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Tracing marine flooding surface equivalents across freshwater peats and other wetland deposits by integrated sedimentological and pollen data

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Abstract

Large volumes of peatland deposits characterise the Holocene stratigraphy of the Po Plain. A combination of sedimentological and pollen-based paleoenvironmental analyses enables recognition and stratigraphic correlation of small-scale (2-5 m thick) packages of peat-bearing strata, stacked rhythmically in a retrogradational to progradational set and bounded by chronostratigraphically significant surfaces. Across these repetitive lithofacies successions, the proportion of facies-controlled palynomorphs is used as a diagnostic signature to characterise marine flooding surface equivalents (helophytes and hydrophytes) and shoaling-upward (terrestrialization) trends (trees and mesophilous herbs) that record systematic variations in groundwater table associated with increasing/decreasing accommodation. Paludification surfaces at the base of peats delineate the updip (freshwater) equivalents of brackish/marine flooding surfaces recognized at seaward locations atop peat layers (give-up transgressive surfaces). Peat beds exhibit maximum thickness in aggradational strata of the lowermost highstand systems tract, above the maximum flooding surface (MFS). An extrinsic control due to eustatic rise can be inferred for peat development in transgressive deposits: peats, in particular, reveal warmer climates at flooding surfaces (specifically around the MFS) that invariably coincide with rapid shifts to deeper depositional environments. Under highstand conditions, autogenic mechanisms affected base-level changes in the paralic swamps. At this stratigraphic level, peat-bearing strata primarily reflect subtle changes in accommodation due to distributary-channel avulsion, subsidence, and peat autocompaction. Detailed patterns of Holocene peat distribution on millennial timescales can help decipher multiple high-resolution accommodation cycles developed in the rock record on sub-seismic scales, resulting

in an improved stratigraphic analysis and prediction of chronologically less constrained non-marine successions.

Keywords: Sequence stratigraphy, Peat depositional environments, Peat facies, Palynological composition, Holocene, Po Plain

1. Introduction

Significant volumes of organic matter can accumulate in freshwater, low-lying depositional environments. Beyond any obvious marine influence, widespread peat formation takes place in mire in the coastal plains.

Peat formation is sensitive to even subtle changes in accommodation, sediment supply, and climate (Fielding, 1987; Fielding and Webb, 1996; Gibling et al., 2004). The organic matter in peat-forming environments, in particular, is highly sensitive to groundwater oscillations (Jager and Bruins, 1975; Clymo, 1984; Moore et al., 1996; Moore and Shearer, 2003; Zhuang et al., 2020). For mires and the accumulation of peat, the base level of deposition is specifically the groundwater table (Mc Cabe, 1984; Bohacs and Suter, 1997), which in paralic settings is governed primarily by the regional base level, precipitation/evaporation ratio and autocompaction of the peat (Bohacs and Suter, 1997; Davies et al., 2006; Dai et al., 2020). Water level changes in high-frequency cycles may reflect sea-level fluctuations due to the hydrological connection to the sea (Kosters and Suter, 1993; Wadsworth et al., 2002; Li et al., 2020). As relative sea level rises, so does the connected groundwater level and this effect can extend at least 150 km inland (Törnqvist, 1993; Kosters and Suter, 1993; Wadsworth et al., 2003). Significant accumulation of terrigenous organic matter may occur only below water table, because of reduced oxygen availability and low pH generated by plant decomposition (Moore, 1989; Diessel, 1992; Bohacs and Suter, 1997). Waterlogging is typically considered important to peat accumulation (Waksman and Stevens, 1929; Moore and Shearer, 2003).

Organic-matter-rich strata are prominent marker beds that can often be correlated over thousands of square kilometres (Hamilton and Tadros, 1994; Bohacs et al., 2005). In a sequence-stratigraphic view, thick coal seams developed on a regional scale are generally associated with the transgressive systems tract (TST) and lower highstand systems tract (HST) of the depositional sequence (Bohacs and Suter, 1997), highlighting the continental portion of the maximum flooding surface (MFS - Catuneanu, 2019 and references therein). The MFS forms at the peak of transgression and is marked by the deepest-water facies. This surface can be tracked landward from marine deposits into the marine-to-fluvial transition zone, i.e. the brackish realm, where a tongue of lagoonal or interdistributary bay deposits is sandwiched within freshwater facies. Farther inland, where flooding surfaces lose their marine component, identification of MFS in continental strata is inherently more difficult than for marine/brackish deposits and pinpointing the landward limit of the marine influence remains highly controversial.

This study was designed with the aim of investigating peat-layer distribution in a chronologically constrained framework and thus refine sequence-stratigraphic interpretation of non-marine deposits landwards of the maximum marine ingression. Specific objective is to use pollen data as a tool for tracing marine flooding surface equivalents in the continental realm, a concept that has never been satisfactorily defined in the literature.

To develop such concepts, we used published material from the Holocene, peat-bearing, cored succession of the Po Plain (Fig. 1). This region was chosen because of the very well-known stratigraphy and high-resolution chronology derived from hundreds of radiocarbon dates (Amorosi et al., 2017a, 2021; Bruno et al., 2017). In the Po Plain, laterally extensive peat horizons of Holocene age were mapped and peat-based stratigraphic correlations were used to assess post-burial strata deformation (Bruno et al., 2019). Previous work, however, focused uniquely on peat-bed identification and correlation, placing no emphasis on the stacking patterns of intervening deposits.

In this study, we used combined sedimentological and palynological observations with the aims (i) to characterise in detail the rhythmic, shoaling-upward signature of peat-bearing deposits developed on millennial to sub-millennial timescales and (ii) to examine the evidence for indirect marine influence within the Holocene freshwater succession, through the analysis of accommodation, deepening/shallowing and wetting/drying trends. Several papers have dealt with modern plant and pollen distribution in various types of peatlands, but these studies generally lack a (sequence) stratigraphic perspective, with very few exceptions (Holdgate et al., 1995, 2014; Morley, 2013; Korasidis et al., 2017).

An initial attempt to examine the palynostratigraphic relationships of the flora in the Po Plain was undertaken on core EM2 (Fig. 1) by Cacciari et al. (2020), who carried out a paleoclimatic reconstruction of the Late Pleistocene-Holocene succession. In this paper, we used the same pollen dataset from a completely different perspective, removing the paleoclimatic signature and focusing, instead, on the use of pollen data to infer peat depositional environment (Moore and Shearer, 2003).

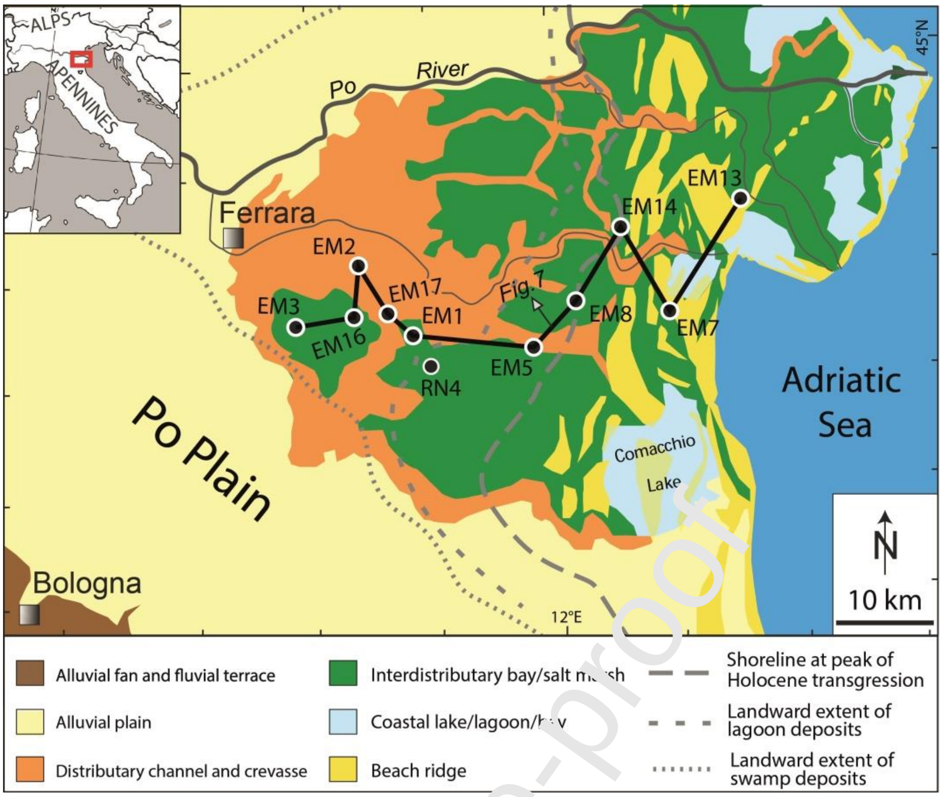

Fig. 1. Surficial geological map of the Po coastal plain (modified from Regione Emilia-Romagna, 1999), with location of core EM2 (Figs. 3 and 4) and the section trace of Fig. 7. The maximum landward migration of the shoreline during the Holocene is traced after Amorosi et al. (2008) and Bruno et al. (2017).

This paper expands on sequence-stratigraphic concepts from paralic coal seams, where several key surfaces with chronostratigraphic potential have been used for the sequence-stratigraphic analysis of non-marine sediments (Bohacs and Suter, 1997; Diessel et al., 2000; Wadsworth et al., 2003; Jerrett et al., 2011). Unlike ancient coal measures, however, Holocene peatland deposits provide a much higher resolution chronologic control that can help to improve predictive capability of coal-bearing cycles and carbonaceous mudstones in the ancient record.

2. Holocene stratigraphy of the Po Plain

The Holocene succession of the Po Plain accumulated under a phase of pronounced eustatic rise, during the Early Holocene, and subsequent highstand phase, in the Middle-Late Holocene. The Pleistocene alluvial plain was transgressed close to the Boreal-Atlantic transition, when a wide estuarine depositional system formed, about 9 cal kyr BP (Amorosi et al., 2017a; Bruno et al., 2017). This resulted in a variety of landward-stepping (offshore, beach-barrier, lagoon) depositional environments, between about 9-7 cal kyr BP, that migrated up to 50 km west of the modern shoreline (Figs. 1 and 2). The landward migration of the shoreline was followed by widespread progradation (post-6 cal kyr BP) of wave-dominated, deltaic and strandplain depositional systems (Campo et al., 2017; Amorosi et al., 2019).

