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Evolution of the Po–Alpine River System during the Last 45 Ky Inferred from Stratigraphic and Compositional Evidence (Ostiglia, Northern Italy)

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Abstract: The stratigraphic and compositional study of three sediment cores recovered close to the Po River near Ostiglia provides clues on changes in fluvial dynamics at the transition from the last glacial to the present interglacial. Upper Pleistocene units are dominated by sands with high content in volcanic lithics, denoting high sediment supply from the south-Alpine fluvio-glacial tributary system. The Early–Mid Holocene unit, peat-rich and barren in fluvial sands, results from low sediment supply and waterlogging, encompassing the maximum marine ingression. The Late Holocene unit, characterized by fluvial-channel sands with lower content in volcanics and relatively abundant metamorphic lithics, records the Po River sedimentation since the Late Bronze Age. Late Holocene sands show a lower content in siliciclastic lithic fragments (supplied mainly by Apennine tributaries) compared to modern Po River sands. This distinctive composition could reflect the diversion of Apennine sediments into a southern Po River branch during the Late Bronze Age and into an Apennine collector flowing south of Ostiglia during Roman times and the Middle Ages. The integrated stratigraphic-compositional methods used in this study permitted to reconstruct the major climate-related changes in sediment dispersal and may be potentially applied to other alluvial and coastal settings.

Keywords: Upper Pleistocene–Holocene stratigraphy; sand composition; Po River; Alpine–Apennine tributaries

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1. Introduction

Alluvial and coastal plains store in their subsurface evidence of past environmental changes. In multi-sourced alluvial basins, compositional data, framed in a detailed stratigraphic picture, may provide clues on changes in sediment provenance that reflect past modifications of the river network [1–4]. An integrated stratigraphic-compositional approach is particularly effective in late Quaternary studies for two main reasons: (i) drainage basins did not experience significant modifications during this relatively short time window, and the composition of preserved deposits is essentially comparable with composition of modern rivers [5,6]; (ii) the availability of high-resolution dating permits a chronological control on alluvial stratigraphy at the scale of the millennia/centuries [7–9]. In this perspective, every single sediment body can potentially be related to the activity of a specific watercourse during a precise time interval.

The Po Basin, in northern Italy, is a multi-sourced sedimentary basin fed by the Po River and a dense network of tributaries. Most of these rivers flow unconfined in the alluvial plain for large tracts of their courses [10]. This configuration resulted in frequent nodal avulsions before the construction of metre-high embankments [11,12]. As a consequence, different watercourses deposited their load in different areas through time [5,6,13,14]. The aim of this work is the reconstruction of the depositional history of the area around the town of Ostiglia, located on the eastern side of a Po meander

(Figures 1 and 2). Historians Polybius and Plinius document that the Po River already flowed in the Ostiglia area in Roman times (*Naturalis Historia*, XXI-73). However, historical notes and archaeological data allow the stepping back in time for just a few millennia. In this work the major hydrographic changes in the Ostiglia area during the last 45 millennia were reconstructed through combined stratigraphic and petrographic analysis on three 30-m long cores recovered along the northern embankment of the Po River. The aims of this paper are: (i) to contribute to the reconstruction of the sedimentary evolution of the Po alluvial plain during the Late Pleistocene and Holocene; (ii) to highlight how the major changes in the Po River network are reflected in the sedimentary record of a relatively narrow 20 km^2 area; (iii) to discuss the main factors controlling fluvial architecture.

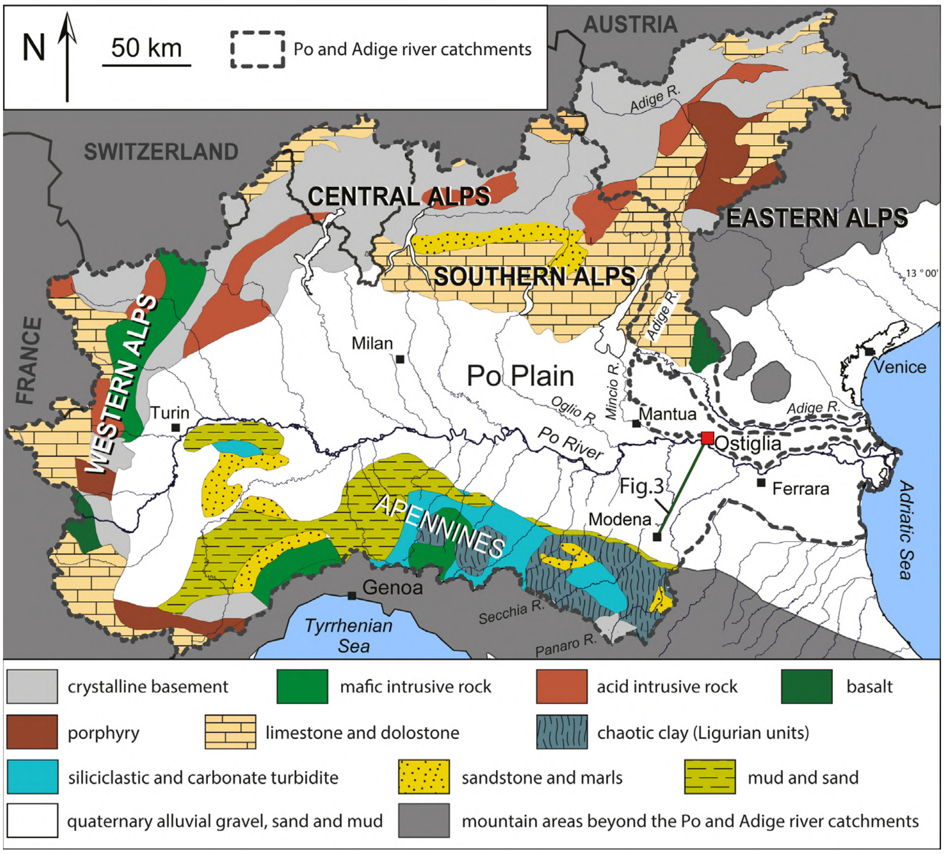

Figure 1. Lithological map of the Po and Adige river catchments. Lithological units cropping out in the drainage basin of the Po and Adige rivers (modified after [14]).

2. Background

2.1. The Po Basin

The Po Basin in Northern Italy (Figure 1) is a foreland basin bounded by two mountain chains, the south-verging Southern Alps to the north and the north-verging Northern Apennines to the south [15]. This structural setting originated in response to the collision between the Adria microplate and Eurasia, which began in the Cretaceous [16] and references therein). High subsidence rates in the Po Plain were generated by the tectonic loading of the two chains [17–19].

