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NATURAL AND ANTHROPOGENIC FORCING DURING THE LAST TWO CENTURIES IN THE OMBRONE DELTA (SOUTHERN TUSCANY - CENTRAL ITALY)

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EXTENTED ABSTRACT

Il bacino del Mar Mediterraneo presenta numerosi delta che si differenziano per forma e dimensione, ma che hanno in comune un'evoluzione in ambiente microtidale. I grandi fiumi, come il Nilo, il Rodano, l'Ebro o il Po sono caratterizzati da foci deltizie che sono il risultato di una complessa interazione tra la dinamica fluviale e l'azione del moto ondoso; i fiumi minori (come il Tevere, l'Ombrone ecc.) hanno, invece, un tipico delta a dominio ondoso.

In Italia, l'assetto morfologico e topografico del territorio e la conformazione costiera favoriscono la presenza di numerosi delta a dominio ondoso che, proprio per la loro morfologia subpianeggiante, sono stati fortemente antropizzati tanto nel passato quanto nel presente.

L'intensa urbanizzazione di queste aree va considerata sotto un duplice aspetto: da un lato le strutture insediative hanno nascosto l'assetto morfologico originario e, quindi, ne impediscono la ricostruzione morfoevolutiva di dettaglio. Altro aspetto riguarda la ricostruzione morfoevolutiva di queste aree: essa costituisce uno strumento fondamentale per l'individuazione delle zone a più elevata vulnerabilità da erosione costiera, fenomeno quest'ultimo estremamente diffuso e cospicuo. In quest'ottica lo studio dei sistemi deltizi minori, come quello dell'Ombrone, riveste un'importanza non solo locale, ma anche esportabile a livello più regionale del bacino del Mediterraneo.

Questo lavoro costituisce non solo un aggiornamento, ma anche un ampliamento di precedenti studi a carattere geomorfologico ed evolutivo condotti sul delta del F. Ombrone (Italia centrale - Toscana meridionale).

L'area di studio, sita nella piana di Grosseto, è compresa tra la propaggine settentrionale dei Monti dell'Uccellina a Sud e il canale San Rocco a Nord. Le ali del delta presentano morfotipi diversi, in particolare l'assetto dei cordoni dunari è sensibilmente differente nelle due ali del delta: l'ala settentrionale ha cordoni dunari ben delineati (con quote che raggiungono mediamente i 4-5 metri) e presenta due piccoli bacini lacustri (la cui profondità media è di circa 4 m) disposti uno in una depressione interdunare (*Chiaro Grande*) e l'altro trasversale alla linea di riva (*Chiari del Porciatti*); l'ala meridionale presenta una morfologia più pianeggiante con cordoni dunari decisamente meno rilevati, depressioni interdunari mal definite e poco profonde e una mancanza di specchi d'acqua significativi.

Gli studi hanno riguardato diversi aspetti: variazioni delle linee di rive, confronto tra morfologie emerse e sommerse, comparazione di cartografia storica, analisi del moto ondoso.

Le variazioni della linea di riva dal MedioEvo, con un maggiore dettaglio per gli ultimi 200 anni, ciò per definire le principali fasi di progradazione ed erosione del delta; con un'analisi di dettaglio delle ultime decadi sono stati calcolati e comparati i tassi di erosione/accrescimento della parte apicale del delta. In ultima analisi sono state quindi ipotizzate le forzanti naturali e/o antropiche responsabili dell'assetto attuale dell'area.

Il confronto della morfologia dei fondali del *Chiaro Grande*, già ricostruita in un precedente lavoro, con la morfologia dei fondali antistanti l'apice deltizio (1977, dati dell'IIM; 2010, nuovi dati) e del DEM del delta sommerso con le fotoaeree dell'apice deltizio (volo ALISUD, 1995), ha permesso di evidenziare analogie che confermerebbero l'ipotesi secondo cui il *Chiaro Grande* si sarebbe formato a seguito della chiusura di un braccio di mare; tale ipotesi troverebbe ulteriore conferma nelle forme che di producono stagionalmente e che sono state osservate più volte: spit, barre sommerse e piccoli specchi d'acqua nella spiaggia emersa.

La comparazione della cartografia storica (1823, 1832, 1851, 1871, 1883 - Archivio di Stato) con le immagini da satellite, unitamente a dati morfobatimetrici, ha permesso di definire con certezza che i *chiari* non possono essere considerati forme relitte del lago costiero riportato nella cartografia storica, in quanto questo lago occupava una posizione più interna.

L'analisi del moto ondoso ha permesso di definire la direzione dell'ondazione prevalente e di come questa contribuisca all'erosione asimmetrica del delta.

ABSTRACT

This study describes advances in understanding of the recent evolution of the Ombrone River delta. Several aspects have been studied and updated: the stages of progradation and retreat of the shoreline from the Middle Ages, with particular reference to the last 200 years, have been reconstructed and the natural and/or human forcing responsible for the area's evolution have been hypothesized.

The processes that led to the formation and evolution of some small coastal lakes and the more recent evolution of the shoreline are defined. Monitoring of shoreline variations in the Ombrone Delta apex has been achieved by comparing aerial photos acquired in 1995, 1998, 2004, 2006 and 2010. The progressive landward migration of the shoreline has resulted in a realignment of the coast. Comparison with older erosion and progradation rates shows decreasing erosion rates along the delta apex with time: the erosion rate of the northern wing has reached peaks of around 14 m/yr (2004-2006), and then fallen to 4.5 m/yr in the latest period (2006-2010).

The Ombrone River delta is characterized by the presence of beach ridges, ponds and, in the past, of a coastal lake. Morpho-bathymetric analysis and comparison with historical maps shows that during the XIX century, the historical lake preserved its geometry; only in the 1883 map seaward side presents an irregular geometry, while in the 1929 map the ponds have been represented for the first time and are located seaward with respect to the XIX century beach ridge.

Comparing morpho-bathymetric data of Chiaro Grande pond and submerged apical mouth, this study confirmed the hypothesis about Chiaro Grande pond genesis in which its formation is based on the closure of a narrow sea stretch consequent to the emergence of a bar. The independence between the genesis of ponds and lake evolution, highlighting the importance of mouth bar growth as a recurrent mechanism for confining narrow sea stretches.

The orientation of morphological features and the prevailing wave climate suggest a sediment transport from south to north.

Key words: Ombrone River Delta, shoreline evolution, ponds, historical maps, Grosseto plain; Central Italy (UTM 32T wgs84 top left 662237E, 4730755N; bottom right 669373E, 4722606N)

INTRODUCTION

The Mediterranean coasts present several deltas characterized by different shapes and sizes but all evolved in a typical microtidal regime. The largest Mediterranean rivers (e.g. Nile, Rhone, Ebro and Po) develop deltas with a complex fluvial-wave interaction (Stanley *et alii*, 2008; Stanley & Warne, 1993; Gensous, 1993; Arnaud-Fassetta *et alii*, 2005; Somoza *et alii*, 1998; Diaz *et alii*, 1990; Bondesan *et alii*, 1995; Correggiari *et alii*, 2005), while minor and abundant Mediterranean deltas (e.g. Tiber, Ombrone, etc.) show the typical shape of a wave dominated delta (Galloway, 1975). Small fluvial-dominated deltas develop only in locally well protected areas, as for instance, the Isonzo River in Trieste Gulf (Italy), and the Thyamis River in Sayada Bay (Greece).

The Holocene evolution of the main Italian deltas is widely discussed by Marinelli (1926), Della Rocca *et alii* (1987), Firpo *et alii* (1992), Bellotti *et alii* (1994, 2003 and 2004), Romano *et alii* (1994), Bellotti (2000), Kukavicic & Pranzini (2003), Correggiari *et alii* (2005), Brambati (2011), Bellotti *et alii* (2012), Ferrari *et alii* (2013), Di Bella *et alii* (2014) and Sacchi *et alii* (2014). Due to the Italian orographic setting, several wave dominated deltas present cuspidate or arched configuration. The development of these deltas started after the 6 ka high-stand culmination (Amorosi *et alii*, 2012; Bellotti 2000; Lambeck *et alii*, 2004, 2011; Milli *et alii*, 2013; Sacchi *et alii*, 2014), and has significantly progressed in the last 3 ka, during which progradational and erosional phases have alternated under the control of climate, geological and anthropogenic processes. In many delta areas the intense urbanization (as, for instance, Arno, Centa, Tiber and Volturno deltas) has overprinted the primary morphological features, thereby hampering the detailed identification of the morpho-sedimentary processes driving their evolution.

