, Northern Italy). Earth Sci. Rev. 105, 25–48.

Germani, D., Angiolini, L., 2003. Guida Italiana alla Classificazione e alla Terminologia Stratigrafica. Quaderni del Servizio Geologico d'Italia ser. III (9), 1–155.

Ghielmi, M., Minervini, M., Nini, C., Rogledi, S., Rossi, M., Vignolo, A., 2010. Sedimentary and tectonic evolution in the eastern Po Plain and northern Adriatic Sea area from Messinian to Middle Pleistocene (Italy). Rendiconti Fis. Accademia dei Lincei 21, 131–166.

Ghielmi, M., Minervini, M., Nini, C., Rogledi, S., Rossi, M., 2013. Late Miocene–Middle Pleistocene sequences in the Po Plain–Northern Adriatic Sea (Italy): the stratigraphic record of modification phases affecting a complex foreland basin. Mar. Petrol. Geol. 42, 50–81.

Giardini, M., 2007. Late Quaternary vegetation history at Stracciacappa (Rome, central Italy). Veg. Hist. Archaeobotany 16, 301–316. https://doi.org/10.1007/s00334-006-0037-y.

Gibbard, P.L., Lewin, J., 2016. Partitioning the quaternary. Quat. Sci. Rev. 151, 127–139.

Gibling, M.R., Tandon, S.K., Sinha, R., Jain, M., 2005. Discontinuity-bounded alluvial sequences of the southern Gangetic Plains, India: aggradation and degradation in response to monsoonal strength. J. Sediment. Res. 75, 369–385.

Gibling, M.R., Fielding, C.R., Sinha, R., 2011. Alluvial valleys and alluvial sequences: towards a geomorphic assessment. In: Davidson, S.K., Leleu, S., North, C.P. (Eds.), From River to Rock Record: the Preservation of Fluvial Sediments and Their Subsequent Interpretation, 97. SEPM Special Publication, pp. 423–447.

Guido, M.A., Molinari, C., Moneta, V., Branch, N., Black, S., Simmonds, M., Stastney, P., Montanari, C., 2020. Climate and vegetation dynamics of the Northern Apennines (Italy) during the Late Pleistocene and Holocene. Quat. Sci. Rev. 231.

Gunderson, K.L., Pazzaglia, F.J., Picotti, V., Anastasio, D.A., Kodama, K.P., Rittenour, T., Frankel, K.F., Ponza, A., Berti, C., Negri, A., Sabbatini, A., 2014. Unraveling tectonic and climatic controls on synorogenic growth strata (Northern Apennines, Italy). Geol. Soc. Am. Bull. 126, 532–552. https://doi.org/10.1130/B30902.1.

Heinrich, P.V., 2006. Pleistocene and Holocene fluvial systems of the lower Pearl River, Mississippi and Louisiana, USA. Gulf Coast Association of Geological Societies Transactions 56, 267–278.

Hijma, M.P., Cohen, K.M., 2011. Holocene transgression of the Rhine river mouth area, the Netherlands/Southern North Sea: palaeogeography and sequence stratigraphy. Sedimentology 58, 1453–1485.

Hodder, T.J., Gauthier, M.S., Ross, M., Kelley, S.E., Lian, O.B., Dalton, A.S., Finkelstein, S.A., 2024. Unravelling the fragmented sediment–landform assemblage in an area of thick Quaternary sediment, western Hudson Bay Lowland, Canada. Can. J. Earth Sci. 61, 1156–1183.

