Anatomy of a compound delta from the post-glacial transgressive record in the Adriatic Sea

Pellegrini Claudio ^{1,2,*}, Maselli Vittorio ², Cattaneo Antonio ³, Piva Andrea ⁴, Ceregato Alessandro ², Trincardi Fabio ²

¹ ISMAR (CNR), v. Gobetti 101, 40129 Bologna, Italy

² University of Bologna, Dipartimento di Scienze della Terra e Geologico-Ambientali, Piazza di Porta San Donato 1, 40126, Bologna, Italy

³ IFREMER, Géosciences Marines Centre de Brest, BP70, 29280 Plouzané, France

⁴ Eni, Exploration and Production Division, Sedimentology, Petrography & Stratigraphy Dpt., 20097 S. Donato Milanese, Italy

* Corresponding author : Claudio Pellegrini, email address : claudio.pellegrini@bo.ismar.cnr.it

Abstract :

On the Mediterranean continental shelves the post-glacial transgressive succession is a complex picture composed by seaward progradations, related to sea level stillstands and/or increased sediment supply to the coasts, and minor flooding surfaces, associated to phases of enhanced rates of sea level rise. Among Late Pleistocene examples, major mid-shelf progradations have been related to the short-term climatic reversal of the Younger Dryas event, a period during which the combination of increased sediment supply from rivers and reduced rates of sea level rise promoted the formation of progradations up to tens-meter thick. While the documentation of coastal and subaqueous progradations recording the Younger Dryas interval are widely reported in the literature, the model of compound progradation within transgressive deposits is not proposed so far. Here we present the documentation of a deltaic system where both delta front sands and related fine-grained subaqueous progradations (prodeltaic to shallow marine) have been preserved. The Paleo Gargano Compound Delta (PGCD) formed offshore the modern Gargano Promontory (southern Adriatic Sea), and is composed by a coastal coarse-grained delta of reduced thickness and a muddy subaqueous clinoform, up to 30 meters thick. The PGCD, probably the first worldwide documentation of a compound delta within the transgressive record, provides the opportunity to investigate the processes controlling the formation of a compound delta system during an overall sea level rise and the factors that allowed its preservation. The finding of the PGCD provides the opportunity of a comparison with modern worldwide compound systems.

Highlights

► The Paleo-Gargano Compound delta (PGCD) formed within transgressive deposits. ► The PGCD is the first documentation of a compound delta in transgressive deposits. ► The PGCD formed in few centuries during the Younger Dryas event. ► The PGCD leads the opportunity of a comparison between ancient and modern deltas.

Keywords : Compound delta, Mediterranean Sea, Younger Dryas, Subaqueous clinoform, Transgressive deposits

1. Introduction

Modern and ancient river deltas represent one of the most intriguing sedimentary archives in the geological record, as their internal geometry and evolution reflects the interplay between river dynamics, sediment availability, grain size distribution and the oceanographic regime of the receiving basin (Orton and Reading, 1983; Cross et al., 1993; Trincardi et al., 2004; Slingerland et al., 2008). After the first process-driven classification of Wright and Coleman (1972), and Galloway (1975), another important step in understanding delta dynamics was introduced with the concept of compound deltas (Swenson et al., 2005), i.e. deltas composed by shallow-water progradations that are genetically related to deeper subaqueous clinothems. The transition in grain-size, mostly related to the oceanographic regime of the basin, is also reflected by the overall geometry, characterized by two main roll-over points (i.e. breaking in slope at the topset/foreset transition; Swenson et al., 2005; Cattaneo et al., 2007; Walsh and Nittrouer, 2009). The depth of the subaqueous rollover point is assumed to reflect the seaward limit beyond which wave-current shear

stress decreases allowing sediment deposition (e.g., Nittrouer et al., 1986; Kuehl et al., 1986; Alexander et al., 1991; Pirmez et al., 1998; Walsh et al., 2004).

Along the western Adriatic basin, the modern highstand deposits are organized in shelf-wide progradations that locally show variations in the stratal geometry; from North to South on bidimensional profiles it is possible to identify: 1) a single rollover point, where the delta front and the prodelta are “attached” (Fig. 1 section A-A'); 2) two rollover points (coastal and subaqueous rollover point), where the delta front and the prodelta are separated, and their distance is governed by the oceanographic regime (Fig. 1 section B-B', the 2D compound delta); 3) a single subaqueous rollover point where the subaqueous delta disconnected from the delta front (Fig. 1 section C-C', purely subaqueous delta). In a section parallel to the modern shoreline from the modern Po River delta down to the Gargano Promontory, the Adriatic subaqueous clinoform has been interpreted as a "distorted" compound system (Fig. 1 section D-D'; Cattaneo et al., 2007).

The understanding of the physiographic parameters of the compound system is crucial to explain the main processes govern a couplet progradation on the modern shelf. Steckler et al. (1999) noticed that a subaqueous clinoform may prograde simultaneously with the coastal delta system depending on the oceanographic regime of the receiving basin; Swenson et al. (2005) highlighted that such genetically-connected clinoforms (coastal and subaqueous) may be geometrically disconnected depending on fair-weather and storm wave bases (10/15 m to 30 m water depth, respectively; Cattaneo et al., 2003) exhibiting a dominantly along-shore thickness distribution and a typical convex seaward morphology (Cattaneo et al., 2003). Examples of compound delta systems may be found in both open ocean settings and enclosed basins: e.g., Amazon River, (Nittrouer et al., 1996); Ganges-Brahmaputra River (Goodbred and Kuehl, 2000); Yellow River – Shandong subaqueous clinoform (Liu et al., 2004); Po River– Gargano subaqueous delta (Cattaneo et al., 2003). Furthermore, many authors focused on the subaqueous clinoforms that constitute tens of meter thick sediment successions with kilometric alongshore distributions far from the main Rivers: e.g.; Ganges-Brahmaputra Rivers subaqueous delta (Kuehl et al., 1997; Palamenghi et al., 2011); Fly,

Kikori and Purari Rivers (Walsh et al., 2004); Yellow River subaqueous delta (Yang and Liu, 2007); Mekong River subaqueous delta (Xue et al., 2010); Rhone River subaqueous delta (Fanget et al., 2014). While compound and subaqueous deltas are increasingly recognized on modern continental margins, their identification in ancient sedimentary records is more difficult, mainly for two reasons: the difficulty of pinpointing the position of the feeder system and the poor geometric resolution in depicting the low angle of muddy subaqueous progradations (Mellere et al., 2002; Morris et al., 2006; Hampson, 2010).