The Ombrone Delta is a wave-dominated delta located within the Grosseto plain in Southern Tuscany (Fig. 1). It is one of the main deltas on the Tyrrhenian Sea coast, which include the Arno River Delta (130 km to NW) and the Tiber River Delta (140 km to SE), altogether termed the "*Tuscany-Latium delta system*" (Alessandro *et alii*, 1990). In the past, the Ombrone Delta was one of the most cuspate deltas of Italy (Bellotti, 2000; Chiocci *et alii,* 2001; Bellotti *et alii*, 2012); nowadays it has a gentle planform due to strong erosion of the apex. Several dune/beach ridges characterize the delta plain whereas, in the northern apex, small internal water bodies, i.e. ponds locally named "*chiari*", are present: the ponds, intra-ridge and inter-ridge, interrupt the transverse continuity of beach ridges.

Nevertheless, it is one of the few deltas conserving natural features (as part of it falls within a protected area), thereby providing an exceptional opportunity to study the morphological evolution of a Mediterranean wave dominated delta.

The Ombrone Delta shows marked morphological differences between the southern and northern wings, especially as regarding beach ridges. Continuous beach ridges, smoothly bended toward the river mouth, are present in the northern wing, as well as sand ridges that are separated by the *chiari* (Fig. 2). The latter sometimes show a branched geometry and cut across the beach ridges (A in Fig. 2); in other cases they are elongated, with minor branches, and slightly transverse to sub-parallel to the beach ridges (B and C in Fig. 2).

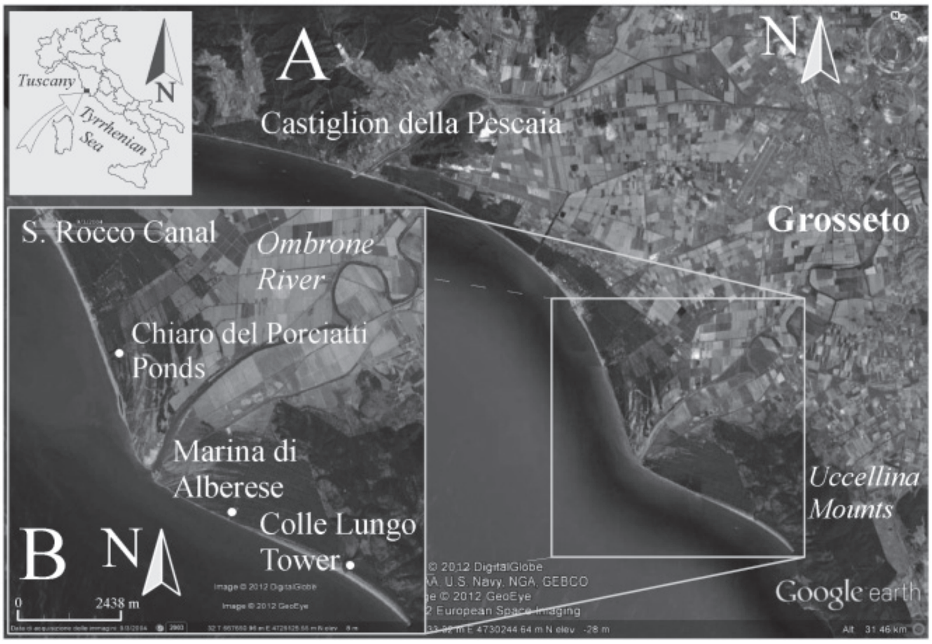

Fig. 1 - Location of the study area (A) and close-up of the Grosseto plain and Ombrone delta (B)

Fig. 2 - View of the study area in 1998. A: Chiaro del Porciatti ponds; B: Chiaro Grande pond; C: most recent pond; D: spit and submerged part of a bar extending northward from the delta apex; E: smaller spit on the southern wing of the delta apex (http://www.bing.com/maps/. June, 1998. October, 2010)

The southern wing is characterized by beach ridges abruptly bending to WSW and, near the mouth, sand ridges separated by smaller and narrow depressions.

The aim in this paper is to investigate the evolution of the Ombrone Delta apex during the last 2 centuries, focusing on the morpho-sedimentary processes and driving factors, with particular attention to those controlling the development of submerged sand bars, *chiari*, shorelines and beach ridges. Based on historical maps, aerial photos of the area and bathymetric data, we define also investigate short-term variations, including the disappearance of a coastal lake reported in historical maps until 1883 and hereafter termed "historical lake".

METHODS AND MATERIALS

Morphological analysis of the inner delta front and plain has been carried out using the following bathymetric data: single beam echo-sounding maps from IIM (Istituto Idrografico della Marina, 1977), bathymetric and topographic profiles perpendicular to the shoreline (Pranzini, personal comunication) and newly acquired profiles (June, 2010).

Comparing the evolution of the historical lake, the existence of which is documented up to 1883, and the genesis of the ponds, first recorded in a 1929 topographical map, is based on the analysis of historical maps of 1823, 1832, 1851, 1871, 1883 (Archivio di Stato) and topographic maps of 1929 and 1985 (IGM - Istituto Geografico Militare). Three historical maps (1823, 1832