Houben, P., Hoinkis, R., Santisteban, J.I., Salat, C., Mediavilla, R., 2011. Combining allostratigraphic and lithostratigraphic perspectives to compile subregional records of fluvial responsiveness: the case of the sustainably entrenching Palancia River watershed (Mediterranean coast, NE Spain). Geomorphology 129, 342–360.
Huckleberry, G., Onken, J., Graves, W.M., Wegener, R., 2013. Climatic, geomorphic, and archaeological implications of a late Quaternary alluvial chronology for the lower Salt River, Arizona, USA. Geomorphology 185, 39–53.
Hughes, P.D., 2010. Geomorphology and Quaternary stratigraphy: the roles of morpho-, litho-, and allostratigraphy. Geomorphology 123, 189–199.
Hughes, P.D., Gibbard, P.L., Ehlers, J., 2020. The "missing glaciations" of the middle Pleistocene. Quat. Res. 96, 161–183. https://doi.org/10.1017/qua.2019.76.
Hunt, D., Tucker, M.E., 1992. Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall. Sediment. Geol. 81, 1–9.
ISPRA, 2015. Modello Geologico 3D e Geopotenziali Della Pianura Padana Centrale (Progetto GeoMol), 234/2015. Rapporti ISPRA, p. 104 e Appendice.
Kent, D.V., Rio, D., Massari, F., Kukla, G., Lanci, L., 2002. Emergence of Venice during the Pleistocene. Quat. Sci. Rev. 21, 1719–1727.
Krumbein, W.C., Sloss, L.L., 1951. Stratigraphy and sedimentation. Soil Sci. 71, 1–401.
Labourdette, R., Jones, R.R., 2007. Characterization of fluvial architectural elements using a three-dimensional outcrop data set: escanilla braided system, southcentral Pyrenees, Spain. Geosphere 3, 422–434.
Lamothe, M., 2016. Luminescence dating of interglacial coastal depositional systems: recent developments and future avenues of research. Quat. Sci. Rev. 146, 1–27.
Legarreta, L., Uliana, M.A., 1998. Anatomy of hinterland depositional sequences: upper Cretaceous fluvial strata, Neuquen Basin, West-Central Argentina. In: Shanley, K.W., McCabe, P.J. (Eds.), Relative Role of Eustasy, Climate, and Tectonism in Continental Rocks, 59. SEPM Spec. Publ., pp. 83–92
Lehmkuhl, F., Nett, J.J., Pötter, S., Schulte, P., Sprafke, T., Jary, Z., Antoine, P., Wacha, L., Wolf, D., Zerboni, A., Hošek, J., Marković, S.B., Obreht, I., Sümegi, P., Vere, D., Boemke, Z.C., Schaubert, B.V., Viehweger, J., Hambach, U., 2021. Loess landscapes of Europe – mapping, geomorphology and zonal differentiation. Earth Sci. Rev. 215, 103496. https://doi.org/10.1016/j.earscirev.2020.103496.
Leighton, C.L., Thomas, D.S., Bailey, R.M., 2013. Allostratigraphy and Quaternary dune sediments: not all bounding surfaces are the same. Aeolian Research 11, 55–60.
Lisiecki, L.E., Raymo, M.E., 2005. A pliocene-pleistocene stack of 57 globally distributed benthic δ18O records. Paleoceanography 20. https://doi.org/10.1029/2004PA001071PA1003.
Livani, M., Scrocca, D., Arecco, P., Doglioni, C., 2018. Structural and stratigraphic control on salient and recess development along a thrust belt front: the Northern Apennines (Po Plain, Italy). J. Geophys. Res. Solid Earth 123, 4360–4387.
Livio, F.A., Berlusconi, A., Michetti, A.M., Sileo, G., Zerboni, A., Trombino, L., Cremaschi, M., Mueller, K., Vittori, E., Carcano, C., Rogledi, S., 2009. Active fault-related folding in the epicentral area of the December 25, 1222 (Io = IX MCS) Brescia earthquake (Northern Italy): seismotectonic implications. Tectonophysics 476, 320–335.
Livio, F., Berlusconi, A., Zerboni, A., Trombino, L., Sileo, G., Michetti, A.M., Rodnight, H., Spötl, C., 2014a. Progressive offset and surface deformation along a seismogenic blind thrust in the Po Plain foredeep (Southern Alps, Northern Italy). J. Geophys. Res. Solid Earth 119, 7701–7721.
Livio, F., Michetti, A.M., Ticozzi, E., Porfido, S., 2014b. The ESI Macroseismic Field for the 1624 AD Argenta Earthquake (Po Plain – N Italy): an Integrated Macroseismic Approach to Overcome MCS Misfitting, 31. Rendiconti Online della Società Geologica Italiana. https://doi.org/10.3301/ROL.2014.140.
Lucchi, F., 2019. On the use of unconformities in volcanic stratigraphy and mapping: insights from the Aeolian Islands (southern Italy). J. Volcanol. Geoth. Res. 385, 3–26.
Mack, G.H., Leeder, M.R., 1999. Climatic and tectonic controls on alluvial-fan and axial-fluvial sedimentation in the Plio-Pleistocene Palomas half graben, southern Rio Grande Rift. J. Sediment. Res. 69, 635–652.
Macklin, M.G., Fuller, I.C., Lewin, J., Maas, G.S., Passmore, D.G., Rose, J., Woodward, J. C., Black, S., Hamlin, R.H.B., Rowan, J.S., 2002. Correlation of fluvial sequences in the Mediterranean basin over the last 200 ka and their relationship to climate change. Quat. Sci. Rev. 21, 1633–1641.
Maesano, F.E., D'Ambrogi, C., 2016. Coupling sedimentation and tectonic control: pleistocene evolution of the Central Po Basin. Italian Journal of Geosciences 135, 394–407. https://doi.org/10.3301/IJG.2015.17.
Maesano, F.E., D'Ambrogi, C., Burrato, P., Toscani, G., 2015. Slip-rates of blind thrusts in slow deforming areas: examples from the Po Plain (Italy). Tectonophysics 643, 8–25.
Maesano, F.E., Zuffetti, C., Abbate, A., D'Ambrogi, C., Bersezio, R., 2024. Quaternary slip-rates probabilistic estimation for the Northern Apennines frontal thrust in the Po Plain (Northern Italy) by integrating surface and subsurface data. Tectonophysics 873, 230227.
Magri, D., 1999. Late Quaternary vegetation history at Lagaccione near Lago di Bolsena (central Italy). Rev. Palaeobot. Palynol. 106, 171–208.
Magri, D., Sadori, L., 1999. Late Pleistocene and Holocene pollen stratigraphy at Lago di Vico, central Italy. Veg. Hist. Archaeobotany 8, 247–260.
Magri, D., Di Rita, F., Aranbarri, J., Fletcher, W., González-Sampériz, P., 2017. Quaternary disappearance of tree taxa from Southern Europe: timing and trends. Quat. Sci. Rev. 163, 23–55.
Malinverno, A., Ryan, W.B.F., 1986. Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking of the litosphere. Tectonics 5, 227–245.
Mancini, E.A., Puckett, T.M., 2002. Transgressive-regressive cycles in Lower Cretaceous strata, Mississippi Interior Salt Basin area of the northeastern Gulf of Mexico, USA. Cretac. Res. 23, 409–438.