The aim of this paper is to document a compound delta system (the Paleo Gargano Compound Delta, PGCD), formed during the post-glacial sea level rise, offshore the Gargano Promontory in the South Adriatic continental shelf. This study provides the opportunity to investigate the conditions that led to the formation and preservation of a complex deltaic system during a period of overall sea level rise and to develop new concepts for the study of ancient sedimentary archives. Among Late Pleistocene to Holocene examples, a growing body of evidence suggests that mid-shelf progradational deposits of variable thickness develop during the overall last post-glacial sea level rise (Fig. 2; Cattaneo and Trincardi 1999; Hernandez-Molina et al., 1994; Aksu et al., 2002; Labaune et al., 2005; Berné et al., 2007; Maselli et al., 2011; Somme et al., 2011) although no documentation of compound deltas has been proposed so far in these contexts.

2. Background

2.1. Geological setting

The Gargano Promontory peaks at 1050 m above sea level and has constituted a morphologic relief since the Middle Pliocene (Bertotti et al., 1999). The outcropping stratigraphic succession consists of Mesozoic carbonate rocks and includes four main lithostratigraphic units: the Maiolica Formation (Fm), the Marna a Fucoidi Fm, the Scaglia Fm and the Peschici Fm, characterized by thin- to thick-bedded lime mudstone, with Calcarene and Breccia intervals (Eberli et al., 1993). The same lithology extends offshore the Gargano Promontory to form the Gargano Structural High

(GSH) of the study area: a shallow plateau in ca. 50 m of modern water depth with steep flanks to the North and to the East (Fig. 1). The GSH represents an area of no or reduced sediment deposition during the modern highstand (Fig. 1; Cattaneo et al., 2003), where carbonate related karst features are exposed on the sea floor (Taviani et al., 2012).

2.2. Modern Hydrology of the Adriatic Sea and sedimentation patterns

The oceanographic circulation of the Adriatic Sea is dominated by three main elements (Artegiani et al., 1997a,b): 1- a superficial cyclonic gyre with a component that flows parallel to the western Adriatic shoreline, mainly generated by the wind pattern; 2- the Levantine Intermediate Water (LIW), a salty water that forms in the Eastern Mediterranean Sea (Levantine Basin) and intrudes in the Adriatic basin flowing at depths of 200-600 m (Lascaratos, 1993); 3- the North Adriatic Dense Water (NAdDW), that forms in the northern Adriatic through winter cooling (Vilibich and Supich, 2005; Benetazzo et al., 2014) and then, once a density threshold is reached, flows southward until cascading toward the deep southern Adriatic Basin (Trincardi et al., 2007; Canals et al., 2009). The overall thermohaline circulation, under the Coriolis apparent force, runs along the Italian coast constraining the main sediment flux to deposit in a prism parallel to the Apennine coast (Fig. 1; Correggiari et al., 2001; Cattaneo et al., 2003).

2.3. Stratigraphic setting of Adriatic TST deposits

In the Adriatic basin the Late Pleistocene–Holocene transgressive units comprise backstepping barrier lagoon deposits with large reworked sand dunes, in the northern low-gradient shelf (Trincardi et al., 1994; Correggiari et al., 1996), and subaqueous progradational deposits, in the western Adriatic shelf and in the Mid Adriatic Deep (MAD, Trincardi et al., 1996; Cattaneo and Trincardi 1999; Maselli et al., 2011), where continuous chronological controls are available (Asioli et al., 1996; Blockley et al., 2004; Lowe et al., 2005). The transgressive systems tract (TST) is

floored by an unconformity of regional extent (lowstand unconformity ES1) and topped by the maximum flooding surface (mfs).

On the central Adriatic shelf the TST unit records the impact of sea level and sediment supply fluctuations on sub-millennial scales resulting in a tripartite TST (Cattaneo et al., 1999; Maselli et al., 2011). The lower and upper TST units (lTST and uTST unit, respectively) record an abrupt landward shift of the shoreline, while the middle unit (mTST unit) is prograding seaward and represents a regressive sedimentary body within the TST (Cattaneo and Trincardi, 1999). The three TST units are separated by two prominent, and extensively erosional, surfaces (S1 and S2 surface, Cattaneo and Trincardi, 1999; Maselli et al., 2011; see Figure 3 and Table 1 for a summary of the main stratigraphic surfaces and depositional units within the Late Pleistocene-Holocene TST record). In particular the mTST unit is characterized by two sub-units (mTST-1 and mTST-2 sub-unit) separated by an erosional surface (Si) that, possibly, records a minor sea level fall during the Younger Dryas interval (Maselli et al., 2011). The mTST-1 unit records the Bölling-Allerød interval, while the mTST-2 unit progrades during the Younger Dryas interval (Maselli et al., 2011).

From the central Adriatic to the southern Adriatic shelf the lTST and mTST units are organized in depocenters which reflect the interaction between sediment distribution, oceanographic processes and sea floor morphology. In particular, the Gargano Promontory is characterized by an articulated slope morphology and approaching the GSH the low TST and the mTST-1 units tend to diminishing in thickness and disappear, locally.

3. Data and Methods

The database is composed by a dense network of high-resolution chirp-sonar profiles (acquired with a 16-transducer hull-mounted Benthos sound source), and sediment cores (both piston and gravity corers) acquired during the last decades by ISMAR-CNR with R/V URANIA (Cruises YD97, AMC99, CSS00, COS01, KS02 and SA03). The seismic profiles analyzed in the study area offshore Gargano Promontory sum to a total length of 1300 km over an area of 3200 km², with an

average spacing between the lines of 2.5 km. A D-GPS allowed accurate positioning of the profiles and sediment cores.

