MORPHODYNAMIC FEEDBACKS ON DELTAIC COASTS: LESSONS FROM THE WAVE-DOMINATED DANUBE DELTA

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Abstract: In natural conditions, the dynamics of the Danube delta coast has been largely determined by the interaction between fluvial deposition and a strong southward wave-induced longshore transport near the mouths of the river. River-mouth morphodynamics is highly nonlinear, involving multiple feedbacks on the longshore sediment transport. These include a groin effect of the river plume and subaqueous delta, a shoaling effect of the downdrift offset subaqueous delta, and a barrier steering effect of the downdrift barrier islands or spits. As a result, a net sequestration of sediments occurs near the river mouth that aids and speeds up delta lobe development. Downdrift of the mouth, barriers may form after extreme river floods, but also due to increased shoreline instability under high angle waves. Although river mouth processes are complex, the resulting morphology of wave-dominated delta lobes exhibits a tendency to self-organize.

INTRODUCTION

Deltas are home to a disproportionate fraction of the world’s population. Moreover, a few remaining less developed deltas have some of the highest biodiversity on the planet. However, deltas are fragile geomorphic features, which can change dramatically with modest modifications in boundary conditions. Their complex morphology is the result of a dynamic equilibrium between fluvial discharge, marine energy conditions, accommodation, and the overall geological framework. Low relief makes deltas susceptible to floods, storms and sea level change, vulnerabilities exacerbated by sediment deficits following extensive river damming. Understanding the influence of waves on deltaic coasts, in particular, is critical as deltas are increasingly becoming
wave-dominated under these large fluvial sediment deficits (e.g., Ericson et al. 2006). In spite of the importance of deltas, a quantitative understanding of deltaic deposition is limited due to their intrinsic complexity (see e.g., Overeem et al. 2005).

Morphodynamics of deltaic coasts and shelves has been a less explored aspect in the evolution of deltas, although the morphodynamic paradigm has been widely used in coastal studies (e.g., Carter and Woodroffe 1994; Cowell et al. 2004). Feedbacks between the evolving morphology of a delta forced by the continuous sediment output from the river and modified by basinal hydrodynamics remain inadequately known, as are the interactions between contemporaneous lobes within a delta (e.g., Komar 1973; Wright 1985; Cowell et al. 2004) or the influence exerted by a delta on the dynamics of adjacent non-deltaic coasts and vice-versa (e.g., Penland and Suter 1989; Corregiari et al. 2005). While there has been much recent progress in understanding suspended sediment deposition from river plumes (e.g., Syvitski and Bahr 2001; Geyer et al. 2004), the dynamics of coarse sediments at river mouths (Wright 1977) has received little attention recently, in large part due to the inability of conventional techniques to provide direct reliable measurements.

Existing morphodynamic models (e.g., Komar 1973; Cowell et al. 2003) identify the rotation of the shoreline as the principal phenomenon associated with delta development. Shoreline rotation is responsible for changes in longshore drift along deltaic coasts. Several other hydrodynamic-morphodynamic feedback loops related to bedload sedimentation at river/distributary mouths by have been identified by Giosan et al. (2005) and are explored herein for the particular case of the Danube delta. Furthermore, numerical modeling (Ashton and Murray 2005; Ashton and Giosan 2006) suggested that shoreline instability is more to be expected on the downdrift coast of wave-dominated lobe than updrift of the feeding river mouth. A conceptual model for wave-dominated deltas proposed by Bhattacharya and Giosan (2003) is modified in here to account for this latest understanding of delta coast morphodynamics.

**BACKGROUND**

**Danube River**
The Danube river is the second largest European river after the Volga in terms of catchment area (817,000 km2) and length (2870 km) as well as water and sediment discharge. The average annual discharge reported between 1840 and 1995 is ~6240 m3/s, with the highest measured annual discharge of ~9250 m3/s in 1970 (Bondar and Blendea 2000). The peak discharge during the year occurs in late spring (Vörösmarty et al. 1998), following snowmelt and there is a factor of 2 variability between the spring (high) and the fall (low) discharge (Reschke et al. 2002).
Fig. 1. Danube delta coast: shoreline changes from 1856 to 2003/05 (after Giosan et al. submitted). Cartography: S. Constantinescu. Inset: Danube delta morphology and sand facies distribution (after Giosan et al. 2006)
Extensive damming, especially in the lower basin, has reduced the suspended sediment discharge at the apex of the delta from \( \approx 67 \times 10^6 \) t/year between 1921 and 1960 to \( \approx 25-35 \times 10^6 \) t/year at present. The bed-load sediment discharge at the Danube mouths has been estimated to range between \(-4.6 \) and \(-5.3 \times 10^6 \) t/year (Bondar et al. 1992).

