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# Ephemeral rollover points and clinothem evolution in the modern Po Delta based on repeated bathymetric surveys

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## Abstract

Reconstructions of ancient delta systems rely typically on a two-dimensional (2D) view of prograding clinothems but may miss their three-dimensional (3D) stratigraphic complexity which can, instead, be best documented on modern delta systems by integrating high-resolution geophysical data, historical cartography, core data and geomorphological reconstructions offshore. We quantitatively compare three precisely positioned, high-resolution multi-beam bathymetry maps in the delta front and pro delta sectors (0.3 to 10 m water depth) of *Po di Pila*, the most active of the modern Po Delta five branches. By investigating the detailed morphology of the prograding modern Po Delta, we shed new light on the mechanisms that control the topset to foreset transition in clinothems and show the temporal and spatial complexity of a delta and its pro delta slope, under the impact of oceanographic processes. This study documents the ephemeral nature of the rollover point at the transition between sandy topset (fluvial, delta plain to mouth-bar) and muddy seaward-dipping foreset deposits advancing, in this case, in >20 m of water depth. Three multibeam surveys, acquired between 2013 and 2016, document the complexity in space and time of the topset and foreset regions and their related morphology, a diagnostic feature that could not be appreciated using solely 2D, even very high-resolution, seismic profiles. In addition, the comparison of bathymetric surveys gathered with one-year lapses shows the migration of subaqueous sand dunes on the clinothem topset, the formation of ephemeral cut-and-fill features at the rollover point (few m below mean sea level), the presence of collapse depressions derived by sagging of sediments and fluid expulsion (possibly induced by storm waves) on the foreset, and splays of sand likely reflecting gravity flows on the lower foreset. Though the modern Po Delta is anthropogenic in many respects, its subaqueous clinothem can be studied as a scale model for ancient clinothems that are less resolved geometrically and far less constrained chronologically.

**KEYWORDS**

modelling, sea-level, sediment flux, sedimentology, sequence stratigraphy, stratigraphy

# 1 | INTRODUCTION

Delta clinothems are extremely dynamic depositional environments undergoing rapid modification under the influence of both riverine and oceanographic regimes (Fagherazzi et al., 2015; Nittrouer & DeMaster, 1996; Wright et al., 1988). Seen in cross section, the construction (progradation) of a delta leads to the formation of clinothems, strata that gently prograde seawards and that, in turn, can be subdivided into three geometric elements: the topset, representing the most shallow-water, gentler, sector; the foreset, representing the steepest sector; and the bottomset, an almost flat, deeper and most distal sector (Barrel, 1912; Pirmez, Pratson, & Steckler, 1998; Rich, 1951). Delta clinothems are typically identified in conventional seismic profiles, outcrop data, numerical modelling and tank experiments. The break in slope between the topset and the foreset is termed 'rollover-point' (Patruno, Hampson, & Jackson, 2015 for a review).

Clino-stratification on vertical scales from tens to thousands of metres has long attracted the interest of geologists and geophysicists intrigued by the explanation of how sediment dispersed offshore results in the growth of delta and compound delta clinothems, shelf-margin clinothems and continental-margin-scale clinothems (Patruno & Helland-Hansen, 2018 for a review). Regardless of their spatial scales, clinothems are commonly portrayed as relatively simple depositional features (e.g. Figure 1b in Patruno et al., 2015). Indeed, conceptual models derived from experiments and stratigraphic reconstructions represent one single rollover point between the topset and forest of a subaerial delta-scale clinoform (e.g. Kenyon & Turcotte, 1985; Nittrouer et al., 1996; Patruno & Helland-Hansen, 2018; Pirmez et al., 1998), though (a) studies on modern (upper Holocene) clinothems have revealed at places a complex foreset stratigraphy, with the presence of irregularities explained either as sediment waves or gravity-driven deformation (Urgeles et al., 2011), and (b) studies of the ancient outcrop record have documented the presence of channelized conduits in foreset regions and sand splays in the bottomsets (Dixon, Steel, & Olariu, 2012, 2013; Petter & Steel, 2006).

In the last decade, clinothems have received great attention and systematic classifications have been proposed (e.g. Patruno et al., 2015; Patruno & Helland-Hansen, 2018), based on modelling results as well as outcrop, subsurface and offshore data sets. Modern depositional environments are not pristine and appear mildly to pervasively impacted by human activities (Syvitski, Vörösmarty, Kettner, & Green, 2005a). Nevertheless, such deposits can be analysed and mapped, offering the possibility of recognising the 3D complexity of delta clinothems. The study of modern deltas has led, in particular, to the distinction between subaerial and subaqueous rollover points; where two such rollover points coexist on a given dip-oriented profile they form a compound delta (e.g. Cattaneo, Correggiari, Langone, & Trincardi, 2003). However, less attention has been paid, so

**Highlights**

- Precisely positioned time-lapse bathymetric surveys document the marked temporal and spatial 3D variability of the subaqueous portion of the modern Po Delta.
- The Po Delta shows a short-distance (km-scale) variability in rollover point morphology at any given time.
- Coastal and subaqueous rollover points are both ephemeral and can be reworked, destroyed or rebuilt even on sub-annual scales.
- Rollover-point trajectories and sea-level variations reconstructed from low-resolution datasets and flume and modelling experiments should consider also the case of nearshore compound clinothem configurations.
- Quantitative chronologic information about clinothem evolution can be used as a guide to the interpretation of the ancient stratigraphic record.

far, to the variability in space and time (seasons to decades) of delta-scale subaerial clinothemmorphology and its relation to river discharge and oceanographic events. For instance, fewer investigations have been undertaken in shallow-water environments of modern deltas (e.g. Ganges–Brahmaputra Delta, Allison, 1998; Squamish Delta, Brucker et al., 2007; Yangtze Delta, Yang, Milliman, Li, & Xu, 2011; Wax Lake Delta, Shaw, Mohrig, & Wagner, 2016), leaving a gap of knowledge in their most dynamic sector.

In this work, a 4-year time-lapse survey of the *Po di Pila* clinothems based on the acquisition of high-resolution multibeam bathymetry and backscatter data sheds light on the annual and inter-annual extreme modifications that the entire delta clinothem may undergo, offering a significantly more dynamic view of how clinothems evolve and may eventually be preserved in the stratigraphic record (Figure 1). *Po di Pila* lobe is the youngest of the five lobes of the modern Po Delta. This lobe prograded rapidly (10 km) during the last 120 years, since the end of the Little Ice Age, reaching a thickness of 30 m. Like older lobes of the Po Delta, the offshore distribution of the *Po di Pila* clinothem is markedly asymmetric, reflecting a dominance of coastal currents to the south (Correggiari, Cattaneo, & Trincardi, 2005a, 2005b; Trincardi, Cattaneo, & Correggiari, 2004). Previous studies concentrated on the stacking pattern of millennial-scale parasequences in the delta plain (Amorosi et al., 2019; Stefani & Vincenzi, 2005) and on the stacking of offshore prodelta lobes in water depths greater than 10 m (Correggiari, Cattaneo, & Trincardi, 2005b; Trincardi et al., 2004), leaving the most proximal subaqueous portion of the
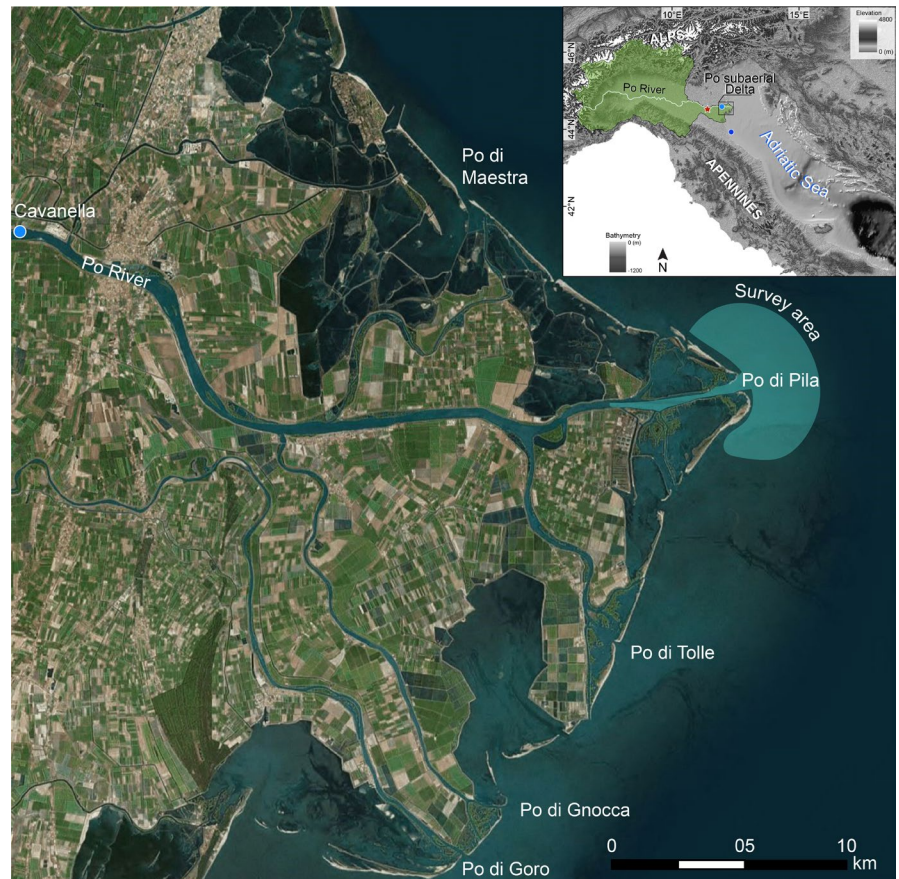
depositional system substantially unexplored. By investigating the transition between the delta mouth bar and the upper reaches of the muddy foreset, we aim at discussing the definition of rollover point, its origin and preservation potential, and to show its strong morphological variability in space and time within a modern fluvio-deltaic system.