Chirp profiles are imaged with a metric vertical scale assuming a 1500 m/s propagation sound velocity within sediment. By using a total length of 1300 km of seismic profiles, we constructed the structural map of the ES1 surface (the sequence boundary above which the transgressive record developed, Fig. 4), and the isopach maps of the main stratigraphic units composing the post-glacial stratigraphy offshore the GSH. The maps are stored in a GIS and projected in UTM with a WGS84 datum. In the lack of more precise velocity analyses on the sediments, volumes are quantified by assuming a constant 1500 m/s propagation sound velocity through superficial sediment.

Piston cores YD97-16 and KS02-330P were recovered on the GSH flank in 78.5 m and 79 m water depth using a 10 m barrel. The penetration of the corer was 7 m in the first site, and 11 m in the second, with a core recovery of 3.91 m and 6.6 m, for a total recovery of 70% in both cases. Both cores were sampled every 10 cm; core KS02-330P for grain size analysis and both cores for lithological and paleo-environmental reconstructions based on micro and macro faunal assemblages. Calcimetry and grain size analyses were performed at Ifremer; the sampled fractions were disaggregated with a Retsch MM200 mixer mill at 17 cycles per second for 4 min. The CaCO₃ content was measured with an automatic pressure calcimeter (Dream Electronique model 2.1) while grain size analyzes were made using a Coulter LS200 laser microgranulometer. Radiographies of the lowermost 3 meters of core KS02-330P allow detection of bottom-current structures.

The correlation between cores and seismic profiles is performed after decompacting the total recovery versus the total penetration by assuming a linear compaction (the compaction is given by the ratio between the total penetration and the total core length). Correlation among YD97-16 and KS02-330P cores relied on wiggle matching of the magnetic susceptibility logs.

4. RESULTS

4.1. The middle TST unit offshore the Gargano Promontory

Offshore Gargano Promontory a prominent erosional surface (ES1), characterized on seismic profiles by a continuous and high amplitude seismic reflector, formed during the last glacial sea level lowstand, when the shelf underwent subaerial exposure, as highlighted for the northern and central Adriatic shelf by Trincardi and Correggiari (2000) and Ridente and Trincardi (2002). On the steep flanks of the GSH the ITST unit and the mTST-1 unit are not recorded and consequently the ES1 coincides with the S1 and Si surfaces ($ES1 \equiv S1 \equiv Si$, Figs. 5A, B, C). Locally, the recognition of ES1 surface is hampered by the occurrence of biogenic gas in the upper TST deposits (Figs. 5A, B).

In this setting the mTST unit is confined between surface ES1 (below) and surface S2 (above), the latter corresponding to a high amplitude reflector of regional extent (Figs. 5A, B). In the proximal area of GSH the coastal deposits of the mTST unit show seismic facies with opaque discontinuous reflectors characterized by local and small scale steep reflectors (Fig. 5B). The seismic pattern of the costal deposits shows high-angle foresets with a pronounced costal rollover point at ca. 60 m bsl (below sea level; Figs. 5A, B). The transition area between coastal and subaqueous deposit of the mTST unit is characterized by discontinuous reflectors in part due to the presence of gas charged sediment (Figs. 5A, B). In the area seaward of the GSH the subaqueous deposits of the mTST unit are characterized by complex sigmoid-oblique seismic pattern reflector (*sensu* Mitchum et al., 1977; Figs. 5A, B). Within this subaqueous progradational deposits the subaqueous rollover point is detected at an average water depth of 90 m bsl (Figs. 5A, B, C). The subaqueous rollover point shows an ascending trajectory that may suggest the onset of a relative sea level rise (Figs. 5A, B; Helland-Hansen and Hampson, 2009).

The mTST unit develops in the proximal area and seaward of GSH over an area of $5 \times 10^5 \text{ km}^2$ and with a total volume of about 4.6 km^3 . This unit reaches a maximum thickness of up to ca. 30 m close to the GSH, where a bidirectional progradation develops (Fig. 5C), and then becomes thinner

and spread over a broader area further to the south (Fig. 6). The bidirectional downlap is accompanied by an asymmetric internal geometry with steeper foresets (up to 2.2°), and a reduced seaward progradation toward the NW and gentler foresets (0.7°), with a greater seaward progradation toward the SE. Furthermore, the direction of progradation within the clinothemes (*sensu* Slingerland et al., 2008), determined from apparent angles measured along perpendicular profiles, is parallel to the coast. Interestingly, the mTST unit partly developed in the area where no HST units develop and presents two features indicative of highly energetic environments: a karst zone submerged about 12,500 years ago (Taviani et al., 2012), and a wave-cut terrace lie in the upper slope of the GSH at a modern water depth of about -55 m bsf (detail in Fig. 7).

In the YD97-16 and KS-330P sediment cores the mTST unit, below 2.20 m downcore and below 4.20 m downcore, respectively, is composed by fine to medium poorly-sorted sand (Fig. 8). The benthic assemblage shows the occurrence of species tolerating a high content of organic matter, i.e. *Stainforthia complanata*, *Melonis padanum*, *Bulimina marginata*, and *Globobulimina spinescens*, in addition to the inner shelf benthic species of *Ammonia* and *Elphidium* genera and miliolids, possibly indicating enhanced dysoxic conditions at the sea floor. The mTST unit is characterized by very few planktonic foraminifera typical of cold climate conditions (e.g. *Neogloboquadrina Pachyderma*, *Globigerina Bulloides*, *Turborotalita Quinqueloba*). The discontinuous occurrence of opportunistic species like *Valvulineria complanata* and *Nonionella turgida*, coupled with episodes of dysoxic conditions, could either highlight a open mud-belt setting, characterized by a substantial content of organic matter and by reductive conditions at the sea floor, or be a consequence of repeated depositional events linked to river floods. The overall assemblage suggests that deposition occurred in an inner shelf environment. X-ray analysis highlights the pronounced cross lamination possibly reflecting the influence of tractive bottom currents (see detail in Fig. 8) and high sediment accumulation rates (Rhoads et al., 1985; Kuehl et al., 1986).