In sequence-stratigraphic terms, the Holocene succession occupies the TST and HST of the Late Pleistocene-Holocene depositional sequence (Amorosi et al., 2017a). Two key stratigraphic surfaces are recognized (Fig. 2): the transgressive surface (TS) and maximum flooding surface (MFS). The TS is a sharp surface that marks the onset of a retrogradational stacking pattern of shallow-marine and coastal-plain deposits and that can be traced through a large part of the basin, atop lowstand (LST) alluvial deposits (Fig. 2). In interfluvial position, above floodplain deposits, the TS coincides with a weakly-developed paleosol (Amorosi et al. 2017b). This hiatal surface encompasses the Pleistocene-Holocene boundary and is typically overlain by peat bearing, swamp strata (Fig. 2).

The MFS separates TST from HST (Fig. 2) and marks a change between transgressive and normal regressive shoreline trajectories (Helland-Hansen and Martinsen, 1996). In more distal position, it is part of a condensed, shell-rich horizon (CS) within offshore/prodelta deposits (Scarponi et al., 2017). At more proximal locations the MFS is commonly well expressed in a distinct facies contrast, where brackish (lagoon/bay) clays intertongue with swamp deposits. Upstream, in an entirely freshwater succession, the MFS has no clear sedimentological signature (Fig. 2). Organic-matter-rich swamp facies display in this area their maximum thickness (up to 15 m in Fig. 2), due to the development and persistence of a wave-dominated estuarine setting with a variety of freshwater sub-environments (Amorosi et al., 2017a; Bruno et al., 2019). At peak transgression, in the microtidal Mediterranean system, the Po River debouched at the head of a wave-dominated estuary (Bruno et al., 2017), where narrow entrance restricted marine flushing and storage of clastic sediment up-dip caused clastic starvation in the marine system. With continuing progradation, virtually the whole study area turned into a peatland. Organic-matter enrichment occurred across large portions of the basin area (Bruno et al., 2019).

Since about 6 cal kyr BP, relative sea-level rise in the Po region slowed down and nearly stable sea-level conditions were conducive to delta initiation, as recorded worldwide (Stanley and Warne, 1994). Lower rates of sea-level and groundwater table rise, combined with a greater stability of the paralic environment, allowed the establishment of peat-rich intervals, as predicted by sequence stratigraphic models (Kosters and Suter, 1993; Bohacs and Suter, 1997; Tibert and Gibling, 1999). Peat formation continued until the 19th century, when humans started to lower groundwater tables to reclaim arable land (Bondesan, 1990), resulting in the development of the modern alluvial plain. Swamp deposits make up about one third of the total Holocene succession (Fig. 2), with volumes up to ca. 15 km^3 (Campo et al., 2020).

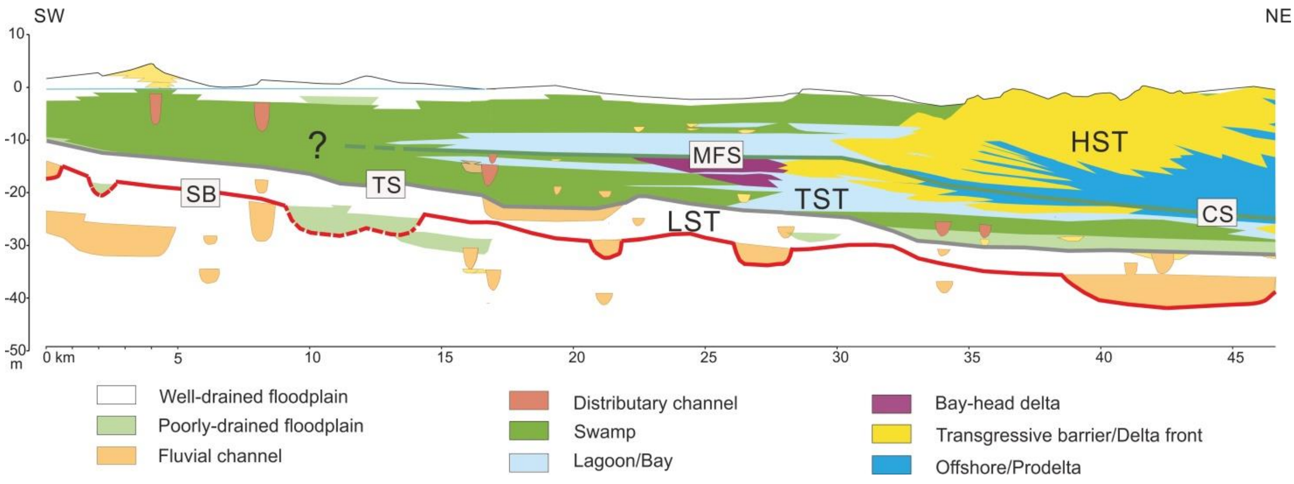

Fig. 2. Stratigraphic architecture of the late Quaternary succession of the Po Plain in a dip-oriented section (modified from Amorosi et al., 2017a), showing thick swamp (peat-bearing) deposits in the landward area that intertongue downstream with brackish (lagoon/bay) facies. The seaward area includes coastal (transgressive barrier/delta front) and shallow-marine (offshore/prodelta) depositional systems. Above Pleistocene alluvial deposits of the lowstand systems tract (LST), the Holocene succession depicts a basinwide transgressive-regressive cycle that comprises the transgressive systems tract (TST) and highstand systems tract (HST). SB: sequence boundary. TS: transgressive surface, MFS: maximum flooding surface, CS: condensed section.

Based on a chronologically constrained stratigraphic framework, it has been shown that Early Holocene parasequences mostly reflect stepped, post-glacial eustatic rise, flooding surfaces being correlative with periods of rapid, global sea-level rise reported in the literature (Amorosi et al., 2017a). On the other hand, no relation has been observed between relative sea-level change and parasequence development for the last 6000 years (Amorosi et al., 2019). This supports a mixed, dominantly allogenic (TST) *versus* dominantly autogenic (HST) development for Holocene estuarine and deltaic peat-bearing parasequences, respectively.

Further descriptions of the sedimentology, stratigraphy, and depositional environments of the Holocene succession can be found in Amorosi et al. (2017a, 2021), Bruno et al. (2017, 2019), and Campo et al. (2020).

3. **Materials and methods**

This study is based primarily on the sedimentological analysis of undisturbed core material. In this work, we focused on the proximal part of the paralic system described at length in previously published papers (Amorosi et al., 2017; 2019; Bruno et al., 2017; 2019), updip of any brackish incursion. For the stratigraphic analysis of this freshwater environment, we also used archived borehole descriptions and piezocone penetration tests.

Ten sediment cores, up to 35 m thick, aligned contiguously along one transect with W-E orientation (Fig. 1), were investigated through combined sedimentologic and paleontologic analysis. Core facies analysis was carried out through description of lithology, grain size, primary sedimentary structures, lamination styles and accessory components. Paleoecological features of brackish-marine facies assemblages mainly relied upon meiofauna analysis (i.e., benthic foraminifers and ostracods) to provide detailed paleoenvironmental information in terms of salinity oscillations, vegetation coverage (e.g., *Posidonia oceanica* seagrass), water depth and riverine organic-matter content (Holmes and Chivas, 2002; Murray, 2006; among others).

The paleoecological characterization of freshwater, organic-rich deposits strongly benefited from the palynological analysis of 39 samples collected from the 26 m-long succession of core EM2 (Fig. 1 – for detailed pollen counts of 35 samples from the same core the reader is referred to Cacciari et al., 2020). If possible, at least 300 primary pollen grains (i.e., pollen production coeval to sedimentation) were counted for each sample, defining the total pollen sum. Grains bearing traces of transportation, such as crumpling or fragmentation, whose determination was not possible, were labeled as “undeterminable”. Those redeposited from older deposits, characterized by enhanced reddening due to acetolysis or belonging to extinct taxa, were labeled as “secondary” deposition. Both categories were excluded from the total pollen sum and their percentages were calculated with respect to their own sums (Berglund and Ralska-Javorcekowa, 1986).

A total of 14100 grains were counted, including Pteridophyte spores, primary, undeterminable and secondary pollen grains. For a complete description of sample preparation techniques, taxonomical determination and ecological attribution, the reader is referred to Cacciari et al. (2020).

Plant ecological groups were elaborated considering autoecology of taxa (Table 1).

To obtain a full expression of lowland vegetation, relative abundances of facies-related groups (Hygrophytes, Hyg+hyg; Aquatics, Aq: hel+hyd; Mesophilous herbs, MesoH; and Mediterraneans+mesophilous trees, M+Q) were calculated on the local sum obtained by clearing from the matrix the climate signature (i.e., Montane taxa, Mt) and taxa of uncertain provenance (*Alnus* sp. and Betulaceae undiff., potentially belonging to different vegetation belts).

Local pollen spectra were then elaborated by expanding the classic Arboreal pollen/Non-arboreal pollen relation (Table 2).

Through the cored succession, the relative proportions of trees+shrubs (T+sh) – Wet herbs – Dry herbs were considered indicators of changes in both vegetation physiognomy (i.e., forest expansion/contraction) and wetlands extension.

Finally, on a matrix composed of selected ecological groups (Aq, MesoH, Mt) *plus* the physiognomic parameter T+sh, Q-mode cluster analysis (CA from here onwards) was performed with PAST (PAleontological STatistic – version 3.10 by Hammer et al., 2001) to investigate the relations between local vegetation dynamics (T+sh), environmental/facies variability (i.e., degree of immersion - Aq *versus* MesoH) and paleoclimate conditions (Mt).

Table 1. Plant ecological groups, their composition and ecologic significance.