Marcolla, A., Miola, A., Mozzi, P., Monegato, G., Asioli, A., Pini, R., Stefani, C., 2021. Middle Pleistocene to Holocene palaeoenvironmental evolution of the south-eastern Alpine foreland basin from multi-proxyanalysis. Quat. Sci. Rev. 259, 106908. https://doi.org/10.1016/j.quascirev.2021.106908.
Martelli, L., Bonini, M., Calabrese, L., Corti, G., Ercolessi, G., Molinari, F.C., Piccardi, L., Pondrelli, S., Sani, F., Severi, P., 2017. Seismotectonic Map of Emilia Romagna Region and Surrounding Areas to Scale 1:250.000. D.R.E.Am. MAP, Pistoia, Italy.
Martinson, D.G., Pisias, N.G., Hayes, J.D., Imbrie, J., Moore, T.C., Shackleton, N.J., 1987. Age dating and the orbital theory of the ice ages - development of a high-resolution 0 to 300,000 year chronostratigraphy. Quat. Res. 27, 1–29.
Maslin, M.A., Brierley, C.M., 2015. The role of orbital forcing in the Early Middle Pleistocene Transition. Quat. Int. 389, 47–55.
Massari, F., Rio, D., Barbero, R.S., Asioli, A., Capraro, L., Fornaciari, E., Vergerio, P.P., 2004. The environment of Venice area in the past two million years. Palaeogeogr. Palaeoclimatol. Palaeoecol. 202, 273–308.
Miall, A.D., 1985. Architectural-element analysis: a new method of facies analysis applied to fluvial deposits. Earth Sci. Rev. 22, 261–308.
Miall, A.D., 1997. The Geology of Stratigraphic Sequences, first ed. Springer-Verlag, Berlin, p. 433p.
Michelangeli, F., Di Rita, F., Lirer, F., Lubritto, C., Bellucci, L.G., Cascella, A., Bonomo, S., Margaritelli, G., Magri, D., 2022a. Vegetation history of SE Sicily from feudal land management to post-war agricultural industrialization. Rev. Palaeobot. Palynol. 296, 104547. https://doi.org/10.1016/j.revpalbo.2021.104547.
Michelangeli, F., Di Rita, F.D., Celant, A., Tisnérat-Laborde, N., Lirer, F., Magri, D., 2022b. Three millennia of vegetation, land-use and climate change in SE Sicily. Forests 13, 102. https://doi.org/10.3390/f13010102.
Milana, J.P., Tietze, K.W., 2007. Limitations of sequence stratigraphic correlation between marine and continental deposits: a 3D experimental study of unconformity-bounded units. Sedimentology 54, 293–316.
Mitchum, Jr. R.M., Vail, P.R., Thompson III, S., 1977. The depositional sequence as a basic unit for stratigraphic analysis. In: Payton, C.E. (Ed.), Seismic Stratigraphy-Applications to Hydrocarbon Exploration, 26. AAPG Memoir, pp. 53–62.
Monegato, G., Ravazzi, C., Donegana, M., Pini, R., Calderoni, G., Wick, L., 2017a. Evidence of a two-fold glacial advance during the last glacial maximum in the Tagliamento end moraine system (eastern Alps). Quat. Res. 68, 284–302.
Monegato, G., Scardia, G., Hajdas, I., Rizzini, F., Piccin, A., 2017b. The Alpine LGM in the boreal ice-sheets game. Sci. Rep. 7, 2078.
Monegato, G., Gianotti, F., Ivy-Ochs, S., Reitner, J.M., Scardia, G., Akçar, N., 2023. The early and Middle Pleistocene glaciations in the Alps. Alpine and Mediterranean Quaternary 36, 1–22.
Mozzi, P., Bini, C., Zilocchi, L., Becattini, R., Mariotti Lippi, M., 2003. Stratigraphy, palaeopedology and paynology of Late Pleistocene and Holocene deposits in the landward sector of the lagoon of Venice (Italy), in relation to the Caranto Level. Il Quat. 16, 197–214.
Muhs, D.R., Bettis III, E.A., 2003. Quaternary loess-paleosol sequences as examples of climate-driven sedimentary extremes. In: Chan, M.A., Archer, A.W. (Eds.), Extreme Depositional Environments, Mega End Members in Geologic Time, 370. Geological Society of America Special Paper, Boulder, Colorado, pp. 53–74.
Muttoni, G., Carcano, C., Garzanti, E., Ghielmi, M., Piccin, A., Pini, R., Rogledi, S., Sciunnach, D., 2003. Onset of major Pleistocene glaciations in the Alps. Geology 31, 989–992. https://doi.org/10.1130/G19445.1.
North American Commission on Stratigraphic Nomenclature, 2005. North American stratigraphic code. AAPG (Am. Assoc. Pet. Geol.) Bull. 89, 1547–1591.
Novellino, M.D., Fontana, A., Bertuletti, P., Furlanetto, G., Pini, R., Felja, I., Juračić, M., Ravazzi, C., 2025. Vegetation and climate history during the Last Interglacial on the Istrian coast (Northern Adriatic Sea). Palaeogeogr. Palaeoclimatol. Palaeoecol. 659, 112671. https://doi.org/10.1016/j.palaeo.2024.112671.
Ojala, A.E., Saresma, M., Virtasalo, J.J., Huotari-Halkosaari, T., 2018. An allostratigraphic approach to subdivide fine-grained sediments for urban planning. Bull. Eng. Geol. Environ. 77, 879–892.
Oomkens, E., 1970. Depositional sequences and sand distribution in the postglacial Rhone delta complex. In: Morgan, J.P. (Ed.), Deltaic Sedimentation, Modern and Ancient, 15. SEPM Special Publication, pp. 198–212.
Orain, R., Lebreton, V., Ermolli, E.R., Combourieu-Nebout, N., Sémah, A.M., 2013. Carya as marker for tree refuges in southern Italy (Boiano basin) at the Middle Pleistocene. Palaeogeogr. Palaeoclimatol. Palaeoecol. 369, 295–302.
Ori, G.G., 1993. Continental depositional systems of the Quaternary of the Po Plain (northern Italy). Sediment. Geol. 83, 1–14.
Ori, G.G., Friend, P.F., 1984. Sedimentary basins formed and carried piggyback on active thrust sheets. Geology 12, 475–478.
Pasquarè, G., Abate, E., Bosi, C., Castiglioni, G.B., Merenda, L., Mutti, E., Orombelli, G., Ortolani, F., Parotto, M., Pignone, R., Premoli Silva, I., Sassi, F.P., 1992. Carta Geologica d'Italia-1:50.000 - guida al rilevamento. Quaderni del Servizio Geologico d'Italia ser. III (1), 1–203.
Peeters, J., Busschers, F.S., Stouthamer, E., Bosch, J.H.A., Van den Berg, M.W., Wallinga, J., Versendaal, A.J., Bunnik, F.P.M., Middelkoop, H., 2016. Sedimentary architecture and chronostratigraphy of a late Quaternary incised-valley fill: a case study of the late Middle and Late Pleistocene Rhine system in the Netherlands. Quat. Sci. Rev. 131, 211–236.
Perini, S., Muttoni, G., Livio, F., Zucali, M., Michetti, A.M., Zerboni, A., 2023. High-resolution magnetochronology detects multiple stages of Pleistocene tectonic uplift and deformation in the Po Plain of northern Italy. Quat. Res. 113, 191–205.
Picotti, V., Pazzaglia, F.J., 2008. A new active tectonic model for the construction of the Northern Apennines mountain front near Bologna (Italy). J. Geophys. Res. 113, B08412.