## 2 | SETTING

### 2.1 | The Po River and Delta

The Po River is 673 km long, drains a watershed of 71,000 km$^2$ from the Western Alps, debouching into the North Adriatic Sea (Figure 1), with an average discharge of 1,540 m$^3$/s (Cattaneo et al., 2003 and reference there in). The modern Po Delta, with up to $15 \times 10^6$ t y$^{-1}$ of suspended sediment load, is the most important delta in the Adriatic Sea (Cattaneo et al., 2003). The Po River yearly hydrograph records two peaks of discharge in autumn, due to increased precipitation, and in spring, resulting from combined snow-melt and precipitation (Figure 2; Milligan, Hill, & Law, 2007). These discharge peaks are associated, particularly in the fall, with storminess resulting in transient seafloor cm-scale erosion and deposition affecting the active layer at the Po River mouth (Palinkas, Ogston, & Nittrouer, 2010).

Po River discharge is variably distributed through five river branches. *Po di Pila* is the most active branch, with 61% of the total freshwater discharge and 74% of the total sediment load (Falcieri, Benetazzo, Sclavo, Russo, & Carniel, 2014; Syvitski, Kettner, Correggiari, & Nelson, 2005b; Tesi et al., 2011). Suspended sediments at the farthest upstream gauging station (Pontelagoscuro) are composed of approximately 7% clay, 70% silt and 23% sand (Nelson, 1970). The relatively limited amount of sand received by the modern Po delta rests mainly confined in the topset (especially at mouth bars), whereas fine-grained deposits characterize the prodelta (Palinkas, Nittrouer, Wheatcroft, & Langone, 2005). Recent analyses of Po River floods based on satellite imagery show peaks in suspended sediment in the Po River prodelta and about 2 km offshore from the river mouth (Braga et al., 2017). Sedimentological analyses and numerical modelling have shown that sediment accumulation at the Po River mouth takes place in shallow water depths of 4–6 m (Friedrichs & Scully, 2007). The sediment can be further transported across-shelf under wave-supported gravity flows (Traykovski, Wiberg, & Geyer, 2007). Overall, the modern Po delta is characterized by sediment deposition rates of ~2 cm/year, and 100-y accumulation rates are ~0.5 cm/year (Palinkas et al., 2005, 2010).

The modern Po Delta is one of the largest Mediterranean deltas (Maselli & Trincardi, 2013). Following the end of the

Little Ice Age, a growth rate of 47 m/year is reported for the *Po di Pila* lobe, after 1886 AD (Correggiari, Cattaneo, & Trincardi, 2005a; Correggiari et al., 2005b), when the anthropic E-W straightening of the main branch of the Po River was carried out to protect the delta plain from flooding (Visentini & Borghi, 1938). After 1945, the entire Po Delta, including *Po di Pila*, underwent a generalised phase of degradation and partial retreat, primarily reflecting a decrease of sediment supply caused by dam construction (Maselli et al., 2018; Maselli & Trincardi, 2013), rapid subsidence of up to 1.5 cm/year (Teatini, Tosi, & Strozzi, 2011), and riverbed mining activities and channelization of watercourses (Stefani & Vincenzi, 2005). The most significant retreat phase, with rates in the order of tens of metres per year, reached its peak between 1954 and 1978. Recently, based on satellite images of the delta coastline integrated with flow discharge and meteo-marine data, Ninfo, Ciavola, and Billi (2018) inferred a new phase of progradation of the northern portion of the *Po di Pila* mouth, possibly due to restoring of bed sediment transport to the river mouth. During the last few years, the delta has shown aggradation of a new mouth-bar at the main distributary mouth, a clear evidence of constructional phase. This last phase of local growth does not appear to have affected the entire delta, and rather enhance sits 3D complexity.

## 2.2 | Oceanographic setting

The hydrodynamic of the northern Adriatic region, where the Po Delta is located, reflects the activity of wind-driven waves and currents in a micro-tidal environment. The dominant cyclonic circulation of the basin has a marked southward component in the delta area (Artegiani et al., 1997; Boldrin at al., 2005). In addition, dense waters form in the shallow (<30 m) northern Adriatic shelf (North Adriatic Dense Water – NAdDW, Benetazzo et al., 2014) and flow along the western side of the Adriatic basin, reinforcing the process of sediment sequestering and redistribution along the eastern Italian coast (Cattaneo et al., 2003). In the Po area, the dominant winds are the north-easterly Bora wind and the south-easterly Sirocco wind (Orlić, Kuzmić, & Pasarić, 1994).

Under bora and sirocco winds and during major storms, the significant wave height can reach up to 3 m within one or two hours (Pomaro, Cavaleri, Papa, & Lionello, 2018), exceptionally reaching values higher than 7 m in winter as the result of storm surges forced by Sirocco wind (Figure 2; Cavaleri et al., 2010). Maximum wave heights of 12 m were recorded in 1979 at the CNR Aqua Alta Tower, NE of the Po Delta (Cavaleri et al., 2010).

## 3 | DATA, METHODS AND APPROACH

Previous investigations on the Po Delta, concentrated in areas deeper than 10 m, show a relatively simple clinothem shape in 2D views perpendicular to the shore. A more complex 3D structure, however, is revealed by seismic profiles parallel to the shore, which document laterally-overlapping, southward-skewed lobes within late-Holocene deposits (Correggiari et al., 2005b; Trincardi et al., 2004). In this
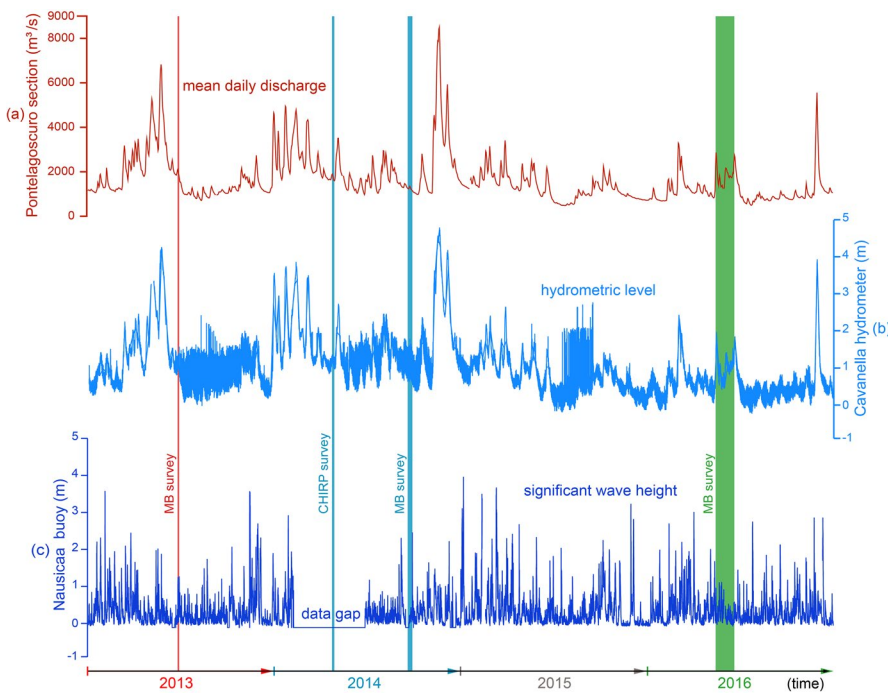


