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Review article

Wave influence in the construction, shaping and destruction of river deltas: A review

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ABSTRACT

Waves are an important agent in the construction, shaping and destruction of river deltas. Notwithstanding the commonality of waves in oceans and seas, wave influence on deltas varies considerably depending on the coastal morphology and nearshore bathymetry. Although there have been advances in understanding the way waves approaching a delta shape its shoreline, much still remains to be known of the interactions between waves and river deltas. Deltas are built essentially from sediments supplied by rivers. Sand-sized and coarser sediments may also be derived from nearby abandoned delta lobes or from older relict nearshore deposits, transported by wave reworking and longshore currents. Alternatively, delta erosion by waves can also release sediment that is redistributed alongshore or that accumulates offshore. The extent to which bedload is supplied to and sequestered in, or lost by, deltas through waves and longshore transport strongly depends on interactions between waves and fluvial discharge at the river mouth. These interactions and the mutual adjustments they engender are not only important in the overall balance between delta retreat, progradation or aggradation but also in processes such as avulsion and channel switching, as well as in the eventual survival of a delta in the face of sea-level rise. Where waves are important, fluvial liquid discharge is high, and sediment supply is rich in bedload, two important aspects are the blocking of waves and longshore currents by strong river discharge and the formation of bars at the river mouth. Field studies of the complex interactive processes prevailing where river flows encounter waves are, however, non-existent and numerical modelling, though promising, hampered by scale constraints and the difficulty of replicating them and generating mouth bars in the presence of longshore currents. This interaction influences the seaward extent of the delta mouth protuberance and its stability; this protuberance then forming the regional shoreline template to which waves and longshore currents adjust. Longshore currents can redistribute wave-reworked mouth bar deposits emplaced during strong river flow. Transport may be either divergent from the mouth or may be regionally unidirectional but wherein the symmetry of some deltas, probably rare, may be maintained by a strong river blocking effect on transport from the updrift flank. The mouth protuberance may be such as to foster transport reversal (counter-drift) at the delta margins that contributes to sediment sequestering within the delta. These interactions largely contribute in shaping delta shorelines, and together with the abundance of sediment supply and grain size, determine the resultant wave-formed shoreline barrier types, which include spits, more or less closely-spaced beach ridges, and barrier islands and cheniers in situations of punctuated progradation or retreat. Where several distributary mouths occur, pronounced longshore variability in wave processes and wave-induced sediment transport may ensue, resulting in multiple drift cells that assure the retention of sand and coarse-grained sediments within the delta. Waves can also be an important agent in the reworking and retreat of mud-rich deltas that generally conform in morphology to the ‘river-dominated’ (such as the Mississippi) or ‘tide-dominated’ (such as the Ganges–Brahmaputra or Chao Phraya) types, resulting in the episodic formation of sandy cheniers and beach ridges.

Although sea-level rise is likely to lead to enhanced wave reworking of deltas, the possible prevalence of aggradation (in lieu of progradation), channel switching and avulsion, and washover processes, may contribute to the disorganization of waves and longshore transport, fostering deltaic sequestering of sand and coarser-sized sediment and delta survival. The weakening of river discharges resulting from human activities will invariably lead, however, to enhanced wave reworking of deltas and to deltaic sediment redistribution by longshore currents. The massive swing towards significant reductions in fluvial sediment supply today may signify the ultimate demise of many deltas in the coming decades through a process of delta

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shoreline straightening by waves, in addition to accelerated sinking. These various foregoing aspects of the relationship between waves and river deltas are reviewed here across a range of timescales, and new interaction concepts proposed, using numerous examples of deltas in the world and on the basis of case studies, conceptual studies and numerical modelling studies in the literature spanning more than forty years.

1. Introduction

River deltas are characterised by low topography, by commonly high productivity, and potentially rich and biodiverse ecosystems, and may offer a wide range of ecosystem services such as coastal defence, drinking water supply, recreation, green tourism, and nature conservation. Many deltas support rural settlements, agriculture and fisheries, and are food baskets for many nations. Industry and transport in some deltas can also be very important, leading to the development of major urban centres, ports, and harbours. These potentially rich economic and ecological functions are assured by the ability of deltas to trap fluvial sediment en route from upland sources to coastal, nearshore, continental shelf and abyssal plain sinks (Fig. 1). The retention of river-borne sediments essential to the growth of deltas on the world's present coasts under conditions of a stable eustatic sea level depends on numerous conditions such as the morphological and tectonic characteristics of the coast, subsidence, but also the relative influence of the parent river, waves and tides (Coleman, 1981), the three cornerstones of delta morphological classification (Galloway, 1975). This classic tripartite classification scheme (Fig. 2) has formed a simple conceptual basis for categorizing deltas in many studies throughout the world. Deltas prograde on coasts where waves and currents are either not energetic enough to disperse all of the sediment brought down by rivers, or where the fluvial liquid and solid discharge are so high as to dampen even large waves. Even where the nearshore wave climate is important in terms of energy, delta morphology can be as much a product of fluvial as of marine processes. Since, by far, the most important sources of sediments to the world ocean are rivers (Milliman and Farnsworth, 2011), the redistribution of this sediment from river deltas to adjacent coasts is primarily vested in waves and wave-generated longshore currents. Delta erosion by waves can also release sediment that is redistributed alongshore or accumulates offshore. Whilst modern river deltas are primarily products of fluvial sediment sequestering on the present coasts, they may also trap exogenous sediments transported alongshore by currents and/or derived from the inner shelf by wave reworking. This sediment trapping capacity is fundamental to their maintenance in the face of climate change and sea-level rise. Although deltas may develop resilience and adapt to changes in sediment supply and sea level, commonly through re-organization of their channels and their patterns of sedimentation, they have become increasingly vulnerable economic and environmental hotspots (Foufoula-Georgiou, 2013). The hundreds of millions of people living in deltas today are increasingly exposed to the hazardous impacts of a large range of events to which deltas are usually exposed, such as flooding, subsidence, and coastal erosion, but the intensity of which is being exacerbated as a result of reduced sediment flux from rivers caused by humans (Evans, 2012; Anthony, 2014). This reduction in fluvial sediment flux, sometimes combined with lower liquid discharges, is becoming detrimental to the balance between the river and wave influence in delta dynamics, thus rendering many of the world's deltas vulnerable to the aforementioned hazards (Syvitski et al., 2009).

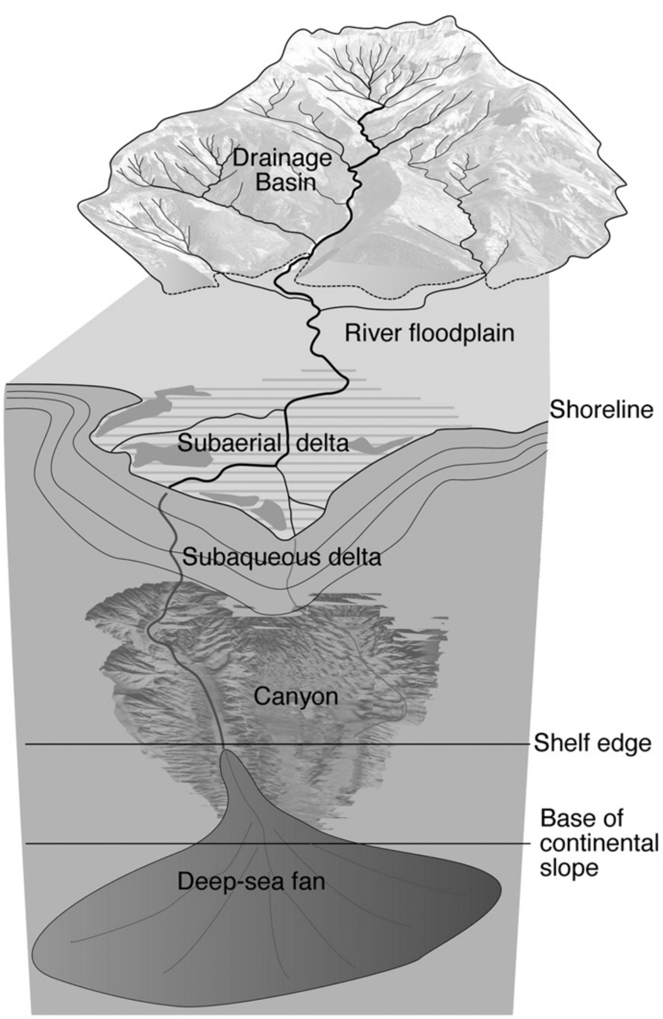


Fig. 1. River deltas in the fluvial source-to-sink continuum from catchment to deep-sea fan.

