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Tracing clinothem geometry and sediment pathways in the prograding Holocene Po Delta system through integrated core stratigraphy

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Abstract

Though clinothem geometry represents a key control on fluid flow in reservoir modeling, tracing clinothem boundaries accurately is commonly limited by the lack of sufficiently precise outcrop or subsurface data. This study shows that in basin systems with strongly heterogeneous compositional signatures, the combination of bulk-sediment geochemistry and benthic foraminiferal distribution can help identify clinothem architecture and generate realistic models of 3D deltaic upbuilding and evolution.

Middle-late Holocene deposits in the Po Delta area form an aggradational to progradational parasequence set that reveals the complex superposition of W-E delta progradation, S-directed longshore currents (from Alpine entry points) and Apennine rivers supply. Unique catchment lithologies (ophiolite rocks and dolostones) were used to delineate basin-wide geochemical markers of sediment provenance (Cr and Mg) and to assess clear detrital signatures. The geochemical characterization of cored intervals across different components of the sediment routing system enabled a direct linkage between clinothem growth, transport pathways and provenance mixing to

be established. On the other hand, abrupt microfaunal variations at clinothem boundaries were observed to reflect the paleoenvironmental response to sharp changes in sediment flux and fluvial influence.

This study documents the ability of an integrated geochemical and paleoecological approach to delineate the different sources that effectively contributed to coastal progradation and to outline the lithologically cryptic geometries of clinothems that using conventional sedimentological methods it would be virtually impossible to restore.

Introduction

Prograding coastal and deltaic depositional systems are commonly examined across their downdip components, which afford the observation of clinoforms, stratal terminations and stacking patterns (Catuneanu et al., 2019). In contrast, scarce attention is generally paid to their development parallel to depositional strike. Clinothems are key sedimentary elements of prograding systems that are typically bounded by hiatal surfaces. Clinothem boundaries mark abrupt shifts in depositional systems configuration and sediment dispersal pathways that might impact significantly oil exploration and production. Changes in outbuilding directions within sets of clinothems, in particular, are likely to generate heterogeneities that represent potential barriers to fluid flow (Enge et al., 2010).

In subsurface studies, at the resolution of data commonly available, the geometry of individual clinothems can hardly be assessed on a sub-seismic scale. This is increasingly evident in mudstone-dominated systems (Bohacs et al., 2014; Lazar et al., 2015; Birgenheier et al., 2017; Pellegrini et al., 2017; 2018), where the presence of subtle heterogeneities within seemingly homogeneous sediment bodies cannot be deciphered based on physical sedimentary structures alone.

Sequence-stratigraphic models assume that nearshore strata have relatively consistent and laterally persistent stacking at the systems tract scale (Madof et al., 2016). However, a significant 3D variability of the stratigraphic architecture commonly develops in response to variations in accommodation and sedimentation across a sedimentary basin (Olariu and Steel, 2009). In along-strike direction, the autogenic shift of distributary channels or delta lobes may affect the pattern of sediment distribution. Furthermore, rates of accommodation and sedimentation may change significantly at any particular location within a basin, resulting in highly diachronous sedimentary units (Catuneanu et al., 2019).

The middle-late Holocene highstand succession of the Po Plain, in northern Italy, is a 30 m-thick, mud-prone depositional system that records a complex pattern of coastal progradation and delta upbuilding. The stepped progradation of the coastal plain includes a set of five millennial-scale parasequences that have been well portrayed by depositional dip-oriented (SW-NE) cross-sections (Amorosi et al., 2017). Recent dynamics of deltaic progradation have been outlined in detail by Correggiari et al. (2005a). Since the Bronze Age, the Po Delta occupied a broad stretch of the Adriatic coastal system, nourishing cuspate and arcuate (wave-dominated) deltas. After 2,000 ky BP, changes in sediment discharge and the evolution of the Po Delta took place under considerable anthropogenic influence (Maselli and Trincardi, 2013).

Clinothem stacking patterns transversal to transport direction have been portrayed accurately from the adjacent Adriatic Sea through high-resolution seismic stratigraphy. Individual prodelta lobes overlap laterally and can be traced along-strike as identifiable seismic-stratigraphic units over relatively short (10-20 km) distances (Correggiari et al., 2005b). Along the mud-dominated Adriatic coastline, inner-shelf mud belts are typically elongated downdrift of the Po River mouth, reflecting prevailing sediment dispersal to the south (Cattaneo et al., 2003). Based on seismic-stratigraphic studies, Cattaneo et al. (2003) documented that individual prodelta lobes emanating from the southward oriented delta outlets are more easily preserved compared to those advancing episodically to the NE. When a newly activated lobe is located updrift (north), the abandoned lobe

is sheltered by the new one. In contrast, when the retreating lobe is updrift, it is partly cannibalized and transported downdrift to the new active lobe (Correggiari et al., 2005b).

The aim of this study, which is focused on the high-resolution sequence stratigraphy of the prograding, middle-late Holocene Po Delta system, is to examine the potential of an integrated geochemical and paleoecological approach to decipher clinothem boundaries within lithologically homogeneous, mud-prone successions. Specific objective is to document the along-strike variability of sediment composition and foraminiferal distribution as a function of the natural complexity and interplay of fluvial dynamics and delta evolution, which may have profound impact on reservoir heterogeneity.

Holocene stratigraphy

The Po River Basin is a foreland basin system bounded by two mountain chains: the Alps to the north and the Apennines to the south (Fig. 1A). The Po River watershed is generated by the catchments of tens of tributaries extending from the Western Alps to the Adriatic Sea. The Po River is the longest river in Italy, and flows from west to east for 652 km.