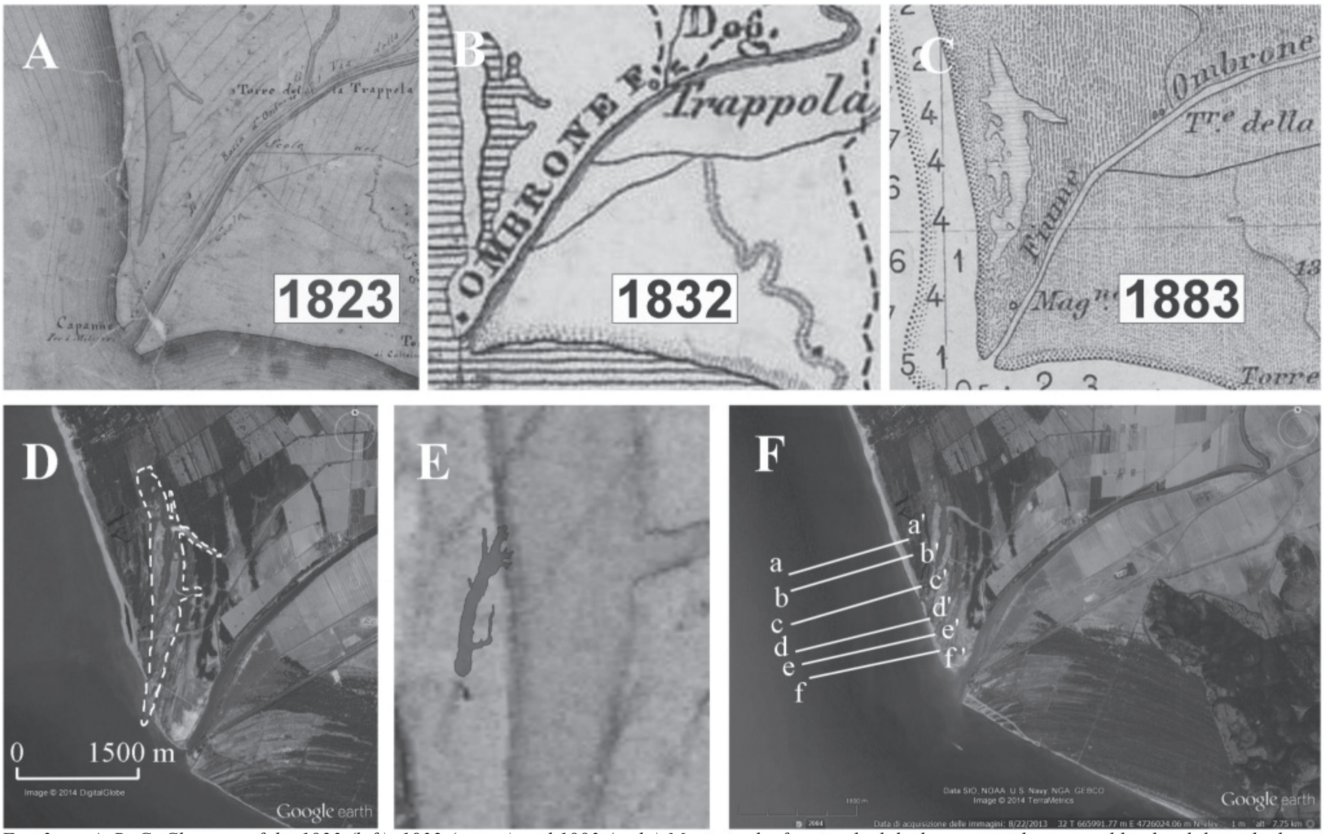

Fig. 3 - A, B, C: Close-up of the 1823 (left), 1832 (centre) and 1883 (right) Maps; in the former, the lake has a straight seaward bank, while in the latter, the seaward side of the lake is strongly irregular. D: location of depression in the Ombrone River mouth. E: relative position of Chiaro Grande pond and depression (1823). F: Location of bathymetric profiles acquired in 2010

and 1883) of the Ombrone delta were reduced to the same scale, softly distorted, made partially transparent and superimposed on a modern image from Google Earth of the same area for comparison using fixed control points. The stretching mean errors value (less than 5 m) has been assumed acceptable. These maps have been imported in Google Earth for digitization of the shoreline, the historical lake and the *chiari*. The evolution of ancient shorelines has been defined based on the geometric relationship between beach ridges, some of which could be dated by means of archaeological data, ancient maps and chronicles.

The reconstruction of the recent shoreline change has been obtained by the comparison of images from different years; we have used air photographs (ALISUD flight, 1995) and available satellite images (*http://maps.live.it*, 1998; Google Earth, 2004 and *http://www.visual.paginegialle.it*, 2006; *http://it.bing.com*, 2010). Images from different websites (23 images from *http://www.visual.paginegialle.it*; 14 images from *http://maps.live.it* and 41 images from *http://it.bing.com*) and air photographs (ALISUD flight, 1995) have been geo-referenced with the software Global Mapper, which was also used for digitizing the shorelines.

Also previous shoreline reconstructions (Bellotti *et alii*, 1999a,b) have been taken into account for comparison aimed at detecting significant changes in shoreline dynamics (Fig. 5).

RESULTS

LAKE - PONDS

The historical maps (1823, 1832, 1851 and 1871) show a more cuspate shape of the delta and the presence of a lake in the northern wing that presents, always, a regular. Linear seaward side; only in the 1883 map is the seaward side of the lake shown as irregular (Fig. 3C). From the comparison of these maps, the position of the lake is always landward of the ponds (which are first represented in the 1929 map) and the XIX century beach ridge (Innocenti & Pranzini, 1993).

The single beam echo-sounding survey was carried out in the Chiaro Grande pond and the adjoining landward depressed and submerged area (hereafter called “depression”) in May 2009. The data acquired was used to produce a DEM (3x3 m) of the morphobathymetry of the Chiaro Grande pond (Tarragoni *et alii*, 2009, 2011; AA.VV., 2010), whereas for the rear lake no DEM has been created. These two areas, connected by a narrow breach in the XIX century beach ridge, have the same orientation (N-

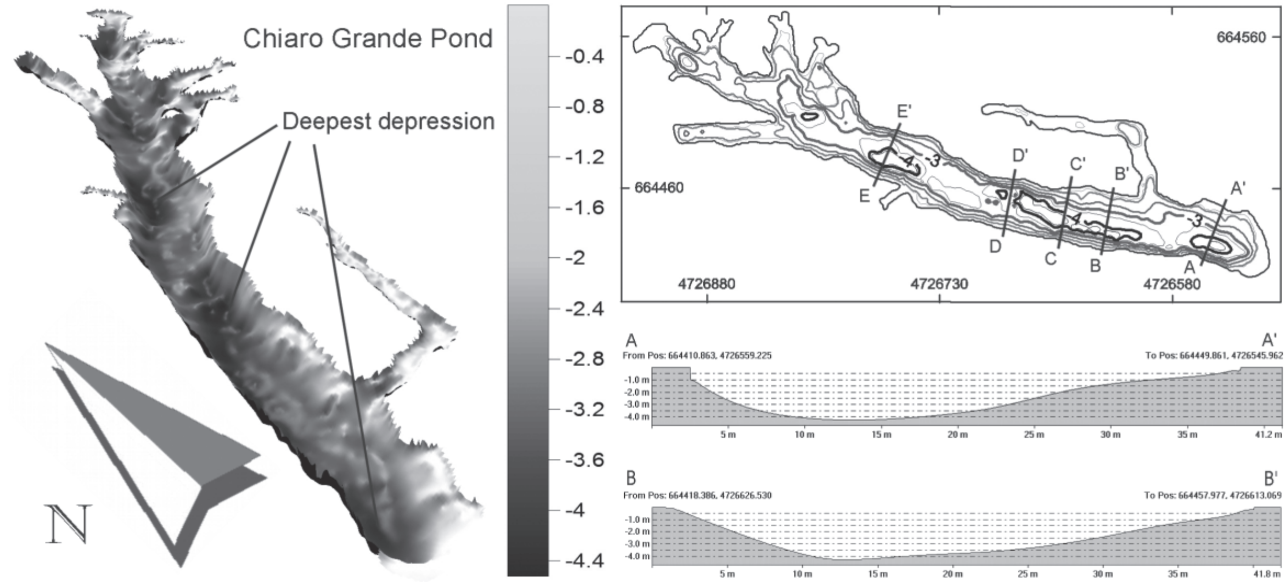

Fig. 4 - DEM of the Chiaro Grande pond (left) showing the elongated shape, the deeper depression and the shallower branching (maximum depth of 70 cm). The bathymetric map (right, above) shows the distribution and shape of the deepest depressions. Two examples (A-A' and B-B') of profiles that show transversally the asymmetric shape of Chiaro Grande; seaward bank to the left)

S) but show marked differences. The pond, characterized by a branched geometry (Fig. 4), has a mean depth of 3.5 m, with two main axially elongated depressions of 4 and 4.5 m depth. The pond occupies an inter-ridge position separating an external ridge, located close to the present shoreline, from an internal, landward-sited, ridge. The seaward side of the pond is at the toe of the external ridge lee face which shows a higher slope than the landward side. This grades laterally into the stoss side of the internal ridge (Fig. 4). Sandy sediments characterize the floor of the pond. The landward depression is characterized by an extremely regular bathymetry and was found to be submerged under a thin water table of about 30-40 cm during the wet season; its flat floor is characterized by silty-clay sediments.

A second survey was carried out in the two Chiaro del Porciatti ponds in June 2009. The presence of copious vegetation (up to water surface) hampered the acquisition of high resolution data, therefore no DEM has been created, but some observations have been done: the bathymetry is similar to that of Chiaro Grande pond (mean depth about 4 m) but the general morphology is different (there is no asymmetry in shape and there are several branches); no samples were taken because of vegetation.

SHORELINE VARIATIONS

LONG TERM SHORELINE VARIATIONS

The trend of the ancient shorelines is revealed by the presence of the beach ridges and analysis of their geometrical relationships, allows the identification of former prograding and erosive phases. From this point of view, some authors (Bellotti, 2000; Kukavicic & Pranzini, 2003) describe different patterns related to river input and longshore transport at the river mouth. On the basis of the beach ridge geometric patterns proposed (Kukavicic & Pranzini, 2003) the following evolutionary phases (from 1283, date of construction of Torre Trappola) have been recognized (Fig. 5):

Phase 1. Progradation stage (post Upper Middle age - "Dark Ages") characterized by beach ridges organized according to converging geometric pattern (type B and C, in northern wing, and C and D in southern one).