From a process point of view, the early works of Wright and Coleman (1972, 1973) and Galloway (1975) provided the basis for many case studies in considering the extent to which waves influence the development of individual river deltas. With regards to this process approach, which is central to our review, attempts to understand the role of waves in shaping the shorelines of river deltas and in modulating large-scale delta development have essentially revolved around the extent to which waves approaching the delta shoreline can generate currents that redistribute fluvial and coastal sediments. Based on work on the strongly wave-influenced coast of Brazil, Martin et al. (1987) and Dominguez (1996) drew attention to the importance of the 'groyne' effect caused by river flow in obstructing longshore currents and in generating accumulation of what they considered as inner shelf-derived sand on the updrift flanks of four river deltas in Brazil, whereas downdrift shoreline growth was generated by sediment of fluvial origin. The hydraulic groyne effect refers to the ebb jet effect on longshore currents across tidal inlets (Todd, 1968), and the term was later employed by Komar (1973) in his model of river delta growth under the influence of longshore currents. Bhattacharya and Giosan (2003) conceptualised the role of oblique wave approach on delta evolution in terms of delta asymmetry that reflects the extent to which adjustments between wave-generated longshore currents and river liquid discharge determined the plan shape of the delta shoreline. More so than a case study, the example of the Danube delta in the Black Sea has been used by Giosan et al. (2005) and Giosan (2007) to draw attention to the highly non-linear nature of the morphodynamics involved in delta lobe growth. These authors showed that the evolution of the Danube delta has been determined largely by the interaction between fluvial deposition and a strong and persistent southward wave-induced longshore transport that has led to the facies asymmetry displayed by the marine lobes of the delta. The authors concluded that although the sedimentation processes are complex, the resulting morphology at the mouth exhibits a tendency to self-organize that is reflected and preserved by the facies architecture of wave-influenced lobes. A similar reasoning based on morphodynamic feedbacks between river sediment supply, wave incidence angles, longshore transport and delta shoreline orientation was also employed by Pranzini (2001) to elucidate the updrift migration of the mouths of sandy river deltas in Tuscany, Italy. Ashton and Giosan (2011) used a numerical model to demonstrate that obliquely approaching waves can impart a morphological fingerprint on deltaic form. Ashton et al. (2013) further showed from two-way coupling of wave-induced longshore processes with sediment routing through multiple distributaries that complex interactions can arise due to feedbacks between distributary channels connected along the evolving shore. Finally, Nienhuis et al. (2013) numerically explored modes of wave reworking of abandoned delta lobes via longshore transport.

Much still remains to be known, however, of the relationship between waves and delta morphodynamics. In this paper, the role of interactions between waves and river discharge in shaping river deltas are taken further by pursuing a morphodynamic logic similar to that of Pranzini (2001), Giosan et al. (2005) and Giosan (2007) that attempts to show how balances hinging on wave-river flow interaction at the deltaic river mouth, sediment supply fluctuations relative to waves, and wave energy gradients along the delta shoreline determine overall delta development by leading to the sequestering of sediments within the confines of, or loss of such sediment by, river deltas. The review is based on numerous case studies, conceptual studies and numerical modelling studies in the literature spanning more than forty years, and is illustrated by numerous examples of deltas in the world.

To demonstrate the relationship between waves and river deltas, the review is divided into eight sections. Following this introduction (Section 1), Section 2 presents a synopsis of the broad-scale relationships between waves and deltas. Sections 3 to Section 7 progressively build up on these relationships, using a background timescale frame, from a process approach at the river mouth to the long-term plan shape of deltas and overall delta evolution. Section 3 looks at the relationship between waves and river discharge at delta mouths, and the crucial process of mouth-bar formation. Section 4 reviews the relationship between waves and delta shoreline forms, whereas Section 5 considers this relationship in terms of the plan shape of deltas. These considerations are then extended to deltas with multiple river mouths in Section 6. Section 7 adopts a broader perspective that reviews the potential relationship between waves and distributary mouth instability in influencing overall delta evolution. Section 8 examines the consequences of decreasing river influence relative to waves on delta development, essentially within the contemporary era of large-scale anthropogenic disturbance of river systems. Section 9 proposes a summary and conclusion.

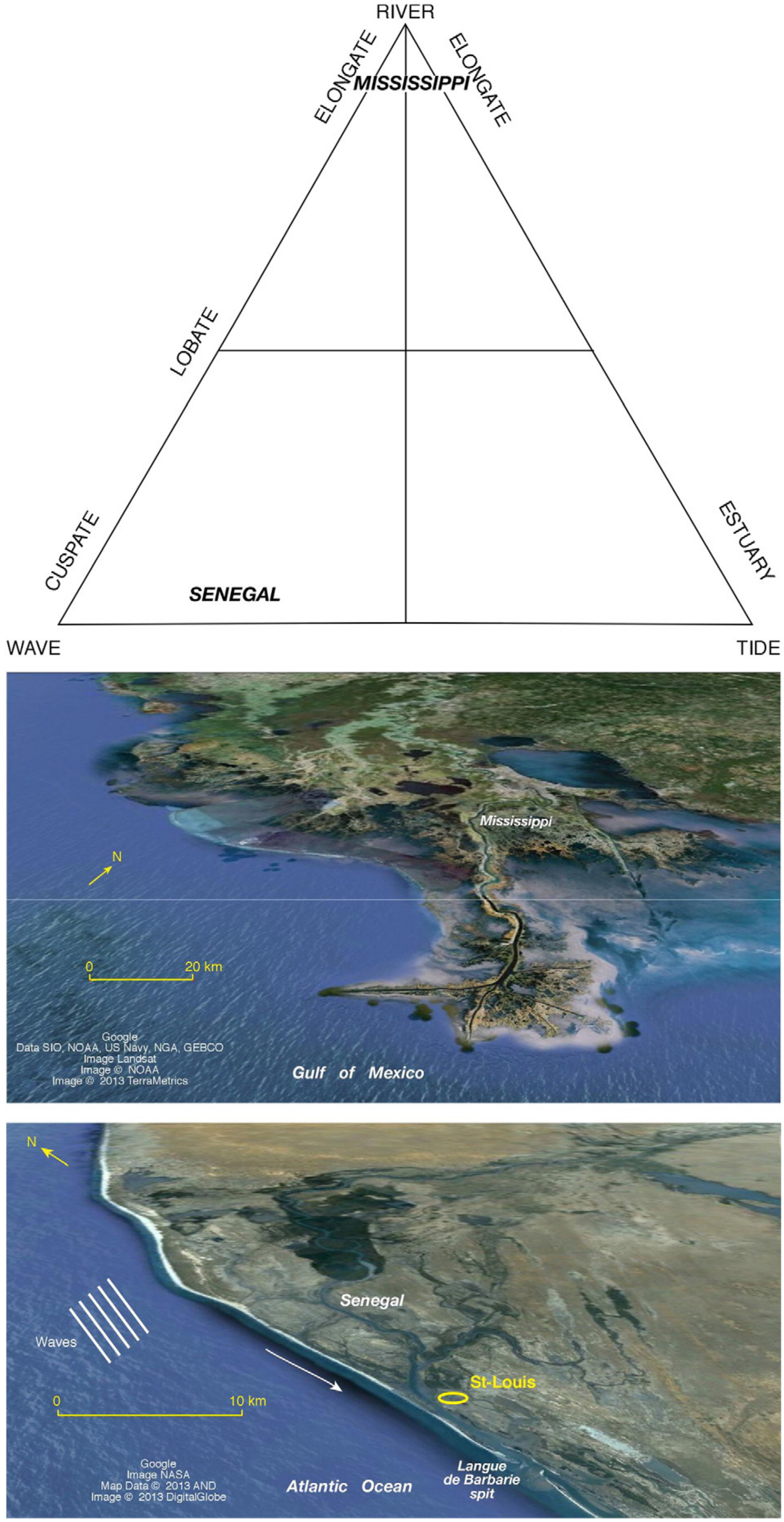
The review will not examine the stratigraphy and facies architecture of wave-influenced deltas, thorough treatments of which are provided by Bhattacharya and Giosan (2003) and Bhattacharya (2006), as well as by numerous earlier conceptual and case studies. Reference will be made throughout to wave-influenced, rather than wave-dominated deltas, except where wave 'domination' is reported from the literature. Longshore drift throughout the text references the product of the process of longshore transport. All deltas cited in the text are shown in Fig. 3.