Pieri, M., Groppi, G., 1981. Subsurface geological structure of the Po Plain (Italy): C.N.R. Progetto. Finalizzato Geodinamica 414, 1–13.
Pini, R., Ravazzi, C., Donegana, M., 2009. Pollen stratigraphy, vegetation and climate history of the last 215ka in the Azzano Decimo core (plain of Friuli, north-eastern Italy). Quat. Sci. Rev. 28, 1268–1290.
Pini, R., Ravazzi, C., Reimer, P.J., 2010. The vegetation and climate history of the last glacial cycle in a new pollen record from Lake Fimon (southern Alpine foreland, N-Italy). Quat. Sci. Rev. 29, 3115–3137.
Plink-Björklund, P., 2005. Stacked fluvial and tide-dominated estuarine deposits in high-frequency (fourth-order) sequences of the Eocene Central Basin, Spitsbergen. Sedimentology 52, 391–428.
Plint, A.G., Nummedal, D., 2000. The falling stage systems tract: recognition and importance in sequence stratigraphic analysis. In: Gawthorpe, R.L., Hunt, D. (Eds.), Sedimentary Responses to Forced Regressions, 172. Geological Society of London Special Publications, pp. 1–17.
Posamentier, H.W., Jervey, M.T., Vail, P.R., 1988. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (Eds.), Sea-level changes: An integrated approach, 42. SEPM Special Publication, pp. 109–124.
Posamentier, H.W., Vail, P.R., 1988. Eustatic controls on clastic deposition II — sequence and Systems Tract models. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.S.C., Posamentier, H.W., Ross, C.A., C Van Wagoner, J. (Eds.), Sea Level Changes: an Integrated Approach, 42. SEPM Special Publication, pp. 125–154.
Räsänen, M.E., Auri, J., Huitti, J., Klap, A., Virtasalo, J.J., 2009. A shift from lithostratigraphic to allostratigraphic classification of Quaternary glacial deposits. GSA Today (Geol. Soc. Am.) 19, 4–11.
Regione Emilia-Romagna, ENI-AGIP, 1998. Riserve Idriche Sotterranee Della Regione Emilia-Romagna. S.EL.CA, Florence.
Regione Lombardia, ENI-Divisione AGIP, 2002. Riserve Idriche Sotterranee Della Regione Lombardia. S.EL.CA, Florence.
Reille, M., Andrieu, V., De Beaulieu, J.-L., Guenet, P., Goeury, C., 1998. A long pollen record from Lac du Bouchet, Massif Central, France: for the period ca. 325 to 100 ka BP (OIS 9c to OIS 5e). Quat. Sci. Rev. 17, 1107–1123. https://doi.org/10.1016/S0277-3791(97)00093-0.
Reille, M., Beaulieu, J.-L.D., Svobodova, H., Andrieu-Ponel, V., Goeury, C., 2000. Pollen analytical biostratigraphy of the last five climatic cycles from a long continental sequence from the Velay region (Massif Central, France). J. Quat. Sci. 15, 665–685. https://doi.org/10.1002/1099-1417(200010)15:7<665::AID-JQS560>3.0.CO;2-G.
Rhee, C.W., Jo, H.R., Chough, S.K., 1998. An allostratigraphic approach to a non-marine basin: the north-western part of Cretaceous Kyongsang Basin, SE Korea. Sedimentology 45, 449–472. https://doi.org/10.1046/j.1365-3091.1998.00180.x.
Ricci Lucchi, F., 1986. Oligocene to recent foreland basins of northern Apennines. In: Allen, P., Homewood, P. (Eds.), Foreland Basins, 8. International Association of Sedimentologists Special Publication, pp. 105–139.
Rijsdijk, K.F., Passchier, S., Weerts, H.J.T., Laban, C., Van Leeuwen, R.J.W., Ebbing, J.H. J., 2005. Revised Upper Cenozoic stratigraphy of the Dutch sector of the North Sea Basin: towards an integrated lithostratigraphic, seismostratigraphic and allostratigraphic approach. Neth. J. Geosci. 84, 129–146.
Rittenour, T.M., Blum, M.D., Goble, R.J., 2007. Fluvial evolution of the lower Mississippi River valley during the last 100 ky glacial cycle: response to glaciation and sea-level change. Geol. Soc. Am. Bull. 119, 586–608.
Rizzini, A., 1974. Holocene sedimentary cycle and heavy mineral distribution, Romagna-Marche coastal plain, Italy. Sediment. Geol. 11, 17–37.
Roberts, C.A., Zanchetta, G., Giaccio, B., Nomade, S., Mannella, G., Sadori, L., Drysdale, R., Maslin, M.A., Albert, P.G., Smidt, C., Smith, V.C., Flynn, M., Sottili, G., Wagner, B., Tzedakis, P.C., 2025. A radiometrically-constrained reference record of Last Interglacial climate and vegetation changes from the Fucino Basin, Central Italy. Quat. Sci. Rev. 363, 109377. https://doi.org/10.1016/j.quascirev.2025.109377.
Rohling, E.J., Grant, K., Bolshaw, M., Roberts, A.P., Siddall, M., Hemleben, C., Kucera, M., 2009. Antarctic temperature and global sea level closely coupled over the past five glacial cycles. Nat. Geosci. 2, 500–504.