Ecological groups	Main taxa	Ecological niche
Hygrophytes (Hyg+hyg)	Sum of woody taxa (Hyg: *Alnus glutinosa* and *Salix*) and herbs (hyg: Cyperaceae and most Pteridophytes)	Taxa thriving in moist environments with little or no standing water table
Aquatics (Aq: hel+hyd)	Sum of helophytes (hel: mainly Typhaceae, a few Cyperaceae and Isoetes) and hydrophytes (hyd: Callitrichaceae, *Hydrocharis,* Nympheaceae, *Potamogeton* and a few Typhaceae)	Helophytes: living periodically with an immersed radical apparatus; associated to shallow-water environments. Hydrophytes: living permanently in water, either floating or immersed; indicate the deepest waters in the mire
Mesophilous herbs (MesoH)	Mix of pasture-meadow and/or disturbed environment taxa (Apiaceae, Asteroideae, Brassicaceae, Caryophyllaceae, Cichorioideae, Chenopodiaceae, Fabaceae and Urticaceae). Poaceae are excluded, as they include hygrophytes and helophytes, often indistinguishable from other wild species	Herbs typical of emerged soils, slightly moist or dry
Mediterraneans + mesophilous trees (M+Q)	Mediterranean taxa (mainly *Quercus ilex*) + mesophilous trees (deciduous *Quercus* species plus various species of *Carpinus, Fraxinus, Tilia* and *Ulmus*)	Trees belonging to the Potential Natural Vegetation of the coastal-alluvial plain, mostly developed on well-drained soils during interglacials
Montane taxa (Mt)	Trees and shrubs (*Alnus incana*, *A. viridis*, *Betula*, *Castanea sativa*, *Fagus sylvatica* and most Pinaceae) or herbs (*Dryas octopetala* and Saxifragaceae)	Taxa living in middle- to high-altitude vegetation belts. This is the only truly climate-related group (taxa are hardly found in the plain during the Holocene)

Table 2. Local pollen spectra, their composition and ecologic significance.

Local pollen spectra	Main taxa	Ecological niche
Trees + shrubs (T+sh)	Woody taxa living in the plain (holm oak-mixed oak forest and hygrophilous woods)	Forest development
Wet herbs	Wetland herbs (hygrophytes and aquatics)	Humid and/or submerged environments
Dry herbs	All herbaceous plants other than wet herbs	A variety of generally emerged, minor environments

Herbaceous hygrophytes were excluded from CA, as they are significantly present throughout the study succession, thus reflecting generally humid conditions typical of wetlands.

A firm chronologic control was obtained through tens of radiocarbon dates available from previous studies. All the study boreholes were radioisotopically calibrated (Amorosi et al., 2017a; Bruno et al., 2017; 2019). These chronologic constraints ensured a high degree of confidence in correlation between sampled cores on sub-millennial time scales.

4. Sedimentary facies and depositional systems of the Holocene peat-bearing succession

Organic-matter rich strata within Holocene deposits of the Po Basin occur in a variety of depositional settings with high silt and clay content, in the proximal part of two large-scale depositional systems: (1) a backstepping, wave-dominated estuary (TST in Fig. 2), where waves were the dominant force shaping the gross geomorphology, and (2) a prograding, wave-dominated (arcuate) to river-dominated (cuspate) deltaic system (HST in Fig. 2 - Amorosi et al., 2017a). Four main facies assemblages (distributary channel, crevasse/levee, poorly-drained floodplain, and swamp) were identified through facies analysis of sediment cores (Fig. 3). Each facies association shows vegetation communities unique to that unit, defined by distinctive pollen assemblages. The modern well-drained floodplain environment originated from land reclamation.

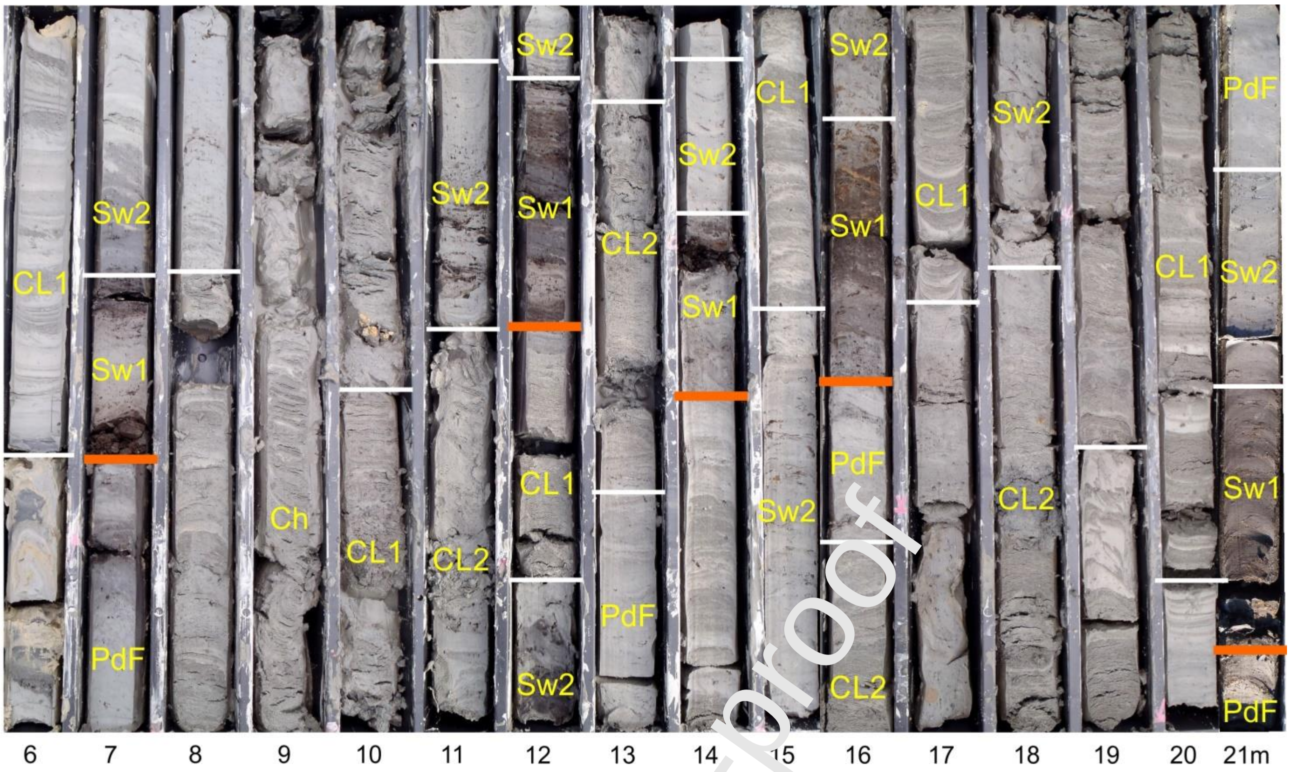

Fig. 3. Facies associations and lithofacies from the Holocene succession of core EM2 (for location, see Fig. 1) and their vertical stacking into shoaling-upward packages bounded by flooding surface equivalents (in orange) at the base of basin swamp peaty units (lithofacies Sw1). Sw2: swamp margin clay, CL1: distal crevasse/levee silt/sand alternations, CL2: proximal crevasse/levee sand, PdF: poorly-drained floodplain clay. Core length is 1 m.

4.1. Distributary-channel facies association (Ch)

4.1.1. Description

This facies association consists of moderately sorted, fine to medium sand bodies (Fig. 3), 2-5 m thick, with erosional base, characteristic fining-upward (FU) trend, and generally sharp top. Sedimentary structures are poorly preserved, but generally include unidirectional, high-angle cross-stratification (Fig. 3). Finer-grained (silt and clay) deposits are highly subordinate. Large wood fragments are commonly observed at the base of this facies association. The meiofauna is characterized by sparse fragments of freshwater ostracods. Individual FU sequences typically show upward transition to organic-rich layers. This unit is commonly associated with (or sandwiched between) organic-rich layers and peats.

The pollen assemblage is characterized by moderately high arboreal cover (ca. 60%) and by the dominance of mesophytes (both trees and herbs) over hygrophytes; aquatics are very scarce (< 6%).

4.1.2. Interpretation

Given the inherent difficulty of preserving sedimentary structures in loose sands, interpretation of this facies association is based on the distinctive combination of lithology, nature of stratigraphic contacts, body fossils and accessory components. The erosional lower boundary of sand bodies, combined with high-angle trough cross-stratification, FU trends, abundance of woods and the rare presence of freshwater fossils, all are characteristic features of high-energy, mostly isolated (non-amalgamated) distributary-channel deposits.

Consistently, the palynological content points to the presence of a mixed oak, alder and willow forest with woodland clearances that mostly developed on dry or slightly moist soils at the channel margin. The extreme scarcity of halophyte taxa (< 2%), such as *Artemisia* and chenopods, as well as the absence of a brackish meiofauna, support a fluvial source for these deposits.

4.2. Crevasse/Levee facies association (CL)

4.2.1. Description

This facies association, generally < 2 m thick, is typically associated with organic-rich clay and includes two distinct lithofacies. Lithofacies CL1 is made up of light-dark grey banded deposits that denote the lithologic alternation, in various proportions, of varicolored silty sand and silt layers, a few cm thick, with climbing-ripples cross-lamination, abundant plant debris and the presence of rootlets (Fig. 3). Fossils are absent. Lithofacies CL1 commonly shows diagnostic coarsening-upward (CU) and thickening-upward trends toward the overlying lithofacies CL2. This latter includes very fine to medium-grained sand bodies, less than 1 m thick, with gradational or erosional lower boundary. This facies association is generally barren of fossils and can be erosionally overlain by distributary-channel sands.

The pollen assemblage is characterized by rather high arboreal cover (commonly ranging between 50-70%) and by the dominance of mesophilous trees over their hygrophilous counterparts. By contrast, this pattern is less straightforward within the herbaceous community, where hygrophytes are often co-dominant. Aquatics are rather scarce, with highly variable abundance (1-11%) and peaks at the transition to peat swamp deposits.

4.2.2. Interpretation

Based on vertical facies relations with distributary-channel and organic-matter-rich deposits, the lack of fossils and the common occurrence of indicators of subaerial exposure (rootlets and plant debris), this facies association is believed to reflect distal (lithofacies CL1) to proximal (lithofacies CL2) overbank/crevasse sedimentation. Heterolithic sand-silt deposits with climbing ripples (CL1) indicate sediment deposited by initially high-energy sheet flows from waning flood currents and then, as flow energy decreased, by suspension fallout (Allen, 1973). Lithofacies CL2 represents crevasse splays (gradational lower boundary) or crevasse channels (erosional lower boundary) in a proximal flood-basin environment. Core analysis does not allow distinguishing unequivocally distal levee deposits from the fringe of crevasse splays. The overall thickening-upward trend of this facies association, as a whole, is suggestive of progressive infilling of ephemeral bodies of water by the nearby presence of a river (Fielding, 1984).