4.2. The upper TST unit offshore the Gargano Promontory

The uTST unit is confined by surface S2, at the base, and the maximum flooding surface, on top. In the central Adriatic Sea, the uTST unit is a mud drape characterized by marine-onlap terminations onto pre-existing morphological structures (Cattaneo and Trincardi, 1999; Maselli et al., 2011). Offshore the GSH, the uTST unit shows sub-parallel and low-angle continuous reflectors with a progradational stacking pattern (Figs. 5A, B, C and detail in Fig. 7).

The maximum flooding surface at the top of the uTST unit constitutes a prominent and continuous regional surface above which the highstand systems tract develops (Figs. 5A, C and detail in Fig. 7). The maximum flooding surface displays an erosional character in the area close to the GSH, where the uTST unit shows a toplap termination (Figs. 5A, 5C). This evidence is indicative of a strong interaction between coast parallel currents and the pre-existing topography, resulting in an area of no deposition and or submarine erosion of the uTST unit (Fig. 7).

The thickness distribution of the uTST defines distinct depocenters separated from each other (Fig. 7). In the north-eastern portion of the GSH an area of no deposition or submarine erosion is evidenced by the lack of the uTST unit. Because of the presence of this bypass area the uTST unit shows a detached geometry separated by the edge of the GSH (Fig. 7).

The uTST unit advances mainly in southward direction, where the GSH is less prominent, showing a depocenter elongated in a N-S direction reaching ca. 21 m of thickness (Fig. 7). At regional scale the uTST depocenter marks a landward migration of the depositional area with respect to the underlying mTST unit, indicating a possible jump of the relative sea level (Fig. 7).

In the YD97-16 and KS-330P sediment cores the uTST unit, between 1.20-2.20 m and 1.70-4.20 m, respectively, consists of fine to medium poorly sorted sand (Fig. 8). The foraminifera assemblage of *Ammonia* spp., *Elphidium* spp., *Nonion* spp., agglutinated taxa and miliolids testified a shallow water depositional environment. The uTST unit is characterized by a benthic fauna of *S. complanata*, *M. padanum*, *B. marginata*, *Ammonia tepida*, *A. perlucida*, *A. papillosa*, *A. beccarii*,

E. decipiens and Miliolidae. This faunal assemblage is typical of a inner-shelf environment with nearby sediment input.

4.5. Chronological framework of the mTST unit

On the Adriatic margin, seismic stratigraphic correlations supported by ^{14}C dating and biostratigraphic reconstructions allowed the correlation of the main TST units, and bounding surfaces, at a basin scale (Fig. 3 and Tab. 1; Trincardi et al., 1994; Cattaneo and Trincardi, 1999; Asioli 1996; Asioli et al., 2001; Correggiari et al., 2001; Cattaneo et al., 2003; Piva et al., 2008; Maselli et al., 2010; Trincardi et al., 2011). In the central Adriatic the mTST unit comprises two subunits each recording two intervals of sea level rise during the Bölling-Allerød and Younger Dryas events; these two mTST sub-units are separated by the Si erosional surface that developed during a minor sea level fall within the Younger Dryas cold spell (Maselli et al., 2011).

In the south Adriatic, offshore the Gargano Promontory, the ES1, S1 and Si surfaces coincide and the lower TST and mTST-1 sub-units are not recognized (Fig. 5). This may be related to a total cannibalization of the lower transgressive deposit during the Younger Dryas sea level fall proposed by Maselli et al. (2011) or a reduced deposition during the first phases of the post-glacial sea level rise, that may suggest that only the upper mTST unit proposed by Maselli et al. (2011), formed offshore the Gargano Promontory. As suggested by several Authors, transgression do not necessarily coincide in time along every part of a basin margin (Helland-Hansen and Gjelberg, 1994; Posamentier and Allen, 1999) and, in turn, the relate transgressive deposits may be characterized by different expressions in terms of presence or absence of ravinement surfaces and facies (Cattaneo and Steel, 2003).

Seaward the GSH the mTST unit shows its maximum stratigraphic variability and complexity, with a well-preserved sandy costal deltaic deposit spatially-connected and genetically related to a progradation wedge deeper on the shelf (Fig. 5). By analogy of modern compound systems, we propose that coarse-grained deposits formed at the shoreline, while fine-grained sediments

accumulate in deeper shelf environments (typically in water depths of 25-30 m or deeper; Fig. 9). Given that the coastal rollover point of this compound delta is in a modern water depth of ca. 60 m, we can approximate its age to be ca. 11.8-12.6 kyr BP (Fig. 10, PGCD), by correlating the depth of the subaerial delta to global sea level curves (Fairbanks, 1989; Camoin et al., 2004; Liu and Milliman, 2004; Maselli et al., 2011), assuming that the vertical movements of the substrate in the area are negligible compared with the eustatic component.