Holocene deposits in the Po coastal plain form a typical transgressive-regressive sedimentary wedge made up of coastal to shallow-marine facies assemblages that are vertically stacked onto Pleistocene alluvial deposits and that extend both updip and downdip into the fully continental and fully marine settings. Transgressive facies architecture reflects a dominant role of eustasy on sequence development (Amorosi et al., 2017). Highstand deposits, instead, denote a dominantly autogenic control. These latter are genetically related to the rapidly deposited mud wedge that accumulated on the shelf for 600 km along the Adriatic coast of Italy (Trincardi et al., 1996; Cattaneo et al., 2003; Amorosi et al., 2016).

Major architectural components of the Holocene succession are sediment packages developed on millennial timescales and framed by flooding surfaces, i.e. surfaces of chronostratigraphic significance (parasequences 1-8 in Amorosi et al., 2017). In along-strike direction, beneath the modern shoreline, the Holocene transgressive-regressive cycle translates into a muddy (offshore/prodelta) unit sandwiched between laterally continuous, transgressive barrier sands below and highstand beach-ridge/delta front units above (Campo et al., 2017 - Fig. 1B).

The switch from continental to early Holocene, estuarine depositional systems (Bruno et al., 2017) is documented by the retrogradational stacking of thin parasequences 1-3 (Amorosi et al., 2017). Above a condensed offshore succession, five middle-late Holocene parasequences (4-8 in Fig. 1B) stack and shingle to form, instead, a thick and complex, aggradational to progradational highstand systems tract (HST) that preserves evidence for deltaic and coastal progradation, with thick prodelta clay packages overlain by sand-prone, delta front facies. Within the HST, fossil assemblages depict an upward trend from wave-influenced (lower HST) to river-dominated (upper HST) coastal systems (Amorosi et al., 2017).

Highstand clinothems form shallowing-upward packages that are typically represented by thickening-upward trends in sand layers and by general coarsening-upward patterns (parasequences in Fig. 1B). Heterolithic facies typically develop between prodelta clays and extensive sheet sands made up of delta front deposits (Bhattacharya and Giosan, 2003). Clinothem boundaries are locally characterized by the sharp decrease in the sand/mud ratio, which reflects a lateral shift in associated environments. In most cases, however, clinothem boundaries occur at mud-on-mud or sand-on-sand contacts (Fig. 1B). Assessing their potential geometry from core data, thus, relies exclusively on the interpolation of radiometric data (Amorosi et al., 2017).

Methods

A total of 166 core samples were analyzed for bulk-sediment geochemistry. Samples were collected at depths < 30 m from 12 cores (Fig. 1B): P13N, P14N, P10N, P8N, P4N, CB, and 205-S10 (Greggio et al., 2018), core 187S1 (Amorosi et al., 2007), Barr (Core1 in Amorosi et al., 2008), EM7, EM12, and 187S3 (this study). The dataset includes 51 additional modern river sediment samples that were used as reference samples for the geochemical characterization of source areas (Fig. 2). With the aim of making geochemical data from modern river sediments comparable with the variety of lithofacies assemblages identified in cores, sampling covered a broad grain-size spectrum, from coarse sand to clay. Recent to sub-recent river sediments were collected from subaqueous channel beds, exposed bars, and overbank fines.

Samples were analyzed at Bologna University laboratories for 10 major element oxides, the loss on ignition (LOI) and 21 trace elements. LOI, evaluated after overnight heating at 950°C (LOI_{950}), represents a measure of volatile substances (weight %, wt%), including pore water, inorganic carbon and organic matter. The estimated precision and accuracy for trace-element determinations was 5%, except for elements with low concentrations (< 10 ppm), for which the accuracy was lower (10%).

A review of micropaleontological data from cores 187S1, 205S9, 205S10, 223S3 and Barr (e.g. Campo et al., 2017; Barbieri et al., 2017), with a special emphasis on benthic foraminiferal assemblages from core 187S7, was carried out to refine facies interpretation and, specifically, to characterize parasequence boundaries within muddy intervals.

Geochemical tracers of sediment provenance

Owing to its situation in a complex tectonic setting, the Po Basin is supplied by a variety of sediment sources that display strongly heterogeneous compositional signatures. Mafic and ultramafic rocks crop out extensively in the western Alps and at the northwestern tip of the Apennines, and represent exclusive catchment lithologies that were adopted to delineate basin-wide

markers of sediment provenance. These ophiolite successions consist primarily of peridotite, gabbro, basalt and ophiolitic breccia, and deliver large volumes of Cr-rich (and Ni-rich) detritus to the alluvial and coastal systems (Amorosi et al., 2002; Curzi et al., 2006; Amorosi and Sammartino, 2018; Greggio et al., 2018).

Thick dolostone and limestone successions are largely exposed in the Eastern (and Central) Alps, where they make a substantial portion of Triassic platforms and build-ups. Therefore, major elements, such as Mg and Ca (and their oxides MgO and CaO), can be used to discriminate these source areas. Calibration with mineralogical data (Marchesini et al., 2000) has shown that Mg enrichments in modern coastal deposits reflect erosion and transport of detrital dolomite from the North Adriatic river catchments, which acted as sources of particular detritus to the Po coastal plain (Amorosi et al., 2002; 2007; Curzi et al., 2006; Amorosi and Sammartino, 2018; Greggio et al., 2018).