Phase 2. Erosion stage characterized by the truncation of protruding ridges and the emplacement of straighter ones (type G and H).

Phase 3. Progradation stage with complex beach ridge pattern. Both wings show converging geometric patterns (type C and D in northern and D in southern) but also local truncation of beach ridges (type H).

Phase 4. Erosion stage with truncation of beach ridges in northern wing while in southern the truncation is less clear (type G). Probably, this phase is related to the construction of the "La Steccaia" dam (1875-1879; http://www.wadi.unifi.it/grosseto_plain_ital.pdf) and the great drainage works that occurred between 1830 and the beginning of the XX century.

Phase 5. Progradation stage in which the northern wing shows a converging geometric pattern (type C and D) while the southern one presents sub parallel beach ridges (type D). Modern ponds (Chiaro Grande and Chiaro del Porciatti), located in the beach ridges of the northern wing, are represented for the

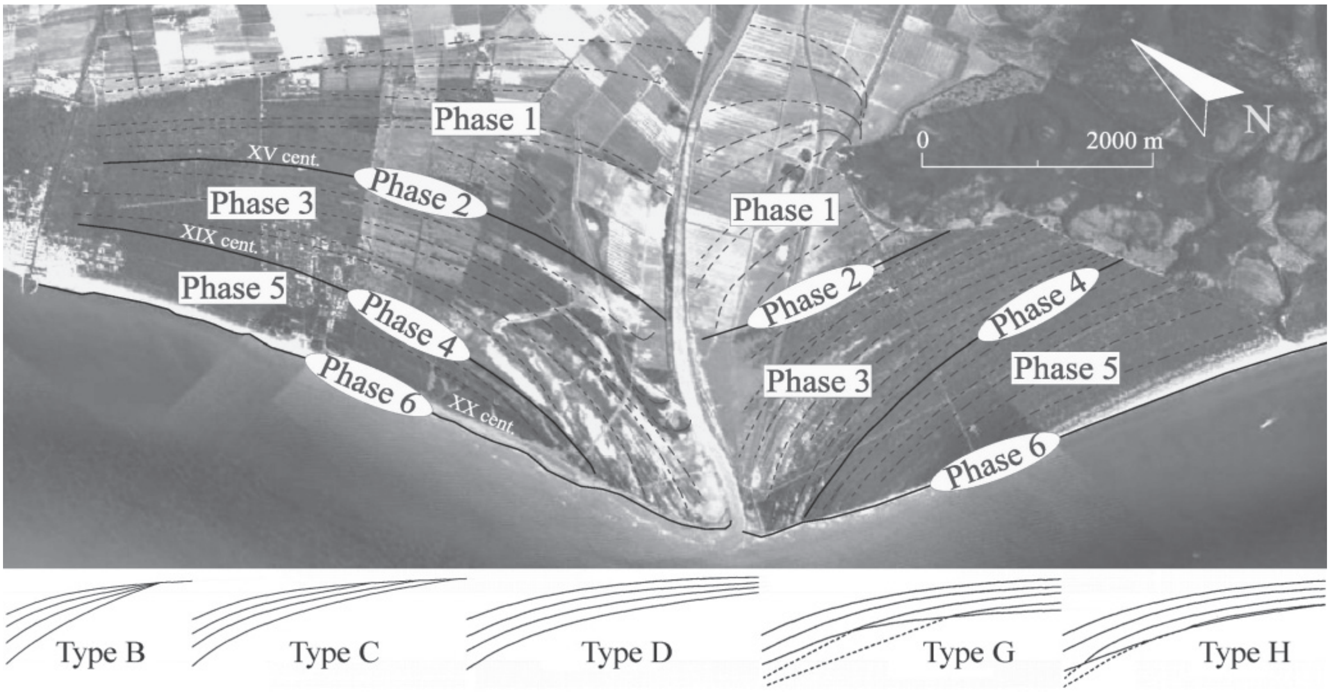

Fig. 5 - Ombrone River delta: main beach ridges and shoreline positions in different erosion phases

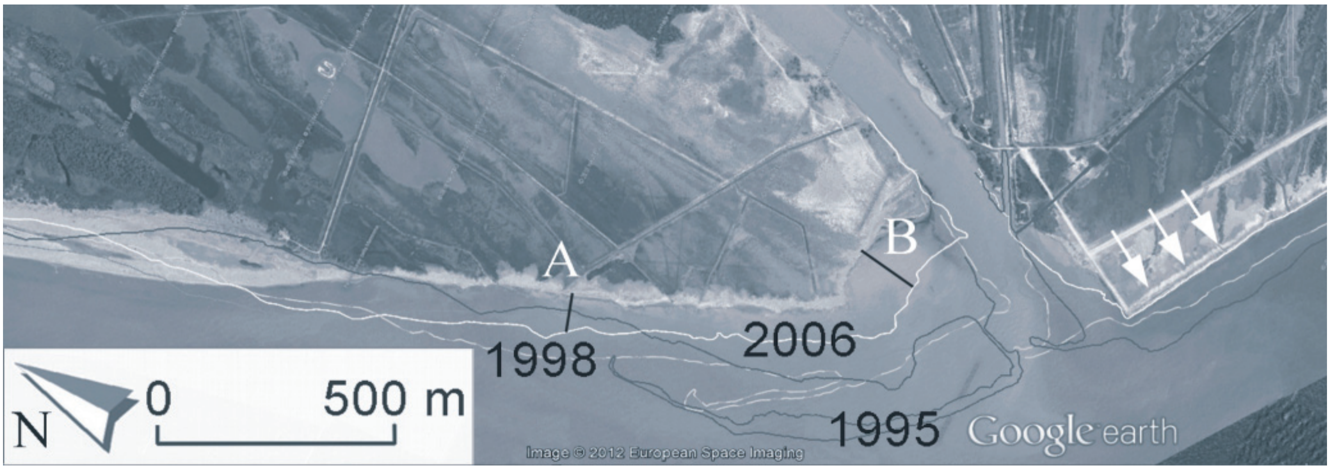

Fig. 6 - View of the delta apex in 2010. The 1995 (white lines), 1998 (dash light grey lines) and 2006 (dark grey lines) shorelines are represented. The shoreline of 2004, being very similar to that one of 1998, has not been represented in order to make the figure clearer. Along the line A the retreat is about 85 m and along B it is about 125 m. On the right, the hard structures have been indicated by white arrows

first time in the 1929 map: this suggests that the progradation phase started around the end of XIX century when the main drainage works were finished.

Phase 6. Erosion stage with truncation of beach ridges (type G), probably started around the second half of the XX century.

RECENT SHORELINE VARIATIONS

Five shoreline positions have been compared so as to investigate the most recent evolution trend of the apex of the Ombrone mouth (between 1995 and 2010): alternating periods of coastal erosion and progradation have been identified (Fig.6 and Table 1). The study area has been divided in 4 sectors from North to South (Fig. 1B; **a** - From S. Rocco Canal to Chiaro del Porciatti ponds; **b** - From Chiaro del Porciatti ponds to Ombrone River mouth; **c** - From Ombrone River mouth to Marina di Alberese; **d** - From Marina di Alberese to Colle LungoTower). For each sector erosion/progradation rates have been calculated.