The Po Basin records a complete foredeep cycle, from underfilled (deep marine) to overfilled (continental) stage [20]. The beginning of continental sedimentation is marked by a regional unconformity dated to ca. 870 ky BP [21–24]. Continental deposits are up to 400 m thick [14].

Upper Pleistocene to Holocene continental deposits in the study area display a clear bipartition between a mud-dominated southern sector fed by Apennine rivers [14], and a sand-dominated northern sector (Figure 3) fed by the Po River and its Alpine tributaries [13,14,25]. The Po River deposited a 20-km wide channel-belt sand body during the Würmian glaciation (Figure 3; [14]). Holocene deposits are instead characterized by ribbon-shaped fluvial channel bodies enclosed in abundant poorly drained floodplains and swamp muds [26]. The boundary between the Po and the South-Alpine deposits has been locally reconstructed. West of the study area it corresponds to an erosional surface which separates Upper Pleistocene fluvio-glacial (South-Alpine) deposits to the north from Holocene fluvial deposits to the south [25]. East of the study area, in the coastal plain, stratigraphic and compositional data highlight a dynamic system fed by a distal paleo-Po River with episodic sediment input from the South Alpine and Apennine rivers [6].

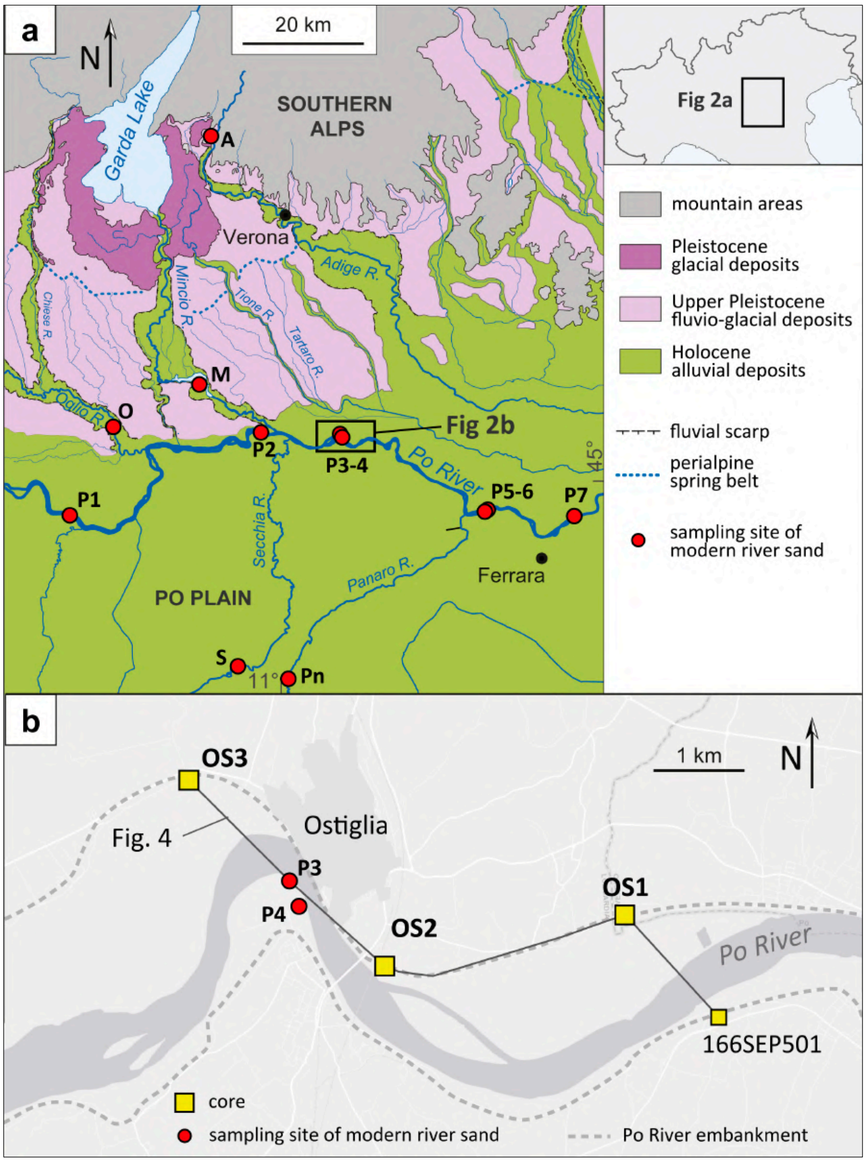

Figure 2. Location of study area. (**a**): Geological map of the Po Plain with location of the study area and of sampling sites of modern river sands (modified after [27]). (**b**): close-up on the study area with the locations of the analyzed cores.