The pollen assemblage associated with this facies association is indicative of an open to dense mixed oak-holm oak forest, with a remarkable hygrophilous component, both arboreal and herbaceous. Peaks in aquatics may locally reflect filling of topographically depressed areas, rather than being indicative of actual submersion.

4.3. Poorly-drained floodplain facies association (PdF)

4.3.1. Description

This facies association, generally < 2 m thick, includes soft silt and subordinate clay, with a uniform grey color (Fig. 3), rare sand layers and a lack of woody material, Fe-Mn oxides or carbonate nodules. It is generally barren in fossils or may contain at most a few opercula of freshwater molluscs, including *Hydrobia* and *Planorbis*. Freshwater ostracods, such as *Candona* and *Ilyocypris*, are locally abundant.

Pollen assemblages in this facies association are not indicative of a single vegetation type, because of remarkable variations in afforestation (9-62%). Nonetheless, the co-dominance of hygrophyte and mesophyte trees is commonly mirrored by herbs (i.e., hyg, hel and hyd vs MesoH). Specifically, hygrophytes are always a significant component of the landscape (5-22%), accompanied by low amounts of helophytes and hydrophytes (0-6% and 0-8%, respectively, < 11% altogether).

4.3.2. Interpretation

The paucity of sand beds suggests that this facies association accumulated in a low-energy depositional environment, not influenced by active channel processes and dominated by fallout, with highly subordinate traction processes. The absence of pedogenic features, such as carbonate concretions and yellowish or brownish alteration colors, indicates a poorly-drained flood basin with a lack of oxidation under a high groundwater table. Low-lying, frequently submerged areas, such as a wet (or poorly drained) floodplain environment, may account for these features.

The palynological signature supports this interpretation, as a significant degree of hygrophily is still present, despite vegetation shifts from a grassland to a woodland. The local abundance of mesophyte trees likely reflects rapid afforestation marked by the lowland recolonisation of the mixed oak forest during the Holocene climate optimum. It also accounts for the strong connection of this facies to drier and more emerged facies, where the mesophilous forest thrived at its best.

4.4. Swamp facies association (Sw)

4.4.1. Description

This facies association is characterized by an abundance of organic-rich clay and peat and includes two distinct lithofacies. Lithofacies Sw1 is a peat, with yellowish brown to brownish black colors and typical fibrous consistency. It is made up almost entirely of plant material in a good state of preservation, locally interbedded with dark clay horizons. Vegetation remains mainly consist of wood fragments, roots, stems and leaves (Fig. 3). Individual peat layers are less than 1 m thick. Loss-on-ignition (LOI) carried out through X-ray fluorescence on 28 core samples yielded values in the range of 20-70%. Lithofacies Sw2 is unlaminated, grey to dark grey silty clay that includes wood debris, such as leaves and twigs (Fig. 3). Pedogenic features are lacking. Freshwater ostracods, including few valves of *Candona* and *Pseudocandona*, and subordinate *Ilyocypris* locally typify this facies association. LOI values from 33 core samples (4 of which from core EM2) were invariably < 25%.

Lithofacies Sw1 shows high percentages of aquatics (helophytes 4-12%, hydrophytes 4-18%). Herbaceous hygrophytes are co-dominant or slightly subordinate to aquatics (5-27%), but they can occasionally peak high at > 40% where Pteridophytes are particularly abundant. The tree cover is invariably low (commonly around 20%). Within lithofacies Sw2, the abundance of hygrophytes is comparable to Sw1 (ca. 8-26%, with peaks around ca. 50% and an abundance of Pteridophytes), but aquatics exhibit significantly lower values of (5–18%). The tree cover is remarkably higher, generally between ca. 40-70%, rarely with lower values.

4.4.2. Interpretation

The abundance of peat beds in lithofacies Sw1 indicates concentrated accumulation of terrigenous plant material in a low-energy environment under low detrital input conditions. High LOI values indicate an abundance of volatile substances, including inorganic carbon and organic matter. Incomplete decomposition of plant remains, combined with the highest amounts of aquatics (up to 33%) reflects waterlogged conditions in standing water. The lack of brackish body fossils and of a brackish meiofauna, as well as scarcity of halophytes (< 3%), point to a freshwater environment. The abundance of plant roots indicates that peat formation was evidently *in situ*. The palynological content is diagnostic of a herbaceous peatland community within a vegetation landscape shaped by the presence of numerous waterlogged depressions. Communities of both peatland fringes (helophytes) and fully inundated depressions (hydrophytes) are well-developed. At the edges (i.e., local highs) a hygrophilous and mesophilous vegetation is present and, within the canopy, mixed oak taxa show an abundance comparable to hygrophilous woodland taxa, likely pointing to a highly stabilised forest in the nearby poorly-drained floodplain. The relatively high abundance of hygrophytes and the significant presence of oaks and other mesophilous elements suggest mean annual groundwater levels between 10 cm above or below the surface and water depths up to 2-3 m. Specifically, the pollen assemblage in lithofacies Sw1 indicates high groundwater levels and standing conditions typical of a basin swamp (i.e., a more or less forested fen). The limited thickness of individual peat beds suggests that peat accumulation was temporarily interrupted by muddy waters due to river flooding.

Lithofacies Sw2 records deposition of fine-grained sediment and subordinate organic matter (suggested by significantly lower LOI values than in Sw1) in a shallow subaqueous, freshwater floodbasin, such as a swamp (fen) margin. The excellent preservation of organic and plant material, concurrently with the high proportion of inorganic material, the diagnostic palynological content and a lack of pedogenic features are consistent with sedimentation at the margin of a semipermanently flooded peatland. The pollen assemblage is typical of a more densely forested environment than the one that characterized deposition of lithofacies Sw1: an open to dense oak-alder woodland with a mixed oak-holm oak ecological component often in a dominant position. This feature, combined with low percentages of aquatics, reflects relatively low water table levels and proximity to river channels (especially where willow overcomes alder as the dominant hygrophilous tree) or other stable, emerged interfluvial areas.

5. Pollen signature of upward-shoaling, peat-bearing strata

Though interpretation of peat-bearing depositional environments based on palynology alone can be complicated by localized events, plant migrations, and plant community changes through time (Dai et al., 2020), the detailed palynological profile from core EM2 (Fig. 4) reveals a well-defined correlation of vegetation communities with lithofacies/depositional environments. In particular, the repetitive vertical stacking pattern of peat-bearing lithofacies shown in Fig. 3 is paralleled by a distinctive pollen distribution that reflects diagnostic shoaling-upward trends on millennial to centennial timescales (Fig. 4).

Peats (lithofacies Sw1) are characterized by the highest contents in aquatics (hydrophytes + helophytes), scarce afforestation, and generally few secondary grains (Fig. 4). This suggests that accumulation of peat and organic-rich sediment most likely took place in permanently flooded areas associated with relatively deep water (2-3 m), far from a direct fluvial influence.

A shoaling-upward tendency from constantly high water tables to periodically fluctuating water tables is recorded by the lower abundance of aquatics, in particular hydrophytes, within overlying lithofacies Sw2 (Fig. 4). The absence or scarcity of helophytes and hydrophytes in the uppermost, coarser strata (lithofacies CL1 and CL2 in Fig. 4) reflect flood-basin filling by crevasse splays and, ultimately, subaerial exposure. This interpretation is corroborated by generally increasing proportions of secondary grains and by the highest abundance of tree pollen (especially mesophilous taxa), indicative of the transition to more oxic and drier conditions above the water table (Fig. 4).