In the delta, Danube splits into three main distributaries (Fig.1): the Chilia (Kilia), the Sulina and the St. George (Sf. Gheorghe). Since 1856 when the first estimates of the flow were made by the European Danube Commission, discharge through main navigation route, the Sulina arm, has steadily increased (from 7% to 19%), while St. George and Chilia have compensatorily decreased their flow (from 30% to 23% and from 63% to 57% respectively) as a consequence of sustained maintenance and improvement projects for navigation on Sulina and intensive channelization in the delta. After similar human interventions on the St. George arm in 1980’s, the discharge of this distributary started to increase. Reported values for suspended and bed-load sediment discharge on the three distributaries are 55% and 57-65% for Chilia, 21% and 19-25% for Sulina, and 23% and 19%-21 for St. George, respectively (Bondar and Harabagiu 1992).

**Black Sea**

Danube flows and builds its delta into the Black Sea, a semi-enclosed basin connected to the World Ocean via the Sea of Marmara and the Mediterranean. Black Sea is a microtidal basin with a semi-diurnal tide with a range between 7 and 12 cm. Long term relative sea-level rise has been minimal at the Danube delta (Giosan et al. 2006), although a recent acceleration to 2.7 mm/year has been observed (Cazenave et al. 2002). The average wind speed along the Danube coast is between 5 and 6.5 m/s (Bulgakov et al. 1992). Winds from the north-east quadrant are dominant. Based on visual observations offshore Constantza, the wave regime is highly skewed (82%) arriving dominantly from the left hand side relative to the regional direction of the coast (i.e., north-east quadrant); for the 1972-1981 measurement period, the annual average significant wave height was 0.8 m, with an annual standard deviation of 1 m, and a mean period of 5 seconds (Giosan et al. 1999).

**Danube Delta**

Two distinct delta plain regions have been classically recognized (Antipa 1915) based on distinct morphologies defined by the distribution of channels, flood basins and lakes, and sand ridge geometries. The “fluvial delta”, composed of the Tulcea, Chilia I and II, and Dunavatz lobes (Fig. 1; Giosan et al. 2006), developed in the former Danube Bay, which was probably sheltered by a barrier (Spratt 1860). The “marine delta” developed largely outside the Danube Bay and exhibits a clear wave-influenced morphology (Fig. 1). After reaching the barrier coast, Danube distributaries built four laterally offset lobes. Open-coast delta lobes are wave-dominated (Fig. 1), with the exception of the Chilia III, the youngest lobe, which shows primarily a fluvial-dominated morphology. The wave-dominated lobes exhibit an asymmetric morphology (Bhattacharya and Giosan 2003). Amalgamated beach ridges formed extensive beach ridge plains updrift (north) of (paleo)distributary mouths and are capped in places by dune fields with heights up to \( \approx 12 \) m (Fig. 1). Non-amalgamated beach ridges organize in barrier beach plains located...
downdrift (south) of (paleo)distributary mouths. They resemble chenniers, with a succession of elongate sandy ridges separated by mud-filled marshy/lacustrine elongate depressions (Fig. 1). Beach ridges have been recognized to represent former shorelines of the delta (Bratescu 1922); their groupings in sets that are laterally juxtaposed allows the identification of the lobe development sequence for the “marine delta” (Fig. 1). Early interpretations of beach ridge juxtaposition patterns established a relative chronology for the open-coast lobes (de Martonne 1931; Zenkovich 1956). The St. George I was the first lobe built at the open-coast, followed by Sulina; subsequently, the St. George arm was reactivated developing a second lobe St. George II (Fig. 1). Chilia III is the youngest lobe built at the open coast. Based on AMS radiocarbon and optical dating, Giosan et al. (2006) have established that the “marine” part of the delta has started to develop no earlier than 5500 years BP.