Rohling, E.J., Foster, G.L., Grant, K.M., Marino, G., Roberts, A.P., Tamisiea, M.E., Williams, F., 2014. Sea-level and deep-sea-temperature variability over the past 5.3 million years. Nature 508, 477–482.
Roucoux, K.H., Tzedakis, P.C., Lawson, I.T., Margari, V., 2011. Vegetation history of the penultimate glacial period (Marine isotope stage 6) at Ioannina, north-west Greece. J. Quat. Sci. 26, 616–626. https://doi.org/10.1002/jqs.1483.
Royden, L., Patacca, E., Scandone, P., 1987. Segmentation and configuration of subducted lithosphere in Italy: an important control on thrust-belt and foredeep-basin evolution. Geology 15, 714–717.
Salvador, A. (Ed.), 1994. International Stratigraphic Guide: a Guide to Stratigraphic Classification, Terminology, and Procedure. Geological Society of America. No. 30.
Scarciglia, F., Sauer, D., Zerboni, A., 2023. Pleistocene paleosols of Italy: pedostratigraphy, genesis, paleoclimate and geoarchaeology. Alpine and Mediterranean Quaternary 36, 1–35. https://doi.org/10.26382/AMQ.2023.06.
Scardia, G., Muttoni, G., Sciunnach, D., 2006. Subsurface magnetostratigraphy of Pleistocene sediments from the Po Plain (Italy): constraints on rates of sedimentation and rock uplift. Geol. Soc. Am. Bull. 118, 1299–1312.
Scardia, G., De Franco, R., Muttoni, G., Rogledi, S., Caielli, G., Carcano, C., Piccin, A., 2012. Stratigraphic evidence of a Middle Pleistocene climate driven flexural uplift in the Alps. Tectonics 31. https://doi.org/10.1029/2012TC003108. TC6004.
Scardia, G., Festa, A., Monegato, G., Pini, R., Rogledi, S., Tremolada, F., Galadini, F., 2015. Evidence for late Alpine tectonics in the Lake Garda area (northern Italy) and seismogenic implications. Geol. Soc. Am. Bull. 127, 113–130.
Scrocca, D., Carminati, E., Doglioni, C., Marcantoni, D., 2007. Slab retreat and active shortening along the central-northern Apennines. In: Lacombe, O., Lavé, J., Roure, F., Vergés, J. (Eds.), Thrust Belts and Foreland Basins. from Fold Kinematics to Hydrocarbon Systems. Springer Verlag, Berlin, Heidelberg, Germany, pp. 471–487.
Servizio Geologico d'Italia, 2002. Carta geologica D'Italia 1:50.000, F. 223 "Ravenna. Presidenza del Consiglio dei Ministri, Roma. https://doi.org/10.15161/oar.it/185918.
Servizio Geologico d'Italia, 2003a. Carta geologica D'Italia 1:50.000, F. 157 "Trino". APAT, Roma. https://doi.org/10.15161/oar.it/143633.
Servizio Geologico d'Italia, 2003b. Carta geologica D'Italia 1:50.000, F. 237 "Sasso Marconi". APAT, Roma. https://doi.org/10.15161/oar.it/188878.
Servizio Geologico d'Italia, 2004. Carta geologica D'Italia 1:50.000, F. 219 "Sassuolo". APAT, Roma. https://doi.org/10.15161/oar.it/85568.
Servizio Geologico d'Italia, 2005a. Carta geologica D'Italia alla Scala 1:50.000, F. 240-241 "Forlì-Cervia". APAT, Roma. https://doi.org/10.15161/oar.it/203468.
Servizio Geologico d'Italia, 2005b. Carta geologica D'Italia Alla Scala 1:50.000, F. 256 "Rimini". APAT, Roma. https://doi.org/10.15161/oar.it/203860.
Servizio Geologico d'Italia, 2005c. Carta geologica D'Italia Alla Scala 1:50.000, F. 179 "Ponte Dell'Olio. APAT, Roma. https://doi.org/10.15161/oar.it/149190.
Servizio Geologico d'Italia, 2005d. Carta geologica D'Italia Alla Scala 1:50.000, F. 199 "Parma Sud. APAT, Roma. https://doi.org/10.15161/oar.it/150114.
Servizio Geologico d'Italia, 2007a. Carta geologica D'Italia Alla Scala 1:50.000, F. 128 "Venezia". APAT, Roma. https://doi.org/10.15161/oar.it/211694.
Servizio Geologico d'Italia, 2007b. Carta geologica D'Italia Alla Scala 1:50.000, F. 148-149 "Chioggia-Malamocco". APAT, Roma. https://doi.org/10.15161/oar.it/211700.
Servizio Geologico d'Italia, 2008a. Carta geologica D'Italia Alla Scala 1:50.000, F. 086 "San Vito Al Tagliamento. APAT, Roma. https://doi.org/10.15161/oar.it/211690.
Servizio Geologico d'Italia, 2008b. Carta geologica D'Italia Alla Scala 1:50.000, F. 204 "Portomaggiore". APAT, Roma. https://doi.org/10.15161/oar.it/74469.
Servizio Geologico d'Italia, 2008c. Carta geologica D'Italia Alla Scala 1:50.000, F. 255 "Cesena". APAT, Roma. https://doi.org/10.15161/oar.it/203744.