As absolute Cr, Ni, Mg and Ca concentrations also reflect hydraulic sorting and can be affected by changes in grain size, normalization of geochemical data using one element as grain size proxy is necessary to compensate for mineralogical and granular variability of metal concentrations. Al_2O_3, which is routinely used as an efficient normalization factor, proved very effective in reducing the grain size effect and to differentiate sediment sources with distinct parent-rock compositions (Fig. 2).

Plots of modern river samples from three different catchments (Po River, Apennines, Central/Eastern Alps) display poor overlap in composition, and distinctive geochemical signatures can be observed across all grain-size grades (Fig. 2). The geochemical composition of modern stream sediments, thus, delineates primary end-members and strongly constrains provenance inferences from Holocene deposits (Fig. 2). River sediment from the Po River invariably exhibits high Cr/Al_2O_3 levels (> 12) and is associated with relatively low MgO/Al_2O_3 values. On the other hand, samples from modern Alpine rivers plot considerably off this general trend, revealing a distinctive geochemical facies with significantly higher MgO/Al_2O_3 values (> 0.35) that can be

readily differentiated from modern Po River samples. Modern Apennine river sediment is, instead, typified by comparatively lower Cr/Al_2O_3 (< 12) and MgO/Al_2O_3 (< 0.4) values.

Compositional features of fluvial end-members were adopted to trace detrital signatures of Holocene cored samples across along-strike segments of the sediment dispersal system (Fig. 3). Chemostratigraphic correlations, in particular, were employed to trace provenance shifts across lithologically uniform prodelta muds. As an example, a cut-off value of the MgO/Al_2O_3 ratio targeted around 0.35 (Fig. 2) represents an effective tool for the discrimination on vertical profiles between the Po River sediment source and dolostone-derived detritus from the Central/Eastern Alpine rivers (Fig. 3): relatively high MgO/Al_2O_3 values denote sediment supplied, in part at least, by Alpine sources and are interpreted to reflect a mixed signature of chiefly Po-derived sediment, with a considerable supply from Eastern Alps sources. The abrupt upward decrease in the MgO/Al_2O_3 ratio (Fig. 3), which is paralleled by a remarkable increase in Cr/Al_2O_3 values, has stratigraphic significance and is inferred to reflect primarily the shift in sediment provenance from a wave-influenced coastal environment, where S-directed longshore dispersal was an important transport mechanism, to a fluvial-dominated, deltaic system, fed almost uniquely by the Po River.

Foraminiferal distribution as a key to clinothem boundary identification

In prograding deltaic successions characterized by fast, relatively continuous sedimentation, clinothem boundaries are represented by hiatal stratigraphic surfaces of short duration and small areal extent. As these surfaces commonly occur within relatively homogeneous lithosomes, clinothem geometries may locally have poor physical expression. In such instances, based on comparison with the modern Po Delta area, foraminiferal distribution can be used to delineate clinothem boundaries that are independent of lithology.

Modern deltaic sediments are typified by low-diversity benthic assemblages indicative of highly-stressed and unstable environments (Jorissen, 1988). Notably, high concentrations (> 40%) of

Ammonia tepida and *Ammonia parkinsoniana* have been observed to reflect remarkable sediment discharge related to flood events, in relatively shallow waters (< 20 m depth), in front of modern Po river mouths (Barbieri et al., 2017). In contrast, relatively high amounts of *Aubignyna perlucida*, *Cribroelphidium granosum* and *Nonionella turgida* (ca 20% considered together) are typically abundant far from river outlets. In distal prodelta environments, these taxa are commonly associated with inner shelf species, such as *Textularia* spp. and miliolids (e.g. Campo et al., 2017, Barbieri et al., 2017).

The possible use of paleocologic criteria for the delineation of clinothem boundaries is exemplified by the vertical distribution of benthic foraminifers in core 187-S7 (Fig. 4 - see Barbieri et al., 2017, for details). At this location, the middle-late Holocene HST consists almost entirely of mud deposits (Fig. 1B), which makes stratigraphic correlations and parasequence boundary identification very difficult. Paleoenvironmental changes in this homogeneous muddy interval can be tracked using changes in benthic foraminiferal distribution as indicators of proximity to/distance from the river mouth. Notably, the upward increase in *A. tepida* and *A. parkinsoniana* is taken as an indication of upward shoaling, and hence, it is interpreted to reflect delta lobe progradation (Fig. 4). This trend is predictably paralleled by the decrease of subordinate species, such as *A. perlucida*, *C. granosum*, and *N. turgida*. Localized, sharp declines in the dominant species (*A. tepida* and *A. parkinsoniana*) concurrent with the occurrence of inner shelf species are, instead, indicative of lower riverine influence and sudden drops in fluvial discharge, likely related to distributary channel avulsion and delta lobe switching (Fig. 4).

Insight into delta evolution from the geochemical and paleoecological record

The integration and mutual calibration of two independent data sets (bulk-sediment geochemistry and benthic foraminiferal analysis) can be used to generate a model of deltaic and coastal evolution in the Po coastal plain, over the last ca. 6 cal ky BP (parasequences 4 to 8 in Fig. 5). Cyclic

depositional patterns are interpreted as driven by autogenic processes (Amorosi et al., 2017), and compensation stacking of mouth bars is proposed as the origin of these packages (Enge et al., 2010).