**FIGURE 2** River discharge and wave conditions at *Po di Pila* mouth for the 4-year interval encompassing the three bathymetric surveys offshore (2013–2016): (a) mean daily discharge at closure point (Pontelagoscuro); (b) hydrometric level near the delta outlet (Cavanella); and (c) significant wave height (Nausicaa). Major storms (significant wave height above 2 m) and major river floods (discharge above 5,000 m³/s) represent the events of most rapid change in delta geomorphology

study, we concentrated on three repeated surveys of the topset, delta slope and bottomset off the mouth of the *Po di Pila* distributary, between 2013 and 2016 (Figures 3 and 4). High-resolution multibeam bathymetries and CHIRP sonar profiles were acquired and integrated with independently constrained hydrographic and oceanographic data (Figures 2 and 3), shedding light on extremely rapid changes experienced by a modern delta at annual and inter-annual time scales.

Modern multibeam sonar data provide unprecedented opportunities to document, with a vertical resolution of few cm in our case, very rapid morphological changes on short time spans. These data improved our understanding of how sediment is transferred from the distributary channel to the mouth area, delivered to the mouth bars and reworked by marine processes.

## 3.1 | Multibeam bathymetry

Multibeam swath bathymetry was collected in June–July 2013 and September 2014 (Figure 4) with a Kongsberg EM2040 MBES pole-mounted on the vessel R/V Litus, used in equidistant mode with a frequency set to 300 kHz with 800 beams (400 per swath). During June-July 2013, a second multibeam survey was carried out in very shallow water using a small, 6-m long boat with 0.4 m draft, equipped with Teledyne Reson SeaBat 7125 SV2 pole-mounted (400 kHz) and Applanix POS MV. The positioning was carried out in Real Time Kinematic (RTK) by means of a ground control station located near the harbour. Subsequently, the Inertial Motion Unit and GNSS data-set were processed by POSPac MMS software to achieve a horizontal positioning with centimetre-level accuracy (Bosman et al., 2015). A Valeport tidegauge appropriately calibrated was installed near the study area to measure and correct sea-level changes in response to the bi-diurnal tidal excursion. In May 2016, the multibeam swath bathymetry was collected with a Kongsberg EM2040 single head system (frequency 300 kHz) hull-mounted in the vessel 1213.

The positioning system adopted for the 2013, 2014 and 2016 surveys was a Kongsberg Seapath 300, with the correction of a Fugro HP Differential Global Positioning System (horizontal accuracy: 0.2 m). A Kongsberg Seatex IMU (MRU 5) corrected pitch, roll, heave and yaw movements. A Valeport mini SVS sensor mounted close to the transducers measured continuously the sound velocity for the beam forming. Sound velocity profiles were systematically collected with an AML oceanographic Smart-X sound velocity profiler.

The multibeam data were processed using *Caris H&S* hydrographic software to obtain high-resolution Digital Elevation Models (DEMs) corrected through sound velocity

profilers, patch test and the application of statistical and geometrical filters to remove coherent/incoherent noise (Bosman et al., 2015). The soundings were merged and gridded for the generation of DEMs at 0.3–1 m cell size resolution (Figure 4). The gradients map was generated from high resolution Digital Elevation Models (DEM) using a slope map function of the seafloor.

## 3.2 | CHIRP sonar profiles

High-resolution CHIRP sonar profiles were collected in May 2014 during the CP14 cruise. They were positioned through a Trimble DSM-232 GPS receiver with the EGNOS differential correction, sufficient for the purpose of depth characterization. The seismic survey was performed through a sub-bottom profiler with CHIRP technology that allowed resolving clinoform geometry with a high resolution through the emission of a frequency modulated pulse (2–7 kHz). The system consists of a model topside 'Benthos DSP-662 chirp III' from 4 kw (DSP + Transceiver). The seismic profiles were converted in depth using a sound speed of 1,500 m/s.

## 4 | RESULTS

The short-term evolution of the modern Po Delta is documented by bathymetric maps acquired in 2013, 2014 and 2016 accompanied by CHIRP sonar profiles, and integrated with hydrographic and oceanographic data (Figures 2–4). The maps show substantial changes in bathymetry between the surveys, and may reflect changes in mean daily discharge, as well as the occurrence of storm events, as recorded by hydrometer and buoy measures, respectively (Figure 2). The main morphological features are described on the oldest, 2013 bathymetry and matched with the progressively younger bathymetries, highlighting the main changes through time. The terms northern, central and southern sectors are related to the *Po di Pila* mouth.

The multibeam bathymetry map 2013 shows a clinoform whose gradient changes basinwards from ~0° to 8° to 0.6° from the river mouth (topset) to the delta slope (foreset) and the distal sector (bottomset), respectively (Figures 3b and 4a,b). The main subaerial break in slopes (rollover point) typically occurs in 3–m deep waters in the northern sector, whereas it appears more scattered in the central and southern sectors, ranging between nearly 0.4 to 8 m of water depth, resulting in a more complex clinoform profile (compound clinoforms with subaerial and subaqueous rollover points). The main morphological features highlighted by the bathymetry include a longshore bar elongated for more than 4 km, parallel to the coast and submerged at an average water depth of 2.5 m, and reaching a maximum water depth of 4 m in the southern sector of the delta
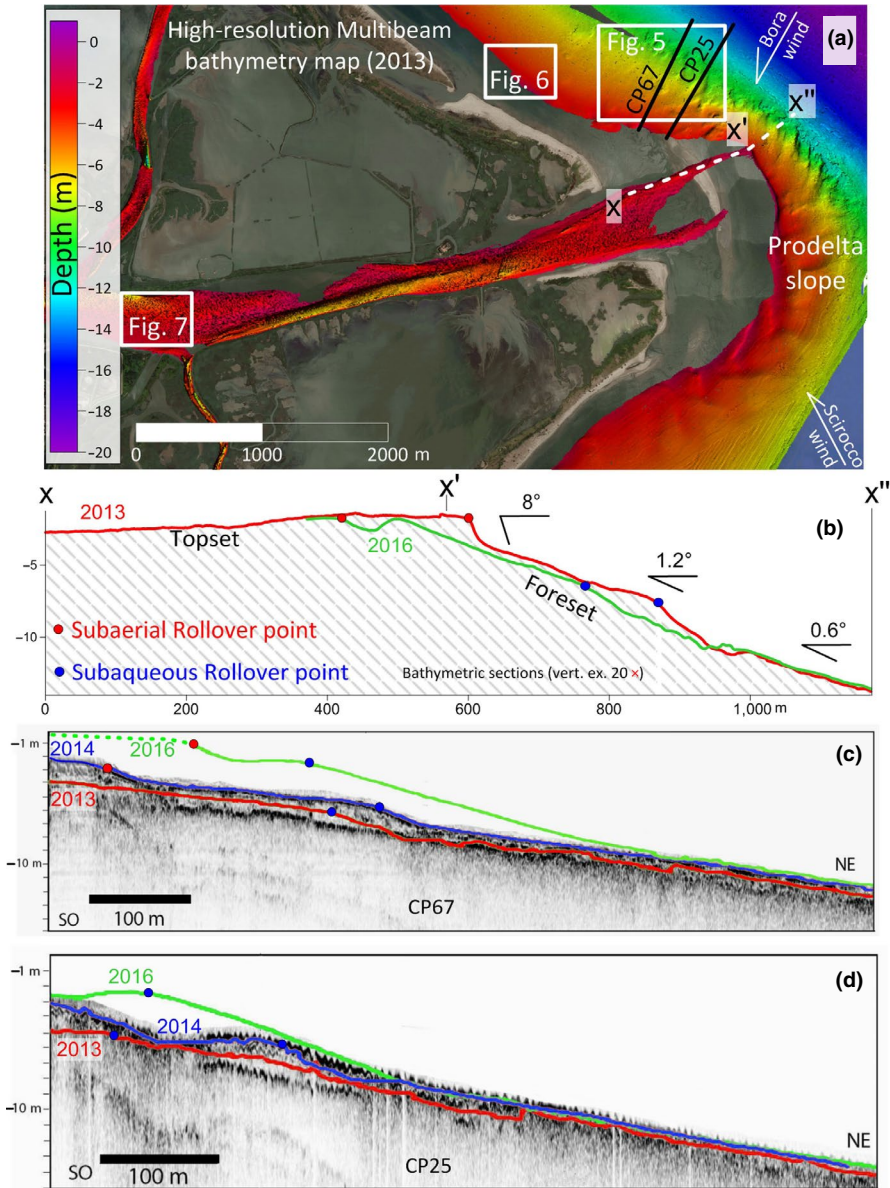
**FIGURE 3** (a) bathymetric map of the *Po di Pila* lobe from the 2016 dataset (DEM resolution 1 m, vertical exaggeration 15×); (b) comparison between the oldest (2013) and most recent (2016) bathymetric profiles showing substantial retreat and smoothing of the rollover points; (c and d) along-dip CHIRP sonar profiles showing the architecture of the *Po di Pila* clinothem from the 2014 survey, along with surfaces extracted from the 2013 (red), 2014 (blue) and 2016 (green) bathymetric surveys