As demonstrated for other Mediterranean margins, changes in precipitation rates and vegetation cover related to the Younger Dryas event may have resulted in enhanced sediment production in the catchments and/or enhanced rates of sediment export to the sea that favored the formation of thick progradational deposits (Cattaneo and Trincardi 1999; Labaune et al., 2005; Berné et al., 2007; Somme et al., 2011). Within this short time interval (ca. 800 yrs), the mTST subaqueous clinotheme offshore the Gargano Promontory recorded a short phase of higher sediment accumulation rates (0.5 cm yr^{-1} , with a maximum of ca. 3 cm yr^{-1} in the area where bidirectional downlap develops; Fig. 5C). The increased sediment supply in a relatively small interval of time can be explained by referring to the climatic reversal of the Younger Dryas event that promoted increased rates of sediment discharge from the rivers draining the high altitude areas of the Gargano Promontory that favored the development of compound delta (Fig. 9). In particular the subaqueous counterpart consists of basinward downlapping strata, indicating, for some time, that the sediment supply was able to counteract with the new accommodation space created by the ongoing sea level rise. Moreover, a greater sediment accumulation rate is also favored by focused deposition against the GSH: in this area the thickness of mTST unit reached ca. 30 m. Similar examples of focused sedimentation in depocenters down-current of obstacles like the GSH come from the modern subaqueous delta south of the Shandong Peninsula (Yang and Liu, 2007; Liu et al., 2009). These values are comparable with the sediment quantified accumulation rates recorded in modern subaqueous deltas worldwide (Fig. 11: at least 5 cm yr^{-1} in the Ganges Brahmaputra foreset area,

Michels et al., 1998; 7 cm yr⁻¹ in the Indus clinoform foreset, Giosan et al., 2006; up to 10 cm yr⁻¹ in the Amazon foreset area, Nittrouer et al., 1986).

5. Discussion

5.1. Compound delta progradation and oceanographic regime

Seminal papers in seismic stratigraphy suggested that the presence of a rollover point at the topset-foreset transition may occur in marine environments and thus does not necessarily represent the shoreline (Mitchum et al., 1977; Vail et al., 1977; Pratson et al., 2007), and that the rollover point may form at different water depths with several trajectories for a given trend of relative sea level rise, depending on supply rates and oceanographic regime, depending by sediment supply rates and oceanographic regime. Following this concept, Steckler et al. (1999) underlined that the ratio between sediment supply and accommodation space plays a fundamental control on the distance between the shoreline and its time equivalent subaqueous rollover point and assumed this distance to be at a minimum during intervals of sea level lowstand. While in these models the oceanographic regime is scarcely considered, Swenson et al. (2005) highlighted the importance of the wave and current fields as the main factor affecting the lateral separation between the coastline and the subaqueous rollover point. The extent of this separation depends on the shear stress on the seafloor that prevents the deposition in the foreset region, as pointed out by Pirmez et al. (1998). In Cattaneo et al. (2007) the compound delta model proposed by Swenson et al. (2005) was modified into a “distorted geometry” where the energetic geostrophic circulation limits the accommodation of sediment in the clinoform bottomset; in this view the seaward progradation is not limited by the lack of sediment but by increased energetic conditions.

The concept of compound delta can be applied also to the mTST unit offshore the Gargano Promontory, where a coastal sandy deposit is genetically linked to a distal subaqueous progradation (Figs. 9, 12). The difference in water depth of ca. 25 m between the coeval coastal and subaqueous

rollover points is similar to the distance found in the modern Adriatic compound delta (ca. 25-30 m; Cattaneo et al., 2007). The two systems show comparable directions of progradation, with the two subaqueous clinothems elongated parallel to each other and to their shorelines (Fig. 13A). These evidences suggest that during the deposition of the PGCD the oceanographic regime was characterized by a wave-current field similar to the modern one, and the interaction between wave energy and along-shore currents governed sediment partitioning between the subaerial and its subaqueous counterpart.

5.2. The main factors favored the PGCD preservation

The variability of transgressive deposits, driven by numerous factors influencing the shoreline migration, may be high for coeval deposits over relatively small distances within the same sedimentary basin (Heward, 1981). Minor changes in one controlling factor or a combination of the controlling factors may modify the preservation of transgressive deposits. The preservation of transgressive deposits is strongly influenced by a number of factors such as the depth of erosion, the wave-energy, the rate of relative sea level rise, the sediment supply, the along shore transport and the erosion resistance of bed material (Belknap and Kraft, 1981). Notwithstanding the preservation of coastal transgressive deposits is considered unlikely as a result of intense ravinement during shoreline transition, example of costal deposits within transgressive units on worldwide shelves are reported in the literature by several authors (e.g. Steel et al., 2000; Aksu et al., 2002; Salzmann et al., 2013; Gamberi et al., 2014). Finally, progradational (regressive) coastal deposits are more likely to be fully preserved than those of transgressive coasts (Davis and Clifton, 1987); indeed if the sediment supply compensates or overwhelms the increasing accommodation space related to relative sea level rise an aggradational or progradational succession is expected, respectively (Curry and Moore, 1964; Galloway and Hobday 1983).

The costal counterpart of the PGCD is characterized by an along-coast sandy deposits connect to a muddy subaqueous clinoform (Fig. 9). We suggest that the preservation of this shallower unit may

be related to a prevailing vertical component of submergence rather than the horizontal component of reworking deposits during the shoreface retreat. This is possible in contexts where the rates of sea level rise and sediment supply overwhelm the sediment dispersion rates of the currents (Davis and Clifton, 1987). This interpretation is in agreement with the "cliff overstep" model proposed by Zecchin et al. (2011) for steep shelves where relative high sea level rise connected to the Meltwealter pulses promotes a rapid drowning of cliff portions with related rapid excursion of the shoreline; and with the documentations of the high sediment supply recorded on the Mediterranean shelves during the Younger Dryas interval (e.g. Labaune et al., 2005; Berné et al., 2007; Lericolais et al., 2010; Maselli et al., 2011; Somme et al., 2011). The further jump in sea level highlighted by the subsequent landward migration of the uTST unit depocenter (Fig. 7), leads to the burial of the mTST unit and, in turn, promotes its preservation. Furthermore, the internal reflector architecture and the external geometry of the uTST unit highlight that an along-shore currents governed the directions of the subaqueous clinotheme progradation, as observed for the underlying mTST unit and the overlaying HST unit. In this view, the PGCD highlight a peculiar case study where the interaction between a step-like sea level rise and a pre-existing morphology may favored the preservation of a coupled progradations in the area present down-current respect to the structural high.