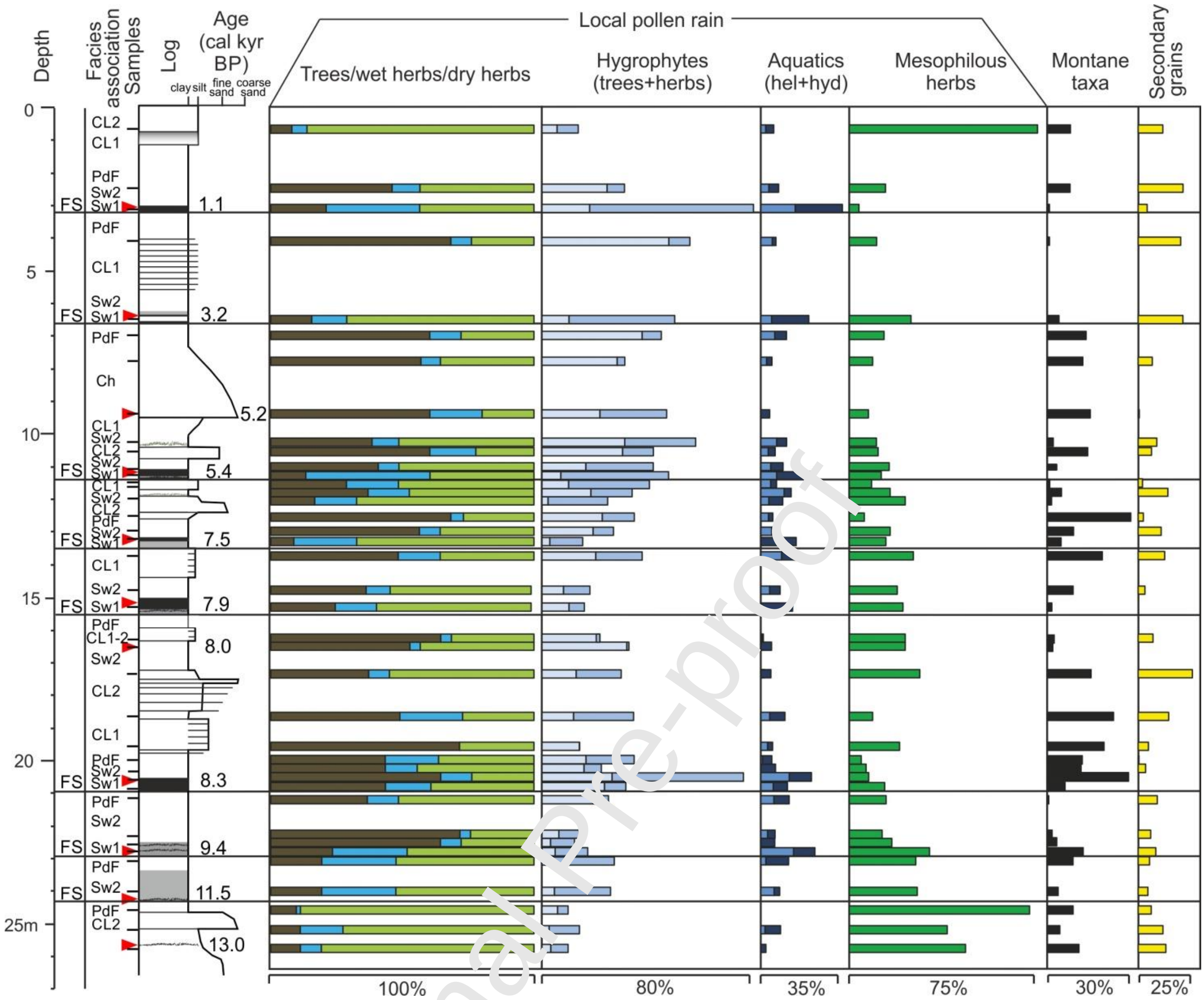

Fig. 4. Columnar section of Core EM2, showing sedimentary facies and palynological characteristics of the shoaling-upward packages illustrated in Fig. 3. Based on pollen data, basin swamp peats (lithofacies Sw1) reflect the deepest depositional environments and their lower boundaries are interpreted as flooding surface equivalents (FS). Red arrows are radiometric ages (cal kyr BP) from Bruno et al. (2019). For the complete pollen record of core EM2, see Cacciari et al. (2020).

Drying-up and wetting-up depositional cycles developed on sub-seismic scales represent high-resolution accommodation cycles that have been recognized in several peat-rich successions (Esterle and Ferm, 1994; Moore, 1994), based on changes in maceral properties of coals and, more in general, coal petrology (Esterle and Ferm, 1986; Diessel, 1992; Banerjee et al., 1996; Frank and Bend, 2004; Davies et al., 2006; Wadsworth, 2010). These cycles are defined by key stratigraphic surfaces that commonly lie in intra-peat position (Diessel et al., 2000) and can be correlated over distances greater than 100 km (Jerrett et al., 2011). A period close to that of climatic precession for Milankovitch cycles, spanning from 20 kyr to 30 kyr, has been invoked by Li et al. (2020) to account for coal-bearing cycles from the Permian of North China. The shallowing-upward, peat-bearing successions illustrated in this paper share some similarities with the drying-upward cycles from the brown coals of the Latrobe Valley, described from southeastern Australia (Holdgate et al., 1995; 2014). However, the Latrobe coal, which often exceeds 100 m in total thickness, formed as ombrogenous tropical mires and has cycles that are an order of magnitude larger, ranging between 10 to 30 m.

The accumulation of peat-bearing strata in the Holocene succession of the Po Plain was analyzed in relation to modern environments and their detailed palynological zonation (Fig. 5). Most peatlands exhibit plant successions that are driven by water levels and that may lead to interpretation of peat-forming depositional environments based on water table position (Diessel, 1992, Banerjee et al., 1996; Rich, 2015). Modern vegetation communities, in particular, represent an analog for pollen successions preserved in Holocene deposits, spanning the last ca. 10 kyr. In this respect, stacked packages of peat-bearing deposits may contain palynological signatures and distinctive successions of plant communities that reflect high-resolution record of accommodation change (Anderson and Müller, 1975; Demchuk and Moore, 1993; Diessel et al., 2000; Holz et al., 2002).

Combined facies (Fig. 3) and pollen (Fig. 4) indices from the Holocene freshwater succession of the Po Plain corroborate the hypothesis that peat-bearing successions developed on millennial to centennial timescales reflect water table fluctuations, upward shoaling and a corresponding increase in clastic sediment input. In general, clastics and peat compete to fill the available space for sediment/organic matter accumulation in peatland environments. In the Holocene succession of the Po Plain, rhythmically stacked peat-bearing units record a phase in which rising base level or reduced coarse sediment input generate accommodation, followed by a phase of generalized depositional filling. This shallowing-upward trend is reflected by a series of paleoenvironments ranging from basin swamps to mesophilous forests (Fig. 5).

The typical, complete succession of lithofacies is 2-5 m thick and displays a well-developed lightening-upward trend (Figs. 3 and 5). It starts at its base in a dark peat (lithofacies Sw1) that is overlain by a homogeneous, organic-rich grey clay deposit (lithofacies Sw2) grading upwards into a thickening-upward succession of silt-sand heterolithic facies (lithofacies CL1). Where clastic input dominates the system, sand beds become coarser and more abundant upwards, with only thin mud intercalations (lithofacies CL2). The entire succession is locally capped by poorly-drained floodplain deposits (facies association PdF) or can be overlain erosively by a distributary-channel sand body (facies association Ch). In general, the organic-matter content appears to be inversely related to the sand content and sand-bed thickness.

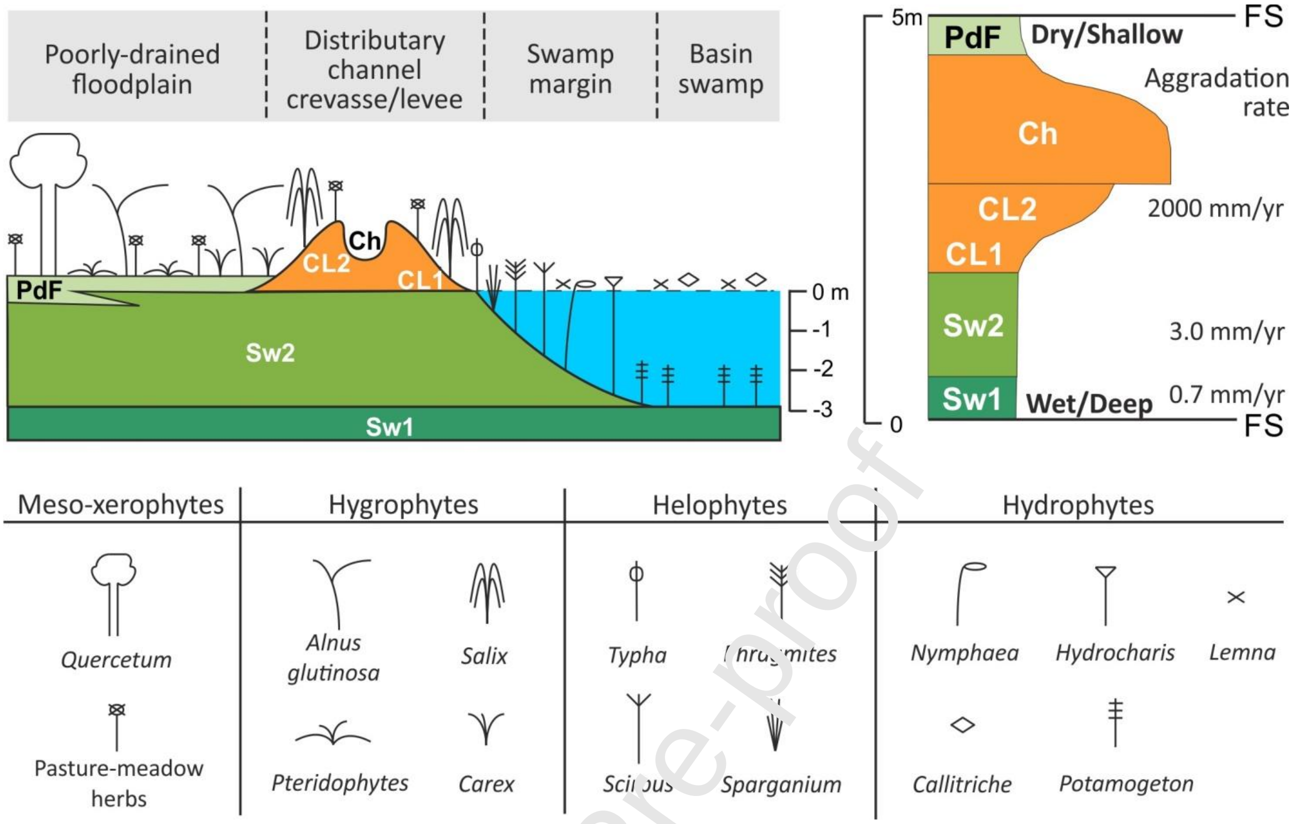

Fig. 5. Depositional model for shoaling-upward, peat-bearing successions bounded by flooding surface equivalents (FS), with major plant contributors to individual facies associations and idealized, depositional motif. Accumulation rates for the distinct lithofacies. calculated on the basis of radiocarbon dates in Fig. 7, may differ by orders of magnitude.

The overall facies architecture suggests that organic-matter-rich layers developed primarily from low-lying swamp mires associated with crevasse splays, in close proximity to distributary channels (Fig. 5). Abrupt lower boundaries of peats, partly due to differential compaction between organic-rich and clay/silt laden sediments, indicate deepening conditions in non-marine wetlands (flooding surface equivalents), such as swampy and marshy mires developed atop sediment-infilled interdistributary areas. In some cases, however, the basal parts of shallowing-upward packages show a gradational wetting-upward trend, a few cm thick, with a smooth transition upsection from a grey clay to a darker clay with an upward increase in dispersed organic matter that culminates into a peaty interval that reflects the most drowned conditions (Fig. 3).

Based on multiple ^{14}C dates from previous work (Amorosi et al., 2017, 2019; Bruno et al., 2019), deposition of Holocene shoaling-upward successions took place between about 500 and 2000 years. Peat accumulation rates are distinctly lower than those for associated clay horizons (Diessel et al., 2000). In particular, accumulation rates of lithofacies Sw1 have average values of 0.7 mm/yr (Fig.

5). In contrast, the overlying lithofacies Sw2 is characterized by significantly higher average aggradation rates (3.0 mm/yr). The accumulation of the 1-3 m thick coarsening-upward, sandy succession that filled the low-lying, swampy areas can be effectively instantaneous. Although the above values may reflect, at least in part, contribution of peat compaction (van Asselen et al., 2009; 2011), strong differences in accumulation rates between the different lithofacies suggest that peat-bearing horizons can be interpreted as short-lived condensed intervals where a certain amount of geologic time can be 'missing' (Scott and Stephens, 2015). Sediment accumulation rates calculated for the Po-River system are strikingly similar to the regional floodbasin aggradation rates reconstructed for the Holocene record of the Rhine-Meuse system (Hijma et al., 2009), where individual shallowing-upward successions record considerably lower sediment accumulation rates for peats (0.8 mm/yr) than for freshwater-swamp muds (4.0 mm/yr).