clinothem (Figure 4a,b). Metre-scale transverse bars of reduced extent (300–500 m long and ca. 1 m high, with a wavelength of ca. 100 m), form on the delta slope and between 5–10 m of water depth. These transverse bars are oriented at ca. 20° and 60° relative to the coast strike in the northern and southern sectors of the delta, respectively (Figure 4a).

The multibeam 2014 bathymetry map documents the presence of slightly shallower (5 m water depth) subaqueous rollover points than the older 2013 bathymetry, with a compound clinoform geometry in the central sector (Figures 3c and 4c,d). The longshore bar shows a more regular rim in the sector that experienced sediment accumulation and that partially obliterated the transverse bars resulting in a smoother delta slope, especially in the southern sector (Figure 4d). Small submarine landslide scars and associated deposits are identified in the northern sector on

the delta slope (Figures 4c and 5). In shallow water, between 3 and 6 m, slide scars impact areas from 30,000 to 80,000 m$^2$ (Figure 5), typically with a low-gradient seabed, from 0.5° to 1.5° (Figure 4d). Slide scars are 100 to 500–m wide near the coast and just a few tens of meters in width at greater depths. Genetically related, lobe-shaped debris deposits have been identified deeper on the delta slope: they are 150–200 m in extent and few decimetres thick (Figure 5). Along the foreset–bottomset transition, closely spaced depressions, up to 1 m deep, exhibit a flat bottom (Figure 5).

The multibeam 2016 bathymetry map is characterized by a more uneven topography compared to the 2013 and 2014 bathymetries. In the northern sector, this bathymetry shows shallower values than the 2014 bathymetry, suggesting local deposition of a delta lobe up to 4 m thick (Figures 3d and 4e,f).
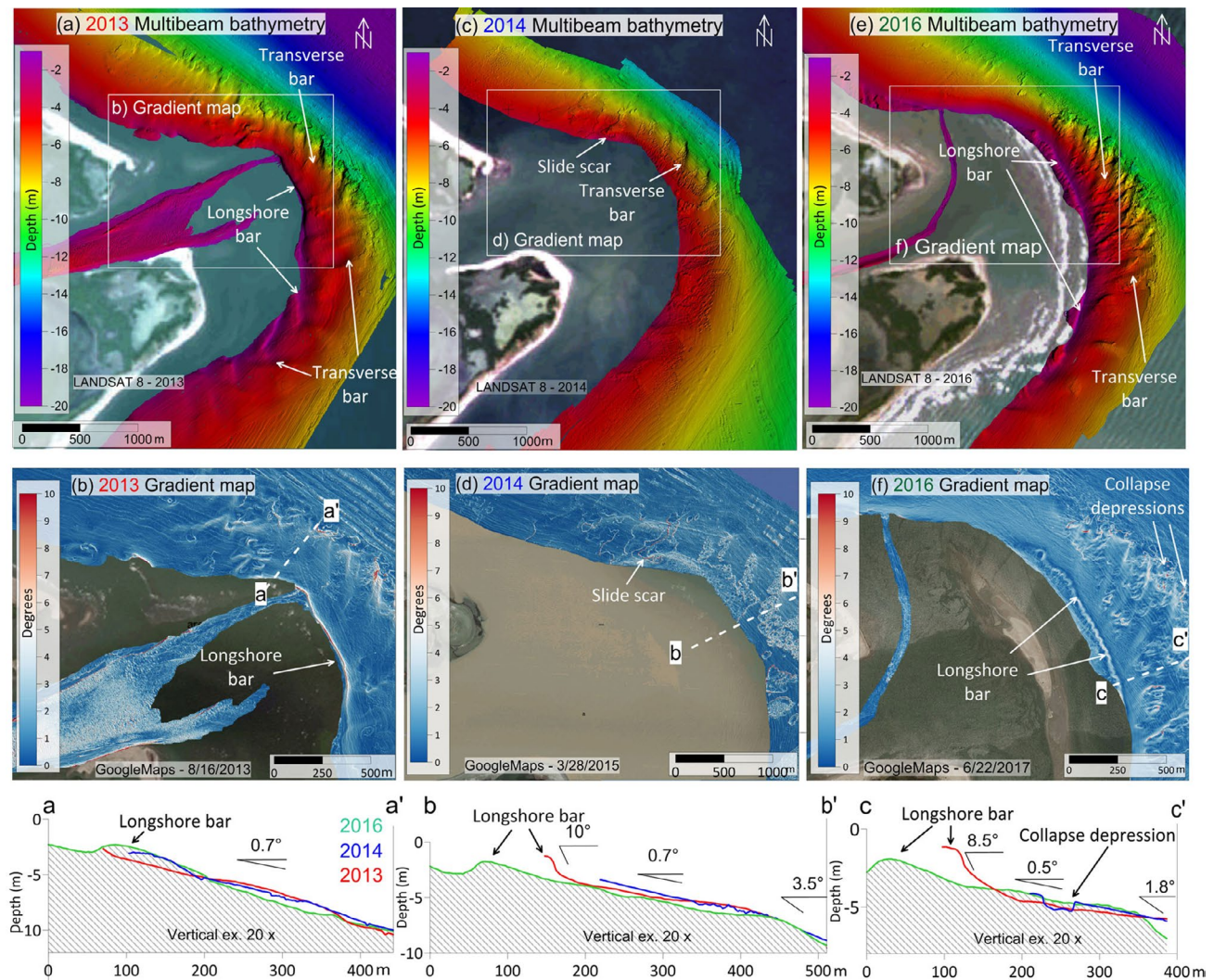
**FIGURE 4** Time-lapse bathymetric data (above) and gradient maps (below) illustrating the significative geomorphological changes that occurred in the upper prodelta slope in 2013 (a and b), 2014 (c and d) and 2016 (e and f). Main morphological features are highlighted by arrows and labels. Landsat 8 images define the delta plain extent at the time of each survey. Bathymetric sections highlight main changes of the clinothems at the mouth bar and prodelta slope during 2013, 2014 and 2016

The subaerial rollover point is well highlighted by a sharp break in slope at 0.4 m water depth in the northern sector (Figure 3c) whereas, in the southern sector, there are two closely spaced breaks at 0.4 and 3 m water depths due to the sinuosity of the longshore bar (Figure 3b). The longshore bar shows a more subdued morphology than in 2014. In the central and southern sectors, it is characterized by a ca. 30-m wide and 1.5-m deep scour oriented parallel to the coast (Figure 4f). Collapse features of variable size are present on the delta slope (Figure 4f). Larger depressions are observed at the delta slope foreset–bottomset, with widths ranging from 50 to 150 m and depths varying from 0.3 m to about 1.5 m (Figure 6). Repeated surveys revealed that such large depressions can be filled and buried in a very short time span (e.g. 7 days; Figure 6). Finally, surveys repeated with just a 3-day lapse in the *Po di Pila* channel, about 4–5 km upstream of river mouth, highlighted the migration, toward the river mouth, of dunes up to 0.5 m high and 10–20 m in

wavelength with slightly sinuous crests (Figure 7). The migration rate is up to 5 m in 3 days (Figure 7).