5.3. The PGCD in three dimensions

The PGCD and the modern Gargano subaqueous delta shares also a comparable internal geometry with the strike of the clinoform sub-parallel to the axis of the depocenters. This evidence implies that the transport of sediment occurs over significant distances parallel to the clinoform strike instead of perpendicular (or at high angle) to it. Figure 13B shows an interesting implication of this concept: in a depocenter growing from a feeding point located upcurrent (the subaerial delta) the successive steps of deposition may lead to the formation of clinoforms that are normal to the direction of sediment transport and, therefore, have the youngest reflector located further away

downcurrent (Fig. 13B, left). In this case, the time lines are progressively younger ride off the subaerial delta in a fashion that is reminiscent of a subaerial Gilbert type delta. In the Adriatic basin, both modern and TST examples, instead, show time lines with a more radial pattern and display an increasing distance moving downdrift from the entry points. Examples of a similar progradation pattern are documented for the submarine delta of the Ganges-Brahmaputra (Michels et al., 1998), the modern clinoform of Gulf of Papua (Walsh et al., 2004) and the deglacial deposits of the Gulf of Lyon (Labaune et al., 2005).

When a subaqueous delta is recognized on the continental shelf, it is genetically linked to a time equivalent deltaic or estuarine deposit, through which sediment is fed to the subaqueous counterpart (two examples come from the delta Po-Gargano, Cattaneo et al., 2007; and the Amapa coastal plain-Amazon compound systems, Nittrouer et al., 1996). The morphologic profiles of compound systems are characterized by a couple of rollover points (i.e. coastal and subaqueous rollover points); this evidence is confirmed also in profile of worldwide rivers characterized by an estuarine outflow (e.g Amazon and Columbia River, Fig. 14 A). Moreover, depending on the morphology of the basin, compound systems may be nourished by several point sources, captured by an alongshore current (e.g. Apennine and Po rivers for the Po-Gargano deltaic systems, Cattaneo et al., 2003; Fly, Kikori and Purari rivers, for the Gulf of Papua deltaic systems, Walsh et al., 2004). In compound systems where a well developed costal delta grows, marine currents lead to an asymmetric progradation of both costal and subaqueous systems (Bhattacharya and Giosan, 2003; Cattaneo et al., 2003; Correggiari et al., 2005). Despite all the differences in the oceanographic regime among different systems, subaqueous deltas can always be viewed as the marine components of compound deltas whose coastal counterpart may be located hundreds of kilometers away (e.g. Shandong subaqueous delta and subaerial Yellow river delta, Alexander et al. 1991; Yangtze subaqueous delta and tidal subaerial delta, Hori et al., 2002; Gulf of Papua subaqueous delta and Fly, Kiori and Purari subaerial delta, Slingerland et al., 2008; Indus mid-shelf subaqueous delta and subaerial delta,

Giosan et al., 2006; Ganges-Brahmaputra shallow subaqueous delta and subaerial delta, Palamenghi et al., 2011).

5.4. Sedimentation patterns of the PGCD

Modern compound deltas developed during the last ca. 5-8 kyr BP, and substantially after the post LGM sea level highstand was attained (e.g. Goodbred et al., 2003; Yi et al., 2003; Walsh et al., 2004; Cattaneo et al., 2007). In modern examples of compound systems, sediments carried by rivers are dispersed alongshore far from the river mouths, and accumulated in subaqueous clinoforms 20-40 m thick in water depth ranges of 30-90 (Liu et al., 2009). Fluvial sediment dispersed alongshore may be transported as far as 300 km (Mekong River, Ta et al., 2002), 700 km (Yellow River, Yang and Liu, 2007), and as much as 1500 km (Amazon River, Nittrouer et al., 1996). A particular case comes from the Yellow Sea, where the subaqueous clinoform is characterized by a bidirectional progradation (omega-shaped) due to the interplay between long-shore sediment transport and the physiographic constriction by the Shandong Peninsula (Yang and Liu, 2007).

The sediment accumulation rates calculated on the foreset region of the subaqueous delta is linearly related to the distance between the shoreline and the subaqueous rollover point, as highlighted for modern compound systems in Figure 14B. Interestingly, the PGCD recorded slight higher accumulation rates compared to the modern Gargano subaqueous delta (3 mm/yr and 1.28 mm/yr respectively), possibly because of a smaller distance between the source and the subaqueous clinotheme during the Younger Dryas interval. The post-Younger Dryas sea level rise led to the drowning of the shelf and widening of the basin that triggered the formation of an alongshore current acting as a linear sediment source for the modern compound delta system. For this reason, in the modern Adriatic compound delta the distance between the feeder source and the subaqueous depocenter is larger (in order of 600 km).

During the deposition of the mTST unit, a sandy deposit about 12 m thick and its subaqueous counterpart developed asymmetrically over 50 km (Fig. 6), with the coastal and subaqueous

rollover points separated of ca. 10 km, along a down-current dip section. As for modern analogues, this evidence may suggest the presence of an alongshore current that prevented the seaward progradation of the PGCD. In the up-drift side of the GSH the PGCD appears less developed. Conversely, in the down-drift side of the GSH, the PGCD reaches its greatest thickness (Fig. 6). These evidences suggest a strong interaction between sediment transport from land, alongshore circulation and pre-existing topography, and underline a down-drift deflection of the marine currents, as suggested by Bhattacharya and Giosan (2003). The impact of southeasterly currents has been stronger at the up-drift side of the GSH: conversely the lower energy current has characterized the down-drift side of the GSH leading a greater sediment accumulation of the PGCD.

The substantial absence of microfauna in the PGCD deposits offshore GSH suggests the influence of freshwater discharge, flowing from the continent and nourishing a delta NE of Vieste (Fig. 9). Considering an average sediment density of 2.5 g cm^{-3} , the total sediment load of the river was in the order of less than $10 \times 10^6 \text{ t yr}^{-1}$, a value of one order of magnitude greater than the modern value of Apennine rivers (Frigani et al., 2005). These values may reflect the impact of a rejuvenated fluvial incision excavated during the Younger Dryas cold event documented on land (Amorosi and Milli, 2001).