2. Waves and river deltas: an overview

Although about 45 deltas are used in this review to illustrate the relationship between waves and river deltas spanning levels of wave influence from low to high, the aim here is not to classify these deltas as a function of this influence. Processes generated by waves and tides affect most river mouths to varying extents. Notwithstanding the commonality of waves, wave influence on deltas is extremely variable, and the morphological similarities and contrasts among deltas are only weakly related to the deepwater wave regimes of the receiving basins because the wave climate in the nearshore zone often differs substantially from the deepwater wave climate as a result of modifications caused by the subaqueous topography of the delta front and offshore regions (Wright and Coleman, 1972, 1973; Coleman and Huh, 2004). These authors highlighted a better correspondence between the nearshore wave climate at the 10-m contour and delta morphological similarities and contrasts. Wright et al. (1974) proposed a dimensionless "discharge effectiveness index" based on the ratio of the discharge per unit width of river mouth to the nearshore wave power per unit width of wave crest as a measure of the relative dominance of one or the other of these two agents. This index pointed out the antinomy between the Mississippi and the Senegal deltas, the two iconic examples of what are considered as strongly 'river-dominated' and strongly 'wave-dominated' deltas (Fig. 2). Hori and Saito (2008) proposed quantitative indices based on tidal range, wave height and suspended sediment load to distinguish between wave-influenced, mixed tide- and wave-influenced, and tide-influenced deltas, retaining the valid assumption that all deltas are strongly influenced by fluvial discharge and sediment load. This overarching influence of the river, hinged on the sediment supply that determines delta growth, is also underlined in the river-mouth evolutionary scheme proposed by Boyd et al. (1992), as well as in the rapid growth of numerous deltas mediated by human-induced increases in fluvial sediment supply, especially in the Mediterranean (Anthony et al., 2014b).

In general, as nearshore wave energy increases and offshore slopes steepen, wave-built coastal barriers and interdistributary beach ridges become more abundant, and delta shorelines become more regular and smoother (Fig. 4a). 'Wave-dominated' deltas in the simple classification scheme proposed by Galloway (1975) are generally identified by their arcuate to cuspate planform shapes and their smooth shorelines, with a more cuspate form indicating greater wave influence. It is important at the outset to emphasize that: (1) wave influence on the evolution of river deltas is not just a marginal one of constructing, shaping, and eventually destroying the delta's seaward fringes (Fig. 4a). The extent to which bedload is supplied to and sequestered in, or lost by, deltas through waves and longshore transport can also be important in the overall balance between delta retreat, progradation or aggradation, and in processes such as channel switching and avulsion, which is the wholesale abandonment of a channel in favour of a new path, as well as in the eventual survival of a delta in the face of sea-level rise; (2) alternatively, keeping wave energy constant, the smaller the delta lobe or fan, the more overarching the influence of waves on overall delta evolution is likely to be, whereas the dynamics of large deltas are conditioned by the more complex interplay of sediment supply, aggradation, progradation, channel switching, and subsidence, notwithstanding a potentially strong influence of waves and currents on the shorelines of these large deltas, especially when sediment supply becomes deficient.

Apart from the reworking and redistribution of fluvial bedload, wave energy is also essential in some cases in mobilizing nearshore deposits that are then integrated into the delta sediment budget and redistributed alongshore (Fig. 4b). Eroding headlands can also provide sediments transported alongshore towards deltas. On some open ocean coasts, especially where a strong and constant swell wave regime prevails, and where bedrock headlands are absent, sand supplied in the past in large quantities by rivers has been reworked onshore and transported alongshore for hundreds of kilometres away from deltaic river mouths, forming massive accumulations of successive beach ridges that link deltas, as on parts of the coast of West Africa (Anthony, 1995; Anthony and Blivi, 1999) and the Costa de Nayarit (Curray et al., 1969) on the Pacific shores of Mexico (Fig. 3). The latter coast has been appropriately termed as a 'delta-strandplain' coast by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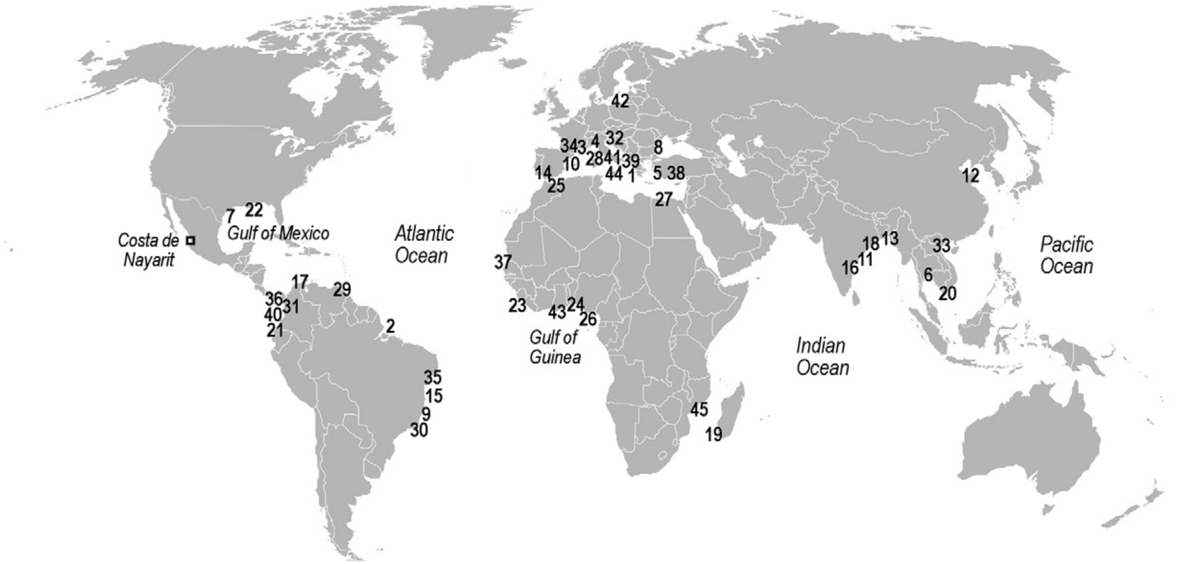


Fig. 3. River deltas cited in the text. In alphabetical order: 1. Acheloos; 2. Amazon; 3. Argens; 4. Arno; 5. Büyük Menderes; 6. Chao Phraya; 7. Brazos; 8. Danube; 9. Doce; 10. Ebro; 11. Godavari; 12. Huanghe; 13. Ganges–Brahmaputra; 14. Guadiana; 15. Jequitinhonha; 16. Krishna; 17. Magdalena; 18. Mahanadi; 19. Mangoky; 20. Mekong; 21. Mira; 22. Mississippi; 23. Moa; 24. Mono; 25. Moulouya; 26. Niger; 27. Nile; 28. Ombrone; 29. Orinoco; 30. Paraibo do Sul; 31. Patia; 32. Po; 33. Red; 34. Rhône; 35. Sao Francisco; 36. San Juan; 37. Senegal; 38. Seyhan; 39. Shkumbini; 40. Sinu; 41. Tiber; 42. Vistula; 43. Volta; 44. Volturno; and 45. Zambezi.

Bhattacharya and Giosan (2003), and this appellation also appears to be applicable to large parts of the coasts of West Africa (Anthony, 1995) and western Brazil described by Martin et al. (1987) and Dominguez (1996), characterised by abundant sand-rich deltas (Fig. 5), as well as to much of the coast of Tanzania described by Alexander (1969).