# 5 | DISCUSSION

## 5.1 | Clinothem geometry in 2D

River mouths are the dynamic dispersal sites of riverine sediments, which contribute to deltas formation (Coleman & Wright, 1975), and consequently represent the fundamental elements of delta-scale clinoforms. Along a down-dip depositional profile, delta-scale clinothems commonly show a transition towards deeper depositional environments (e.g. Rich, 1951). Based on changes in sediment supply and basin configuration, the shoreline of delta-scale clinothems can be located in different sectors of the shelf (Patruno &

Helland-Hansen, 2018). When the shoreline is located on the outer shelf, sediment can nourish delta-scale subaerial clinothems and their coeval and genetically related shelf-edge clinothems, promoting the progradation of compound clinothems, such as in the case of the Adriatic Sea (Gamberi et al., 2019; Pellegrini et al., 2018), and the Gulf of Lion (Jouet et al., 2006) under lowstand sea-level conditions. In these examples, geometry, extent and height of subaerial delta-scale clinothems are comparable to those of the modern Po Delta documented in this work.

Further advances in understanding the development of clinothems rely on the analysis of the rollover-point trajectory (Helland-Hansen & Martinsen, 1996), defined as the study of horizontal and vertical migration of geomorphological features and associated sedimentary environments, with emphasis on the migration paths of the shoreline and shelf-edge inflection points (Henriksen, Hampson, Helland-Hansen, Johannessen, & Steel, 2009). This approach can be used to reconstruct changes in accommodation and paleo environmental conditions recorded by stratigraphic successions and to predict the spatial distribution of lithological anisotropies associated with variations in shoreline position (Cosgrove, Hodgson, Poyatos-Moré, Mountney, & McCaffrey, 2018; Helland-Hansen & Martinsen, 1996; Poyatos-Moré et al., 2016; Steckler, Mountain, Miller, & Christie-Block, 1999; Zhang, Steel, & Ambrose, 2016). Recognizing the nature of rollover points in the study of progradational systems has also

led to the definition of compound clinothems, composed of a coastal clinothem (delta, beach) that is genetically linked to a subaqueous clinothem (Cattaneo et al., 2003; Pellegrini et al., 2015; Swenson, Paola, Pratson, Voller, & Murray, 2005). Despite great attention to shelf clinothems over half a century (Nittrouer et al., 1996), the most proximal and shallow sectors of deltaic clinothems remain substantially unexplored and the formation of the subaerial rollover point, its preservation potential and timing of formation are still poorly understood, though flume tank and modelling experiments tried to bridge this gap (e.g. Pirmez et al., 1998; Swenson et al., 2005). Using the *Po di Pila* as a natural laboratory, we document the extent to which clinothemmorphology may vary rapidly along the delta coast and show a 3D variability that is not captured in most conceptual models. The markedly different shapes of the *Po di Pila* clinoforms are due to a variety of superimposed bedforms. Clinothem profiles also vary depending on the position of the section considered (Figure 8). On a short (km-scale) distance and at any given time, the *Po di Pila* clinothems show marked variability in the rollover point morphology as well as in the gradient of the delta slope. For instance, transects from the same survey (e.g. 2014 survey) located few km apart show profiles with a simple coastal rollover point and 2°–4° seaward-dipping foreset passing, down-current, to a gentler, 0.5°–1° clinothem with a subaqueous rollover point, typically in 5-m water depth (Figure 8). Our dataset suggests, therefore, that double
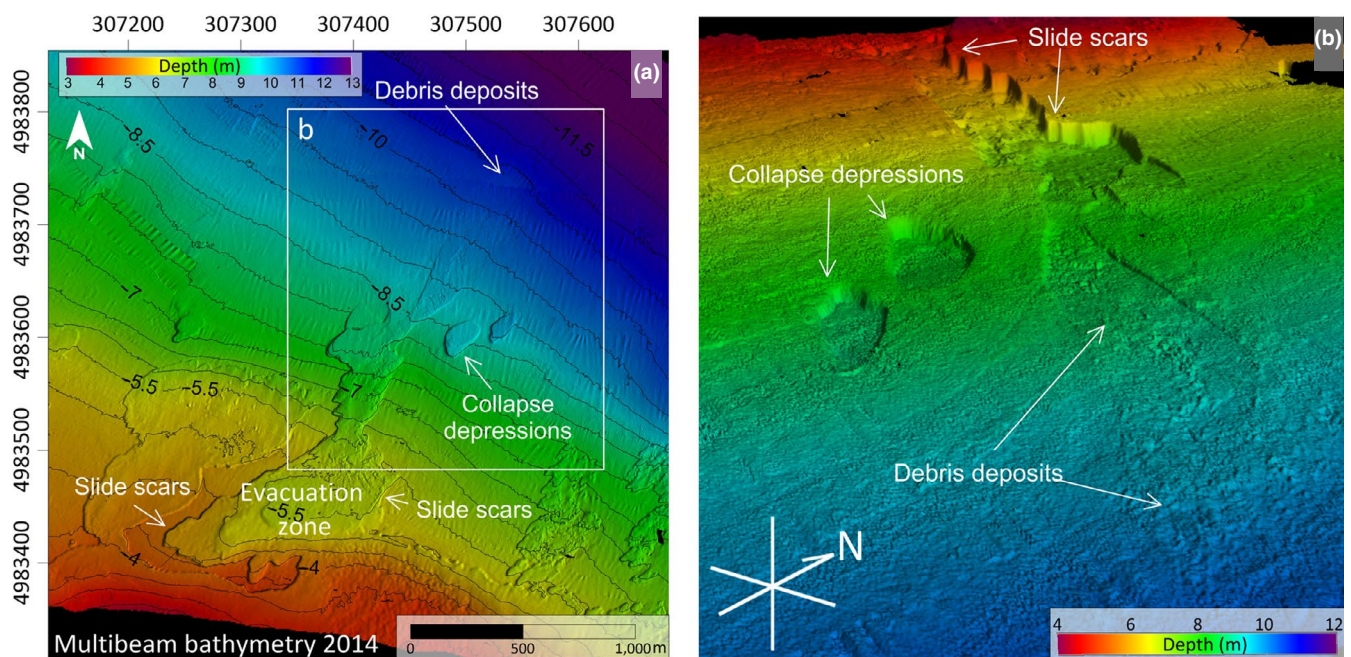


**FIGURE 5** (a) Submarine landslides scars and associated deposits located on the upper part of the prodelta slope and small collapse depressions from the 2014 survey. (b) 3D view of the lower sector of the bottle-neck slide with debris deposits and small blocks; see Figure 3a for the location
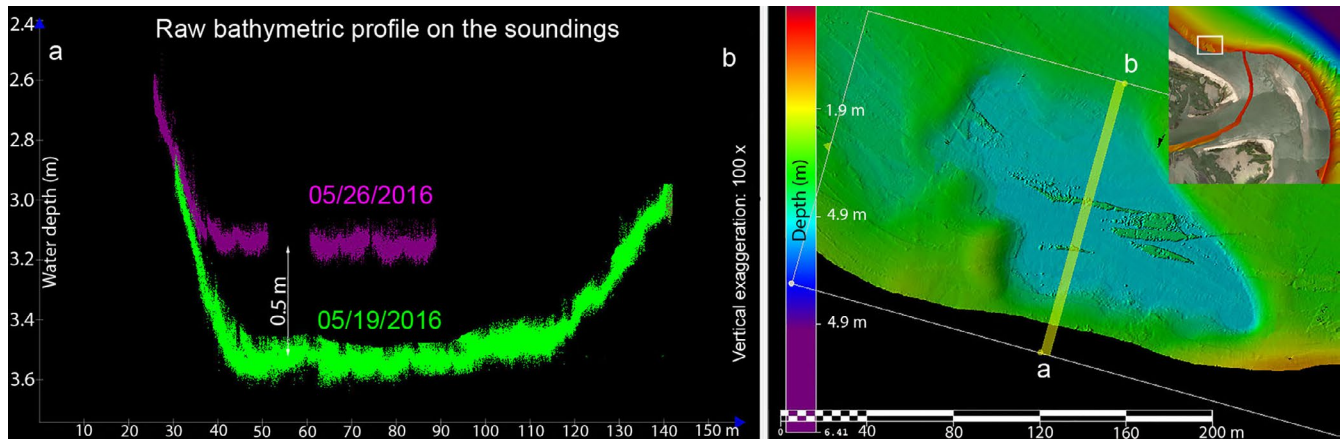
**FIGURE 6** Example of multibeam data processing (bathymetric section a-b on soundings) showing the overlap of two bathymetric surveys conducted near the mouth of the *Po di Pila*, only a few days apart. The large depression fills over 0.5 m in only 7 days (May 19th-26th, 2016). See the inset map for location