Servizio Geologico d'Italia, 2008d. Carta geologica D'Italia Alla Scala 1:50.000. F. 058 Monte Adamello. APAT, Roma. https://doi.org/10.15161/oar.it/211483.
Servizio Geologico d'Italia, 2009a. Carta geologica D'Italia Alla Scala 1:50.000, F. 187 "Codigoro. ISPRA, Roma. https://doi.org/10.15161/oar.it/149874.
Servizio Geologico d'Italia, 2009b. Carta geologica D'Italia Alla Scala 1:50.000, F. 205 "Comacchio. ISPRA, Roma. https://doi.org/10.15161/oar.it/159952.
Servizio Geologico d'Italia, 2009c. Carta geologica D'Italia Alla Scala 1:50.000, F. 155 "Torino Ovest. ISPRA, Roma. https://doi.org/10.15161/oar.it/143629.
Servizio Geologico d'Italia, 2009d. Carta geologica D'Italia Alla Scala 1:50.000, F. 180 "Salsomaggiore Terme. ISPRA, Roma. https://doi.org/10.15161/oar.it/149716.
Servizio Geologico d'Italia, 2009e. Carta geologica D'Italia Alla Scala 1:50.000, F. 181 "Parma Nord". ISPRA, Roma. https://doi.org/10.15161/oar.it/149770.
Servizio Geologico d'Italia, 2009f. Carta geologica D'Italia Alla Scala 1:50.000, F. 187 "Codigoro. ISPRA, Roma. https://doi.org/10.15161/oar.it/149874.
Servizio Geologico d'Italia, 2009g. Carta geologica D'Italia Alla Scala 1:50.000, F. 201 "Modena". ISPRA, Roma. https://doi.org/10.15161/oar.it/150320.
Servizio Geologico d'Italia, 2009h. Carta geologica D'Italia Alla Scala 1:50.000, F. 202 "S. Giovanni in Persiceto. ISPRA, Roma. https://doi.org/10.15161/oar.it/150574.
Servizio Geologico d'Italia, 2009i. Carta geologica D'Italia Alla Scala 1:50.000, F. 203 "Poggio Renatico. ISPRA, Roma. https://doi.org/10.15161/oar.it/150828.
Servizio Geologico d'Italia, 2009l. Carta geologica D'Italia Alla Scala 1:50.000, F. 204 "Portomaggiore. ISPRA, Roma. https://doi.org/10.15161/oar.it/74469.
Servizio Geologico d'Italia, 2009m. Carta geologica D'Italia Alla Scala 1:50.000, F. 205 "Comacchio. ISPRA, Roma. https://doi.org/10.15161/oar.it/159952.
Servizio Geologico d'Italia, 2009n. Carta Geologica D'Italia Alla Scala 1:50.000, F. 220 "Casalecchio Di Reno. ISPRA, Roma. https://doi.org/10.15161/oar.it/185728.
Servizio Geologico d'Italia, 2009o. Carta geologica D'Italia Alla Scala 1:50.000, F. 221 "Bologna". ISPRA, Roma. https://doi.org/10.15161/oar.it/185846.
Servizio Geologico d'Italia, 2009p. Carta geologica D'Italia Alla Scala 1:50.000, F. 238 "Castel S. Pietro Terme. ISPRA, Roma. https://doi.org/10.15161/oar.it/188910.
Servizio Geologico d'Italia, 2009q. Carta geologica D'Italia Alla Scala 1:50.000, F. 239 "Faenza. ISPRA, Roma. https://doi.org/10.15161/oar.it/188936.
Servizio Geologico d'Italia, 2009r. Carta geologica D'Italia Alla Scala 1:50.000, F. 267 "S. Marino. ISPRA, Roma. https://doi.org/10.15161/oar.it/205282.
Servizio Geologico d'Italia, 2011a. Carta geologica D'Italia Alla Scala 1:50.000, F. 099 "Iseo. ISPRA, Roma. https://doi.org/10.15161/oar.it/211521.
Servizio Geologico d'Italia, 2011b. Carta geologica D'Italia Alla Scala 1:50.000, F. 107 "Portogruaro. ISPRA, Roma. https://doi.org/10.15161/oar.it/211722.
Servizio Geologico d'Italia, 2011c. Carta geologica D'Italia Alla Scala 1:50.000, F. 147 "Padova Sud. ISPRA, Roma.
Servizio Geologico d'Italia, 2012. Carta geologica D'Italia Alla Scala 1:50.000, F. 098 "Bergamo. ISPRA, Roma. https://doi.org/10.15161/oar.it/211517.
Servizio Geologico d'Italia, 2014a. Carta geologica D'Italia Alla Scala 1:50.000, F. 065 "Maniago. ISPRA, Roma. https://doi.org/10.15161/oar.it/211710.
Servizio Geologico d'Italia, 2014b. Carta geologica D'Italia Alla Scala 1:50.000, F. 066 "Udine. ISPRA, Roma. https://doi.org/10.15161/oar.it/211714.
Servizio Geologico d'Italia, 2014c. Carta geologica D'Italia Alla Scala 1:50.000, F. 086 "S. Vito Al Tagliamento. ISPRA, Roma. https://doi.org/10.15161/oar.it/211690.
Servizio Geologico d'Italia, 2014d. Carta geologica D'Italia Alla Scala 1:50.000, F. 096 "Seregno. ISPRA, Roma. https://doi.org/10.15161/oar.it/211509.
Servizio Geologico d'Italia, 2014e. Carta geologica D'Italia Alla Scala 1:50.000, F. 097 "Vimercate. ISPRA, Roma. https://doi.org/10.15161/oar.it/211511.
Servizio Geologico d'Italia, 2014f. Carta geologica D'Italia Alla Scala 1:50.000, F. 178 "Voghera. ISPRA, Roma. https://doi.org/10.15161/oar.it/143177.
Servizio Geologico d'Italia, 2014g. Carta geologica D'Italia Alla Scala 1:50.000, F. 222 "Lugo. ISPRA, Roma. https://doi.org/10.15161/oar.it/185878.