6. Pollen cluster analysis

We investigated the response of the vegetation cover to environmental change through cluster analysis (Fig. 6), which was performed on the same palynological dataset (39 pollen samples) shown in Figure 4.

A similarity value of 0.5 produced three clearly separate and distinct clusters of samples (Fig. 6). In particular:

- C1 includes samples from the youngest five peat layers (lithofacies Sw1), dated approximately to 7.9, 7.5, 5.4, 3.2, and 1.1 cal kyr BP (Fig. 4). These samples represent a pure population of basin swamp environments characterized by the highest water table (= highest percentages of aquatics) and lowest afforestation.
- C2 includes the lower part of core EM2 (below about 23 m core depth, with just two exceptions), corresponding to Lateglacial alluvial deposits and to the oldest two peats, dated to the base of the Holocene and to the Boreal, respectively (ca. 11.5 and 9.4 cal kyr BP in Fig. 4). This cluster represents mesophilous or meso-hygrophilous depositional environments with low to intermediate water table and a remarkable degree of disturbance.
- C3 contains Mid-Late Holocene (post-8 cal kyr BP) samples from marginal swamp and crevasse splay sub-environments. This cluster splits into two branches:

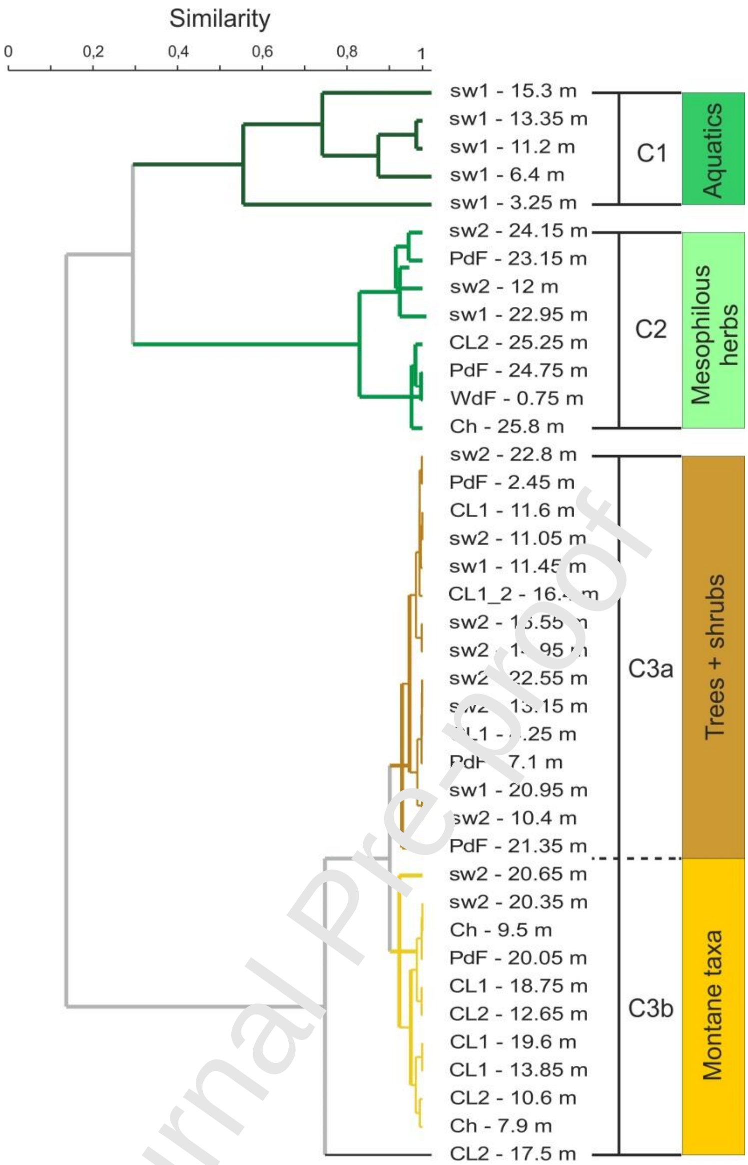

Fig. 6. Cluster analysis of 39 samples from core EM2 investigated for their palynological content. Samples are labeled by facies attribution and core depth (see Fig. 4). Colors of dendrogram indicate related ecological groups: Facies codes: see text. WdF: well drained floodplain.

- C3a consists of a facies heterogeneous assemblage of marginal swamp (lithofacies Sw2) and subordinate floodplain and crevasse/levee deposits, all characterized by a climate optimum-like vegetation (meso-hygrophilous woodland with intermediate to high water table).
- C3b includes fluvial-related (mostly crevasse-levee) facies and two samples from marginal swamp deposits at ca. 8.2 cal kyr BP, all characterized by a mixed oak-alder woodland, slightly more mesophilous than the one from group C3a. This group is typified by prominent montane vegetation.

The sedimentary evolution of the study area (Fig. 4) is punctuated by climate-related vegetation patterns. In particular:

(i) Lateglacial and Early Holocene deposits invariably contain samples from cluster C2, reflecting the development of pioneering grasslands and open woodlands into poorly-drained floodplains under a slight, but constant, increase of tree cover and water table.

(ii) Peatland formation occurred when the Potential Natural Vegetation reached its maximum extent in the plain, around 9 cal kyr BP, followed by a general increase in hygrophily. This phase is reflected by the onset of cluster C3a.

(iii) Vegetation patterns enable recognition of the effects of the 8.2 kyr cooling event (Cacciari et al., 2020): this is clearly reflected by cluster C3b, which exhibits a particular pollen signature indicative of a lowland meso-hygrophilous forest accompanied by an expansion of vegetation montane belts upland. The generalized high amount of montane taxa in fluvial-related deposits suggests a possible climate fingerprint at the scale of millennial peat-bearing successions. This palynological signature was likely enhanced by increasing pollen transportation by wind (see Signell et al., 2010, for the effects of Bora wind in northern Italy) and water (see Brown et al., 2007, for the importance of riverine pollen transportation during floods).

(iv) Peat samples of Middle-Late Holocene age (post-8 cal kyr BP) are invariably grouped into cluster C1. Three of them, in particular, between 15.3-11.2 core depth (i.e., the 7.9-5.4 cal kyr BP interval), exhibit the maximum distance relative to cluster C3b (Fig. 6) and thus denote the relatively warmest climate conditions (Sluiter et al., 1995). Remarkably, this stratigraphic interval marks the phase of maximum peatland expansion and growth across the MFS (Fig. 7).

7. Sequence-stratigraphic significance of Holocene peat-bearing deposits

7.1. Systems tract architecture and controlling factors of peat accumulation

Peat/coal-bearing depositional units can be framed into a hierarchy of temporal scales, varying by several orders of magnitude and corresponding to distinct sequence-stratigraphic units, from depositional sequences to the parasequence scale (Bohacs and Suter, 1997; Catuneanu, 2006, Diessel, 2007; Dai et al., 2020).

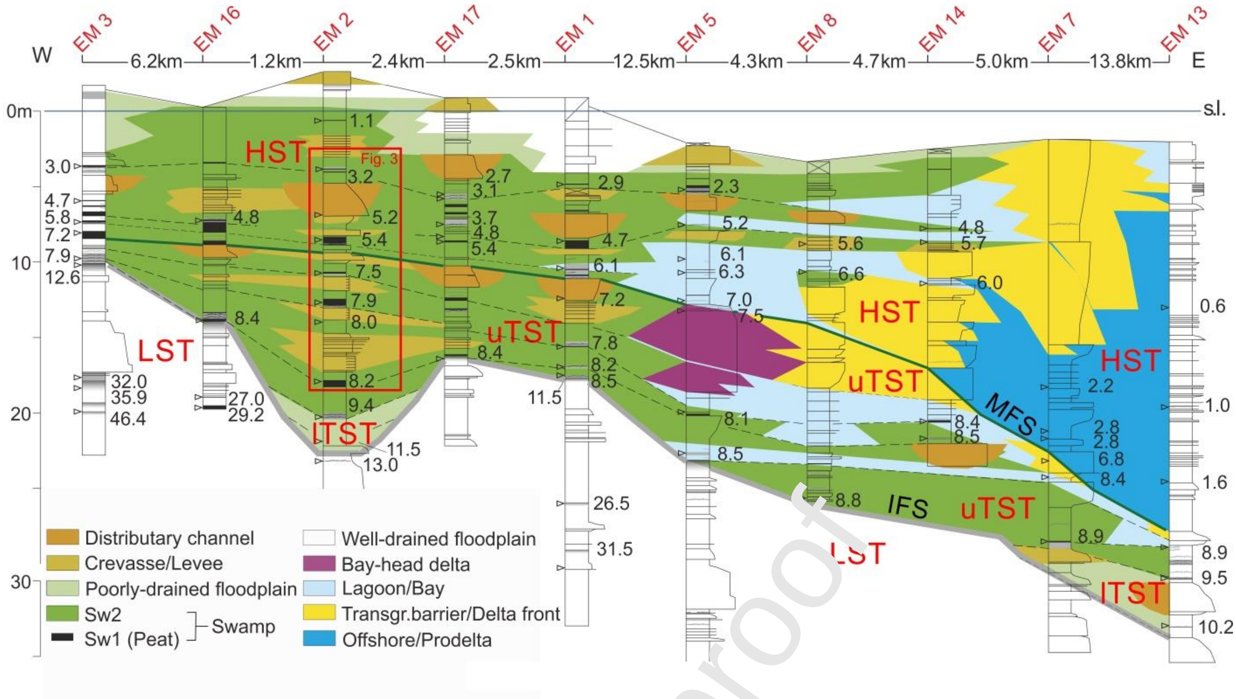

Fig. 7. Depositional dip-oriented cross-section (section trace in Fig. 1) showing the stacking of millennial to centennial-scale, peat-bearing successions (bounded by dashed lines) and equivalent brackish, coastal and shallow-marine units. LST: lowstand systems tract, lTST: lower transgressive systems tract, uTST: upper transgressive systems tract, HST: highstand systems tract. IFS: initial flooding surface, MFS: maximum flooding surface. The maximum flooding surface is traced at the turnaround from retrogradation to progradation. 10.2: calibrated radiocarbon age (kyr BP).