Although bedload materials, sand, and to a lesser extent, gravel, most readily come to mind in a review of wave influence on river deltas, it is important to note that mud brought down to the coast by rivers (and/or reworked from older coastal and nearshore deposits) can also be transported alongshore by wave-induced longshore currents, sometimes for hundreds of kilometres, and finally accumulate in lower-energy settings, sometimes aided by wave dissipation by mangroves, thus contributing to coastal progradation. Examples are provided by two of the world's three largest deltas, the Amazon and the Mekong (Fig. 6). Waves can also be an important agent in the reworking and retreat of mud-rich deltas that are generally considered as either 'river'- (such as the Mississippi, Fig. 2) or 'tide-dominated', such as the Chao Phraya (Uehara et al., 2010), generally through episodic high-energy events such as tropical storms or cyclones impinging on modally low wave-energy settings such as the Gulf of Mexico, the Gulf of Thailand and the Gulf of Bohai.

Each of the three hydrodynamic forces in the ternary diagram (Fig. 2) may also show considerable variation and overlap in space and time. Variations in space (Fig. 4a) are more likely to affect large river deltas and arise as a result of alongshore gradients in wave energy and tidal range and variations in strength between distributary channels, including the effects of channel switching. Morphologically, these are also the most diverse deltas. The Orinoco delta shows a variety of shoreline features that reflect differences alongshore in river, tide and wave influences (Anthony et al., 2014a). The deltas of some large Asian rivers such as the Red (Woodroffe and Saito, 2011) and the Mekong in Vietnam also exhibit alongshore morphodynamic variability. Such alongshore variations complicate the classification of delta types within the tripartite scheme. Temporal variations have also been commonly reported, demonstrating, par excellence, shifts in the balance of forces between fluvial and wave processes in shaping the delta. Short-term shifts, at sub-seasonal, seasonal, or spans of a few years, in river discharge or wave conditions are common, generally mediated by weather and climate. Longer-term (multi-decadal and more) changes more commonly concern river influence and are related to avulsions and to climate- and human-induced liquid and solid discharge variations that have been abundantly documented, especially from the Mediterranean Basin (e.g., Pranzini, 2001; Brückner et al., 2002; Correggiari et al., 2005; Vött et al., 2007; Simeoni and Corbau, 2009; Marriner et al., 2012a, 2012b, 2013; Maselli and Trincardi, 2013; Provansal et al., 2014). The Danube delta has similarly been affected over the last two millennia (Giosan et al., 2012). Changes in wave patterns at such timescales have been less commonly reported. A modern shift to stronger wave influence since the 1980s at the river-dominated Chilia lobe of the Danube delta has been reported by Vespremeanu-Stroe and Preoteasa (in press).

3. Interactions between waves and deltaic river mouths

Understanding of the processes at play when waves interact with deltaic river mouths is still poor, notwithstanding the plethora of river deltas on the world's coasts subject to wave influence. A fair understanding of these mechanisms and of those involved in bedload accumulation at the mouths of deltas and its mobilization by waves and longshore transport is still hampered by the inability of conventional techniques to provide direct reliable measurements (Giosan, 2007; Dodet, 2013). An understanding of such processes is, however,

Fig. 2. Ternary diagram proposed by Galloway (1975) and commonly used in the morphodynamic classification of river deltas on the basis of the relative balance between river, wave, and tide processes, and Google Earth images of the two iconic examples of the strongly 'river-dominated' Mississippi and strongly 'wave-dominated' Senegal deltas. The Mississippi discharges into deep water near the continental shelf edge, following extreme, finger-like progradation of the levee-lined channels, whereas the Atchafalaya, a later branch of the Mississippi, discharges into shallow water. Parts of the delta no longer fed in sediment as a result of channel switching are, nevertheless subject to wave erosion (Roberts, 1997), as in the western sector where barrier islands of sand have formed a lobate shoreline as the delta plain is reworked and the mud dispersed. The Senegal river delta shows strong downdrift mouth deflection behind the Langue de Barbarie spit, but has in fact developed essentially as a bayhead delta behind this barrier spit sourced by 'exogenous' sand from updrift, illustrating efficient back-barrier trapping of fluvial sediment and delta aggradation. According to calculations by Coleman and Huh (2004), the Senegal delta coast gets more wave energy in 3 h than in 365 days in the Mississippi delta.

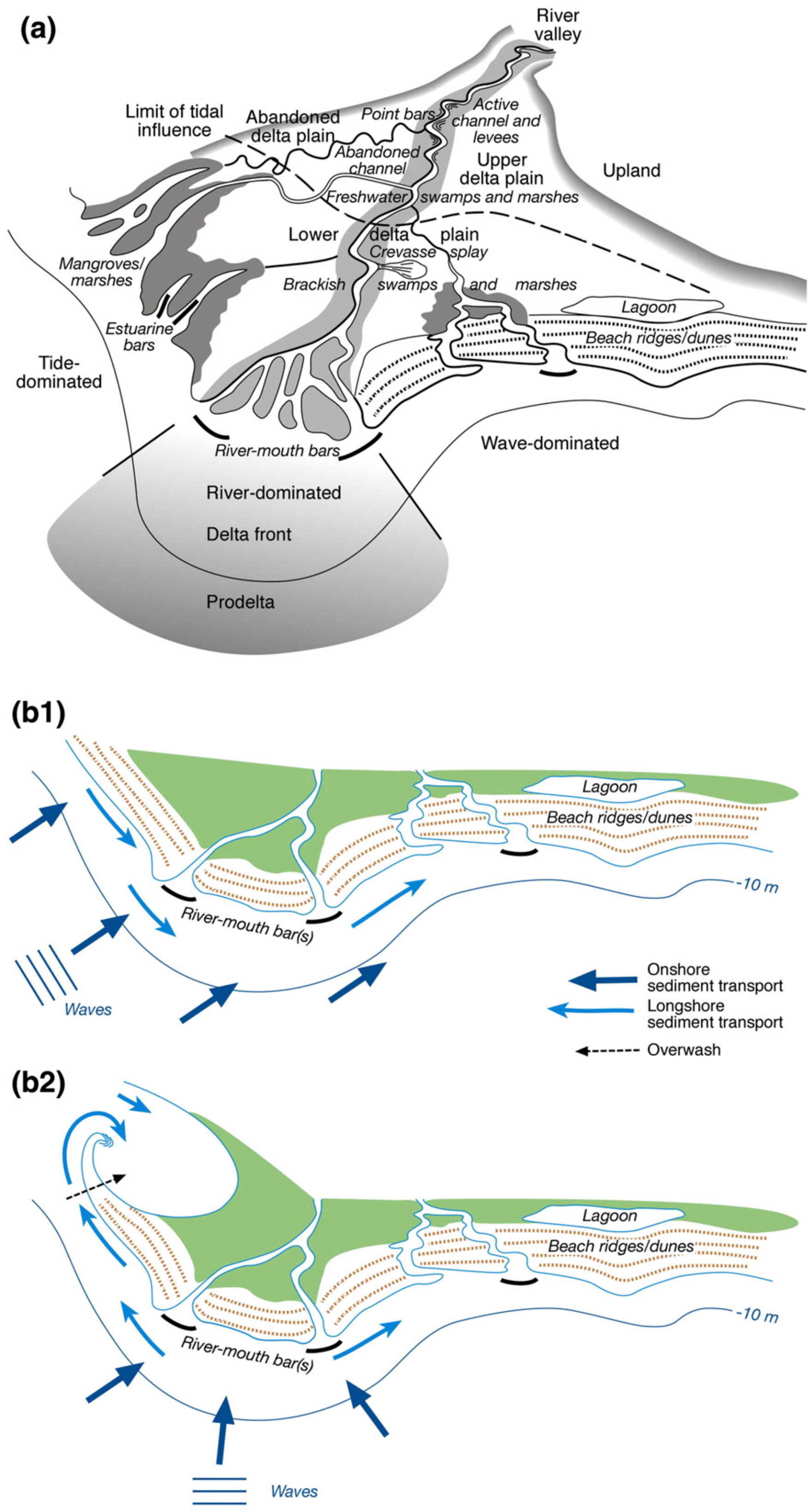


Fig. 4. River delta geomorphic units and schematic shoreline morphology spanning the three domain (river, tides, waves) influences (a), and schematic illustration of processes of wave reworking of bedload of fluvial origin and/or derived from the nearshore shelf (b). In the panel (b1), the regional longshore transport is unidirectional, such that important sediment accumulation on the updrift side (on the left) is assured by 'exogenous' supplies from the nearshore shelf or from the reworking of an abandoned delta lobe or from updrift coastal erosion. Panel (b2) shows a situation of divergent longshore transport from the mouth, the classical situation of river delta supply of bedload to adjoining coasts, although the distal sectors of flaring spits in downdrift embayments may evolve in a context of counter-transport that contributes to bedload sequestering within the confines of the delta. In both situations, the wave-built barriers bounding the delta favour backbarrier inorganic (fluvial sediments) and organic (marsh) sedimentation.