Servizio Geologico d'Italia, 2015. Carta geologica D'Italia Alla Scala 1:50.000, F. 156 “Torino Est. ISPRA, Roma. https://doi.org/10.15161/oar.it/143169.
Servizio Geologico d'Italia, 2016a. Carta geologica D'Italia Alla Scala 1:50.000, F. 118 “Milano”. ISPRA, Roma. https://doi.org/10.15161/oar.it/211525.
Servizio Geologico d'Italia, 2016b. Carta geologica D'Italia Alla Scala 1:50.000, F. 182 “Guastalla. ISPRA, Roma. https://doi.org/10.15161/oar.it/149818.
Servizio Geologico d'Italia, 2016c. Carta geologica D'Italia Alla Scala 1:50.000, F. 200 “Reggio Nell'Emilia. ISPRA, Roma. https://doi.org/10.15161/oar.it/150178.
Servizio Geologico d'Italia, 2024. Carta geologica D'Italia Alla Scala 1:50.000, F. 184 “Mirandola. ISPRA, Roma. https://doi.org/10.15161/oar.it/211806.
Servizio Geologico d'Italia, 2025a. Carta geologica D'Italia Alla Scala 1:50.000, F. 185 “Ferrara. ISPRA, Roma. https://doi.org/10.15161/oar.it/zm674-6z654.
Servizio Geologico d'Italia, 2025b. Carta geologica D'Italia Alla Scala 1:50.000, F. 121 “Brescia”. ISPRA, Roma. https://doi.org/10.15161/oar.it/212519.
Servizio Geologico d'Italia, 2025c. Carta geologica D'Italia Alla Scala 1:50.000, F. 087 “Palmanova. ISPRA, Roma. https://doi.org/10.15161/oar.it/212603.
Shanley, K.W., McCabe, P.J., 1993. Alluvial architecture in a sequence stratigraphic framework: a case history from the Upper Cretaceous of southern Utah, USA. In: Flint, S.S., Bryant, I.D. (Eds.), The Geological Modelling of Hydrocarbon Reservoirs and Outcrop Analogues, 15. IAS Spec. Publ., pp. 21–56
Shanley, K.W., McCabe, P.J., 1994. Perspectives on the sequence stratigraphy of continental strata. AAPG (Am. Assoc. Pet. Geol.) Bull. 78, 544–568.
Slomka, J.M., Eyles, C.H., 2015. Architectural-landsystem analysis of a modern glacial landscape. Sólheimajökull, southern Iceland. Geomorphology 230, 75–97.
Sloss, L.L., 1963. Sequences in the cratonic interior of North America. Geol. Soc. Am. Bull. 74, 93–114.
Stanley, D.J., Warne, A.G., 1994. Worldwide initiation of Holocene marine deltas by deceleration of sea-level rise. Science 265, 228–231.
Stefani, M., Vincenzi, S., 2005. The interplay of eustasy, climate and human activity in the late Quaternary depositional evolution and sedimentary architecture of the Po Delta system. Mar. Geol. 222–223, 19–48. https://doi.org/10.1016/j.margeo.2005.06.029.
Straffin, E.C., 2001. Mapping with allostratigraphic frameworks: implications for understanding alluvial landscapes in southern Burgundy, France. In: Bobrowsky, B. (Ed.), Geoenvironmental Mapping: Method, Theory and Practice. International Union of Geological Sciences (IUGS), Balkema, The Netherlands, pp. 147–167.
Tanabe, S., Nakanishi, T., Ishihara, Y., Nakashima, R., 2015. Millennial-scale stratigraphy of a tide-dominated incised valley during the last 14 kyr: spatial and quantitative reconstruction in the Tokyo Lowland, central Japan. Sedimentology 62, 1837–1872.
Tanabe, S., Nakashima, R., Ishihara, Y., 2022. Transition from a transgressive to a regressive river-mouth sediment body in Tokyo Bay during the early Holocene: sedimentary facies, geometry, and stacking pattern. Sediment. Geol. 428, 106059.
Teatini, P., Tosi, L., Strozzi, T., 2011. Quantitative evidence that compaction of Holocene sediments drives the present land subsidence of the Po Delta, Italy. J. Geophys. Res. Solid Earth 116.
Törnqvist, T.E., Bick, S.J., González, J.L., van der Borg, K., de Jong, A.F., 2004. Tracking the sea-level signature of the 8.2 ka cooling event: new constraints from the Mississippi Delta. Geophys. Res. Lett. 31.
Toscani, G., Burrato, P., Di Bucci, D., Seno, S., Valensise, G., 2009. Plio-Quaternary tectonic evolution of the northern Apennines thrust fronts (Bologna–Ferrara section, Italy): seismotectonic implications. Italian Journal of Geosciences 128, 605–613.
Toscani, G., Bonini, L., Ahmad, M.I., Di Bucci, D., Di Giulio, A., Seno, S., Galuppo, C., 2014. Opposite verging chains sharing the same foreland: kinematics and interactions through analogue models (Central Po Plain, Italy). Tectonophysics 633, 268–282.
Tosi, L., 1994. L'evoluzione paleoambientale tardo-quaternaria del litorale veneziano nelle attuali conoscenze. Il Quat. 7, 589–596.
Tzedakis, P.C., 1994. Vegetation change through glacial—interglacial cycles: a long pollen sequence perspective. Phil. Trans. Roy. Soc. Lond. B 345, 403–432. https://doi.org/10.1098/rstb.1994.0118.
Tzedakis, P., 2007. Pollen records, Last Interglacial of Europe. In: Elias, S.A. (Ed.), Encyclopedia of Quaternary Science. Elsevier, Oxford, pp. 2597–2605. https://doi.org/10.1016/B0-44-452747-8/00190-3.
Tzedakis, P.C., Andrieu, V., De Beaulieu, J.-L., Birks, H.J.B., Crowhurst, S., Follieri, M., Hooghiemstra, H., Magri, D., Reille, M., Sadori, L., Shackleton, N.J., Wijmstra, T.A., 2001. Establishing a terrestrial chronological framework as a basis for biostratigraphical comparisons. Quat. Sci. Rev. 20, 1583–1592. https://doi.org/10.1016/S0277-3791(01)00025-7.