The geochemical characterization of the HST reflects remarkable along-strike variability of dispersal patterns. As a whole, provenance signals proved to be poorly affected by lithologic variation, and are consistent on a depositional system scale, being detectable across both delta front sands and prodelta muds. In general, the prograding Po delta acted as the major source of sediment to the Adriatic coastal system. However, the proportional contribution of Alpine sources to the coastal region varied continuously as the Po River mouths approached or moved away from the study area. Generally high MgO/Al_2O_3 levels and concurrent low Cr/Al_2O_3 values along the relatively flat, distal segments of older clinothems (parasequences 4-5 along profile AA' in Fig. 5) suggest that between about 6.0-2.8 cal ky BP Alpine, dolostone-rich river catchments represented a key sediment delivery system for wave-influenced deltas in the Adriatic area via the south-directed longshore drift. During this phase, the Adriatic coastal system experienced weak progradation, and E-dipping clinothems fed by the Po River (parasequences 4 and 5 along transversal profiles in Fig. 5) were restricted to proximal locations.

Parasequence 6 documents contrasting geochemical signatures in the southern and northern regions along profile AA' (Figs. 3 and 5). Comparatively low MgO/Al_2O_3 values and high Cr/Al_2O_3 levels south of transect DD' exhibit strong affinity with modern Po River sediment composition (Fig. 3) and arguably reflect Po Delta initiation in that area. The southern branch of the Po River (*Po di Spina*) likely represented the fluvial feeder system of these southern clinothems (Correggiari et al., 2005a), as documented by the closer affinity of cored samples with the Cr-rich compositions typical of sediment derived from the Po River catchment (Fig. 2). At more northward locations, geochemical data from both sands and muds suggest mixed, fluvial-wave dispersal, with a dominant Alpine contribution and a subordinate, Po supplied component (Figs. 3 and 5).

Given the counter-clockwise oceanic circulation pattern of the Northern Adriatic Sea (Cattaneo et al., 2003), it is likely that sand of Alpine provenance was transported by S-directed, longshore currents, whereas mud was probably resuspended by storms and wave action above storm wave base, and advected alongshore by geostrophic currents for long distances along the paleoshelf. During this period, the (river-dominated) *Po di Spina* delta system was more protrusive than its wave-dominated counterparts in the north, and likely represented a barrier to southerly directed longshore transport (Fig. 5).

The prominent shift in sediment composition from Alpine feeding sources to a dominant Po River contribution (Fig. 3), which marks the boundary between parasequences 6 and 7 (Fig. 5), reflects the historical activation of the *Po di Volano* branch, north of the *Po di Primaro* river mouth, and denotes the ultimate replacement of S-directed (Alpine) sediment supply with sediment from prograding Po delta lobes. More in general, this change in bulk-sediment composition reflects the switch from wave-dominated (Cr-poor and Mg-rich) to river-dominated (Cr-rich and Mg-poor) depositional systems, which occurred in response to delta upbuilding. From the Middle Ages onwards, sediment composition of parasequences 7 and 8 (Fig. 1B) largely reflects deltaic sedimentation supplied from the Po River, whereas southern regions denote a geochemical signature from Apennine entry points (Fig. 5).

The mid 12th century (ca. 800 yr BP) natural avulsion (*Rotta di Ficarolo*) that shifted the main trunk of the Po River towards its present position (Correggiari et al., 2005a) is marked by the boundary between parasequences 7 and 8 (*Po di Goro* delta system in Fig. 5). This stratigraphic surface has no geochemical expression, as it separates two delta lobes of different age, but similar composition. In this case, shifts in river mouth and delta lobe abandonment were detected by abrupt shifts in benthic foraminiferal distribution (Fig. 4).

The combined geochemical and paleoecologic approach adopted in this work is highly reproducible in the ancient record and has the potential to reliably constrain sediment-budget modeling in sedimentary basins with multiple entry points. It is best suited to subsurface

stratigraphic analysis, where it may enable new insights into the interpretation of clinothem stacking patterns, avoiding arbitrary or unrealistic correlation of sparse core data. In hydrocarbon exploration, this technique may guide the delineation of sediment bodies with distinct sediment composition, predictable lateral extent and well-defined petrophysical properties.

Conclusions

Prograding clinothem sets may have a poor lithologic expression, especially in mud-prone delta systems, and they can be easily missed on a sub-seismic scale. This study shows that sharp changes in parent-rock composition and benthic foraminifera communities can provide the key criteria for deciphering subtle heterogeneities and cryptic stratigraphic patterns at the core scale, allowing for accurate control of three-dimensional stratigraphic complexity.

The chemostratigraphic analysis of the middle-late Holocene succession from the Po Basin documents that methods for source discrimination based on bulk-sediment geochemistry, when calibrated with mineralogical data in a highly constrained sequence-stratigraphic framework, can be effective for a sound assessment of the routing system and can ultimately allow quantification of sediment fluxes below the resolution of seismic data. In multi-sourced sediment-supply systems, unique source rocks control the spatial variation of elemental tracers at the basin scale and carry distinct geochemical fingerprints that may propagate to deltaic, coastal, and shallow marine depositional systems, and that can be applied with equal success to sand, silt and clay fractions. Major and trace element composition of cored samples was matched against geochemical features of samples from the modern river network. Notably, changes in sediment dispersal pathways were detected using key element ratios, such as Cr/Al_2O_3 and MgO/Al_2O_3, where the former is a proxy for the mafic/ultramafic contribution, and the latter is discriminant for dolostone-derived detritus.