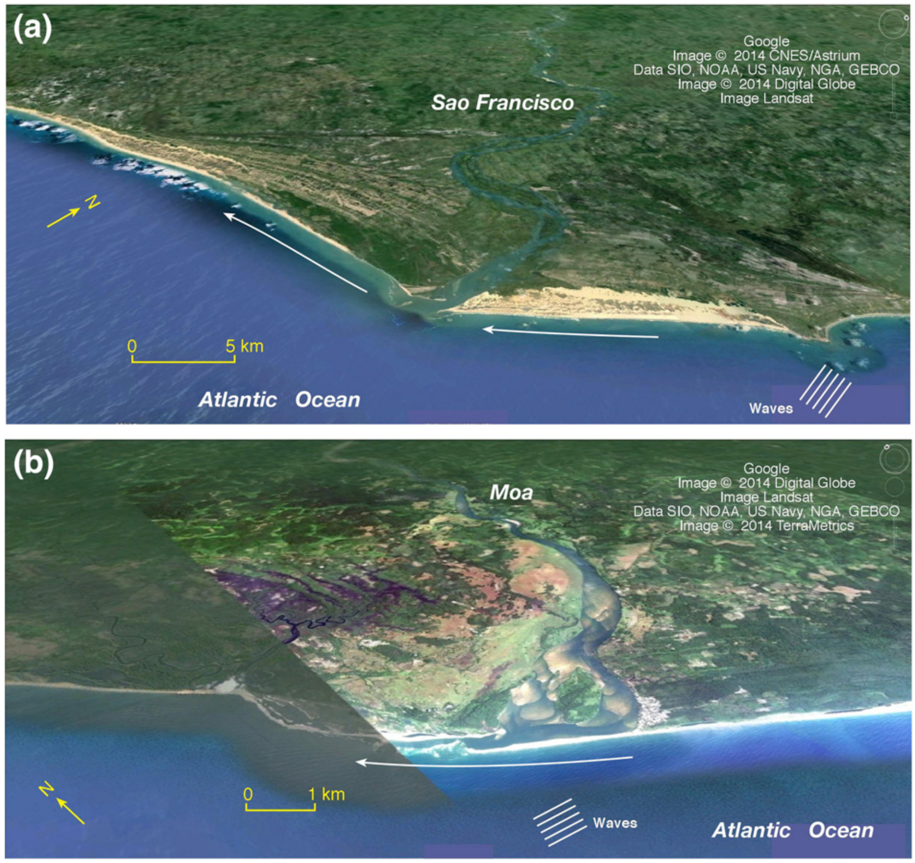


Fig. 5. Two examples of sand-rich deltas in wave-influenced settings characterised by regional unidirectional drift. The updrift flanks of the Sao Francisco delta in Brazil (a) and the Moa delta in West Africa (b) show significant progradation of strand plains with closely spaced beach ridges and, in the case of the former an outer sheet of transgressive dunes, built from exogenous sand from the nearshore shelf, whereas the downdrift flanks comprise deposits of fluvial sand and mud forming beach ridges and inter-ridge depressions in the Sao Francisco and a delta plain in the Moa.

fundamental if we are to better elucidate the pathways of river mouth bedload dynamics in the presence of waves and the long-term development of delta shorelines and of a delta as a whole. The bewildering complexity of the river-mouth environment resides in hydrodynamic interactions involving more or less sediment-charged river plumes, waves, wave-induced currents, wind-induced stress, tides and tidal currents, salinity differences and density currents, bottom friction and bedload transport, commonly under energetic conditions, and morphodynamic feedback among mouth and inner shoreface morphology, bedforms and flow. Leaving aside these complexities and the underlying logistic difficulties, the basic role of the river mouth resides in destabilizing waves and longshore currents, leading to the eventual formation of mouth bars. Fig. 7 proposes a schematic of simplified interactions between river mouth and waves under different potential wave incidence contexts. Ideally, this destabilization engenders just the necessary amount of bedload sequestering fundamental to delta growth, preventing excessive accumulation in the mouth sector that could feedback on upchannel instability and eventually contribute to generating avulsion (Section 7). The interactions between the river and wave action at the mouth may concern both unidirectional and bidirectional longshore transport, the latter characterised by divergence from the mouth (Fig. 4b).

Based on measurements in, and modelling of, tidal inlets, which, unlike river mouths, have been commonly studied for decades, especially from an engineering point of view, river flow is expected, as in the case of strong ebb flow through tidal inlets, to generate energy dissipation through wave blocking and refraction (e.g., Ris and Holthuijsen, 1996; Sabatier et al., 2009; Westhuysen, 2012; Dodet, 2013; Dodet et al., 2013), with attendant disorganization of a wave-driven longshore current caused by the so-called hydraulic groyne effect (Fig. 7). Both wave blocking and longshore current disorganization, a thorough review of which is provided by Dodet (2013), enhance bedload immobilization. The dissipative effect of the river jet on wave energy may be enhanced by viscosity associated with a significant charge in suspended sediment, which is likely to be the case in many deltaic river mouths during events or seasons of strong liquid discharge. Bedload accumulation at the mouth resulting from interactions between river flow and wave blocking should lead to the formation of river-mouth bars, but the mechanisms involved are hard to demonstrate, whether by experimental work or by recent numerical modelling efforts.

The river-mouth bar corresponds to an accumulation of bedload at the mouth of a deltaic channel at a variable distance offshore (Fig. 8). River-mouth bars are important as sources of bedload and as initial forms involved in the construction of wave-built delta shoreline deposits. They have also been shown to be important in mediating distributary channel development and therefore overall river delta evolution (Jerolmack and Swenson, 2007; Edmonds et al., 2009; Jerolmack, 2009). Apart from their fundamental role in redistributing sand and coarser-grained sediments alongshore that contribute to shaping deltas, longshore currents can therefore play an important indirect role in this second aspect by mediating mouth bar development. Following the early synthesis of Wright (1977) and the more recent seminal work of Edmonds and Slingerland (2007), several numerical efforts have been devoted to the genesis and dynamics of river-mouth bars (e.g., Geleynse et al., 2011; Nardin and Fagherazzi, 2012; Leonardi et al., 2013; Nardin et al., 2013; Canestrelli et al., 2014). Edmonds and Slingerland (2007) found from modelling that, in the absence of wave influence, the distance between the river mouth and the mouth bar