From 1973 to 1995 (Bellotti *et alii*, 1999a, b), both wings

*Tab 1 - Variation of the erosion/accretion rates (m/yr) in four reference sectors of the study area (Fig.1B): **A**- From S. Rocco Canal to Chiaro del Porciatti ponds; **B** - From Chiaro del Porciatti ponds to Ombrone mouth; **C** - From Ombrone mouth to Marina di Alberese; **D** - From Marina di Alberese to Colle Lungo Tower. Values from the southern wing (reported in C and D) are affected by the presence of a relict road acting as a barrier that hampers erosion of the shoreline. The dash indicates no significant variation*

Sectors	North wing		South wing	
Time intervals	**A**	**B**	**C**	**B**
1973 – 1995	0.5	-8	-6	0.2
1995 – 1998	5	5	-8	2
1998 – 2004	2	-0.5	-4	-
2004 - 2006	-0.5	-14	-	-
2006 - 2010	-	-4.5	-	-

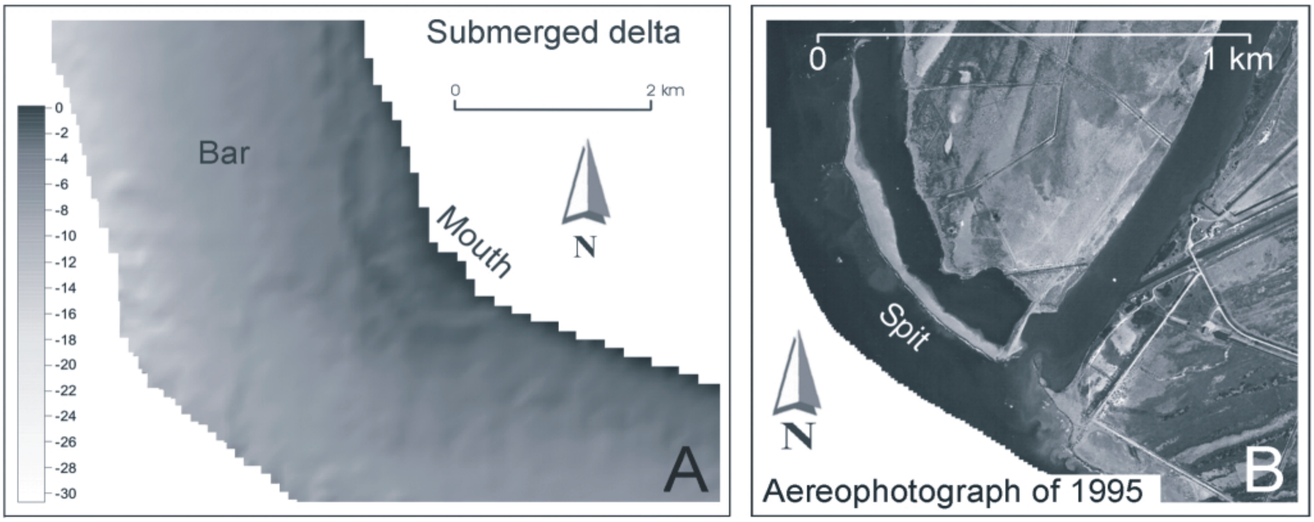

Fig. 7 - DEM of the submerged delta (left) derived from IIM data (1977). The submerged bar extending from south to north around the Ombrone River mouth partially isolates a back-bar depression, interpreted as an embryonic stage of pond formation (see further in the text). Close-up of air photograph of the mouth (Alisud, 1995) showing an elongated spit but at different scale

show an erosional trend (sectors B and C) but in the northern wing the erosion rate is more marked (Table 1); along A and D sectors a very low progradation rate is evident. In the next time-interval there is strong erosion in the C sector (-8 m/yr), while the northern wing is strongly prograding (5 m/yr). The high progradation rates are concomitant with marked erosion of the apex, likely cannibalizing the sediment there eroded. From 1998 to 2004, the northern wing (B) experienced erosion and the sector A showed a lower progradation rate, while in the southern wing the erosion rate of sector C was high (-4 m/yr) and in the last area no significant changes were observed. Comparing shorelines of 2004 and 2006, the entire northern wing experienced erosion particularly in B (-14 m/yr); the southern wing shows variations comparable with the expected seasonal variations; therefore the shoreline may be assumed as stable. This is supported by the presence of a stable barrier at the apex (C). In the last time interval (2006-2010), the northern wing continues to be eroded but at a lower rate near the apex (B), while the northernmost sector (A) and the southern wing appear unchanged.

From the images (1995 and 1998) it is possible to view the presence of emerged and submerged bars from south to north. These bars can be quite elongated, extending from the southern wing to the northern (Fig. 2, 5, 6, and 8). At the apex, the coast north of the mouth has retreated some 230 meters in the last 15 years (Fig. 6).

The data acquired from the IIM (1977) allowed production of a DEM (Tarragoni *et alii*, 2011) of the submerged inner delta front (Fig. 7A). From the observation of DEM (Fig. 7A), bathymetric - topographic profiles (unpublished data, courtesy of Pranzini E., 2006) and new acquired profiles (Fig. 8) a bar similar to that observed in the satellite images (2010) has been identified. These three bars have different size and distance from the shoreline but the characters (i.e. depth, orientation and slope) are comparable.

DISCUSSION

LAKE EVOLUTION AND POND GENESIS

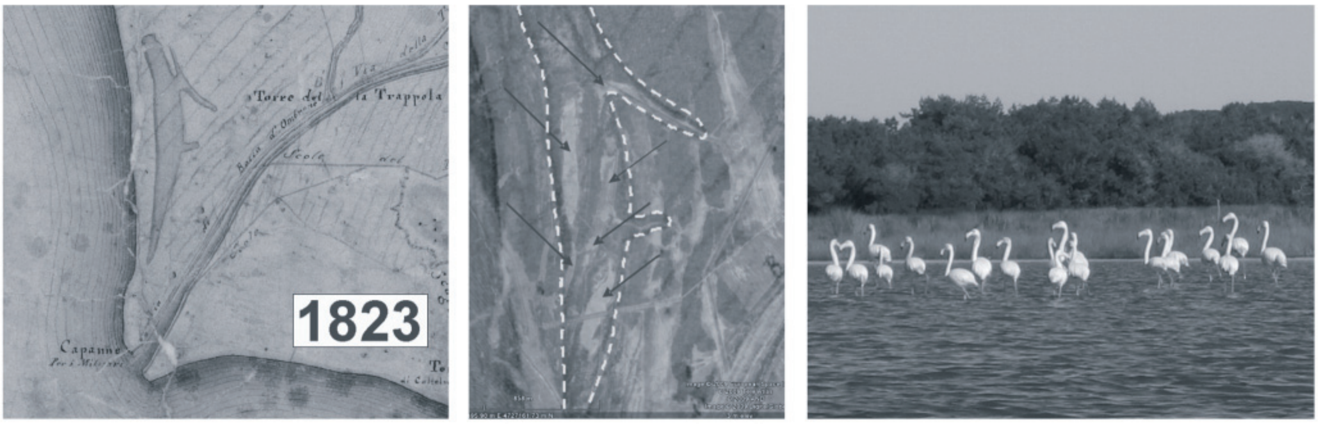

Fig. 8 - View of the flat area: A) Map of 1823; B) Google Earth view whit the location of the lake (1823); C) Photo of depression (May 2012): observing flamingo's leg it is possible to obtain an estimation of water depth

The analysis of historical maps (1823, 1832, 1851, 1871 and 1883) has provided evidence of a lake located landward of the Chiaro Grande pond and XIX century beach ridge (Tarragoni *et alii*, 2011). This evidence is further supported by the current morphology of the area that hosted the lake, which is markedly flat and is still periodically (wet season) drowned under a water table up to 30-40 cm high (Fig. 8).

According to Bellotti *et alii*, (2004), who identified remnants of the lake on historical maps, the historical lake underwent progressive shrinking during the 20th century as shown in the 1883 map (Fig. 3). During the XIX century, the lake preserved its geometry, characterized by an elongated shape and with two branches on the landward side (1823 and 1832); of which the northernmost was divided into two sub-branches oriented NW-SE (the longest) and S-N (the shortest).

In the 1832 maps it is possible to observe the seaward edge becoming more undulated; only at the end of the century (1883) the seaward side presents an irregular geometry likely related to the effects of washover events (Bellotti *et alii*, 1999). This evidence suggests that no other beach ridge existed in front of beach ridge confining the lake in 1883 and suggests an erosional regime existed along this coastal sector (phase 4).