Giosan et al. (1999) analyzed the longshore sediment transport pattern along the Romanian sector of the deltaic and associated lagoonal coast (Fig. 1) and found that the magnitude of the sediment drift was extremely high, with average values of ~900,000 m$^3$/year along sectors of the coast that are not sheltered from the eastern-northeastern dominant waves. Since 1856, when the European Danube Commission first surveyed the Danube delta coast in detail, the Chilia lobe experienced massive progradation (Fig. 1), although it has become increasingly wave dominated since 1940s (Giosan et al. 2005). The St. George lobe, with a new barrier (Sacalin) development, appears to be in a relative equilibrium, while the Sulina lobe has been reworked by waves.

MORPHODYNAMIC FEEDBACKS

Morphodynamics addresses the coupled adjustments between hydrodynamic processes, sediment transport, sedimentation, and morphology, and has become an established paradigm for studying coastal evolution (e.g., Carter and Woodroofe 1994; Wright 1985). Compared to other clastic coasts, the morphodynamics of deltas is complicated by the continuous or episodic delivery of freshwater and sediment to the coast by one or several rivers through one or multiple mouths. The solid load discharged by the river comprises of both suspended fine sediment within the river plume and coarse bed-load. Sedimentation of the coarse-grade sediments appears to be a dominant factor in river mouths evolution (Wright 1995) and further, in determining the facies architecture of wave-dominated deltas (Bhattacharya and Giosan 2003).

At the coast, delta forms a discrete subaqueous protuberance; in most cases, the protuberance is also expressed at the shoreline, which progrades relative to the adjacent coasts. From a hydrodynamical perspective, this deltaic “bulge” can be viewed as a morphological perturbation to the regional circulation system. Morphodynamic adjustments between the deltaic morphology and the fluvial and basinal hydrodynamics are most intense at the river mouths. Morphodynamics of wave-dominated deltaic distributary mouths is highly non-linear, involving multiple feedbacks between subaerial deltaic progradation, deposition on the subaqueous delta, current and wave hydrodynamics as well as wave-current interactions (Fig. 2; Giosan et al. 2005). These feedbacks are particularly well expressed at the St. George mouth/deltaic lobe coast of the Danube delta.
Fig. 2. Effects leading to sediment trapping on the subaqueous delta for a wave-dominated asymmetric deltaic coast with and without barrier. Convergence/divergence of the sediment drift is indicated by shortening/lengthening of arrows and continuous/dashed line circles, respectively.

**Groin Effect**

The morphology of the mouth shows that the submarine lobe built by the St. George branch is completely offset to the south of the mouth (Fig. 3; Constantinescu et al. submitted) in the direction of the longshore drift and the preferred orientation of the distributary’s plume (Fig. 1; Bondar 1964). The coast updrift of the mouth is separated from the mouth by a subaqueous levee, it is multibarred, and evolves much like a beach on a sand-rich non deltaic coast (Giosan et al., submitted; Vespremeanu-Stroe, A., Constatinescu, S., Ovejanu, I., Filip, F., Giosan, L., in prep., Impact of Danube high discharge events on the morphology and sedimentation at the mouth of St. George arm). Sands updrift of the St. George mouth are texturally more mature than the sands downcoast (Giosan 1993) suggesting again that fluvial material from St. George distributary does not contribute significantly to the updrift wing of the delta lobe, but instead has been built by sediment eroded from the Sulina lobe.

To explain the development of the subaqueous levee and the composition of the updrift coast, Giosan (1998) invoked the interaction between the river plume and the surface waves (Fig. 2). The convergence of the longshore sediment transport updrift of the river
mouth due to this interaction has been termed as the hydraulic groin effect of the plume (Todd 1968; Komar 1973). This effect occurs regardless of the presence of suspended sediment in the plume. However, the increase in plume’s density by addition of suspended sediment leads to an increase in the density contrast between the plume and the coastal waters, resulting in a more rapid breaking of the waves when they encounter the plume (e.g., Rodriguez et al. 2000). Furthermore, the subaqueous delta per se developed offshore the river mouth (including the subaqueous levee) also acts like an obstacle to the sediment drift (Fig. 2), much like an ebb shoal restricts bypassing of sediment downcoast (Bruun and Gerritsen 1959; Kraus 2000).

Where the longshore drift reaching the mouth is significant, a positive feedback loop develops between the progradation of the updrift coast caused by this combined groin effect of the river plume and subaqueous delta (Fig. 2), leading to a mouth that is progressively more sheltered from waves, which in turn, results in an increase in sedimentation on the subaqueous delta platform and less sand bypassing around the mouth. Sediment trapping within the delta is one of the net results of this feedback mechanism.