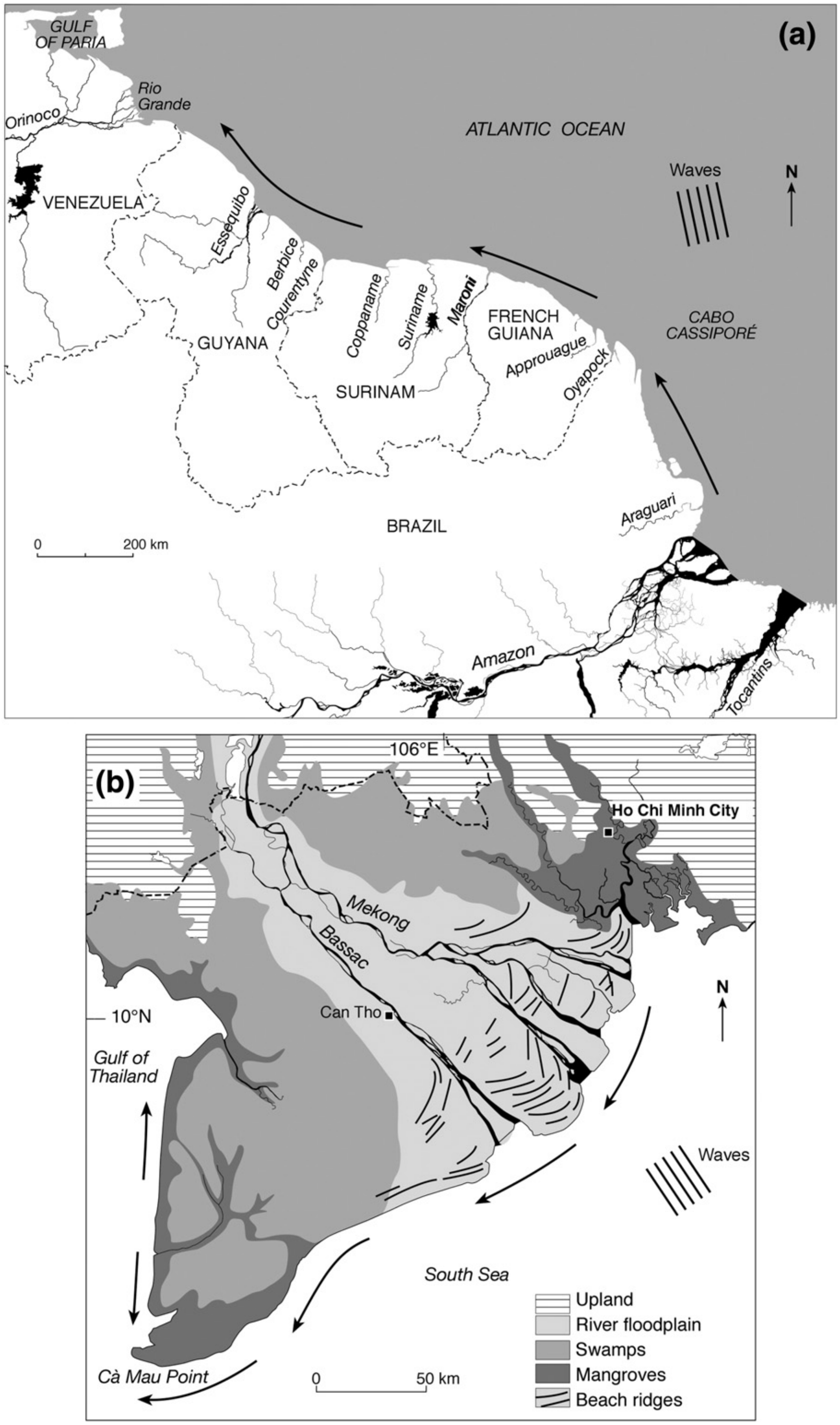


Fig. 6. Two examples of mud-rich deltas in wave-influenced settings characterised by strong regional longshore transport of mud with consequent important downdrift progradation. The Amazon delta (a), the world's largest delta and sourced by the biggest river, shows a morphology typical of strong river and tidal influence. Wave activity is also important and about 15–20% of the nearly 1000 millions of tons of mud supplied annually by the Amazon forms large coastal banks just west of the mouths that migrate towards the Orinoco delta in Venezuela, 1500 km to the northwest under wave-induced longshore transport (Anthony et al., 2014a). The Mekong delta (b) is considered as having the world's third largest delta plain. A high sediment supply and a suitable geological context comprising a relatively wave-sheltered and shallow substrate favoured very rapid growth of the delta over the last 6000 years, which advanced more than 200 km out into the South Sea between 5300 and 3500 years ago at rates of up to 16 m a year, and then at lower average rates of less than 10 m a year as the delta shoreline became increasing exposed to wave influence following this rapid progradation (Ta et al., 2002; Tamura et al., 2012a). Sand transported by the river is essentially sequestered in the northeast sector of multiple river mouths, characterised by individual longshore drift cells between adjacent mouths, materialized by wave-formed beach ridges, whereas wave-induced longshore transport of the much larger muddy load towards the more sheltered western part of the delta has resulted in significant progradation in this direction, inducing the skewed morphology of the delta.

was proportional to the river jet momentum flux and inversely proportional to grain size. The larger the momentum flux and finer the grain size, the larger the distance. Building on this, where waves are significant, the locus of bar formation must be an adjustment between the momentum flux of river discharge, grain size, and wave characteristics such as height, period and incidence angle. The relationships

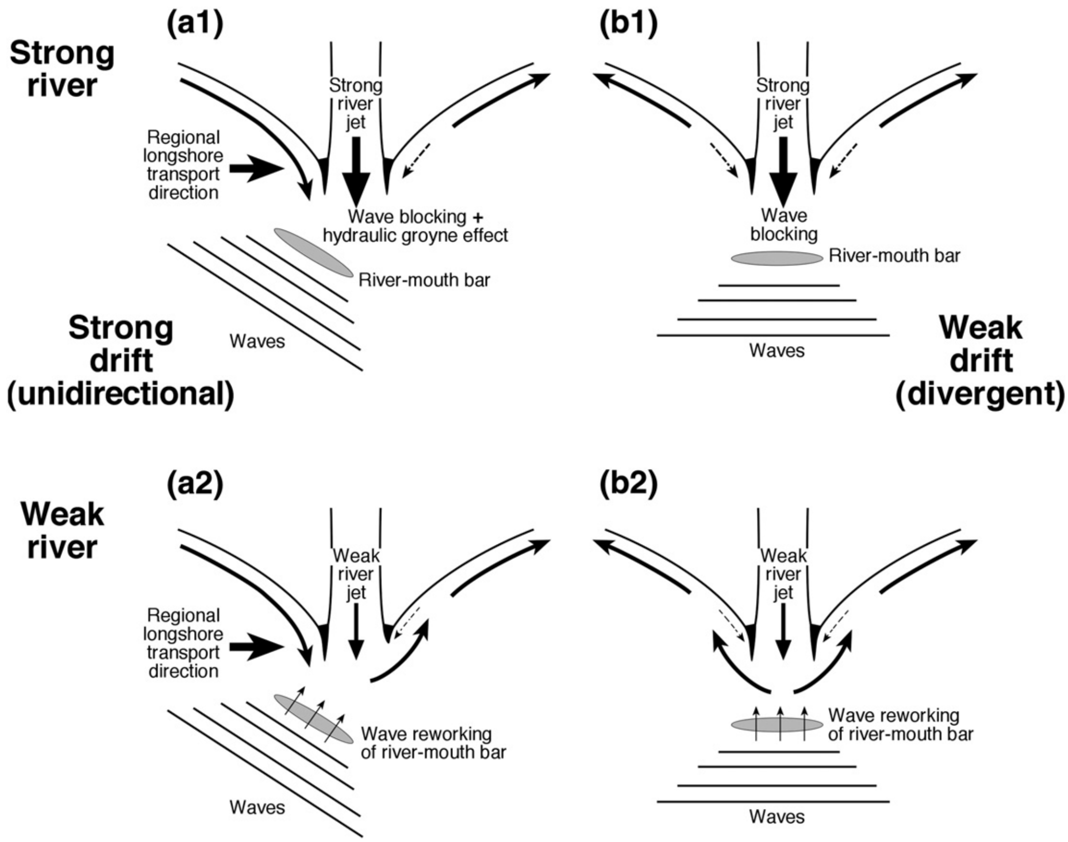


Fig. 7. Schematic illustration of simplified interactions between a deltaic river mouth and waves under conditions of strong (a) and weak (b) longshore drift and strong (1) and weak (2) river influence. Strong river influence is expressed by processes of wave blocking in (a) and (b) and in the hydraulic groyne effect of the river jet on the longshore current in (a), resulting, in both (a) and (b), in the formation of a river-mouth bar, whereas wave reworking and established longshore currents, strong in (a) and weak in (b), prevail under conditions of weak river influence. Counter-drift may locally prevail near the river mouth in all situations as a result of gradients in wave dissipation between the mouth zone and the adjacent coast. River-mouth asymmetry occurs in (a) as a result of the strong unidirectional longshore drift.

between mouth bar formation and growth and wave influence are still not clear, however, and rather poorly quantified, especially as regards the inhibiting role of waves on mouth bar formation found from modelling work. Nardin and Fagherazzi (2012) showed that the presence of waves leads to different bar morphologies depending on the relative importance of wave angle and wave-induced bottom shear stress. They also found from their modelling work that large waves with long periods suppress mouth-bar formation because of deflection of the river mouth jet, in the case of oblique waves, or jet destabilization, in the case of frontal waves. Suppression of bar formation by strong wave action is also supported by modelling work by Geleynse et al. (2011) and by Nardin et al. (2013). The latter authors investigated this relationship on deltas forming in sheltered bays, under conditions of locally generated waves and where both longshore currents and a surf zone are absent. Using a simplified case of a homopycnal river plume subject to frontal wave attack, their models predicted that incoming surface gravity waves increased the spreading of the river jet, and in the presence of waves, mouth bars form up to 35% closer to the river mouth and 40% faster when compared to cases without waves. The distance from the river mouth to the stagnated mouth bar decreased with increasing wave height and wave period. They also found that the timescale of bar formation was inversely proportional to wave height and directly proportional to wave period. They commented on the complexity of wave influence on mouth bar growth, and suggested that the small waves modelled in their study promoted mouth bar formation via increased jet spreading and faster formation time, whereas large waves suppressed mouth bar formation, leading to fewer distributary channels. Jerolmack and Swenson (2007) had shown earlier that wave energy controlled network topology through mouth bar suppression, thus preferentially eliminating small-scale distributaries, as suggested by Syvitski and Saito (2007).