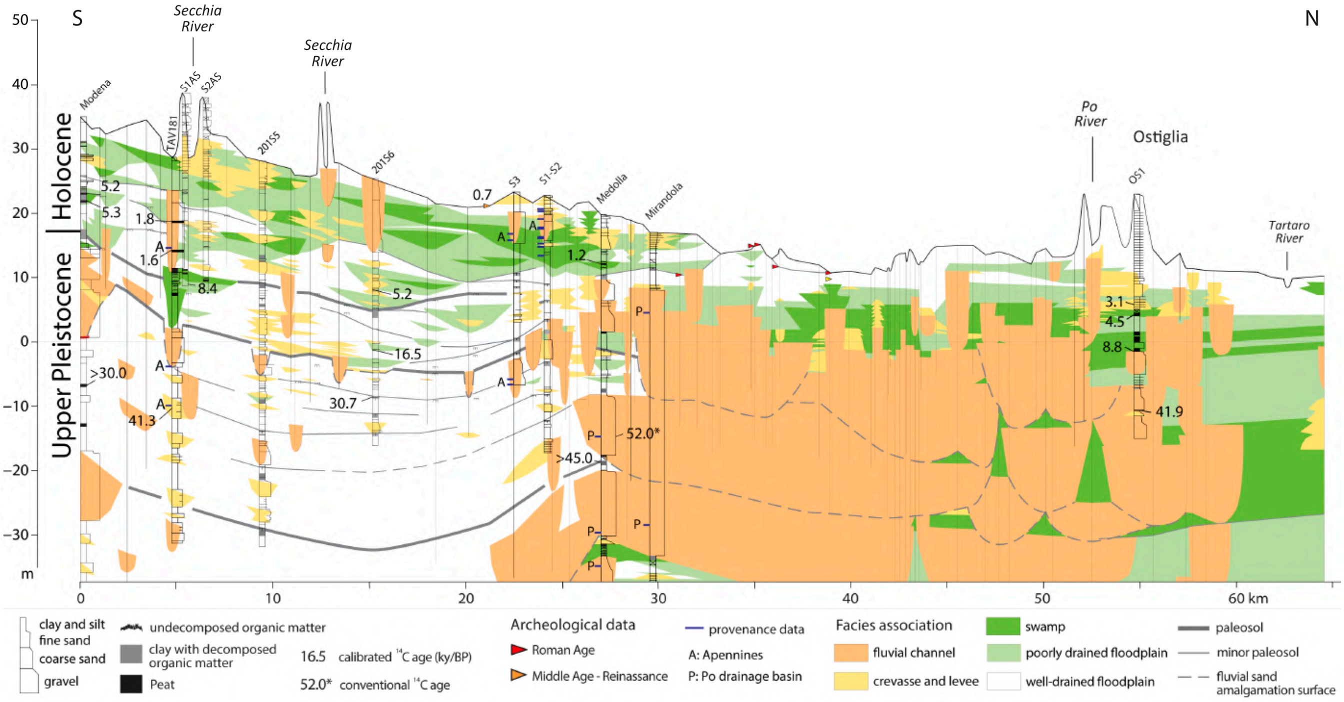

Figure 3. Late Quaternary stratigraphy of the Po Plain. Stratigraphic architecture of Upper Pleistocene and Holocene deposits along a south-north oriented stratigraphic cross section (modified after [14]). Location in Figure 1.

2.2. The Po Drainage System

The Po River, the longest watercourse in Italy, originates in the Western Alps, which are characterized by extensive outcrops of ultramafic and metamorphic rocks (Figure 1). Along its 652-km-long course towards the Adriatic Sea, the Po River interacts with a dense network of transverse tributaries draining catchments with distinct lithotypes. The northern tributaries from the Central and Southern Alps drain an area mainly characterized by carbonate (limestone and dolostone), plutonic-volcanic and metamorphic rocks (Figure 1). In the Po Plain sector, these rivers flow entrenched into Upper Pleistocene fluvio-glacial deposits, bordered by fluvial scarps, with maximum height of about 40 m close to the alpine margin. Based on sparse radiocarbon dates, Alpine rivers' entrenchment is dated to the end of Last Glacial Maximum (LGM, ca. 17–18 ky BP; [25,27]). Close to the Ostiglia area, the main tributaries of the Po River are the Oglio and Mincio rivers. Both rivers are effluent of peri-Alpine lakes (Iseo and Garda, respectively), which formed after the LGM in place of former glacial tongues [27]. The Adige River flows in north-south direction east of the Garda Lake, and then turns eastward, towards the Adriatic Sea (Figures 1 and 2). A set of minor rivers originated by a spring line located few kilometers south of the Alpine piedmont (Figure 2a); among these, the Tione and Tartaro rivers flow close to the Ostiglia area. The main southern tributaries of the Po River flowing through the study area are the Secchia and Panaro rivers. These rivers drain a sector of the northern Apennines dominated by sandstone, limestones, mudstone and flow in the Po Plain, bordered by anthropogenic levees. Whereas the South Alpine drainage system did not experience substantial modifications during the Holocene, the Apennine river system was characterized by a strong channel mobility, as highlighted by a dense network of abandoned fluvial ridges [10].

3. Materials and Methods

The village of Ostiglia is located on the north bank of a Po River meander (Figure 2b) close to the confluence of the Oglio (31 km), Mincio (11 km) and Secchia rivers (9 km) and 58 km south of the Adige valley outlet. The Tione and Tartaro rivers, and a set of minor watercourses originating from the perialpine spring-line, flow only 4 km north of Ostiglia. This particular location makes Ostiglia a key area for assessing Late Pleistocene and Holocene changes in sediment provenance through the analysis of core sediments.

Three cores (OS1, OS2 and OS3, locations in Figure 2b), 38-m-long, recovered along the Po River embankment, have been analysed and sampled for the characterisation of the depositional facies. Each core has been described in terms of lithology, grain-size, colour, consistency and accessory material (vegetal remains, peat and carbonate concretions). This study benefits from a well-known stratigraphy and from 15 radiocarbon dates from previous works [14,26]. The chronological framework has been improved with five new radiocarbon dates from wood, peat and soil samples collected from cores OS1 and OS3, carried out at the Geoanalysis center of the Korea Institute of Geoscience and Mineral Resources (KIGAM). Conventional ^{14}C ages were calibrated using OxCal 4.4 [28] with the IntCal 20 curve (see Table 1; [9]). Facies associations, observed in the analysed cores, were correlated in a 7.3 km-long cross-section with the aid of available ^{14}C data. A nearby core from Campo et al. (2016) [26] has also been considered. Stratigraphic units were defined, based on facies relationships and on the identification and lateral tracking of their bounding surfaces. The latter are marked by: (i) sharp facies change; (ii) erosional surfaces or (iii) amalgamation surfaces.

Table 1. List of radiocarbon dates. Details on radiocarbon dates from cores OS1 and OS3.

Core	Lab	Material	Depth (m)	^{14}C Age	Calibrated Age (mean ± 2σ)	Lab Code
OS3	KIGAM	soil	13.7	2442 ± 25	2520 ± 220	KGM-OSa200128
OS1	KIGAM	wood	17.2	2949 ± 25	3100 ± 50	KGM-OWd200614
OS1	KIGAM	peat	18.8	4030 ± 26	4490 ± 40	KGM-OWd200623
OS1	KIGAM	peat	24.5	7924 ± 34	8780 ± 220	KGM-OSa200130
OS1	KIGAM	peat	33.6	37111 ± 245	41900 ± 400	KGM-OSa200127

Petrographic analyses were carried out on 14 samples: 8 sand samples were collected from cores OS1 and OS2 and 6 from modern rivers. The modal analyses of cores were compared with detrital modes of samples collected from modern rivers: Po (3 samples, this work; 4 samples from [14]), Oglio (sample O in Figure 2a), Mincio (sample M) and Adige (sample A). The composition of modern Secchia and Panaro rivers [29,30] was also considered. Samples were treated with dilute H2O2 to remove organic matter and were dried and sieved to obtain fine-sand fraction (0.250–0.125 mm, 2–3 φ). The selected fraction was impregnated in epoxy resin under vacuum and processed to obtain thin sections. Point counting of 300 grains for each thin section, was performed under transmitted-light microscopy according to the Gazzi-Dickinson method, designed to minimize the dependence of the analysis on the grain-size [31]. Although all grain components were analysed, only those with similar hydraulic behaviour (quartz, feldspars and lithic fragments—volcanic, metamorphic and sedimentary) were considered for provenance analyses (see [32]). Considering that the transport invariant components are essential for provenance analyses as demonstrated by Weltje (2004) [33], Garzanti et al., (2008) [32] and Razum et al., (2021) [34]. Along single core, one sample per stratigraphic unit was collected, based on the assumption of low intra-unit compositional variations, see Lugli et al., (2004, 2007) [29,30], Fontana et al., (2019) [13] and Bruno et al., (2021) [14].