(compound) clinothems can be expected also nearshore, very close to the subaerial deltaic deposit. This configuration of 'proximal' compound delta should be included in flume and modelling experiments and should be taken into account when interpreting shoreline trajectories from low-resolution seismic datasets.
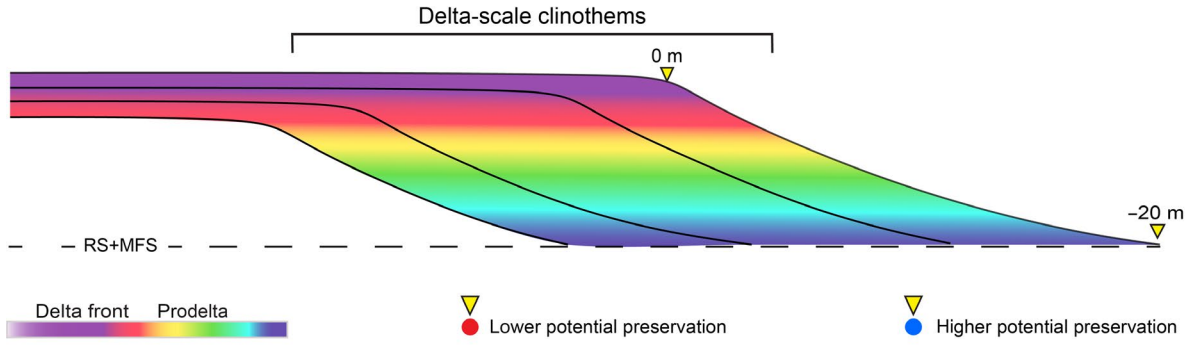
In the topset, flow-transverse dunes migrate daily in the river channel; where the river channel is straight to the mouth bar (Figure 7), the orientation of the dunes on its floor can be a reliable paleo environmental indicator of the direction of delta growth; when the river channel bends to a direction that is parallel to the main delta mouth bar, then the orientation of the dunes would mislead the reconstruction of the main direction of delta growth (Figure 7, 2016).

## 5.2 | Clinothem architecture, shoreline trajectories and inferred relative sea level
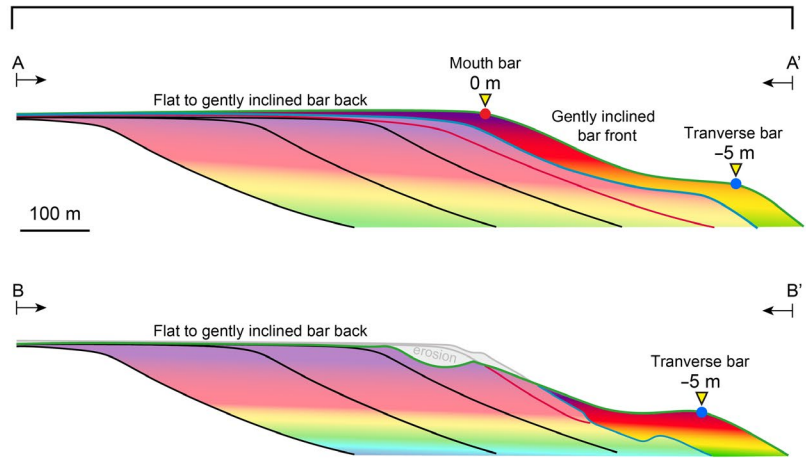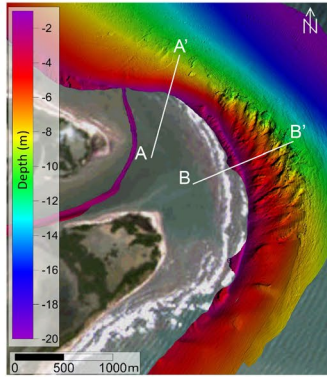
The study of shoreline trajectories coupled with the characterization of strata geometry, the recognition of key geomorphological features (e.g. mouth bar, transverse bar, slump), and depositional environments has led to a better reconstruction of the paleo environmental setting and of the processes governing sediment deposition on geological time scales (Cosgrove et al., 2018, 2019; Dixon, Steel, & Olariu, 2012; Johannessen & Steel, 2005; Pellegrini et al., 2017; Steckler et al., 1999). This approach has been applied successfully to: (a) ancient stratigraphic successions, where an increase in wave and storm dominance impacts deltas that build seawards
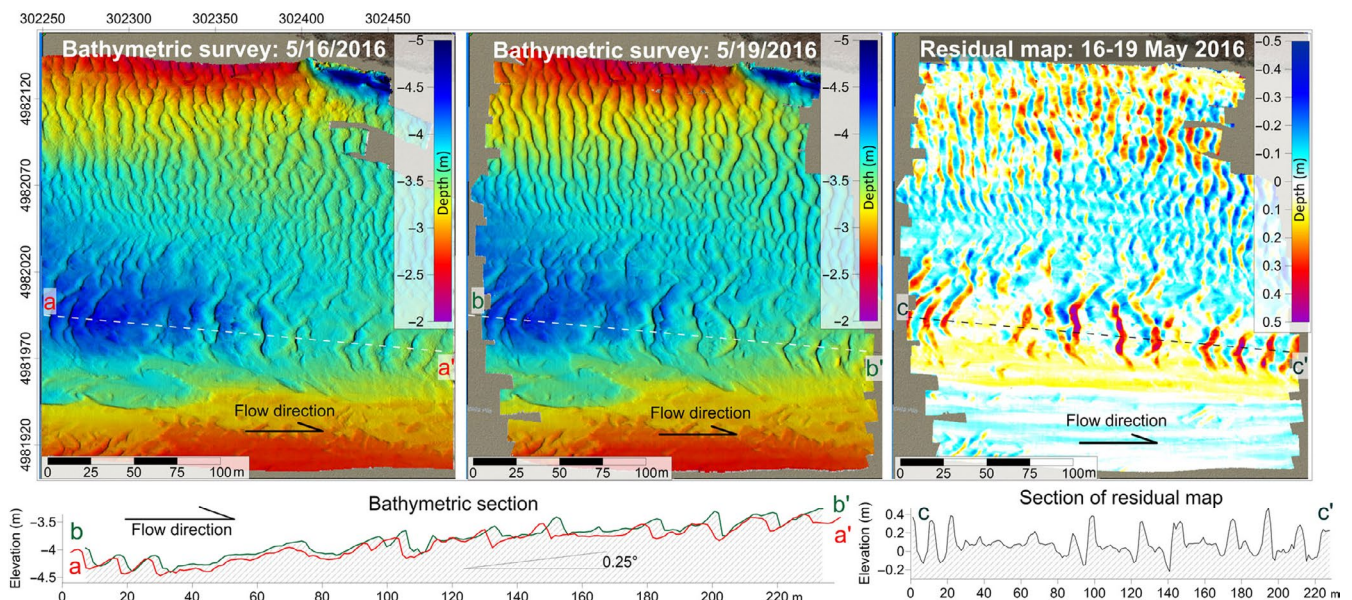