Fluvial supply of bedload to the coast has been shown to be particularly important in the course of strong river flood events, as in the documented cases of the Brazos River (Rodriguez et al., 2000), the Sfantu Gheorghe lobe of the Danube (Bhattacharya and Giosan, 2003; Giosan, 2007; Vespremeanu-Stroe and Preoteasa, in press), and the Grand Rhône lobe of the Rhône delta (Maillet et al., 2006). Under such strong fluvial discharge, complete river domination of the delta channel dynamics may ensue, and estuarine processes that may be involved in the formation of mutually evasive bedload transport pathways within the main delta channel(s) and non-tidal (density) circulation can be suppressed and bedload transported directly to the mouths of the distributary channels to form river-mouth bars. The mouth bar may be linked to the river channel banks through subaqueous levees that act as additional bedload transport conveyors towards the former (Fig. 8). River-mouth bars are commonly sandy to gravelly shallow-water deposits where subject to wave action, which inhibits mud deposition or resuspends mud deposited during preceding phases of lower energy (Geleynse et al., 2011). Bars deficient in mud also occur as a result of rapid muddy sedimentation between the river mouth and the bar, especially when large, rapidly sinking flocs are an important part of the fluvial suspended load, as in the cases of the Po (Fox et al., 2004) and the Red River (van Maren, 2007).

River-mouth bar deposition has been a commonly described feature of many sand-rich deltas in environments where wave action can be significant, such as those of the Paraibo do Sul (Martin et al., 1987), Sao Francisco (Dominguez, 1996), Guadiana (Morales, 1997), Brazos (Rodriguez et al., 2000), Ombrone (Pranzini, 2001), San Juan (Restrepo et al., 2002), Danube (Giosan, 2007; Dolgopolova and Mikhailova, 2008; Dan et al., 2009; Tatui et al., 2011; Vespremeanu-Stroe and Preoteasa, in press), Red (van Maren, 2005), Rhône (Sabatier et al.,

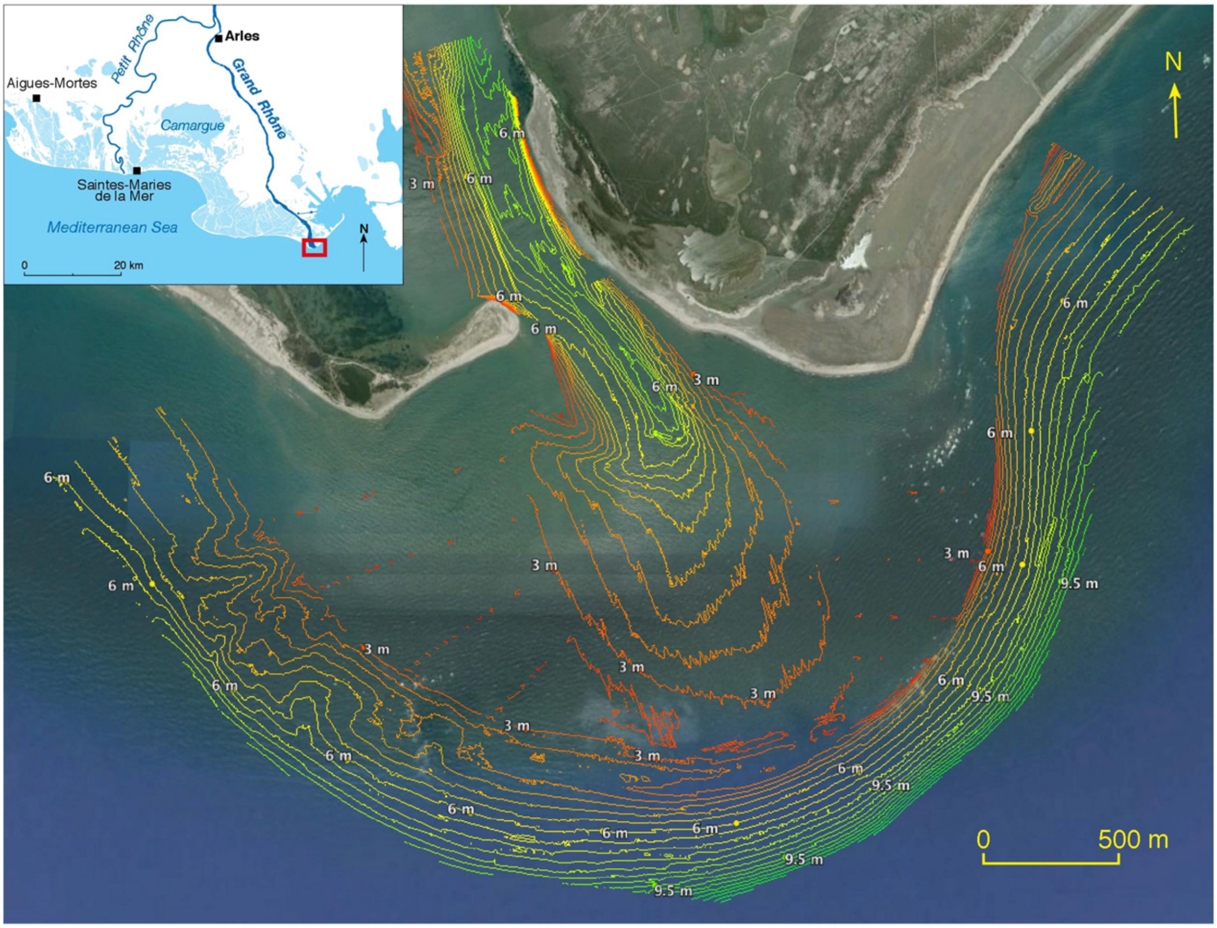


Fig. 8. A combined Lidar and side-scan sonar bathymetric display of the mouth bar of the main Rhône delta distributary, the Grand Rhône. The image shows flanking levees along the river channel linked to the mouth bar (3 m contour) at an offshore distance of about 1 km. The bar is a quasi-permanent feature off the mouth of the Rhône which has been engineered to channel almost all of the river's present discharge.
Courtesy of F. Sabatier.

2009), Seyhan (Evans, 2012), and the Mekong (Tamura et al., 2012b). The abundance of bars facing many river mouths thus clearly suggests that these deposits can develop in settings of strong wave action. River deltas are extremely complex entities, and concerns may be raised about how representative numerical modelling efforts on river-mouth bar interactions with waves are of field-scale real-world deltas. With very few exceptions (e.g., Vassas et al. (2007), Rhône; Traini et al. (2012), Sao Francisco), datasets on river-mouth bar deposits in real-world deltas are lacking. The modelling efforts by Geleynse et al. (2011), Nardin and Fagherazzi (2012) and Nardin et al. (2013) concerning mouth bar formation in wave-influenced settings are based on the DELFT3-SWAN wave model (Booij et al., 1999) to simulate the propagation and dissipation of organized wave energy at the river mouth. Wave heights have been shown to be significantly overestimated in SWAN modelling of strong gradients in opposing, partially blocking currents (Ris and Holthuijsen, 1996; Westhuysen, 2012; Dodet et al., 2013), potentially a source of bias in estimating the impact of waves on mouth bars. Furthermore, modelling may not adequately scale river influence, which must vary significantly between large and small rivers against a background of similar significant wave influence whatever the river flow. Another source of discrepancy between model results suggesting mouth-bar suppression by waves and the commonality of mouth bars on wave-influenced deltas may be the time gap between bar formation and the reworking of bars by waves and longshore currents. Bar formation is likely to be associated with strong river discharge (as indicated above), whereas wave reworking is more likely during periods or seasons of low river discharge. In order to estimate wave-blocking processes and longshore sediment transport in the mouth area of the Rhône affected by the hydraulic flow of the river, Sabatier et al. (2009) used the NMLong-CW model (Numerical Model for simulating Longshore Current–Wave Interaction), a 2D model that calculates wave characteristics (height and direction), longshore currents (velocity) and longshore sediment transport rate in the surf zone with an externally imposed current (Larson and Kraus, 2000). They found that wave height was directly affected by the presence (case 1) or absence (case 2) of river flow, since the breaking waves were significantly lower in case 1 than in case 2, with longshore transport being less active when river flow blocked the waves in the mouth sector.