4. Results

4.1. Facies Associations

This section provides a brief description of facies associations recognized through analysis of cores OS1, OS2 and OS3. Five facies associations have been identified based on lithology, grain-size, grain-size trends, colour, consistency and accessory material (wood, plant remains, peat, carbonate concretions, iron and manganese oxides, macrofossils).

4.1.1. Fluvial Channel (Fc)

This facies association is characterized by sand bodies more than 3.5 m thick (Figure 4). Sand is coarse to fine, with an overall fining-upward (FU) trend. Accessory materials, such as wood, vegetal remains and fragments of freshwater fossils, are rare.

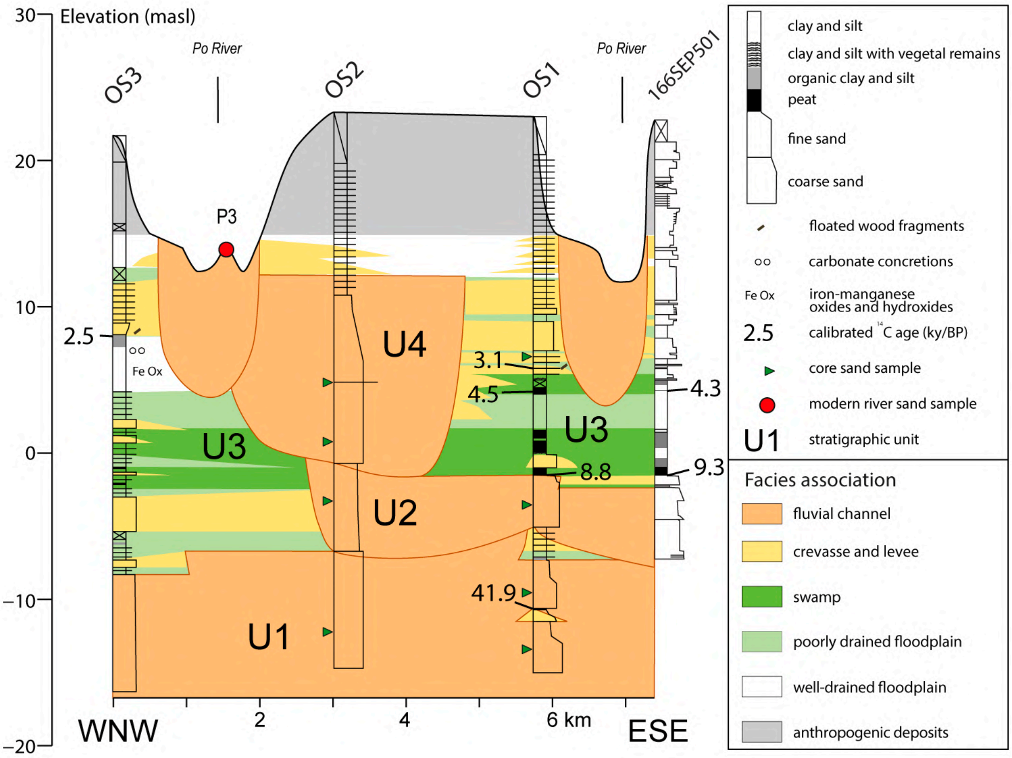

Figure 4. Stratigraphy of the Ostiglia area. Correlation panel showing facies distribution in the subsurface of the study area down to 38 m depth (location in Figure 2b). Details on radiocarbon dates from cores OS1 and OS3 are in Table 1. Stratigraphy and radiocarbon dates from core 166SEP501 are from [26].

Based on lithology, thickness and internal FU trend, this facies association could be interpreted as fluvial-channel deposits [35].

4.1.2. Crevasse and Levee (CL)

This facies association has a maximum thickness of 5 m and has been observed in cores OS1 and OS3; it consists of fine sand, silty sand and sandy silt, with both coarsening-upward (CU) and FU trend, locally arranged in rhythmic alternations at the decimetre scale. This facies association is laterally associated with fluvial-channel deposits (Figure 4). Floated wood fragments are rare.

Grain size, thickness and lateral relationships with fluvial channel facies permit to interpret these deposits as a channel-related facies association. Sand bodies with internal CU trends are interpreted as crevasse splays (the upward increase in grain size registers the progressive breach of the levee), whereas FU sands correspond to crevasse-channel deposits. Sand–clay alternations are interpreted as levee deposits, formed in response to repeated overflow events.

4.1.3. Swamp (SW)

This facies association, observed in cores OS1 and OS3, consists of plastic to very plastic clays and silty-clays, with occasional millimetre-scale sandy silt intercalations. Thickness ranges between 1.3 and 3 m. Colour is grey or dark grey. Organic matter is abundant in the form of sparse vegetal remains and of wood–peat layers. Rare fragments of freshwater fossils have been observed. Iron and manganese oxides are absent.

The grain size of these deposits suggests a low-energy interfluvial environment. The dark colour and the abundance of organic matter indicate reducing conditions, typical of swamp environments, that favoured the preservation of plants remains [36,37].

4.1.4. Poorly Drained Floodplain (PDF)

This facies association, up to 2 m-thick, includes light grey clay and silt with plastic consistency (Figure 4). Plant remains and wood fragments are rare, as well as freshwater mollusc fragments. Iron and manganese oxides and hydroxides are absent. Isolated millimetre-scale carbonate concretions have been observed.

The fine-grained size combined with the presence of carbonate nodules suggest sedimentation in an interfluvial environment. The grey colour, as well as the absence of oxidation-reduction features, indicates poor drainage conditions (poorly drained floodplain).

4.1.5. Well-Drained Floodplain (WDF)

This facies association is observed only in the core OS3 at about 15 m depth. It is about 4 m thick and consists of yellow-brownish clays with compact consistency. Carbonate concretions and iron-manganese oxides and hydroxides were observed. Undecomposed plant remains and body fossils are absent.

Grain-size indicates a low-energy interfluvial environment, while the compact texture, the colour and the presence of carbonate concretions and iron and manganese oxides suggest a low groundwater table. These features are ascribable to a well-drained floodplain environment.

4.1.6. Anthropogenic Deposits

This facies association, corresponding to the uppermost 9 m of the cored succession (Figure 4), is composed of a mixture of clay, silt and silty sand, including anthropogenic material (mainly concrete and brick fragments).

These deposits constitute the modern artificial levees of the Po River.