Through combined sedimentologic, paleontologic and geochemical investigations, chronologically constrained by a wealth of radiocarbon dates, this study demonstrates that tracing clinoformal geometries within stratigraphic units characterized by relatively continuous sediment accumulation is possible even away from seismic imaging. Changes in sediment composition and/or foraminiferal distribution, rather than grain size, are the primary defining features of clinothem boundaries and are diagnostic to the identification of these surfaces. This approach can be applied successfully to analogous Quaternary subsurface successions and also has a strong potential in outcrop studies, where clinothem boundaries may have no obvious lithologic expression and dipping geometries can be too low to be traced confidently.

At the parasequence (millennial) scale of investigation illustrated in this paper, this 'unconventional' approach provides insight into the potential complexities of sediment fluxes that can be useful for guiding interpretation of prograding deltaic and coastal successions in the ancient record. In particular, it can be used to constrain, correlate and map sediment packages that may otherwise be difficult to separate and quantify, and can be applied to developing shale hydrocarbon resources in mudstone-dominated systems.

Figure captions

Fig. 1. A: Regional setting and location of the study area. B: Strike-oriented fence diagram, showing the three-dimensional stratigraphic architecture of the Holocene succession of the Po Basin, and its subdivision into parasequences (based on Amorosi et al., 2017).

Fig. 2. Scatterplots of MgO/Al_2O_3 versus Cr/Al_2O_3, showing contrasting sediment composition of modern Po River, and selected Alpine and Apennine rivers.

Fig. 3. Vertical profiles of MgO/Al_2O_3 in along-strike direction (Fig. 1B), showing the abrupt provenance shift from predominantly Alpine sediment sources to the Po River sediment supply (see Fig. 5). The cut-off value at 0.35 used for the differentiation of Alpine and Po sediment sources is consistent with modern river sediment composition (Fig. 2). Relatively high MgO/Al_2O_3 values in the uppermost two samples from core 187-S3 are associated with extremely high Cr/Al_2O_3 levels, and thus reflect a Po River source.

Fig. 4. Abrupt change in foraminiferal assemblage at the boundary (PB) between *Po di Volano* and *Po di Goro* delta lobes (= boundary between parasequences 7 and 8 in core 187-S7 - Figs. 1B and 5). Sample at 22.10 m depth is dominated by *Ammonia tepida* (At) and *A. parkinsoniana* (Apa), whereas sample at 21.60 m depth, just above PB, shows a significantly more diversified assemblage, involving *Aubignyna perlucida* (Ape), *Nonionella turgida* (Nt), *Textularia agglutinans* (Ta), *Cribroelphidium granosum* (Cg), and miliolids (Al: *Adelosina longirostra*; Qs: *Quinqueloculina seminulum*; Ms: *Miliolinella subrotunda*; Tr: *Triloculina rotunda*; Tt: *T. trigonula*). Scale bar: 200 µm.

Fig. 5. Strike-oriented fence diagram of Figure 1B, which affords the visualization of the sediment-transport system as a function of parasequence architecture and of its evolution through time. The red asterisk shows the stratigraphic location of Figure 4. LST: lowstand systems tract, TST: transgressive systems tract, HST: highstand systems tract.

References

AMOROSI A., SAMMARTINO I., 2018. Shifts in sediment provenance across a hierarchy of bounding surfaces: A sequence-stratigraphic perspective from bulk-sediment geochemistry. *Sediment. Geol.*, **375**, 145–156.

AMOROSI, A., CENTINEO, M.C., DINELLI, E., LUCCHINI, F., TATEO, F., 2002. Geochemical and mineralogical variations as indicators of provenance changes in Late Quaternary deposits of SE Po Plain. *Sediment. Geol.*, **151**, 273–292.

AMOROSI, A., COLALONGO, M.L., DINELLI, E., LUCCHINI, F., VAIANI, S.C. 2007. Cyclic variations in sediment provenance from Late Pleistocene deposits of Eastern Po Plain, Italy. In Arribas J., Critelli S., Johnsson M.J. (Eds.) S*edimentary Provenance and Petrogenesis: Perspectives from Petrography and Geochemistry*. Geol. Soc. America – Spec. Paper **420**, 13–24.

AMOROSI, A., DINELLI, E., ROSSI, V., VAIANI, S.C., SACCHETTO M., 2008. Late Quaternary palaeoenvironmental evolution of the Adriatic coastal plain and the onset of Po River Delta. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, **268**, 80–90.

AMOROSI, A., MASELLI, V., TRINCARDI, F., 2016. Onshore to offshore anatomy of a late Quaternary source-to-sink system (Po Plain–Adriatic Sea, Italy). *Earth-Sci. Rev.*, **153**, 212–237.

AMOROSI, A., BRUNO, L., CAMPO, B., MORELLI, A., ROSSI, V., SCARPONI, D., HONG, W., BOHACS, K.M. & DREXLER, T.M., 2017. Global sea-level control on local parasequence architecture from the Holocene record of the Po Plain, Italy. *Mar. Petrol. Geol.*, **87**, 99–111.

BARBIERI G., AMOROSI A., VAIANI, S.C., 2017. Benthic foraminifera as a key to delta evolution: A case study from the late Holocene succession of the Po River Delta. Micropaleontology, **63**, 27–41.

BHATTACHARYA, J.P., GIOSAN, L., 2003. Wave-influenced deltas: Geomorphological implications for facies reconstruction. *Sedimentology,* 50, 187–210.

BIRGENHEIER, L.P., HORTON, B., MCCAULEY, A.D., JOHNSON, C.L., KENNEDY, A., 2017. A depositional model for offshore deposits of the lower Blue Gate Member, Mancos Shale, Uinta Basin, Utah, USA. *Sedimentology*, **64**, 1402–1438.