The first map reporting the ponds is that of 1929, therefore their genesis occurred between 1883 and 1929; the ponds cut three beach ridges. This suggests a strong progradation occurred in this time interval: indeed, at the end of the first stage of reclamation, at the end of XIX century, the last historical progradation phase occurred (phase 5). Moreover, the presence of ponds marks the end of interaction between the lake and the sea. Therefore, by this time, the filling of the lake had changed the sediment deposition regime. The rate of infilling has depended on local sedimentation. According to Adlam (2014), the volume of accommodation space (intended as total subaqueous volume) is considered including effective accommodation space; this latter could be assumed exhausted but total accommodation space remains due to water table excursions.

As noted above, the single beam eco-sounding surveys (May and June 2009) characterize the different submerged morphology of ponds: the pond-floor, narrow and deep (mean depth 3.5 m), and the depression (markedly flat, periodically drowned under a water table up to 30-40 cm high and coinciding with the lake reported in historical maps). The wide diversity of shape and bathymetry values and the evidence from the analysis of historical and recent maps, indicate that the genesis of ponds is independent from the lake and different between the ponds (Tarragoni *et alii*, 2011).

Both ponds present a depth of about 3.5/4 m but their origins are different.

CHIARO GRANDE POND

The location of the Chiaro Grande pond is between two ridges and parallel to the shoreline of historical maps (e.g. 1832): a pond would form if a bar emerged isolating the stretch of sea behind it.

Some examples of the stages during which such a bar emerges and transforms into a spit are shown in figure 2 where it is possible to observe submerged bar (on the left), incipient spit (D and E) and a new ephemeral *chiaro* (C) (1998).

The figure 6 shows the status of 1995: the spit extends along-strike to the Ombrone River mouth, from the southern wing apex to the northern one. Concomitant with the isolation of the stretch of sea behind it, the river mouth is forced to move ca. 500 m northward, resulting in a 90° bend in the final course of the river. On the northern wing, it is possible to recognize the strong dynamism of the beach during the time interval 1995-2010: several ponds, characterized by different position and size, have been formed according to the mechanism just described.

The geometry of Chiaro Grande pond (B in Fig. 2) is somewhat similar to that recognized analysing the submerged mouth's DEM (Fig. 6) where a narrow and elongated (SE-NW) depression has been observed in front of the northern wing. By analysing several

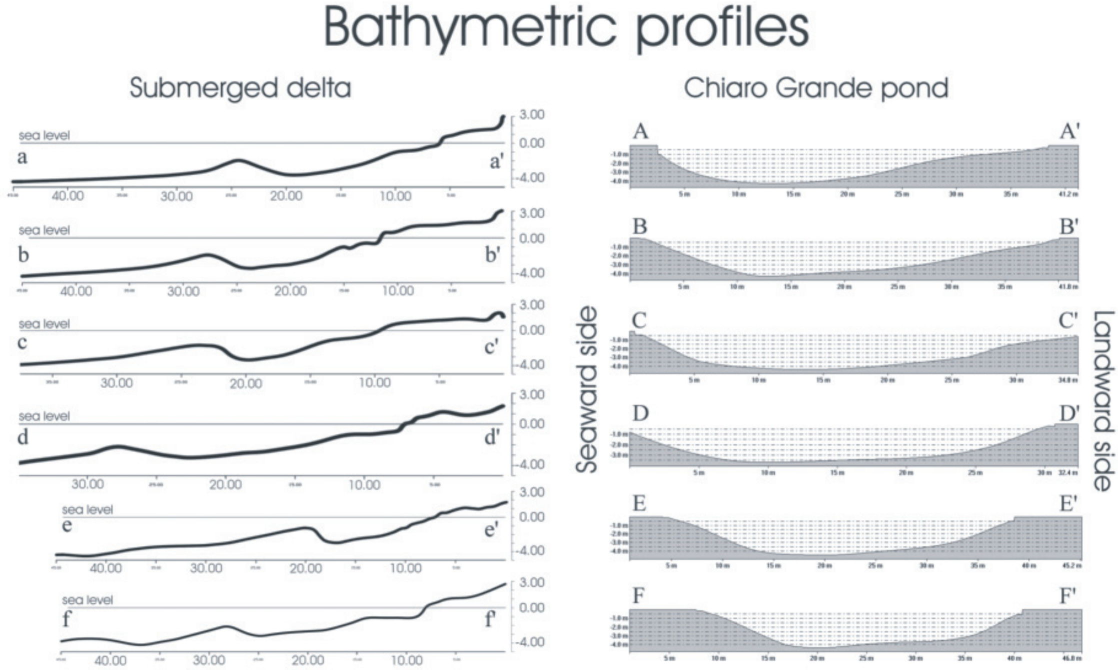

Fig. 9 - Each pair of profiles has the same (horizontal and vertical) scale. The seafloor cross-sections (acquired in 2010) are oriented from SW to NE while that ones of Chiaro Grande pond are oriented from SSW to NNE; both are represented with the seaward side on the left and the landward side on the right. The position of cross-section are shown in figure 3 (seafloor profiles) and figure 4 (Chiaro Grande profiles)

cross sections (drawn through the Chiaro Grande's DEM and submerged mouth's DEM), has been possible to recognize the similar morphology (Fig. 9): 1) same depth (about -4 m); 2) same asymmetric profile with the SW side of Chiaro Grande pond and of submerged depression having higher slope than their NE counter-side. The SW side coincides with the leeward side of the beach ridge in the Chiaro Grande pond and with the downdrift side of the bar in the submerged depression; the NE side coincides with the windward side of the next beach ridge in the Chiaro Grande pond and with the overwash side of the seafloor in the submerged depression (Fig. 8). This consideration supports the suggestion of Tarragoni *et alii* (2011) regarding the mechanism of Chiaro Grande pond genesis.

CHIARO DEL PORCIATTI PONDS

The Chiaro del Porciatti ponds have an orientation transverse to the coast, cutting the ridges, and present a branched structure, in marked contrast to Chiaro Grande pond. On the other hand, the presence of two anthropic structures suggest an anthropic genesis for these ponds. In this area, there were several drainage works and this suggests it is remains of an ancient drainage canal.

SHORELINE VARIATIONS

The evolution of this coastal area has been confirmed by field work carried out during 2007, 2008, 2009 and 2010. Coastal ponds observed during the 2007, 2008 and 2010 surveys appeared of different size, the latter being significantly smaller; in 2010 three new little ponds were observed (Fig. 6). Similar changes have also been observed during shorter (seasonal) time intervals: the current erosive regime acting along the coast does not allow the conservation of these forms.

Several authors recognize climate change as a forcing of a river's solid transport (Ely *et alii*, 1993; Knox, 1993; Milly *et alii*, 2002; Machlin & Lewin, 2003; Piva *et alii*, 2008) due to the increase of precipitation combined with intense forest clearance; other authors consider human activity as a forcing (i.e. Alessandro *et alii*, 1990; Innocenti & Pranzini, 1993).

Based on the review of existing data and integration with newly acquired bathymetric data we propose a re-interpretation of the coastal evolution (Bellotti *et alii*, 1999a) along the area of the Ombrone delta during the past two centuries.

Most of the major Italian deltas (Po, Tiber and Arno), entered a progradational phase during the Medieval cooling which culminated in the Little Ice Age (LIA) and deltaic plains went through significant expansion although hampered by local human activities.