4.2. Stratigraphy of Cores OS1, OS2 and OS3

The correlation of facies associations recognized in cores OS1, OS2 and OS3, combined with those described in core 166SEP501 [26], led to the definition of four stratigraphic units (U1 to U4 in Figure 4).

The deepest unit U1 is dominated by fluvial channel sands, with a thin (~1 m) crevasse-levee lens observed in OS1 at about 34 m depth. This unit extends along the whole cross-section from bottom-cores to about 30 m depth (−7 m asl). The boundary with the overlying unit U2 is erosional in cores OS2 and 166SEP501 and marked by the upward transition to the poorly drained floodplain and crevasse-and-levee deposits in OS1 and OS3. The radiocarbon date of 41.9 ky BP from core OS1 indicates a Late Pleistocene age for this unit.

Unit U2 is characterized by the presence of less extensive fluvial channel deposits, 5–8 m thick, passing laterally to poorly drained floodplain and crevasse-and-levee deposits (Figure 4). The upper contact with U3 is marked by a peat layer in cores OS3, OS1 and 166SEP501 (Figure 4). In OS2, unit U2 is overlain by U4 with erosional contact, which was tentatively placed in correspondence of a subtle grain-size change at 24 m depth. Available radiocarbon dates from the underlying unit U1 and from peat layers of cores OS1 and 166SEP501 (8.7 and 9.3 ky BP, respectively), suggest deposition of this unit during the Late Pleistocene–Holocene transition.

Unit U3, about 7 m thick, is preserved in cores OS3, OS1 and 166SEP501 and is dominated by swamp and PDFP deposits (Figure 4). Crevasse-and-levee deposits are rare and rather thin (<1 m); fluvial channel sands are absent. Peat layers are abundant at the base and at the top of the unit. A paleosol marks the top of the unit in core OS3. Radiocarbon dates permit to assigning this unit to 9–2.5 ky BP.

U4 is characterized by a 11.5 m-thick fluvial-channel sand body in OS2 and by the associated crevasse-levee deposits in OS3, OS1 and 166SEP501 (Figure 4). The lower boundary of the unit is diachronous. Indeed, crevasse-levee deposits attributed to U4 are dated to 3.1 ky BP in OS1 and are younger than 2.5 ky BP in OS3.

Unit U4 is locally overlain by anthropogenic deposits, which represent the modern artificial levees of the Po River (Figure 4).

4.3. Sand Petrography

4.3.1. Core Sands

The results of the modal analysis were plotted in the Q + F (quartz and feldspar)- L –(siliciclastic lithic)-C (carbonate lithic) ternary diagram (Figure 5a) and reported in the barchart of Figure 6a. The distribution of lithic fragments is shown in the diagram of Figure 5a: Lm (metamorphic lithic)–Lv (volcanic lithic)–Ls (sedimentary lithic, carbonate included). Samples were collected from units U1 (3 samples), U2 (2 samples) and U4 (3 samples). Sands suitable for petrographic analyses were not encountered in unit U3.

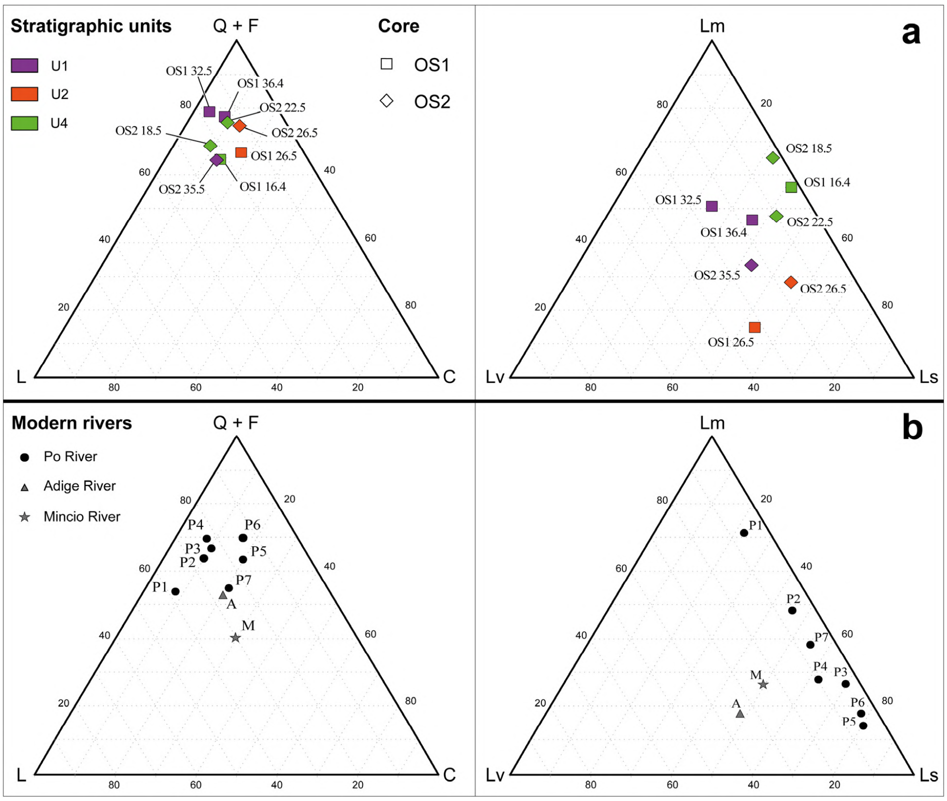

Figure 5. Composition of sands from Ostiglia cores and modern rivers. Ternary diagrams showing composition of sands from cores OS1 and OS2 (**a**) and from modern rivers (**b**). Q + F: quartz and feldspar; L: siliciclastic lithics; C: carbonate lithics; Lm: metamorphic lithic; Lv: volcanic lithic; Ls: sedimentary lithic.

The analysed sands exhibit an overall abundance of quartz and feldspars, with values ranging from 76% of the analysed sand fraction in the deepest unit U1 (OS1 32.5) to 57% in the shallowest unit U4 (OS1 16.4). Quartz is generally more abundant than feldspars and is present mainly as single crystal; both fine- and coarse-grained polycrystalline quartz are subordinate. Feldspars include both plagioclase and k-feldspar, the latter represented mainly by orthoclase and microcline. Metamorphic lithics, consisting of low-grade phillades and micascists, are present in all samples and relatively more abundant in unit U4, reaching values close to 20% in samples OS1 16.4 and OS2 18.5. Volcanic lithics are relatively abundant in units U1 and U2, where they represent up to 10% of the sample, whereas unit U4 shows very low values, <1% (OS1 16.4 and OS2 18.5). Volcanics are mainly acidic aphanitic to microcrystalline, more rarely with porphyritic structure.