Several papers have emphasized the sequence-stratigraphic distribution of coals (and peats) on a systems-tract scale (Diessel, 1992; Bohacs and Suter, 1997) and have tied their stratigraphic position to parasequence stacking patterns (Ryer, 1984; Cross, 1988; Shanley and Mc Cabe, 1994; Flint et al., 1995; Myers, 1996). According to these models, laterally-extensive peat beds primarily form in coastal plain depositional systems within the TST and lower HST, close to the turnaround from retrogradation to progradation (Boyd et al., 1989; Hamilton and Tadros, 1994; Aitken and Flint, 1995; Flint et al., 1995; Bohacs and Suter, 1997; Gibling et al., 2004; Catuneanu, 2006; Diessel, 2007; Wang et al., 2019; 2020), where the rate of waterlogged peat accumulation and the rate of creation of sediment accommodation can balance (Shanley and Mc Cabe, 1994; Hampson, 1995; Bohacs and Suter, 1997). In particular, peats tend to be best developed in parasequence sets with slightly retrogradational to aggradational stacking, with a marked preference of paralic coal formation for the early transgressive and early highstand systems tracts (Bohacs and Suter, 1997; Diessel et al., 2000; Diessel, 2007).

In the Holocene succession of the Po Basin, where sea-level and climate control over millennial time scales can be documented, rather than inferred, clastic swamps with organic-matter-rich deposits have no patchy distribution, but extend continuously along-dip (Fig. 7), forming prominent stratigraphic markers at distinct stratigraphic levels (Bruno et al., 2019). Based on tens of radiocarbon dates, individual organic-rich layers are readily traceable and approximately synchronous.

Early Holocene deposits accumulated between about 10-8 cal ky BP in the upstream portion of wide estuarine areas subject to enhanced accommodation under eustatic rise (Bruno et al., 2017). Absolute (eustatically-driven) sea-level fluctuations directly affected organic accumulation in coastal peatlands, raising the water table and resulting in groundwater emergence landwards of backstepping lagoonal/bay environments (Fig. 7).

The initial flooding surface (IFS), i.e. the landward equivalent of the TS, largely coincides with the prominent facies change from Pleistocene lowstand alluvial deposits (LST) to overlying transgressive, poorly-drained floodplain (lower TST) and inner estuarine peat-bearing facies (upper TST) of early Holocene age (Fig. 7). Consistent with the high-resolution stratigraphic record of core EM2 (Figs. 3 and 4), a high-frequency set of minor flooding surfaces can be identified within the thick package of freshwater deposits (Fig. 7). Facies relations to the open-marine deposits demonstrate that lower boundaries of peat-bearing units correlate distally to thin tongues of brackish water sediments. These latter grade downdip into coastal sands and shallow-marine clays (Fig. 7). As a result, the minor flooding surfaces in the TST at the base of laterally continuous freshwater peats are interpreted to reflect marine flooding surface equivalents.

Peat beds in the TST onlap against the inclined Pleistocene paleosurface (Fig. 7). These beds are only a few decimeters thick and have laterally continuous distribution. Organic-rich packages acquire considerable thickness (about 3 m) in the uppermost TST and lowermost HST, where they stack aggradationally below and above the maximum flooding surface. The maximum enrichment in organic matter represents the inland prolongation of the maximum brackish incursion (Fig. 7). In the overlying portion of the HST, peat layers are more discontinuous, exhibit a slightly progradational stacking pattern and, as in the lower TST, are only few decimeters thick.

The continental portion of the maximum flooding surface is associated with the highest water table relative to the topographic profile (Catuneanu, 2019). The increasing proportion of hydrophytes over helophytes in Early Holocene peats (lithofacies Sw1), with maximum values in swamp deposits dated around 7.9 and 7.5 cal kyr BP (Fig. 4) is consistent with the progressive increase in water table under conditions of eustatic rise, and thus delineates a “maximum flooding zone” around 7.5 cal kyr BP that is correlative with the time of maximum marine ingression in the region shown by the shoreline trajectory (Fig. 7). Upwards, the opposite trend is observed: the superposition of drying-upward trends of decreasing intensity, documented by decreasing hydrophytes/helophytes ratios within successive peat layers (Fig. 4), is interpreted as the vertical expression of a progradational stack of shallowing-upward successions.

Symmetrical changes in stratal thickness of peaty units reflect the paleoenvironmental evolution of the area. The post-Last Glacial Maximum sea-level rise was far too rapid to sustain paralic peat formation (Diessel, 2007). Accommodation was created at a faster rate than could be filled by vegetal matter, thus causing widespread flooding of peatlands. This is clearly reflected in the lower TST, where peat beds are thin and indicate reduced peat accumulation in short-lived, large swamps punctuating the landward fringe of wide lagoonal/estuarine environments during transgression (Bruno et al., 2017).

At the turnaround between retrogradation and aggradation, a high water table and little introduction of clastic material due to retarded river sediment supply made areas landwards of the maximum brackish incursion ideal nucleation sites for widespread, permanent mires (Flint et al., 1995; Jerrett et al., 2011). Clustering of basin swamp peats (lithofacies Sw1) (Fig. 6) suggests that maximum peatland expansion was accompanied by the warmest conditions, thus supporting an overall glacio-eustatic control on peat development. Optimum peat accommodation conditions lasted for a relatively short interval (about 2.5 kyr) of relative sea-level stability that immediately followed maximum marine ingression. The permanency of the innermost barrier system between ca. 7.0 and 4.5 cal kyr BP (Fig. 7) favoured the outbuilding and preservation of the thickest peat-bearing units in a back-barrier position, resulting in a characteristic aggradational trend across the MFS. Autogenic mechanisms, including continuous basin subsidence (enhanced by peat compaction) and abrupt changes in clastic sediment supply (due to river avulsion) or some combination of these two factors likely exerted a major influence in controlling the stacking of small-scale coarsening-upward units during this phase of generalized aggradation (Amorosi et al., 2017a).

Burial by clastics in a high sediment supply regime via crevasse and/or overbank processes is likely to have prevented significant peat production and accumulation in the overlying prograding complex. Compaction rates significantly influenced vertical and lateral stratigraphic trends during deltaic evolution, the fastest compacting layers being composed primarily of peat (Meckel et al., 2007; Van Asselen, 2009; 2011; Bruno et al., 2017). The key to delta-plain construction is avulsion (Bhattacharya, 2006), which resulted in a high potential of forming freshwater swamps and peatlands with only localised peat accumulation. Within the HST, peat layers likely represent flooding surfaces that formed as the progradational bodies were abandoned and drowned (Tibert and Gibling, 1999).

7.2. High-resolution accommodation records: application to paralic coal seams

The development of organic-rich layers can be seen as a precursor to the coal seams and carbonaceous mudstones preserved in the ancient record. Although caution should be taken in considering modern peat-bearing deposits as analogous to coal (Moore et al., 1996) and thickness of peats in the Holocene of the Po Plain is not directly comparable with those in the Tertiary Latrobe Valley coal beds of Australia and in Cretaceous stacked coal beds of U.S. Western Interior, refined stratigraphic and palynological analysis of Holocene, upward-shoaling organic-rich successions can be of help in predicting coal occurrence and geometry within a high-resolution sequence stratigraphic framework. A comprehensive model for the occurrence and distribution of coaly rocks in a depositional sequence that integrates accommodation, groundwater flow and sea-level change has been proposed by Bohacs and Suter (1997) and new surfaces have been added to the sequence-stratigraphic analysis of non-marine sediments (Diessel et al., 2000; Wadsworth et al., 2003; Jerrett et al., 2011).

In the Holocene succession of the Po Plain, peat occurs in both “regressive” and “transgressive” lithofacies successions (Fig. 7). At relatively seaward locations, flooding surfaces primarily reflect the superposition of marine-influenced (interdistributary bay and lagoon) deposits onto “regressive” freshwater peat (Give-Up Transgressive Surfaces of Diessel et al., 2000 - GUTS in Fig. 8). These surfaces, which are readily identified through integrated paleoecological analysis of mollusks, benthic foraminifers, and ostracods (Amorosi et al., 2017a), indicate that peat formation was halted by influxes of brackish water into the mire, as soon as transgression occurred. Under deepening conditions, the overall increase in accommodation overwhelmed the accumulation rate of peat. When peat could not keep up with groundwater table rise, the mire eventually drowned and the peat layer grades into a lagoonal/bay clay through a tidal/bay ravinement surface marked by a veneer of brackish shells (Fig. 9). As a practical matter, these marine flooding surfaces are physically traceable to the top of a peat (Diessel, 1992; Bohacs and Suter, 1997 – Fig. 8).

Farther inland, as documented in this paper (Figs. 3-5), transgressive peat beds occur at or close to the base of rhythmic, upward shoaling successions (Fig. 5), thus marking more or less abrupt increasing accommodation conditions. Based on pollen data (Fig. 4), flooding surface equivalents at the base of peats represent “Paludification Surfaces” of Diessel et al. (2000) (PaS in Fig. 8), which are physically correlative in a distal position with the GUTSs (Fig. 8). The boundary between organic-matter-rich deposits and overlying, modern floodplain facies represents the exposure surface of Diessel et al. (2000) (ES in Fig. 8), whereas the base of "regressive" peats in downdip direction marks the "Terrestrialization Surface" (TeS in Fig. 8).