Probably, the 1823 shoreline (Fig. 3 and 8) limited the plain at the end of phase 3. The delta plain expansion occurred in a cold and rainy interval between the Late Middle Ages and throughout the phase 3. Increased rainfall allowed frequent floods with higher flow rates, which have been historically documented (Arno River: 1333, 1557, 1680, 1758; Ombrone River: 1318, 1333, 1557, 1758;

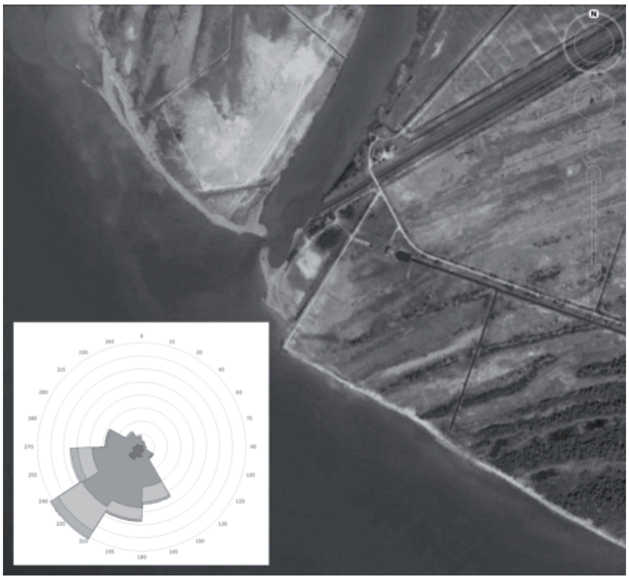

Fig. 10 - View of Ombrone mouth and wave climate of Capo Linaro wave metric station (the nearest one to the study area)

Tiber River: 1422, 1476, 1495, 1530, 1557, 1598, 1606 e 1637). In the same areas, the Late Middle Ages and Renaissance were times of agricultural expansion and consequent deforestation (Sereni, 1987) except for the second half of XIV century, during which the population decreased significantly after the Black Death: Kukavicic & Pranzini (2003) relate the erosion stage of phase 2 to reduced sediment input during the Black Death.

The next erosion stage (phase 4) is probably due to the construction of "La Steccaia" dam and the great drainage works, between 1830 and the end of the XIX century. The new progradation stage (phase 5) starts around the end of XIX century when the main drainage network was completed. The control of fast flowing rivers and the warming climatic conditions have triggered the current erosion stage (phase 6).

Focusing on recent data, five shoreline positions (1995, 1998, 2004, 2006 and 2010) have been analyzed (Fig. 5): the comparison allows identification of beach erosion and progradation periods and associated rates. Comparison of the rates shown in table 1 indicates that the sediment eroded from the apex is largely dispersed toward the north (Aiello *et alii*, 1975). Indeed the spit and bar shapes are elongated toward the north and the sector "A" (between Chiaro del Porciatti ponds and Emissario S. Rocco Canal) has an accretion rate bigger than the erosion rates of the same wing. For the last interval (2006-2010), the reduction in erosion rate is probably due to the combination of some factors such as:

- The orientation of the delta with respect to the direction of the wave front (southern quadrants, Fig. 10);
- The presence of a rigid structure in the southern wing that prevents its retreat and cuts the supply of sediment from longshore drift;
- The northward river sediment dispersion.

The southern wing, in this setting, plays a protective role with respect to the northern one which is in a sheltered position.

CONCLUSIONS

We present new data to update the Ombrone delta apex morphological evolution.

Comparing historical maps and analysing the morpho-bathymetry of submerged delta and ponds, we suggest that the genesis of ponds and lake evolution are independent and in particular:

- during the XIX century, the historical lake preserved its geometry; only in the 1883 map seaward side presents an irregular geometry, probably due to washover events that suggests no other beach ridge existed in front of beach ridge confining the lake. In the 1929 map the ponds have been represented for the first time and are located seaward with respect to the XIX century beach ridge.
- the morpho-bathymetrical study of Chiaro Grande pond and submerged apical mouth confirmed the hypothesis about Chiaro Grande pond genesis in which its formation is based on the closure of a narrow sea stretch consequent to the emergence of a bar.

The orientation of morphological features such as spit, bar and pond together with the spatial distribution of erosion/progradation rates and the prevailing wave climate point top sediment transport from south to north. The progressive landward migration of the shoreline has resulted in a realignment of the coast, reducing drastically the cuspate shape of the Ombrone delta. Recently, the erosion rate of the northern wing has reached peaks of around 14 m/yr (2004-2006), and then fallen to 4.5 m/yr in the latest period (2006-2010). This lower rate is probably due to the orientation of the delta with respect to the direction of the wave front (that is responsible for the northward sediment dispersion) and presence of a rigid structure in the southern wing that cuts sediment supply and stabilizes the shoreline.

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REFERENCES

AA.VV. (2010) - *Final report of VECTOR Project*. V.E.C.T.O.R. Project. Unpublished report.

Adlam K. (2014) - *Coastal lagoon: geologic evolution in two phases*. Marine Geology, **355**: 291-296.

Aiello E., Bartolini C., Caputo C., D'Alessandro L., Fanucci F., Fierro G., Gnaccolini M., La Monica G.B., Lupia Palmieri E., Piccazzo M. & Pranzini E. (1975) - *Il trasporto litoraneo lungo la costa toscana fra la foce del Fiume Magra ed i Monti dell'Uccellina.* Boll. Soc. Geol. It., **94**: 1519-1571.

Alessandro V., Bartolini C., Caputo C. & Pranzini E. (1990) - *Land use impact on Arno, Ombrone and Tiber deltas during historical times*. In: Quélennec, R.E., Ercolani, E., Michon, G., (Eds.), Littoral 1990, Eurocoast, pp. 261-265.

Amorosi A., Pacifico A., Rossi V. & Ruberti D. (2012) - *Late Quaternary incision and deposition in an active volcanic setting: the Volturno Valley Fill, southern Italy.* Sedimentary Geology **242**: 307-320.

Arnaud-Fassetta G., Bruneton H., Berger J., Beaudouin C., Boes X. & Provansal M. (2005) - *A ~8,000-yr record of palaeohydrology and environmental change in fluvialinfluenced sediments from Arles-Piton core, upper Rhône Delta, France.* Z. Geomorph. N.F. **49**: 455-484.

Bellotti P. (2000) - *Il modello morfo-sedimentario dei maggiori delta tirrenici italiani*. Boll. Soc. Geol. It., **119**: 777-792.

Bellotti P., Caputo C., Davoli L., Evangelista S., Garzanti E., Moretti Foggia F. & Valeri P. (1999a) - *La piana deltizia del Fiume Ombrone (Toscana meridionale): morfologia - tessitura e composizione dei sedimenti - architettura del sottosuolo.* Atti del convegno "Le pianure, conoscenza e salvaguardia. Il contributo delle scienze della terra". University of Ferrara, 8 -11 November 1999.

Bellotti P., Caputo C., Davoli L., Evangelista S. & Valeri P. (1999b) - *Lineamenti morfologici e sedimentologici della piana deltizia del Fiume Ombrone (Toscana meridionale).* Boll. Soc. Geol. It., **118**: 141-147.

Bellotti P., Caputo C., Davoli L., Evangelista S., Garzanti E., Pugliese F. & Valeri P. (2004) - *Morpho-sedimentary characteristics and Holocene evolution of the emergent part of the Ombrone river delta (southern Tuscany)*. Geomorphology, **61**: 71-90.

Bellotti P., Caputo C., Davoli L., Evangelista S. & Pugliese F. (2003) - *Evolutionary dynamics of the Crati River Delta (Italy)*. Proceeding of the Sixth International Conference on the Mediterranean Coastal Environment, MEDCOST 03, E. Ozhan (Editor), 7-11 October 2003, Ravenna, Italy, 1805-1816.

Bellotti P., Caputo C. & Valeri P. (2012) - *Tipologie deltizie lungo le coste della penisola italiana. Considerazione sui fattori evolutivi*. Act of 4° International Symposium "Il monitoraggio costiero mediterraneo: problematiche e tecniche di misura". Livorno, 12-14 June 2012, 99-100.

Bellotti P., Chiocci F.L., Milli S., Tortora P. & Valeri P. (1994) - *Sequence stratigraphy and depositional setting of the Tiber Delta: integration of high-resolution seismics, well-logs and archaeological data*. Journ. Sedim. Res., **64** (**B**): 416-432.

Bondesan M., Bavero V. & Viñals M.J. (1995) - *New evidence on the evolution of the Po delta coastal plain during the Holocene.* Quatern. Internat. **29**/**30**: 105-110.