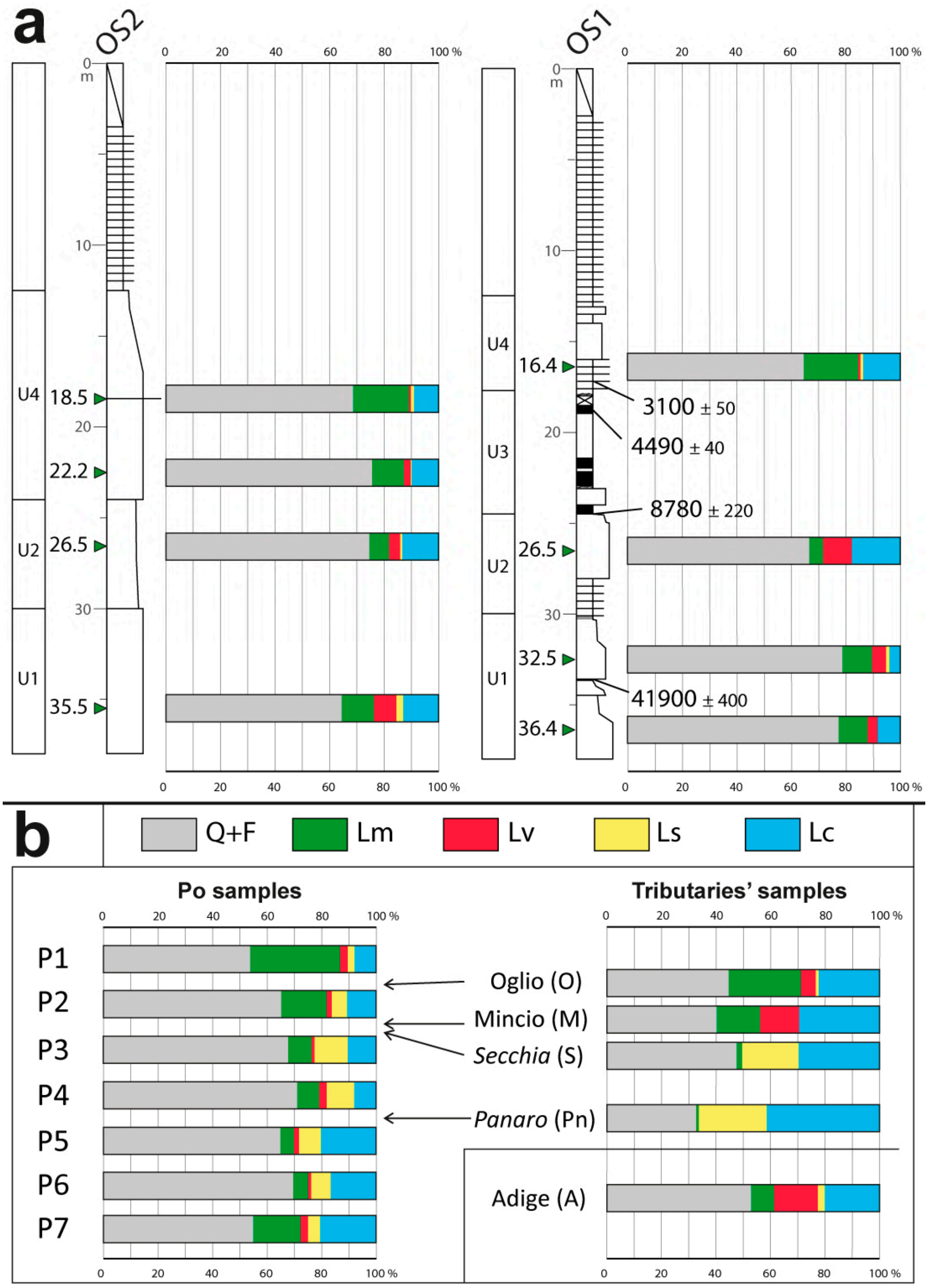

Figure 6. Composition of sand samples reported as barchart (**a**): composition of sands from OS2 and OS1 reported in the logs at the sampling level. (**b**): composition of sands from the modern Po, Oglio, Mincio, Secchia, Panaro and Adige rivers. The arrows indicate river confluences. The Adige River is shown in a separate box as it is not a Po tributary. Apennine rivers are in italics.

Sedimentary lithics consist almost exclusively of carbonate lithics that constitute 10–15% of the examined samples. Values lower than 10% are observed in samples OS1 32.5

and OS1 36.4 (unit U1). Only sample OS1 26.5 yielded a value higher than 15%. Sparitic and microsparitic carbonates represent the most common carbonate grains; micritic carbonates are subordinate. Mesozoic carbonate grains made up of oolitic and peloidal packstones to grainstones, including local Cretaceous foraminifera, have been observed in samples from units U1 and U2. In samples OS2 35.5, OS2 26.5 and OS1 32.5 numerous carbonate grains show a characteristic oxidation as rim and along the cleavage planes. Siltstones, shales and serpentinites are subordinate lithic grains. Other minor components include micas (muscovite, biotite and chlorite) and heavy minerals (largely garnet), whose abundance is highly variable.

Significant differences in the distribution of lithic fragments between samples of units U1 and U2 and samples of unit U4 were observed (Figures 5a and 6a). The sands of units U1 and U2 are characterized by a significant content of volcanic lithics (in particular, samples OS2 35.5, OS2 26.5 and OS1 26.5, Figures 5a and 6a), while unit U4 is rich in metamorphic lithics and very poor in volcanics. The Q/Lsed ratio for all samples is comprised between 2.1 and 5.8. The Q/Lv ratio ranges between 3.5 and 12.8 in units U1 and U2 and between 22.7 and 64.5 in unit U4.

4.3.2. Modern River Sands

In the central Po Plain, the Po River collects water and sediment from Apennine and Alpine tributaries (Figures 1 and 2), which contribute to changing sand composition downstream (Figure 6b). In this work the fluvial-bar sands collected along a sector of the Po River, extending 125 km west of Ferrara (Figure 2), and from the Oglio, Mincio and Adige rivers, were analysed. Composition of Panaro and Secchia rivers (two representative samples, S and Pn, are reported in Figures 2a, 5b and 6b) have been calculated after Lugli et al., (2004; 2007) [29,30].