**FIGURE 7** Top, morphological complexity and short-term evolution of the clinothem topset. Multibeam images on the left and center were gathered 3 days apart during the 2016 survey. The image on the right represents the residual map between the two bathymetric maps, allowing quantification of the migration rate of the bedforms. Bottom, comparison of bathymetric sections a-a' and b-b'. Section c-c' is reported for the residual map. River flow from left to right; see Figure 3a for the location

Delta-scale clinothems

0 m

−20 m

— RS+MFS —

Delta front  Prodelta

▽ ● Lower potential preservation      ▽ ● Higher potential preservation

**YEAR 2016**

A → Flat to gently inclined bar back   Mouth bar 0 m   Gently inclined bar front   Tranverse bar −5 m   ← A'

100 m

B → Flat to gently inclined bar back   erosion   Tranverse bar −5 m   ← B'

**YEAR 2014**

A → Flat to gently inclined bar back   Mouth bar −3 m   Gently inclined bar front   Tranverse bar −5 m   ← A'

100 m

B → Flat to gently inclined bar back   Collapse depresssion −3 m   Collapse depresssion −5 m   erosion   ← B'

**YEAR 2013**

A → Flat to gently inclined bar back   Mouth bar −3 m   Gently inclined bar front   ← A'

100 m

B → Flat to gently inclined bar back   Mouth bar 0 m   Steep mouth bar front   Tranverse bar −8 m   Steep transverse bar front   ← B'
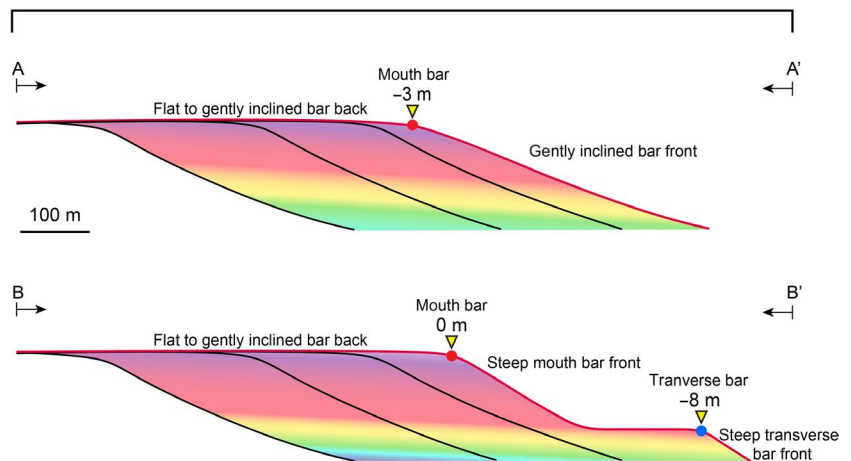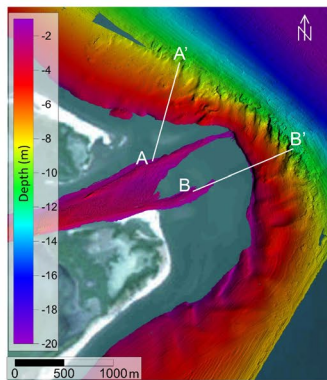
across a deepening shelf (Patruno & Helland-Hansen, 2018; Porębski & Steel, 2006); and (b) modern stratigraphic successions, where the impact of eustatic and climatic changes has been analyzed on delta architecture (Anderson, Wallace, Simms, Rodriguez, & Milliken, 2014; Fanget et al., 2014; Pellegrini et al., 2015).

In the upper foreset of the *Po di Pila*, active bedforms such as transverse bars, migrate dominantly southwards, according to the West Adriatic Current, suggesting continuous reworking of sediment mainly in the 0–5 m bathymetric range (Figure 8); these bedforms are common features in modern deltas (e.g. Brazos Delta, Rodriguez, Hamilton, & Anderson, 2000; Danube Delta, Bhattacharya & Giosan, 2003) despite their documentation from outcrop-scale studies is uncommon. In the lower foreset, collapse depressions and ephemeral incisions, that eventually are rapidly filled (Figures 5 and 6), can be ascribed to fluid-escape processes and thin bottleneck slides (Bosman et al., 2019); in ancient outcrop-scale studies (e.g. Dixon et al., 2012; Dixon, Steel, & Olariu, 2013), such features are taken as indicators of a delta clinothem reaching the shelf-edge where progradation on a steeper slope is expected to lead to gravity instability. The case of the *Po di Pila* Delta shows that gravity-driven processes can complicate the delta stratigraphy even during high-stand conditions and during progradation on a shallow (typically 30 m deep) and gentle continental shelf.

Reconstructing rollover-point trajectories provides a practical proxy of sea-level changes in the geological past; examples of Quaternary deposits on modern continental margins suggest caution, however, because of the marked three-dimensional variability of progradational deposits both on shelf and at the shelf-edge. Examples of such a complexity come from the Gulf of Lions, where 15-m-thick and high-angle progradational deposits (interpreted as shoreface facies) pass laterally into landward-onlapping, low-angle muddy deposits (Berné, Jouet, Bassetti, Dennielou, & Taviani, 2007; Rabineau et al., 1998). The Po Delta during the Last Glacial Maximum also shows marked lateral variability in delta morphology, paleo environments and rollover-point configuration that changed rapidly through time (Gamberi et al., 2019; Pellegrini et al., 2017, 2018). Our data on the active *Po di Pila* lobe of the modern Po Delta show that coastal rollover points are

ephemeral features that, at any given time, can be traced along-strike over distances of just a few km.

## 5.3 | 3D morphological complexity

The dynamic of deltaic systems has been documented using a variety of approaches that include comparison of historic maps (e.g. Johnson, 1891), seismic stratigraphy (e.g. Anderson et al., 2014), sediment core stratigraphy (e.g. Amorosi et al., 2019), outcrop studies (e.g. Plink-Björklund, 2019), sediment budget calculations (e.g. Blum & Roberts, 2009) and satellite data (e.g. Falcieri et al., 2014). Despite the broad consensus on the extremely dynamic nature of deltaic environments, detailed documentation of abrupt 3D changes in modern deltaic systems is poorly available (Bosman et al., 2019). At the outcrop scale, morphological variations are ascribed to changes in basin configuration (e.g. variations in accommodation and or changes in delta location relative to the shelf-edge; Porębski & Steel, 2006). Process variability may depend on variations in river discharge, relative sea-level, sediment supply and/or wave and tide regime, with a resultant high spatial variability of wave- or river-dominated delta fronts (e.g. Ainsworth et al., 2016; Gerber et al., 2008; Hampson & Storms, 2003; Olariu, Steel, & Petter, 2010; Patruno & Helland-Hansen, 2018; Rossi, Perillo, Steel, & Olariu, 2017).

The spatial distribution of sedimentary features documented in *Po di Pila* causes distinctive uneven depth-location of the shoreline rollover and delta front morphology (Figure 8). Changes in the shape of these profiles appear to reflect a variety of processes, such as bottom currents, collapse or erosion, as documented by the three bathymetries (c, b and a, respectively) illustrated in Figure 8. The interplay of these processes, in turn, determines the depth, number and nature (shoreline or subaqueous) of the rollover points (Figure 8). If locked in the stratigraphic record, the *Po di Pila* clinothems would puzzle the interpretation showing, on short distance, clinothemmorphologies suggestive both of wave-dominated and river-dominated conditions (Figures 7 and 8). This finding cautions on the use of bi-dimensional reconstructions of the clinothems to infer regional and time-averaged depositional regimes. The data from the Po River show that the

**FIGURE 8** Conceptual stratigraphic section of the *Po di Pila* clinothem throughout the 4-year bathymetric surveys. Bottom, year 2013: the *Po di Pila* shows compound progradation in the central sector, with a subaqueous Rollover Point (RP) at 8 m, whereas in the northern sector a single RP develops at an average of 3 m water depth. Center, year 2014: the *Po di Pila* shows compound progradation in both (central and northern) sectors, but a destruction phase in the central sector (eroded topset and RPs separated by a collapse depression) and a constructional phase in the northern sector (normal regression with compound clinothems) occur simultaneously. Top, year 2016: the *Po di Pila* shows a subaqueous RP at average 5 m of water depth of the transversebar in the central sector, whereas compound progradation is recorded in the northern sector. Note that in a subaerial delta, such as the modern Po Delta, subaerial RPs correspond to breaks in slope associated with the presence of mouth bars, whereas subaqueous nearshore RPs correspond to breaks in slope due to the presence of transverse bars and delta lobes

influence of river and of meteo-oceanographic conditions (river discharge, wind direction, current activity and wave height; Figure 2) can vary at seasonal, annual or inter-annual scales (Figure 2), which in turn leads to variability of morphological features in the different sectors of the deltaic system and to inter-annual changes of the gradient of the delta slope in the order of 0.5°–1° (Figures 4 and 8). The marked changes documented over a 4-year time span show that both coastal and subaqueous rollover points are more ephemeral that previously thought and that they can be reworked, destroyed and built again on inter-annual scales.