Vail, P.R., Mitchum, Jr. R.M., Thompson, I.I.I.S., 1977. Seismic stratigraphy and global changes of sea level, part 4: global cycles of relative changes of sea level. In: Payton, C.E. (Ed.), Seismic Stratigraphy-Applications to Hydrocarbon Exploration, 26. AAPG Memoir, pp. 83–97.
van Balen, R.T., Busschers, F.S., Tucker, G.E., 2010. Modeling the response of the Rhine–Meuse fluvial system to Late Pleistocene climate change. Geomorphology 114, 440–452.
Vandenberghe, J., 1995. Timescales, climate and river development. Quat. Sci. Rev. 14, 631–638.
Vandenberghe, J., 2015. River terraces as a response to climatic forcing: formation processes, sedimentary characteristics and sites for human occupation. Quat. Int. 370, 3–11.
Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S., Hardenbol, J., 1988. An overview of the fundamentals of sequence stratigraphy and key definitions. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H. W., Ross, C.A., Van Wagoner, J.C. (Eds.), Sea-Level Changes: an Integrated Approach, 42. SEPM Special Publication, pp. 39–45.
Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., Rahmanian, V.D., 1990. Siliciclastic sequence stratigraphy in well logs, cores and outcrops: concepts for high resolution correlations of time and facies. In: AAPG Methods in Exploration Series 7, Tulsa, OK, pp. 1–55.
Vita, L., Battaglini, L., Cipriani, A., Consorti, L., Falcetti, S., Fiorentino, A., Fiorenza, D., Muraro, C., Orefice, S., Pieruccioni, D., Radeff, G., Silvestri, S., Troccoli, A., 2022. Aggiornamento e integrazioni delle Linee Guida per la realizzazione della Carta geologica d'Italia alla scala 1:50.000, Progetto CARG. Quaderni del Servizio Geologico d'Italia ser. III 15, 261 v1.0.
Waelbroeck, C., Labeyrie, L., Michel, E., Duplessy, J.C., McManus, J.F., Lambeck, K., Balbon, E., Labracherie, M., 2002. Sea-level and deep water temperature changes derived from benthic Foraminifera isotopic records. Quat. Sci. Rev. 21, 295–305.
Wang, X., Vandenberghe, J., Yi, S., Van Balen, R., Lu, H., 2015. Climate-dependent fluvial architecture and processes on a suborbital timescale in areas of rapid tectonic uplift: an example from the NE Tibetan Plateau. Global Planet. Change 133, 318–329.
Wegmann, K.W., Pazzaglia, F.J., 2009. Late Quaternary fluvial terraces of the Romagna and Marche Apennines, Italy: Climatic, lithologic, and tectonic controls on terrace genesis in an active orogen. Quat. Sci. Rev. 28, 137–165.
Wilson, L.F., Pazzaglia, F.J., Anastasio, D.J., 2009. A fluvial record of active fault-propagation folding, Salsomaggiore anticline, northern Apennines, Italy. J. Geophys. Res. Solid Earth 114 (B8).
Woodward, J.C., Hamlin, R.H.B., Macklin, M.G., Hughes, P.D., Lewin, J., 2008. Glacial activity and catchment dynamics in northwest Greece: long-term river behaviour and the slackwater sediment record for the last glacial to interglacial transition. Geomorphology 101, 44–67.
Yu, Y., Wang, X., Yang, X., Yi, S., Lu, H., 2024. Diverse fluvial aggradation and incision response to interglacial—glacial transitions in the headwaters of the Yangtze River, SE Tibetan Plateau. Geomorphology 465, 109418.
Zaitlin, B.A., Dalrymple, R.W., Boyd, R., 1994. The stratigraphic organization of incised-valley systems associated with relative sea-level change. In: Dalrymple, R.W., Boyd, R., Zaitlin, B.A. (Eds.), Incised-Valley Systems: Origin and Sedimentary Sequences, 51. SEPM Special Publication, pp. 45–60.
Zerboni, A., Trombino, L., Frigerio, C., Livio, F., Berlusconi, A., Michetti, A.M., Rodnight, H., Spötl, C., 2015. The loess-paleosol sequence at Monte Netto: a record of climate change in the Upper Pleistocene of the central Po Plain, northern Italy. J. Soils Sediments 15, 1329–1350.
Zerboni, A., Amit, R., Baroni, C., Coltorti, C., Ferrario, M.F., Fioraso, G., Forno, M.G., Frigerio, C., Gianotti, F., Irace, A., Livio, F., Mariani, G.S., Michetti, A.M., Monegato, G., Mozzi, P., Orombelli, G., Perego, A., Porat, N., Rellini, I., Trombino, L., Cremaschi, M., 2018. Towards a map of the upper Pleistocene loess of the Po plain loess basin (northern Italy). Alpine and Mediterranean Quaternary 31, 253–256.
Zuffetti, C., Bersezio, R., 2021. Space–time geological model of the Quaternary syntectonic fill of a foreland basin (Po basin, Northern Italy). Sediment. Geol. 421, 105945. https://doi.org/10.1016/j.sedgeo.2021.105945.
Zuffetti, C., Bersezio, R., Trombino, L., 2018a. Significance of the morphological and stratigraphic surfaces in the Quaternary Po Plain: the San Colombano tectonic relief (Lombardy, Italy). Alpine and Mediterranean Quaternary 31, 257–260.
Zuffetti, C., Trombino, L., Zembo, I., Bersezio, R., 2018b. Soil evolution and origin of landscape in a late Quaternary tectonically mobile setting: the Po Plain-Northern Apennines border in Lombardy (Italy). Catena 171, 376–397. https://doi.org/10.1016/j.catena.2018.07.026.