Brambati Antonio (2011) - *La Costa del Friuli Venezia Giulia*. In: *La costa d'Italia* (2011), Delfino, Sassari.

Bravetti L. & Pranzini G. (1987) - *L'evoluzione quaternaria della pianura di Grosseto (Toscana): prima interpretazione dei dati del sottosuolo*. Geografia fisica e Dinamica Quaternaria, **10**: 85-92.

Chiocci F.L., Tommasi P., Melis F. & Ortolani U. (2011) - *Morfologia, sismostratigrafia ed elementi di instabilità gravitativa nella conoide sommersa dei F. Ombrone*. In: "Bilancio sedimentario dei sistemi costieri italiani. Processi naturali e influenze antropiche". Riassunti delle comunicazioni orali, Ischia, 15-17 maggio 2001.

Correggiari A., Cattaneo A. & Trincardi F. (2005) - *The modern Po Delta system: lobe switching and asymmetric prodelta growth*. Marine Geology, **222-223**: 49-74.

Della Rocca B., Mazzanti R. & Pranzini E. (1987) - *Studio geo-morfologico della Pianura di Pisa*. Geografia Fisica e Dinamica Quaternaria, **10**: 56-84.

Di Bella L., Frezza V., Bergamin L., Carboni M.G., Falese F., Martorelli E., Tarragoni C. & Chiocci F.L. (2014) - *Foraminiferal record and high resolution seismic stratigraphy of the Late Holocene succession of the submerged Ombrone River Deltas (Northern Tyrrhenian Sea, Italy).* Quaternary International, **328-329**: 287-300.

Diaz J.I., Nelson C.H., Barber Jr. J.H. & Giro S. (1990) - *Late Pleistocene and Holocene sedimentary facies on the Ebro continental shelf.* In: Nelson, C. H. & Maldonado, A. (eds.), The Ebro Continental Margin, Northwesthern Mediterranean, Spec. Issue. Marine Geol. **95**: 333-352.

Ely L.L., Enzel Y., Baker V.R. & Cayan D.R. (1993) - *A 5000-year record of estreme floods and climate change in the southwestern United States*. Science, **262**: 410-412.

Ferrari K., Dall'Aglio P.L., Bellotti P., Davoli L., Di Bella L., Esu D., Torri P. & Bandini Mazzanti M. (2013) - *Holocene landscape evolution at the Garigliano Rover Mouth*. Annali di Botanica, **3**: 191-198.

Firpo M., Piccazzo M., Bonci M.C., Ivaldi R. & Poggi F. (1992) - *Il delta sommerso del fiume Centa (Albegna): caratteristiche morfologiche e stratigrafiche*. Proceeding of X A.I.O.L. Conference, Alassio, 4-6 November 1992, 587-602.

Galloway William E. (1975) - *Process frame work for describing in the morphologic and stratigraphic evolution of deltaic depositional system*. In: Broussard M.L. Ed. *Deltas, Model for Exploration*. Houtson Geol. Soc., 87-98.

Gensous B., Williamson D. & Tesson M. (1993) - *Late Quaternary transgressive and highstand deposits of a deltaic shelf (Rhône delta, France)*. I.A.S. Special Issue, **18**: 197-211.

Innocenti L. & Pranzini E. (1993) - *Geomorphological evolution and sedimentology of the Ombrone river delta, Italy*. Journal of Coastal Research, **9**/**2**: 481-493.

Knox James C. (1993) - *Large increases in flood magnitude in response to modest changes in climate*. Nature, **361**: 430-432.

Kukavicic M. & Pranzini E. (2003) - *Beach ridges and dunes of the Arno River delta.* Proceeding of the Sixth International Conference on the Mediterranean Coastal Environment, MEDCOST 03, E. Ozhan (Editor), 7-11 October 2003, Ravenna, Italy, 1413-1424.

Lambeck K., Antonioli F., Purcell A. & Silenzi S. (2004) - *Sea-level change along the Italian coast for the past 10,000 ky.* Quaternary Science Reviews, **23**, Issues **14-15**: 1567-1598.

Lambeck K., Antonioli F., Anzidei M., Ferranti l., Leoni G., Scicchitano G. & Silenzi S. (2011) - *Sea level change along the Italian coast during the Holocene and projections for the future*. Quaternary International, **232**, Issues **1**-**2**: 250-257.

Macklin M.G. & Lewin J. (2003) - *River sediments, great floods and centennial-scale Holocene climate change.* Journal of Quaternary Science, **18**: 101-105.

Marinelli Olinto (1926) - *Sull'età dei delta italiani.* La Geografia, **14**: 21-29.

Milli S., D'Ambrogi C., Bellotti P., Calderoni G., Carboni M.G., Celant A., Di Bella L., Di Rita F., Frezza V., Magri D., Pichezzi R.M. & Ricci V. (2013) - *The transition from wave-dominated estuary to wave-dominated delta: the Late Quaternary stratigraphic architecture of Tiber River deltaic succession (Italy).* Sedimentary. Geology **284-285**: 159-180.

Milly P.C.D., Wetherald R.T. Dunne K.A. & Delworth T.L. (2002) - *Increasing risk of great floods in a changing climate*. Nature, **415**: 514-517.

Piva A., Asioli A., Trincardi F., Schneider R.R.. & Vigliotti L. (2008) - *Late-Holocene climate variability in the Adriatic Sea (Central Mediterranean)*. The Holocene **18**: 153-167.

Pranzini E. (1994a) - *The erosion of the Ombrone river delta (Italy)*. Littoral 94, Lisbona, Portogallo, 26-29 September 1994.

Pranzini E. (1994b) - *Bilancio sedimentario ed evoluzione storica delle spiagge*. Il Quaternario, **7**: 197-204.

Pranzini E. (2001) - *Updrift river mouth migration on cuspate deltas: two examples from the coast of Tuscany (Italy).* Geomorphology, **38**: 125-132.

Romano P., Santo A. & Voltaggio M. (1994) - *L'evoluzione geo-morfologica della Pianura del Fiume Volturno (Campania) durante il tardo Quaternario (Pleistocene medio superiore-Olocene).* Il Quaternario, **7** (**1**): 41-56.

Sacchi M., Molisso F., Pacifica A., Vigliotti M., Sabbarese C. & Ruberti D. (2014) - *Late-Holocene to recent evolution of Lake Patria, South Italy: an example of a coastal lagoon within a Mediterranean delta system.* Global and Planetary Change, **117**: 9-27.

Sereni Emilio (1961) - *Storia del paesaggio agrario italiano*. Laterza Editore, Bari 1999.

Somoza L., Barnolas A., Arasa A., Maestro A., Rees J.G. & Hernandez-Molina F.J. (1998) - A*rchitectural stacking pattern of the Ebro delta controlled by Holocene high-frequency eustatic fluctuation, delta-lobe switching and subsidence precesses.* Sedimentary Geology, **117**: 11-32.

Stanley J.D., Bernasconi M.P.E. & Jorstad T.F. (2008) - *Pelusium, an ancient port fortress on Egypt's Nile Delta coast: its evolving environmental setting from foundation to demise.* Journal of Coastal Research, **24**/**2**: 451-462.

Stanley J.D. & Warne A.G. (1993) - *Nile Delta: recent geological evolution and human impact*. Science, **260**: 628-634.

Tarragoni C, Bellotti P., Davoli L. & Chiocci F. L. (2009) - *Recent evolution of the apical area of Ombrone River Delta (Southern Tuscany)*. Epitome Geoitalia 2009, FIST Journal, **3**: 417-418. Rimini, 9-11 September 2009.

Tarragoni C, Bellotti P., Davoli L., Petronio B.M. & Pietroletti M. (2011) - *Historical and recent environmental changes of the Ombrone Delta (Central Italy).* JCR, Special Issue **61**: 344-352.

Web sites

http://it.bing.com, 2010

http://maps.live.it, 1998

http://www.visual.paginegialle.it, 2006

http://www.wadi.unifi.it/grosseto_plain_ital.pdf, 2010

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