BOHACS, K.M., LAZAR, O.R., DEMKO, T.M., 2014. Parasequence types in shelfal mudstone strata—Quantitative observations of lithofacies and stacking patterns, and conceptual link to modern depositional regimes. *Geology,* **42**, 131–134.

BRUNO, L., BOHACS, K.M., CAMPO, B., DREXLER, T.M., ROSSI, V., SAMMARTINO, I., SCARPONI, D., HONG, W., AMOROSI, A., 2017. Early Holocene transgressive palaeogeography in the Po coastal plain (northern Italy). *Sedimentology,* 64, 1792–1816.

CAMPO, B., AMOROSI, A. & VAIANI, S.C., 2017. Sequence stratigraphy and late Quaternary paleoenvironmental evolution of the Northern Adriatic coastal plain (Italy). *Palaeogeogr. Palaeoclimatol. Palaeoecol.,* **466,** 265–278.

CATTANEO, A., CORREGGIARI, A., LANGONE, L. AND TRINCARDI, F., 2003. The late-Holocene Gargano subaqueous delta, Adriatic shelf: sediment pathways and supply fluctuations. *Mar. Geol.*, **193**, 61–91.

CORREGGIARI, A., CATTANEO, A., TRINCARDI, F., 2005a. Depositional patterns in the Late-Holocene Po delta system. In: *River Deltas–Concepts, Models and Examples* (Eds. J.P. Bhattacharya and L. Giosan)*, SEPM Spec. Publ.*, **83**, 365–392.

CORREGGIARI, A., CATTANEO, A., TRINCARDI, F., 2005b. The modern Po Delta system: lobe switching and asymmetric prodelta growth. *Mar. Geol.*, **222**, 49–74.

CURZI, P.V., DINELLI, E., RICCI LUCCHI, M., VAIANI, S.C., 2006. Palaeoenvironmental control on sediment composition and provenance in the late Quaternary deltaic successions: a case study from the Po delta area (Northern Italy). *Geol. J.,* **41**, 591–612.

ENGE, H.D., HOWELL, J.A., BUCKLEY, S.J., 2010. The geometry and internal architecture of stream mouth bars in the Panther Tongue and the Ferron Sandstone Members, Utah, U.S.A. *J. Sedim. Res.*, **80**, 1018–1031.

GREGGIO, N., GIAMBASTIANI, B.M.S., CAMPO, B., DINELLI, E., AMOROSI, A., 2018. Sediment composition, provenance and Holocene paleoenvironmental evolution of the Southern Po River coastal plain (Italy). *Geol. J.*, **53**, 914–928.

JORISSEN, F.J., 1988. Benthic foraminifera from the Adriatic Sea; principles of phenotypic variation*. Utrecht Micropaleontol. Bull.*, **37**, 1–176.

LAZAR, O.R., BOHACS, K.M., MACQUAKER, J.H.S., SCHIEBER, J., DEMKO, T.M., 2015. Capturing key attributes of fine-grained sedimentary rocks in outcrops, cores and thin sections—nomenclature and description guidelines. *J. Sed. Res.*, **85**, 230–246.

MACQUAKER, J.H.S., BENTLEY, S.J., BOHACS, K.M., 2010. Wave-enhanced sediment-gravity flows and mud dispersal across continental shelves: reappraising sediment transport processes operating in ancient mudstone successions. *Geology*, **38**, 947–950.

MADOF, A.S., HARRIS, A.D., CONNELL, S.D., 2016. Nearshore along-strike variability: Is the concept of systems tract unhinged? Geology, **44**, 315–318.

MARCHESINI, L., AMOROSI, A., CIBIN, U., ZUFFA, G.G., SPADAFORA, E., PRETI, D., 2000. Sand composition and sedimentary evolution of a Late Quaternary depositional sequence, northwestern Adriatic Coast, Italy. *J. Sed. Res.*, **70**, 829–838.

MASELLI, V., TRINCARDI, F., 2013. Large-scale single incised valley from a small catchment basin on the western Adriatic margin (central Mediterranean Sea). *Global Planet. Change*, **100**, 245–262.

OLARIU, C., STEEL, R.J., 2009. Influence of point-source sediment-supply on modern shelf-slope morphology: implications for interpretation of ancient shelf margins. *Basin Res.*, **21**, 484–501.

PELLEGRINI, C., MASELLI, V., GAMBERI, F., ASIOLI, A., BOHACS, K.M., DREXLER, T.M., TRINCARDI, F., 2017. How to make a 350-m-thick lowstand systems tract in 17,000 years: The Late Pleistocene Po River (Italy) lowstand wedge. *Geology*, **45**, 327–330.

PELLEGRINI, C., ASIOLI, A., BOHACS, K.B., DREXLER, T.M., FELDMAN, H.R., SWEET, M.L., MASELLI, V., ROVERE, M., GAMBERI, F., DALLA VALLE, G., TRINCARDI, F., 2018.

The late Pleistocene Po River lowstand wedge in the Adriatic Sea: Control on architecture variability and sediment partitioning. *Mar. Petrol. Geol.*, **96**,16-50.

ROSSI, V., VAIANI, S.C., 2008. Benthic foraminiferal evidence of sediment supply changes and fluvial drainage reorganization in Holocene deposits of the Po Delta. *Mar. Micropaleontol.*, **69**, 106–118.

TRINCARDI, F., CATTANEO, A., ASIOLI, A., CORREGGIARI, A. AND LANGONE, L., 1996. Stratigraphy of the Late-Quaternary deposits in the central Adriatic basin and the record of short term climatic events. *Mem. Istit. Ital. Idrobiol.*, **55**, 39–70.