Shoaling Effect
On the updrift side of the mouth, the longshore drift obstructed by the river plume builds a deltaic beach ridge plain mostly of sediments brought in from updrift. Development of
a subaqueous delta strongly offset to the opposite downdrift side of the mouth is accomplished with sediments brought in by the river. The asymmetry of this subaqueous delta relative to the river mouth activates another positive feedback between morphology and wave hydrodynamics (Fig. 3; Fig. 4a). The vast, shallow delta platform offset to the south of the river mouth shelters the mainland deltaic coast as waves dissipate almost completely over it. Although at a larger scale, this phenomenon is similar to the reversal of the wave-driven sediment transport on the downdrift side of ebb-shoals at inlets, due to the sheltering provided by the shoal itself (e.g., FitzGerald 1984).

![Fig. 4. Wave transformation of a typical wave field (NE from 30 m depth, with a 1 m height represent by initial arrow length and 4.5 s period; after Giosan et al. 2005) on bathymetries of St. George mouth: (a) 1856 and (b) 1935. Extent of subaqueous delta platform is shown by the 2 m depth contour (thick line). STWAVE (Smith et al. 2001) runs by F. Buonaiuto.](image)

The convergence of the drift along the subaqueous delta is seen in modeling exercises (Fig. 4a) as waves refract and shoal less updrift of the mouth, where no the subaqueous delta is present, than downdrift of the mouth, where a massive submarine delta exists. This dynamic interaction between the morphology, with an ever expanding subaqueous delta driven by river sediment discharge, and the wave hydrodynamics acts as another positive feedback (Fig. 2), leading to larger entrapment of sands within the delta. The downdrift offset of the subaqueous delta promotes a stronger, more rapid dissipation of waves over it, than updrift of the mouth where no subaqueous delta is present; this results in more quiescent conditions favoring expansion of the subaqueous delta.

**Barrier Steering Effect**
Similar to other deltas (e.g., Rodriguez et al., 2000), the barrier at St. George mouth was probably built by waves reworking sediments delivered by the extreme river floods (at
the end of 19th century; Bratescu 1922). By 1935, Sacalin barrier doubled in length (Fig. 4b) while rolling-over to the mainland under the influence of overwash and breaching processes (Giosan 1998). The submarine lobe appears to have continued to prograde into the dip direction until mid-19th century (Giosan et al., submitted), albeit slowly, but its slope became flatter as the delta platform retreated with the barrier island toward mainland. However, after Sacalin’s emergence, the submarine lobe elongated to southwest (Fig. 4b) at a dramatic rate of over 200 m/year, compared to less than 100 m/year previously.

Wave transformations performed using the STWave model (Fig. 4b) for the case when a barrier is present show that the nearshore is steep along the barrier and incoming waves reach the coast of the island incompletely shoaled and refracted, inducing an intense longshore drift that is steered (guided) and redirected to the south by the barrier island shore (Giosan et al. 1999). This phenomenon, which we term barrier steering (or channeling) of the longshore drift, is another feedback loop developed between morphology and wave hydrodynamics (Fig. 2), contributing to the dramatic southward extension of the submarine lobe after Sacalin’s emergence (Giosan et al. 2005). Development of a shallow subaqueous delta platform downdrift of the mouth allows deposition of mouth bars to be displaced offshore to the edge of the platform during floods, exposing them to a more intense wave activity. Waves elongate these bars into barrier islands fronting the delta platform via the longshore drift. As the emergent barrier becomes the new shoreline for the downdrift half of the delta, it activates this new feedback loop between the wave hydrodynamics and the delta morphology. Waves can no longer dissipate over the shallow delta platform; they reach the barrier shore incompletely refracted resulting in a steering of the longshore drift (i.e., intensification of the drift guided along the shore of the barrier); this in turn leads to a more rapid development of the subaqueous delta in the alongshore direction. This mechanism is also a positive feedback loop because as the subaqueous delta is built alongshore it advances gradually into deeper waters and, thus, immobilizes sand there rather than bypassing it to the downcoast. The barrier also keeps most of the river plume offshore of it and steers it downcoast. This steering forces sedimentation from the suspended load to aid development of the subaqueous delta at its downcoast tip into gradually deepening waters.