6. Conclusions

In the southern Adriatic basin, mid-shelf deposits document the first case of a compound delta deposited within a period of overall sea level rise. Offshore the Gargano Promontory, the landward backstepping architecture of the Late Pleistocene to Holocene transgressive deposits was punctuated by the progradation of a compound delta system characterized by a sandy costal unit of reduced thickness and a subaqueous muddy clinotheme up to 30 meters thick. Seismic-stratigraphic correlations support the hypothesis that the Paleo Gargano Compound Delta (PGCD) formed in a short time window including the Younger Dryas cold spell, when slow rates of sea level rise and enhanced sediment production in the catchments promoted both coastal and subaqueous

progradations. Likely, the increased rates of sea level rise during the post-Younger Dryas interval allowed the rapid drowning and preservation of the PGCD. More in general, our findings support the following conclusions:

- The formation of the PGCD within an overall transgressive record implies that the time required for the development of such deposit may take place during very short windows, likely in the order of centuries; this notion may be useful in interpreting ancient stratigraphic records where a much lower geochronological resolution may lead to assume or imply much slower rates of sediment accumulation.
- Depending on internal reflector geometries and overall architecture, the PGCD may be viewed as the transgressive, small-scale, analogue of the modern highstand Adriatic compound delta, as both records reflect progradations influenced by similar alongshore sediment dispersion with sediment transport occurring dominantly along the strike of the clinoform.
- The findings from the PGCD, in agreement with documentation from the literature (especially for the Amazon delta), suggest that subaqueous deltas are always connected to a costal deposit, characterized by a coastal rollover point, that may be interpreted as the genetically linked subaerial counterpart of a compound delta systems.

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Figure Captions

Fig. 1. Thickness distribution of the Late-Holocene HST wedge (from Correggiari et al., 2001; Cattaneo et al., 2007). Note the area of no deposition NE of Gargano Promontory. The bathymetry of the Adriatic is from Trincardi et al. (2013) and is shown with a 100 m contour on a DTM. The pathways of the NAdDW and LIW currents are highlighted by a blue dashed line and a dark red line, respectively. Bottom left: schematic stratigraphic sections illustrating the difference delta configurations seaward of the Italian coast.

Fig. 2. Map of Mediterranean examples of transgressive (stars; Hernández-Molina et al., 1994; Jouet et al., 2006; Somme et al., 2011; Chiocci et al., 1991; Lykousis et al., 2005; Aksu et al., 2002; Giosan et al., 2009; Lericolais et al., 2010; Schattner et al., 2010; Zecchin et al., 2011; Durán et al., 2013) and highstand clinothememes (green patches; Díaz and Ercilla, 1993; Lobo et al., 2006; Fanget et al., 2014; Cattaneo et al., 2007; Hiscott et al., 2002; Giosan et al., 2013).

Fig. 3. Along shelf correlation of the TST and HST deposits. The mTST unit is completely sampled in the MAD (core CM92-43). In the inner shelf the mTST expands into a thick section, that is partially sampled by borehole PRAD 2-4. The transition from the uTST to the mTST units is marked by an abrupt change in the saturation isothermal remnant magnetization SIRM, due to the transition from fine to coarse-grained sediments (Vigliotti et al., 2008). In deeper environments, the top of the unit is sampled by cores RF95-13, YD9716 and KS02-330P (study area), and AMC99-7. High-resolution chronostratigraphic correlation, obtained by ^{14}C dates and tephra chronologies, support the hypothesis that the mTST unit deposited before the Meltwater Pulse 1B (Asioli et al., 1996). The vertical scale of the PRAD 2-4 is double.

Fig. 4. Digital Elevation Model (DEM, SRTM 90 m, from <http://srtm.csi.cgiar.org>) and structural map of the ES1 erosional surface at the base of the post-glacial TST record (Grid 100 x 100 m), with contours every 10 ms. The Gargano Structural High (GSH) represents the drowned part of the Gargano Promontory. The map shows also the location of the seismic lines and cores discussed in this paper.

Fig. 5. Seismic profiles (see Fig. 3 for location), showing the internal subdivision of the transgressive deposits atop and seaward the GSH, between ES1 and S2 surfaces. Top: seismic profile KS156 (A) across the GSH showing the correlation between the subaerial clinotheme and its subaqueous counterpart. Note the ascending trajectory of the subaqueous rollover point. Center: seismic profile YD06 (B) showing the correlation between the subaerial and subaqueous delta and the position of core YD97-16. Note local small scale subaerial clinostratifications of the coastal deposits within mTST unit. Bottom: seismic profile YD57 (C), seaward the GSH, illustrating the bidirectional downlap of the subaqueous delta that constitutes the marine component of the compound delta; note that the steepness of the clinothemes is higher to the North (up-current) and gentler to the South (down-current) where the deposit becomes thicker and more spread across shelf. Coastal and subaqueous rollover points are highlighted by red and blue dots, respectively. Note the possible presence of gas-charged sediments in the GSH area. Note the ascending trajectory of the subaqueous rollover point (transparent blue dots).

Fig. 6. Thickness distribution of mTST unit. The mTST unit (more than 40 msec in thickness in two-way time offshore Vieste) is elongated parallel to the depth contour of the underlying ES1 surface.

Fig. 7. Map of the shore-parallel uTST wedge (in msec. two-way travel time). The dashed lines represent the main axis along which the depocenters of the mTST and HST around the Gargano

Promontory. Note the landward shift of the depocenters main axes from the mTST unit (dashed blue line, offshore) passing by the uTST unit (darkest blue) to the HST unit (dashed green line, inshore). The area characterized by no deposition NE of Vieste is in the same position of the modern one (see Fig. 1). A simplified bathymetric contour of the lowstand unconformity ES1 is provided for reference. Inset: seismic profile AMC168 investigated an area adjacent to the GSH where the mTST unit is less developed, and the uTST and HST units did not form or were eroded.