The results show a marked difference in the Po sand composition from the westernmost (P1) to the easternmost sample (P7, Figure 5b). Sample P1 is rich in metamorphic lithics (>22% of the examined sand fraction), with a relative moderate content in quartz and feldspars (~37%). Downstream there is an overall increase in quartz + feldspar (up to ~59%) and sedimentary lithics (up to ~25), particularly evident after the confluence of the Secchia and Panaro rivers (Figure 6b), which supply siltstone, shale and carbonate grains, largely made up of micritic limestones of Ligurian affinity (Palombini and Helmintoid). The Q/Lsed ratio varies from 1.2 to 2.7 and Q/Lv from 9.5 to 41.3. The easternmost sample (P7) records a slight increase in metamorphic lithics. Volcanic grains are scarce in all samples (<3%). Heavy minerals are always present, and their content is highly variable (up to 18% in P1).

The Mincio and Adige rivers show a relative abundance of volcanics (~14% of the examined fraction) associated to metamorphic lithics (~15% Mincio and ~8% Adige). The Oglio River shows a higher percentage of metamorphic lithics (~23%) and a lower content in volcanics (~5%). Compared to the Po River, the Mincio, Adige and Oglio sands have a higher content in carbonate grains, and silicoclastic lithics are rare (Figures 5b and 6b) in agreement with the studies of [5,6]. The Q/Lsed and the Q/Lv ratios are lower than 1.4 and 4, respectively).

5. Discussion

Stratigraphy, facies associations and the composition of sands from the Ostiglia cores, dating back to the Late Pleistocene (ca. 42 ky BP)–Late Holocene (ca. 3.1 ky BP), provide clues on past reorganizations of the Po Plain fluvial network.

Stratigraphic units U1, U2 and U4 show distinctive composition (Figure 6a). A markedly higher Q/Lv ratio is observable in unit U4, compared to units U1 and U2. The deepest units show Q/Lsed and Q/Lv values similar to those of the Adige and Mincio rivers sands. The South Alpine signature is also suggested by the occurrence of volcanics and Mesozoic carbonate rocks, which crop out extensively in the South Alpine river catchments and by a low content of siliciclastic sedimentary fragments. Alpine carbonate grains are clearly distinguishable from the those from the Apennine Ligurian units, based on their texture and fossils content. The affinity with modern Adige and Mincio rivers is compatible with the Last Glacial paleogeography, characterized by alpine glaciers extending down to the Po Plain margin and feeding their related fluvio-glacial system (Figure 7a; [27]). While unit U1 is unequivocally attributable to the last glacial period, uncertainties exist for the age of unit U2, which is constrained by radiocarbon dates between ca. 41 and 9 ky BP (Figure 4). If unit U2 was deposited before glaciers retreat and entrenchment of the Alpine rivers (ca. 17 ky BP, [38]), the composition of U2 would indicate the persistence of a direct sediment supply from the Mincio–Adige fluvio-glacial system (Figure 6b; [27]). Otherwise, if unit U2 was deposited after 17 ky BP, the entrenchment of the south Alpine rivers would exclude a direct supply from the Adige River (see Figure 7b). In this case, the Mincio River or minor rivers, such as Tione, draining the Garda frontal moraine, and Tartaro, reworking Late Pleistocene fluvio-glacial sediments, would be the most suitable candidate for supplying the sediments of unit U2 (Figure 7b). Given the limited thickness of U2 sand bodies, their provenance from minor rivers catchments, with the partial reworking of morenic and fluvio-glacial deposits, seems the most likely hypothesis. This assumption is corroborated by the abundance of oxidized grains, probably derived from soil erosion, and by the relatively high quartz and feldspar content in respect to the Mincio and Adige modern sands. Additional chronological and compositional data are required for an unequivocal definition of the paleogeographic setting.

The peat-rich unit U3, barren in fluvial sand, resulted from scarce fluvial sediment supply. Peat formation indeed is favoured by waterlogging and low clastic input [39–41]. Widespread peat formation in the Po coastal plain between ca. 9 to 4 ky BP records the progressive flooding of the area during the last phases of post-glacial sea-level rise, with the consequent setting of estuarine and delta plain environments [14,42–44]. In this phase the Ostiglia area was located at the western edge of the estuary-delta plain (Figure 7c; [14]).

The Late Holocene unit (U4) shows affinity with samples P1 and P7 of the Po River, as indicated by the relative abundance of metamorphic detritus associated to a low carbonate content and by relatively high Q/Lv ratios; the Southern Alpine signature is no longer present. The relatively higher percentage of volcanic lithics in samples OS2 22.5 may indicate partial reworking of underlying unit U2. Thus, unit U4 records the onset of the Po River sedimentation in the Ostiglia area. This phase started during the Late Bronze Age (ca. 3 ky BP, Figure 4) and progressively expanded northward towards core OS3, where the first crevasse deposits attributable to the Po River postdate the Iron Age (ca. 2.8–2.4 ky BP). Low sediment input from the southern Alps may be attributable to sediment trapping by periglacial lakes (e.g., Garda Lake, Figure 2; [5,27]), which formed after glacier retreat.

It should be noted that the composition of unit U4 is similar to the sand of the modern Po River far from the confluence with the Secchia and Panaro rivers. These two rivers supply large quantities of siliciclastic grains (shales and siltstones) and micritic carbonates of Ligurian affinity form the Apennine catchments (Figure 6b). Indeed, Ostiglia fluvial sand bars (samples P3 and P4, Figures 2 and 6b), located 10 km east of the Secchia confluence, present higher percentages of siliciclastic grains compared to samples of unit U4 (OS2 18.5 and OS1 16.4). This indicates that during the Bronze Age Secchia and Panaro rivers were not tributaries of the Po River at Ostiglia. This fact could be explained by the presence of a southern Po branch, which acted as a barrier to the Apennine sediment supply (Figure 7d). Alternatively, an Apennine river could have acted as a local collector flowing parallel to the Po River down to its confluence east of Ostiglia (Figure 7e,f). Both hypotheses are likely and could have occurred at different times. Indeed, several works havereported the existence of paleochannels of the Po River active south of Ostiglia during the Late Bronze and Iron Ages (see Figure 7d; [40,43,45,46]). The trace of several Apennine paleochannels is also observable south of the Po River [10]. These paleochannels, with a W–E orientation, were active in different periods between the Roman period (Figure 7e; [47]) and the Middle Ages (see paleo Secchia 1 and paleo Secchia 2 in Figure 7f; [48]) and merged with the Po

River east of Ostiglia. The present confluence of the Secchia River west of Ostiglia dates back only to the 16th century AD (ca. 0.5 ky BP).