**Shoreline Rotation and Instability**

Morphodynamic models (e.g., Komar 1973; Cowell et al. 2003) identify the rotation of the delta shoreline as a phenomenon responsible for changes in the longshore drift along a wave-dominated deltaic coast. Assuming that the offshore wave regime is not significantly skewed to one side of the regional orientation of the coast, as a delta protrusion advances, the wave angle of attack increases along both sides of the mouth driving a larger drift away from the mouth. Changes in the drift magnitude can be thought as a feedback loop between subaerial morphology of the delta and waves, which ultimately limits the growth of the deltaic protrusion.

For numerical modeling purposes, rotation is generally conceptualized as a two-dimensional problem by assuming that the nearshore profile is invariable for the entire
deltaic coast. Even with such a drastic simplification, recent one-line modeling showed that, for the same sediment supply and wave energy, deltas prograde faster and attain a more pronounced aspect ratio when the proportion of high-angle waves is increased, for wave regimes that remain symmetrical relative to the regional orientation of the coast (Ashton and Murray 2005). In cases where the offshore wave direction is skewed toward one side of the coast, the shoreline instability on the downdrift delta wing is enhanced leading to the development of overwashing spits (Fig.5; Ashton and Murray 2005; Ashton and Giosan 2006). This seems to be the case for the St. George shoreline in 1856 (Fig. 1), when a spit was present on the downdrift wing of the lobe.

Fig. 5. Simulation result for deltas with a one-line model (Ashton et al. 2001; Murray and Ashton 2004; ) with asymmetrical wave distribution (more waves from the left; after Ashton and Murray, 2005).

CONCLUSIONS
Based on a survey of the morphology of several deltas and/or deltaic lobes, Bhattacharya and Giosan (2003) introduced a conceptual model for wave influenced deltas that classifies them into symmetric, asymmetric and deflected types. We modify this model to account for the role played by the subaqueous delta in establishing the morphodynamic feedbacks discussed above (Fig. 5). In cases where the longshore drift is relatively strong at the river mouth asymmetry index >200; Bhattacharya and Giosan, 2003), it can interact with fluvial delivery of sediment leading to an asymmetry in the morphology and facies distribution of the delta (see above for St. George’s case). Furthermore, the shoreline instability on the downdrift delta wing could lead to the development of overwashing spits (Ashton and Murray 2005; Ashton and Giosan 2006). In the extreme case where the longshore drift is dominant over a relatively low or episodic fluvial discharge, a deflected delta develops (Fig. 6). In this case, the mouth of the river runs subparallel to the coast most of the time during the delta evolution with the river being separated from the sea by a sandy spit-levee (Wright 1985). Subaqueous
deposition in this case is not localized and never reaches a volume large enough to have an effect on sediment trapping. The delta progrades as a series of randomly distributed, quasi-parallel sand spits and channel fills.

At river mouths where the net longshore sediment transport is small (asymmetry index <200; Bhattacharya and Giosan, 2003), wave-influenced deltas are symmetric in morphology and facies (Fig. 1). In this case, where the river discharges a significant suspended load besides sandy bed load, a subaqueous delta advances periodically in front of the mouth (Van Maren 2005) with beach ridges or barriers developing subsequent on both sides of the mouth. The mechanism to generate these barriers is still unclear: Van Maren (2005) believes that onshore sediment transport by wave asymmetry is responsible, while we would argue based on Giosan (1998) that river floods are probably the main mechanism for barrier nucleation and longshore transport is the mechanism responsible for their further development. However, in these cases of symmetrical deltas, both the groin effect and the barrier steering effect would apply acting on both sides of the mouth.

![Fig. 6. Process diagram for wave influenced deltas (modified from Bhattacharya and Giosan, 2003). The upper row includes deltas preserving a lower proportion of fluvial mud compared to the cases in lower row that are more typical for rivers with high suspended load.](image)

Asymmetric development of delta lobes has been documented around the world by Bhattacharya and Giosan (2003). In the case of the Danube delta, besides the St. George
lobe, asymmetry with development of downdrift barrier occurs also on the previously fluvially-dominated Chilia lobe coast at several secondary mouths (Fig. 1), indicating a tendency to for river mouth to self-organize at various scales. The asymmetry in facies is also displayed by older marine lobes of the Danube delta (Fig. 1: Giosan et al. 2005) indicating a strong and sustained southward-directed longshore drift and suggesting that the wave-driven morphodynamics of the deltaic coast has always played a fundamental role on the entire development of the external delta plain. In conclusion, morphodynamic feedback mechanisms linked to the existence of a subaqueous delta appear to be essential in determining the morphology and facies of wave-dominated deltas and they should be considered in modeling exercises.

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