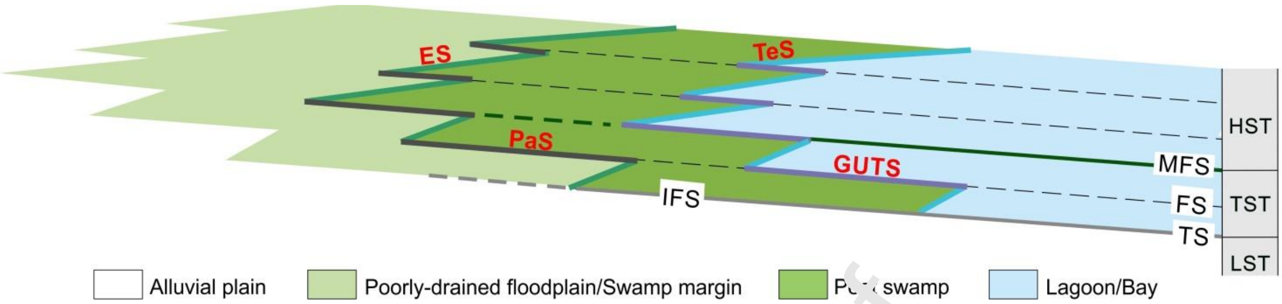

Fig. 8. Diagrammatic stratigraphic architecture of retrogradational, aggradational and progradational paralic depositional systems across the Holocene succession of the Po Plain and related key sequence-stratigraphic surfaces. Along flooding surfaces (FS), give-up transgressive surfaces (GUTS) atop "regressive" peat beds correlate upstream to paludification surfaces (PaS) at the base of "transgressive" peat layers (lithofacies Sw1). TeS: Terrestrialization surface, ES: Exposure surface, TST: Transgressive Systems Tract, HST: Highstand Systems Tract, IFS: Initial Flooding Surface, TS: Transgressive Surface, MFS: Maximum Flooding Surface.

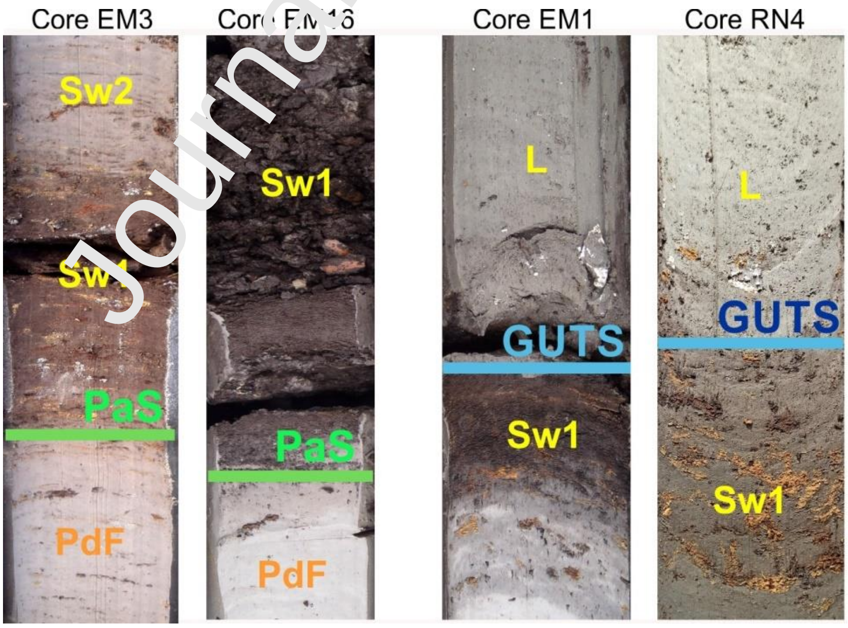

Fig. 9. Abrupt lithofacies changes across marine flooding surface equivalents at the transition from freshwater to brackish depositional systems (see conceptual model in Fig. 8). Paludification surfaces (PaS) at the base of "transgressive" peats (cores EM3 and EM16) reflect abruptly increased accommodation and are laterally correlative with Give-Up Transgressive Surfaces (GUTS) atop "regressive"peat beds (cores EM1 and RN4). Sw1: basin swamp peat, Sw2: swamp margin clay, PdF: poorly-drained floodplain clay, L: lagoon/bay clay.

The peak in aquatics (especially hydrophytes) within the overall deepening-upward trend is considered as the sedimentary expression of the MFS at proximal locations (Fig. 5). This surface can be traced down depositional dip into time equivalent brackish, coastal and shallow-marine strata (Fig. 7).

7.3. Peat-bearing parasequences

The vertical stacking of sedimentary and pollen facies portrayed in the previous sections, with its characteristic shoaling-upward trends punctuated by episodes of transgression (Figs. 3-5), is interpreted as the expression of parasequences in the proximal setting, distant from coastal influences. The terrestrialization trends illustrated in this study are essentially non-marine analogs of shallowing-upward cycles identified in marine successions (Holdgate et al., 2014; Korasidis et al., 2019).

The nature of contacts of sedimentary facies immediately underlying the parasequence boundary is crucial to the use of the term parasequence. Possible equivocal aspects and inconsistencies associated with the parasequence concept and with its usage have been raised by several authors (see Catuneanu and Zecchin, 2020, for a review). In the Holocene peat-bearing deposits of the Po Basin, the lower boundaries of lithofacies Sw1 mark the most waterlogged conditions (Fig. 5) and are assumed to be parasequence boundaries. These surfaces represent short duration events and are associated with significant changes in lithofacies and vegetation patterns. In cross-section, these abrupt contacts of relatively deeper-water facies onto relatively shallow-water deposits translate into substantial landward shifts of facies, i.e. 'non-Waltherian' facies dislocations (Fig. 5). The overlying, peat-free layers locally exhibit evidence for subaerial exposure or elevation above groundwater tables (Fig. 5). The overlying parasequence boundary marks renewed drowning and peat formation.

Holdgate et al. (1995) applied the sequence-stratigraphic nomenclature of Van Wagoner et al. (1988; 1990) to coal-bearing successions and defined similar lithotype cycles as parasequences. Consistent with their work, we extend the parasequence definition to peat-bearing units into the paralic realm, to encompass surfaces across which there is evidence of either abrupt increase in salinity (i.e., sharp change from freshwater to brackish environments) or transition to more waterlogged environments, which also implies substantial facies dislocation. Tight temporal constraints in Holocene transgressive deposits of the Po Plain allow unequivocally to tie shallowing-upward, peat-bearing successions bounded by flooding surface equivalents to the correlative retrogradational parasequence set observed in the nearshore-marine setting, thus supporting their interpretation as parasequences (Fig. 7).

The majority of parasequences display clear shallowing-upward (or drying-upward) trends. However, in this high-subsidence, high-sediment-supply-rate setting, the basal intervals of some parasequences may record some deepening-upward. Where peat is underlain by a transitional boundary, the placement of the parasequence boundary can be ambiguous (Petersen et al., 1998; Diessel et al., 2000; Catuneanu, 2019). In this case, the peat bed that records the gradual transition from deepening to shallowing conditions contains an accommodation reversal surface (Diessel et al., 2000).

In the rock record, it is virtually impossible to distinguish between mechanisms of water table control on the original peat type (Moore and Shearer, 2003). The distinctive pollen signature of Holocene peat-bearing deposits of the Po Plain and overall parasequence architecture suggest a direct link between relative sea-level rise, flooding surface development and peat accumulation at parasequence boundaries.

8. Conclusions

Predicting occurrence and geometry of coals and carbonaceous mudstones within a sequence stratigraphic framework requires refined stratigraphic correlation between sampling localities and an excellent chronostratigraphic control on the stacking patterns of coal-bearing cycles, which is not always available. Sediment core analysis supplemented by palynologic investigations within the fine-scale chronostratigraphic framework of the Holocene succession of the Po Plain system can add refinement to sequence stratigraphic interpretations of non-marine strata that are enriched in organic matter.

In this study, through the examination of rhythmic bedding patterns developed on short (millennial to sub-millennial) timescales, we provide evidence for sharp-based, meter-scale packages of peat-bearing strata that represent synchronous, regionally mappable depositional units that correlate basinwards to coeval brackish and nearshore depositional systems. Major conclusions are as follows:

(1) The vertical stacking of peat-bearing facies primarily reflects overall shoaling-upward (terrestrialization) trends that ideally include: (i) a basal, dark peat bed (lithofacies Sw1), which represents the sedimentary facies formed under conditions of greatest water depth and minimal sediment supply; this is overlain by (ii) a swamp margin clay (lithofacies Sw2), and by (iii) a

thickening-upward succession of crevasse splay (CL) and/or poorly drained floodplain (PdF) or distributary channel (Ch) deposits that may cap the sequence.

(2) Upward shoaling successions, 2-5 m thick, represent variations in the balance between rates of accommodation and peat accumulation that may provide an onshore indication of sea-level variations (TST) and autogenic controlling factors (HST) developed on millennial to sub-millennial timescales.

(3) Vegetation patterns used in conjunction with sedimentary facies enable the precise delineation of “flooding surfaces” that in freshwater environments reflect abrupt rise in groundwater levels. Fluctuations in the relative abundance of aquatics (hydrophytes+helophytes) and woody and herbaceous mesophytes record alternating periods of rising/falling water table, respectively. Peat beds reflect the most drowned conditions and their lower boundaries represent the landward counterparts of marine flooding surfaces developed distally.

(4) Basal peats represent periods of warming. The emplacement of distributary channel and crevasse sand bodies at top of shallowing-upard packages occurred, instead, during periods of expansion of the montane vegetation belts (cooling phases).

(5) In the sequence-stratigraphic terminology of freshwater depositional systems that characterizes coal-bearing units, marine flooding surface equivalents consist of paludification surfaces that are correlative downdip, in the brackish realm, to give-up transgressive surfaces.

Although the Po Plain peat layers would only amount to a very small fraction of the thick, economic deposits of coals for mining/development as exemplified by the Latrobe Valley lignites, the palyno-stratigraphic filter of preserved Holocene strata presented in this paper can be used to construct high-resolution, predictive models for interpreting the geological record of largely non-marine deposits away from detailed chronologic control. Delineating facies architecture of peat-bearing successions through updip tracing of high-frequency flooding surfaces on millennial to centennial timescales can provide insights into the high-resolution record of ancient water table fluctuations at an unprecedented level of detail. It also may allow us to improve our understanding of factors that control accumulation of coal and carbonaceous mudstones in the rock record. The use of ecological groups *in lieu* of taxa can also provide a modern analog to predict peatland response to high-frequency relative sea-level fluctuations.

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Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author.

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Author statement

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

- Using pollen data we traced marine flooding surfaces in freshwater wetland deposits
- Peaks in aquatics at the base of freshwater peats mark flooding surface equivalents
- Peat beds exhibit maximum thickness in aggradational strata of the lowermost HST
- Peat-bearing cycles reflect drying-upward trends due to changes in accommodation
- Paludification surfaces correlate basinwards to give-up transgressive surfaces