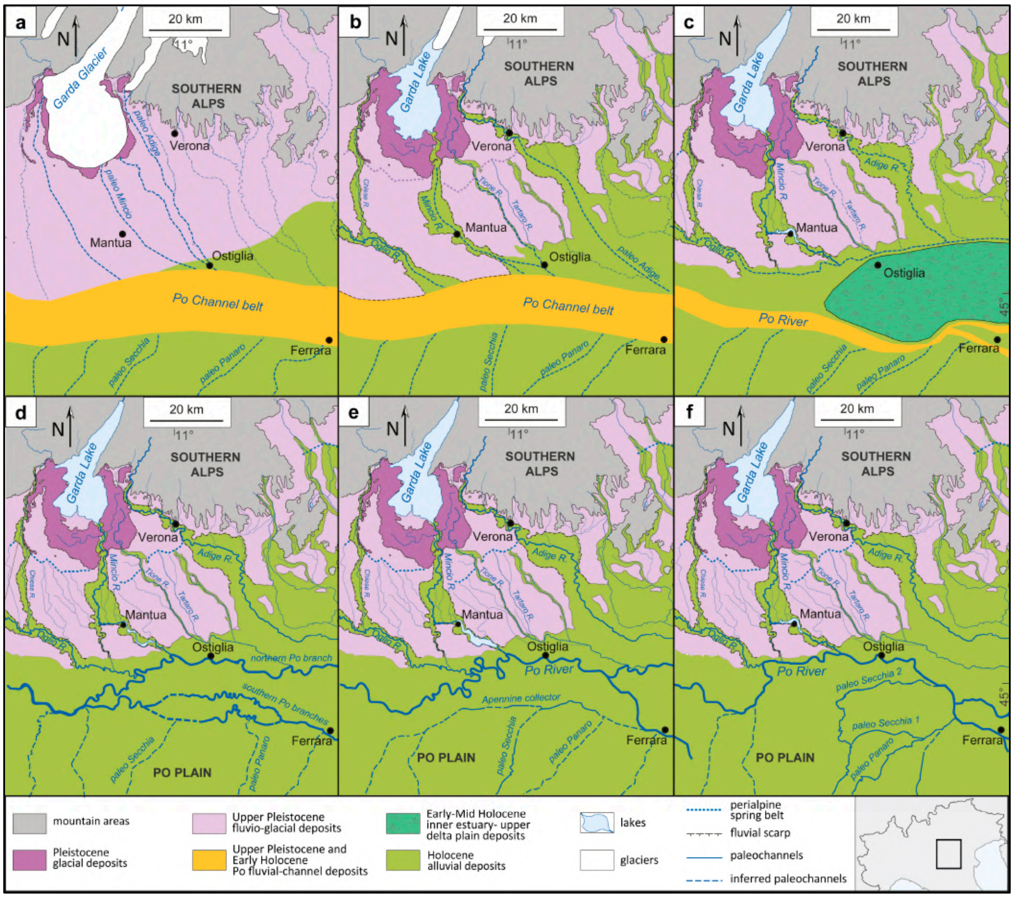

Figure 7. Main hydrographic changes of the Po Plain. Paleogeographic sketch maps showing the Po river network and depositional environment during (**a**): the Würmian glacial stage; (**b**): deglaciation; (**c**): maximum marine ingression; (**d**) Bronze Age–Iron Age; (**e**) Roman period; (**f**) Middle Ages. Extent of the Garda glacier during LGM is from [38]. Extent of Upper Pleistocene fluvio-glacial deposits are from [27]. Hydrography of the Mantua area during the Bronze Age and Roman period is from [45]. Paleogeographic information from [10,14,42,47–49] were also considered.

The integrated stratigraphy and sand composition from the Ostiglia area records an overall transition from a river system marked by a high south-Alpine sediment supply (units U1 and U2) to a fluvial system dominated by the Po sedimentary input, with a not negligible Apennine influence. This tendency reflects: (i) the deactivation of the south-Alpine fluvioglacial systems at the transition from the last glacial to the present interglacial; (ii) the progressive northward migration of the Po River during the Holocene [25,50]; and (iii) an increase in sediment supply by Apennine rivers during the Late Holocene. Some authors argued that the northward migration of the Po River was forced by the growth of buried thrust-related folds (i.e., Mirandola Anticline; [50,51]). Other authors inferred that the numerous avulsions of the Po River and its Apennine tributaries, detected through geomorphological studies [10,42,46–48,52], reflect a dominant autogenic control [14]. The Late Holocene increase in the sediment supply of Apennine rivers may have been enhanced by the widespread deforestation of mountain catchments, which took place during and after the Late Bronze Age [53]. Although the major reorganizations of the Po Plain fluvial systems are reflected in the composition of Ostiglia sands, the poor areal extent of the study area does not permit the unequivocally definition of the relative role of distinct controlling factors.

6. Conclusions

Stratigraphic and petrographic analyses on three cores collected in the Ostiglia area along the Po River allowed the reconstruction the main hydrographic changes that have occurred since the Late Pleistocene.

Four stratigraphic units (U1 to U4) were recognized based on facies distribution. Unit U1, deposited during the Late Pleistocene, is dominated by fluvial sands with high content in volcanic and carbonate lithics. Unit U2 (Pleistocene–Holocene transition), includes thinner and less extensive fluvial-channel bodies, with sand composition similar to U1. Unit U3 (Early–Mid Holocene) is dominated by peat-bearing muds and is barren in fluvial-channel sands. Unit U4 (Late Holocene), consists of fluvial channel-related deposits with abundant metamorphites and scarce volcanic and siliciclastic lithics.

Late Pleistocene deposits (U1) record high sedimentary input from the Garda fluvio-glacial system during the last glacial episode. Thinner sand bodies deposited after glacier retreat (U2) are instead likely attributable to minor rivers, which reworked morenic and fluvio-glacial sediments. Early–Mid Holocene peaty muds (U3) record low fluvial input and waterlogging around the maximum marine ingression. Finally, the Late Bronze Age marks the onset of Po River sedimentation in the Ostiglia area (U4); the fluvial sands of this unit show a lower content in sedimentary grains, supplied by Secchia and Panaro rivers, compared to modern Po River sands. This difference is likely due to a local fluvial collector (Po branch or Apennine river), which impeded Apennine sediments from reaching Ostiglia from the Late Bronze Age to the Middle Ages.

Stratigraphic and compositional data from the Ostiglia cores testify to the transition from a river system characterized by a high south-Alpine clastic input to a fluvial system dominated by the Po sediment supply, with increasing Apennine contributions after the Middle Ages. This tendency reflects the deactivation of the south-Alpine fluvioglacial systems at the transition from the last glacial to the present interglacial, the northward migration of the Po River and an increased sediment supply from Apennine catchments. This study demonstrated that compositional data, framed into a detailed stratigraphic picture, can provide evidence of past changes in fluvial patterns and sediment supply. This multidisciplinary approach may be potentially applicable to other alluvial system worldwide.

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