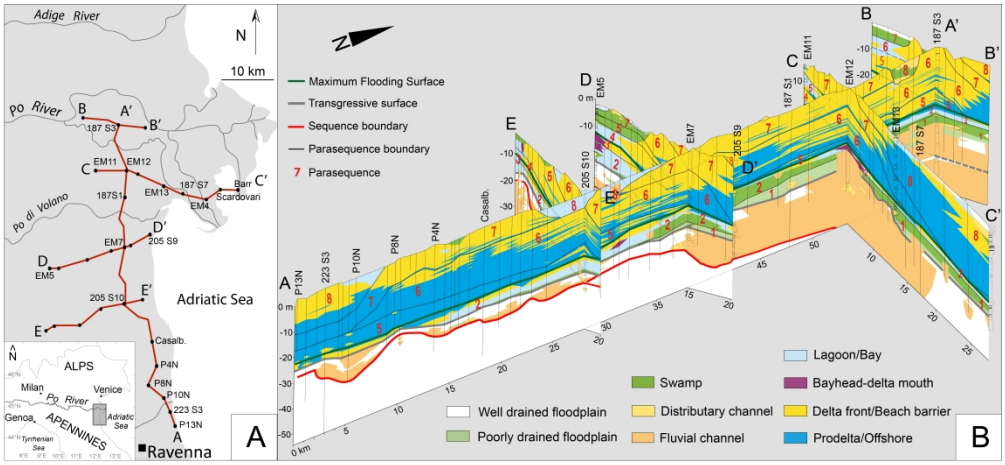

Fig. 1. A: Regional setting and location of the study area. B: Strike-oriented fence diagram, showing the three-dimensional stratigraphic architecture of the Holocene succession of the Po Basin, and its subdivision into parasequences (based on Amorosi et al., 2017).

1065x495mm (150 x 150 DPI)

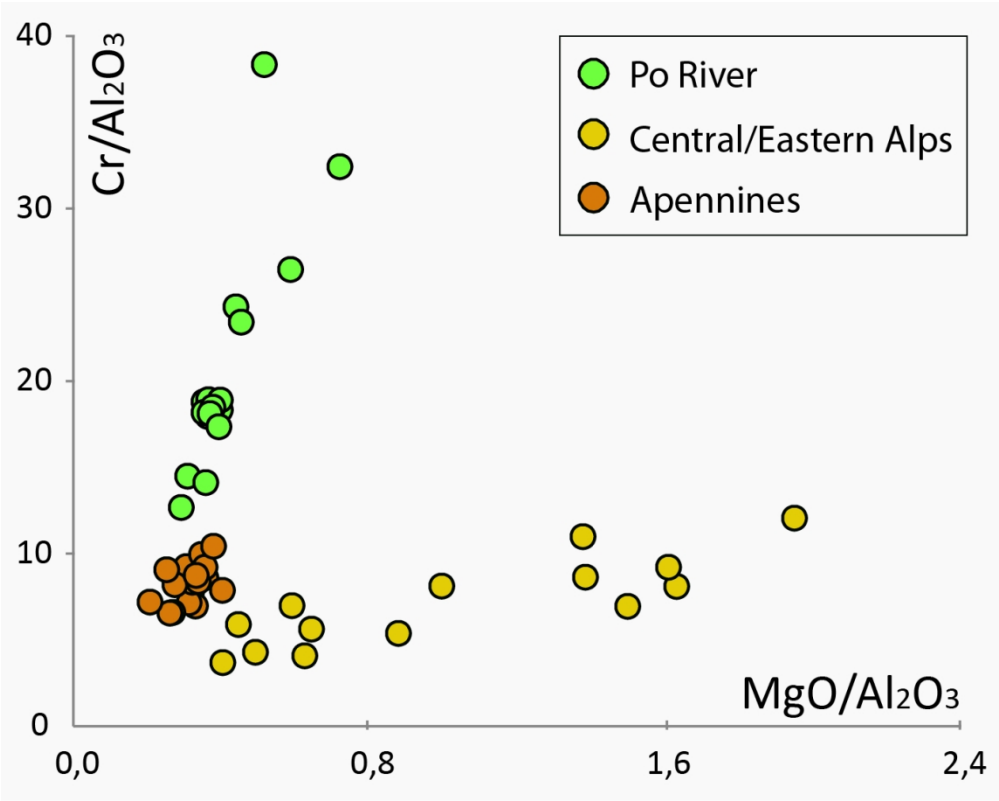

Fig. 2. Scatterplots of MgO/Al2O3 versus Cr/Al2O3, showing contrasting sediment composition of modern Po River, and selected Alpine and Apennine rivers.