Fig. 8. Cores YD97-16 and KS02-330P through the HST, the uTST and the upper portion of mTST unit. The correlation of the cores is based on seismic data and whole-core magnetic susceptibility profiles. The regional erosional surface S2, the maximum flooding surface, the minor flooding surface associated with the onset of the Little Ice Age (LIA) unit and identified tephra layers provide timelines that support the proposed stratigraphic correlation. The last occurrence (LO) of *G. sacculifer* marks the base of the Little Ice Age (Fig. 10; Piva et al., 2008), while the LO of *G. inflata* marks to the attainment of the maximum marine ingression, ca 5.5 kyr B.P. in the Adriatic Sea (Asioli, 1996). On core KS02-330P the calcimetry curve shows the highest concentration above the mfs, the D50 curve shows a fining upward trend with a core bottom characterized by a unimodal grain-size distribution; the X radiography suggests current-generated structures during the deposition of the mTST unit. The photograph detail of core YD97-16 shows a increase in bioturbation rate across the mfs and alternating sandy silt layers characterizing the mTST unit. The depositional environment, deduced from micro and macro paleontological analysis was inner shelf and middle shelf respectively below and above the mfs. The units subdivision is supported by changes in seismic facies on seismic profiles at the corresponding depths.

Fig. 9. Conceptual scheme for the PGCD showing the interplay between costal sediment flux and alongshore sediment dispersal. The paleo-shoreline rims the GSH flank where down-drift current deflection lead to an asymmetrical compound systems characterized by a coastal and subaqueous

rollover point at paleo-water depth of 3 and 28 m (red and blue dots, respectively). Inset: schematic compound delta modified after Nittrouer et al. (1996), and Swenson et al. (2005).

Fig. 10. Correlation between mTST unit and sea level curve (modified after Fairbanks, 1989; Camoin et al., 2004; Liu and Milliman, 2004; Maselli et al., 2011). Average depths of seismic facies interpreted as possible wave-cut terraces (black circle), coastal rollover point (red dot) and subaqueous rollover point (blue dot) record a progradation phase during the Younger Dryas interval. Note that the coastal rollover point and wave-cut terrace occurred at an average depths that imply their formation after the minor sea level fall proposed by Maselli et al., 2011, and during a phase of possible still stand in the sea level curve of Liu and Milliman, 2004. The water column between the coastal and the subaqueous rollover point was about of 25 m deep.

Fig. 11. The comparison between sediment accumulation rates against depth of subaqueous rollover point shows that main worldwide delta and PGCD are characterized by a similar subaqueous rollover point depth of ca. 30 m, and slight similar accumulation rates (with the exception of the Amazon subaqueous delta).

Fig. 12. Top: idealized stratigraphic section perpendicular to the coast offshore Gargano Promontory. Bottom: Wheeler diagram of the same idealized section.

Fig. 13. Top (A): comparison of the thickness distributions of the mTST (left) and the modern HST deposits (right). The middle TST unit is characterized by main depocenters reflecting local deltaic entry points and along-shore sediment redistribution. Right: maps of the HST (thickness more than 6 msec, modified from Cattaneo and Trincardi, 1999; Cattaneo et al., 2007). Compared to the mTST, the HST shows a more continuous depocenter from the Po delta to the area south of the Gargano Promontory (see also Fig. 1). Bottom (B): conceptual scheme of clinoform progradation of

river-dominated “Gilbert-type” delta against subaqueous “advective-type” delta. In the first case (left side) the direction of progradation is parallel to the sediment transport because fluvial energy prevails on along-shore transport. In the second case (right side) the direction of progradation is perpendicular to the sediment transport, as the oceanographic regime dominates on river processes.

Fig. 14. Top (A): down-drift profile of the Amazon and Columbia Rivers deposits highlights the presence of both costal and subaqueous rollover points (bathymetry from GEBCO.net). Bottom (B): correlation between sediment accumulation rates and shoreline-subaqueous rollover point; the PGCD records a small distance between shoreline and subaqueous progradation, suggesting a limited sink area during the Younger Dryas interval.

Table 1: synthesis tables of seismic units, surfaces and their interpretation proposed by Cattaneo and Trincardi (1999), Trincardi and Correggiari (2000), Maselli et al. (2011).

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

B)

Clinofolds develop normal to the direction of sediment transport

Clinofolds develop parallel to the direction of sediment transport

Fig. 13

Fig. 14

Table 1

Seismic surface/ Age (yr BP)	Seismic Unit and subunit	Corresponding sediment core depth (m bsf)	Description	Paleo-environment interpretation and sea level variation	Graphic sketch
	HST	YD97-16 0-1.20 KS02-330P 0-1.70	Prograding unit of the modern Po delta system and Gargano subaqueous muddy clinoform	Shelf-slope
Mfs (ca.5500)		YD97-16 1.20 KS02-330P 1.70	Maximum flooding surface	Maximum Adriatic Sea ingression
	uTST	YD97-16 1.20-2.20 KS02-330P 1.70-4.20	Mud drape unit characterized by marine-onlap terminations onto preexisting sea floor structures	Outershelf-upper slope
S2 (ca. 11300)		YD97-16 2.20 KS02-330P 4.20	Regional erosional surface	MWP-IB

	mTST-2	YD97-16 2.20-3.91 KS02-330P 4.20-6.60	High-angle prograding unit	Inner-shelf (less than 30 m water depth)
Si(12200-12800)		YD97-16 No recorded KS02-330P No recorded	Local erosional surface	Possible sea level fall during the YD interval
	mTST-1	YD97-16 No recorded KS02-330P No recorded	Very low-angle prograding unit	Inner-shelf (melting of Alpine and Apennine glaciers; increased sediment delivery)
S1(ca. 14800)		YD97-16 No recorded KS02-330P No recorded	Regional erosional surface	MWP-IA
	ITST	YD97-16 No recorded KS02-330P No recorded	Prograding unit with shingled reflectors	Early phases of the last sea level rise; influenced by fresh water input
ES1 (ca.18000)		YD97-16 Not reached KS02-330P Not reached	Regional erosional surface	Lowstand subaerial exposure (Sequence Boundary)