## 5.4 | Timing

Delta scale clinothems, characterized by tens of metres of relief (Patruno & Helland-Hansen, 2018), are depositional elements fundamental in understanding ancient physiographic settings (e.g. Patruno et al., 2019; Pellegrini et al., 2015; Rovere, Pellegrini, Chiggiato, Campiani, & Trincardi, 2019; Steel & Olsen, 2002), the evolution of modern coasts (e.g. Coleman, 1988; Correggiari et al., 2005a; Correggiari et al., 2005b; Törnqvist, Bick, González, Borg, & Jong, 2004), and the main processes governing their formation (Burgess, Steel, Granjeon, Hampson, & Dalrymple, 2008; Gerber et al., 2008; Muto & Steel, 2002; Swenson et al., 2005). A recent review of the literature suggests that delta-scale clinothems represent short time spans (1–10$^3$ kyr; Patruno & Helland-Hansen, 2018). Here, we demonstrate that the morphology and stratigraphic architecture of delta clinothems (Figure 8) are sensitive to even much higher-frequency fluctuations in sediment supply and compaction, relative sea-level, storm events and basin hydrodynamics (Figure 2; inter-annual time-scale).

## 5.5 | Implications for ancient delta deposits

Middle to Upper Holocene highstand (Highstand Systems Tract, HST) clinothems in deltaic successions form typical shallowing-upward packages (or parasequences) that are generally represented by coarsening-upward trends at the prodelta-delta front transition, and by sharp lithofacies changes at the boundary between delta front and delta plain deposits. In the Po Delta depositional system, the 3-D complexity of HST prograding clinothem sets across the delta plain/delta front transition is reflected along-strike in the juxtaposition of seaward-bowed delta lobes and associated strand plain sand bodies developed on centennial to millennial time scales (Amorosi et al., 2017; Amorosi, Maselli, & Trincardi, 2016; Correggiari et al., 2005a; Stefani & Vincenzi, 2005). In this context, clinothem boundaries mark abrupt shifts in depositional

systems configuration and sediment dispersal pathways that are typically represented by hiatal stratigraphic surfaces of short duration and small areal extent (Amorosi et al., 2019; Correggiari et al., 2005b; Pellegrini et al., 2017; Trincardi et al., 2004).

The remarkable spatial and temporal changes in rollover point trajectories and paleo bathymetric profiles documented in this study off *Po di Pila* river mouth between 2013 and 2016 demonstrate that internal morphologies of prograding clinothem sets may vary in a short time-span over seasonal to inter-annual time scales, that is, well below the resolution of the dating techniques commonly used to interpret the ancient record. Such spatial and temporal variations are likely to result in internally diachronous clinothem sets, with laterally variable stratigraphic records and unique stratigraphies from place to place.

The extremely variable preservation potential of this changing physiography (Figure 8) suggests caution around the reconstruction of depositional system morphology and orientation based on spatially limited outcrop or core datasets, especially under the poor chronologic control typical of the ancient record. Depositional processes inferred from local lithofacies distribution or parasequence stacking reconstructed from scattered stratigraphic logs may be poorly representative of the complex heterogeneity/history of the whole depositional system. In particular, changes in outbuilding directions or discrimination of the delta regime based on local paleo current patterns or isolated depositional and geometrical data could suffer heavily from insufficient data quality or resolution, leading to erroneous interpretations.

## 5.6 | Anthropogenic impact

Human influence is a pervasive controlling factor on modern delta growth (e.g. Blum & Roberts, 2009; Syvitski, Vörösmarty, et al., 2005a). A recent study has documented that only 23% of worldwide rivers longer than 1,000 km flow uninterrupted to the ocean (Grill et al., 2019). Despite clear evidence of human-induced perturbation, the Po Delta can still be studied to document morphological changes, because the main processes governing delta formation (sensu Galloway, 1975) are still active (Tesi et al., 2012; Trincardi et al., 2004).

The Po River experienced a drastic reduction in sediment yield after the Little Ice Age. This reduction in sediment yield reflects a variety of factors including bed material exploitation, dam construction, landslide stabilization and progressive reforestation of hill and low-mountain areas (Maselli & Trincardi, 2013). These actions resulted in a halt of progradation and a very rapid shrinkage of the deltaic body, as observed in other large delta systems around the world

(e.g. Colorado, Nile, Yangtze and Yellow River; Syvitski, Vörösmarty, et al., 2005a). The Po Delta, therefore, turned into a fragile and vulnerable regime until the 21th century, for which a new progradational phase of the *Po di Pila* has been proposed based on satellite data (Ninfo et al., 2018). Satellite data, however, cannot capture the full depositional history of a delta, especially of its submerged or buried segments. The analysis of high-resolution bathymetries coupled with seismic profiles (Figures 3, 4 and 8) suggests that deposition and erosion after 2013 are operating simultaneously in different parts of the system, leading to local progradation and aggradation of along-shore bars in the northern topset–foreset (see comparison of the 2013 and 2016 data of Figures 3 and 8), and destruction phases, involving comparable thicknesses of sediment, in the southern topset–foreset of the *Po di Pila* (Figures 3 and 8). Our data highlight the importance of acquiring continuous data in such a highly dynamic environment to fully understand the evolution of transient systems such as deltas, especially when facing strong anthropogenic influence.

# 6 | CONCLUSION

Precisely positioned time-lapse bathymetric surveys of the *Po di Pila* clinothem, the most active branch of the modern Po Delta, document the marked 3D variability, in space and time, of the upper portion (topset–foreset transition) of a 30-m thick delta clinothem. In particular, we observed:

1. A short-distance (km-scale) variability in rollover-point morphology at any given time. Transects perpendicular to the shore document the lateral transition, over a kilometre distance, from a simple, coastal rollover point, with regular seaward-dipping foreset morphology, to a clinothem with a subaqueous rollover point in, typically, 5-m water depth;

2. A marked variability in time (annual scale), documented along repeated transects, shows that both coastal and subaqueous rollover points are ephemeral and can be reworked, destroyed or re-built on sub-annual scales;

3. Rollover-point trajectories and sea-level variations reconstructed from low-resolution datasets and flume and modelling experiments should consider near shore compound clinothem configurations as a result of the oceanographic regime;

4. Bedforms in the topset migrate daily in the river thalweg; their orientation is a good indicator of the channel orientation, but not necessarily of the direction of clinothem growth;

5. Mobile coastal bedforms in the Po Delta front migrate dominantly southward, according to the general oceanographic regime, indicating continuous reworking of sediment particularly in the 0–5 m bathymetric range; though structures parallel to the shore are an important feature in modern systems, but not commonly documented in ancient outcrop-scale studies;

6. Delta front sediment failure can be ascribed to fluid-escape processes and thin bottleneck slides resulting in liquefaction structures with contorted and graded beds. The presence of such structures does not imply necessarily, as suggested in some cases in outcrop-scale studies, that a delta clinothem has reached the shelf edge.

The quantitative chronologic information about clinothem evolution presented in this study can be used as a guide to the interpretation of the ancient stratigraphic record. The remarkable spatial and temporal changes in morphology and sedimentary dynamics reconstructed over seasonal to inter-annual time scales suggest that stratigraphic interpretation of older deltaic successions (chronologically constrained at much lower resolution) on the basis of sparse outcrop or core datasets may result in a bias towards estimates of sedimentary evolution or event frequencies that can be incorrect by orders of magnitude.

## DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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