119x95mm (300 x 300 DPI)

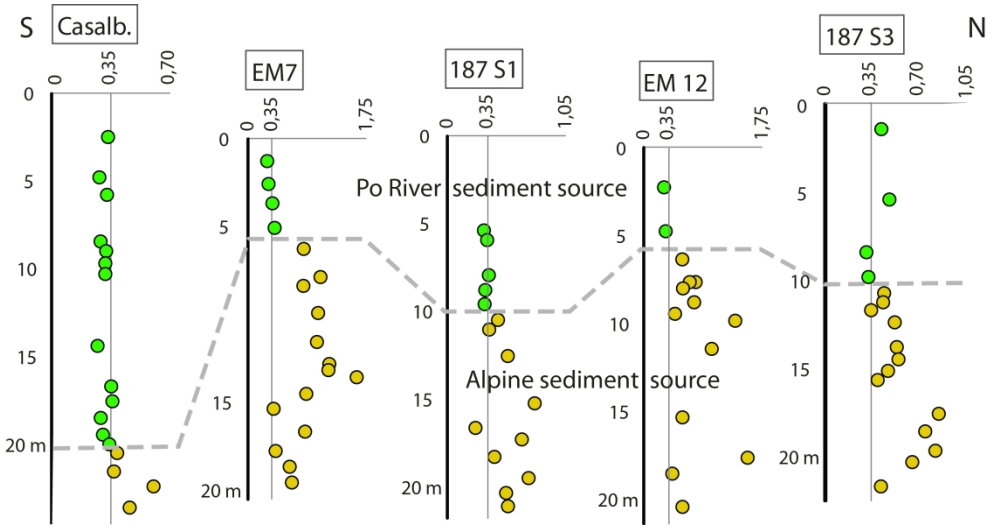

Fig. 3. Vertical profiles of MgO/Al2O3 in along-strike direction (Fig. 1B), showing the abrupt provenance shift from predominantly Alpine sediment sources to the Po River sediment supply (see

249x129mm (300 x 300 DPI)

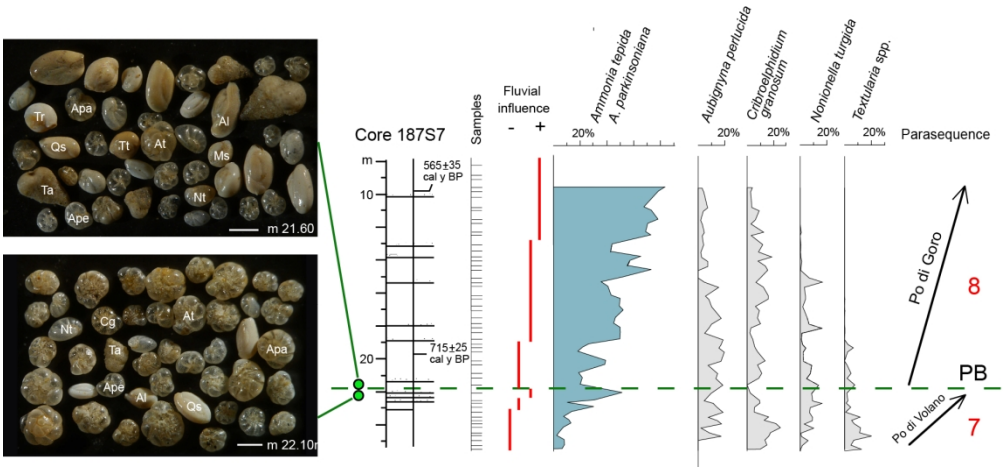

Fig. 4. Abrupt change in foraminiferal assemblage at the boundary (PB) between Po di Volano and Po di Goro delta lobes (= boundary between parasequences 7 and 8 in core 187-S7 - Figs. 1B and 5). Sample at 22.10 m depth is dominated by Ammonia tepida (At) and A. parkinsoniana (Apa), whereas sample at 21.60 m depth, just above PB, shows a significantly more diversified assemblage, involving Aubignyna perlucida (Ape), Nonionella turgida (Nt), Textularia agglutinans (Ta), Cribroelphidium granosum (Cg), and miliolids (Al: Adelosina longirostra; Qs: Quinqueloculina seminulum; Ms: Miliolinella subrotunda; Tr: Triloculina rotunda; Tt: T. trigonula). Scale bar: 200 μm.

162x75mm (300 x 300 DPI)

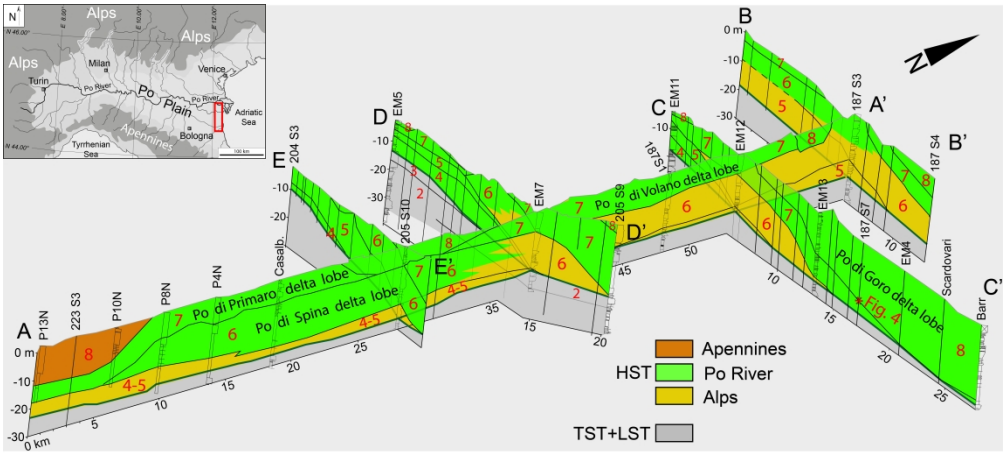

Fig. 5. Strike-oriented fence diagram of Figure 1B, which affords the visualization of the sediment-transport system as a function of parasequence architecture and of its evolution through time. The red asterisk shows the stratigraphic location of Figure 4. LST: lowstand systems tract, TST: transgressive systems tract, HST: highstand systems tract.

589x265mm (300 x 300 DPI)