The long-term morphodynamics of mouth bar contribution to delta growth under conditions of significant wave influence and longshore drift probably require temporal alternatons between strong wave action under conditions of low river flow and significant wave blocking and dissipation by strong river flow. Morphodynamic equilibrium over time between the river mouth (liquid discharge and sediment supply) and wave conditions can determine the timing of event-scale (probably under strong but highly episodic river flow) or seasonal mouth bar formation, the time taken by mouth bars to form and to be reworked, their volume and shape, and the long-term locus of formation and distance from the river mouth. For sand-sized and coarser sediments and keeping wave height constant, the stronger the relative river-mouth jet effect, both in terms of wave blocking and longshore transport disruption, the larger the distance of bar deposits from the mouth is likely to be. Where the regional drift is unidirectional, strong wave energy

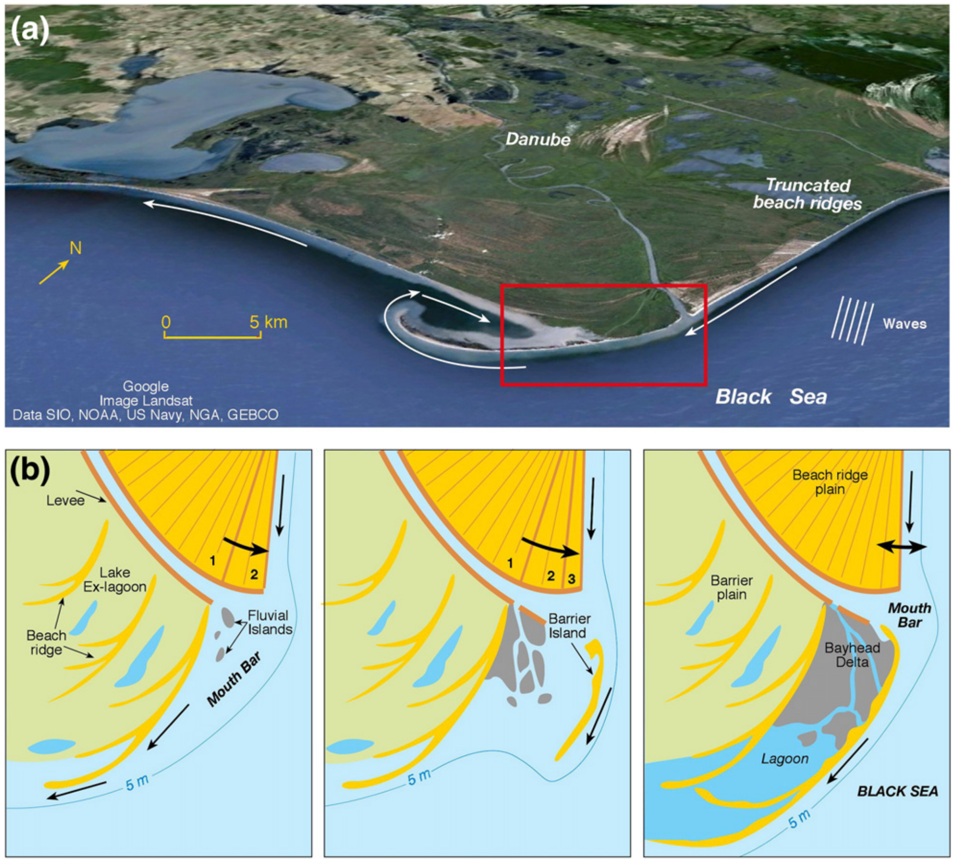


Fig. 9. The Sfantu Gheorghe lobe of the Danube delta. (a) Image showing truncated beach ridges of an earlier lobe updrift that are feeding the delta shoreline in sand further downdrift, and the longshore drift structure associated with the Sacalin spit, the latest barrier spit of the downdrift flank of the lobe; (b) model of formation of the Sacalin barrier spit. From left to right: subaqueous platform growth and subsequent appearance of mouth bar; emergence of a barrier island followed by rapid elongation and shoreward migration; backbarrier infill by fluvial sediments and construction of secondary spits at a downdrift location.
(b) from Vespremeanu-Stroe and Preoteasa, in press

dissipation at the mouth should reinforce transport on the updrift side towards the mouth (Fig. 7a1) because of the resultant alongshore wave energy gradient, but this gradient can also theoretically foster local counter-drift towards the mouth on both flanks where transport divergence occurs at the mouth, thus further enhancing bedload concentration in this zone (Fig. 7b1). Under conditions of weak river influence, active wave reworking of the mouth bar may be expected to simply lead to downdrift bedload transport in the former case (Fig. 7a2), probably involving (sand) bypassing from the updrift to the downdrift flanks across the river mouth, whereas in the latter case, longshore transport redistributes the wave-reworked bar deposits towards the delta flanks, although minor and limited counter-transport in the immediate vicinity of the mouth may still occur on the basis of wave energy gradients involved in bar reworking (Fig. 7b2).

4. Waves and delta shorelines: beach ridges, spits, barrier islands, and cheniers

The morphological shaping of deltas involves processes of construction of shoreline forms that can also play an important subsequent role in promoting delta aggradation (Fig. 4). By acting as barriers, wave-constructed forms along deltas protect back-barrier riverine, generally fine-grained, sediments from wave dispersal thus favouring back-barrier aggradation. Such aggradation is fundamental in maintaining deltaic morphodynamic stability by balancing progradation (Jerolmack, 2009). Delta mouth bedload deposits (especially mouth bars) are the building blocks of most wave-exposed deltaic shorelines. They are generally subject to two modes of development under wave action: (1) they are built up by waves to form longshore barriers that provide shelter for contained fine-grained sedimentation in back-barrier delta plains and lagoons, and (2) serve as sources of, and longshore transport pathways for, sand and coarser-grained deposits that contribute to the development of adjacent beaches and barriers or spits (Rodriguez et al., 2000; Giosan et al., 2005; van Maren, 2005; Dan et al., 2009; Tamura et al., 2012b; Vespremeanu-Stroe and Preoteasa, in press). Whatever the source of the sand or coarser-grained sediment that accumulates in the delta lobe (fluvial, reworking of abandoned delta lobes or of relict inner shelf deposits), the seaward portion of these deposits may be built up by classical wave processes in the surf and swash zones that lead to the accretion of beaches, beach berms, beach ridges and spits, sometimes complemented by aeolian processes (Anthony, 2009).

In some deltas such as the Red (van Maren, 2005) and the Sfantu Gheorghe lobe of the Danube the development stages of which have been well constrained and recently summarised by Dan et al. (2011) and Vespremeanu-Stroe and Preoteasa (in press), distributary-mouth bar deposits evolve into discrete nearshore barriers. The Danube lobe provides a fine and thoroughly documented example of the importance of a river-mouth bar to deltaic barrier development (Fig. 9). The bars aggrade under the influence of waves, and notably swash processes, to finally isolate back-barrier spaces that are eventually filled by mud. Barriers built through the recurrent emergence of bars that channel longshore sediment transport can contribute to the rapid alongshore growth of the subaqueous delta, in the downdrift direction where unidirectional transport prevails (the ‘barrier steering’ effect of Giosan (2007)).

As stated in Section 2, wave influence on deltaic coasts may include the reworking and onshore transport of bedload from the inner shelf (Wright, 1995) that may be, for instance, abandoned deltaic lobes, in addition to bedload transported alongshore from river mouths or from

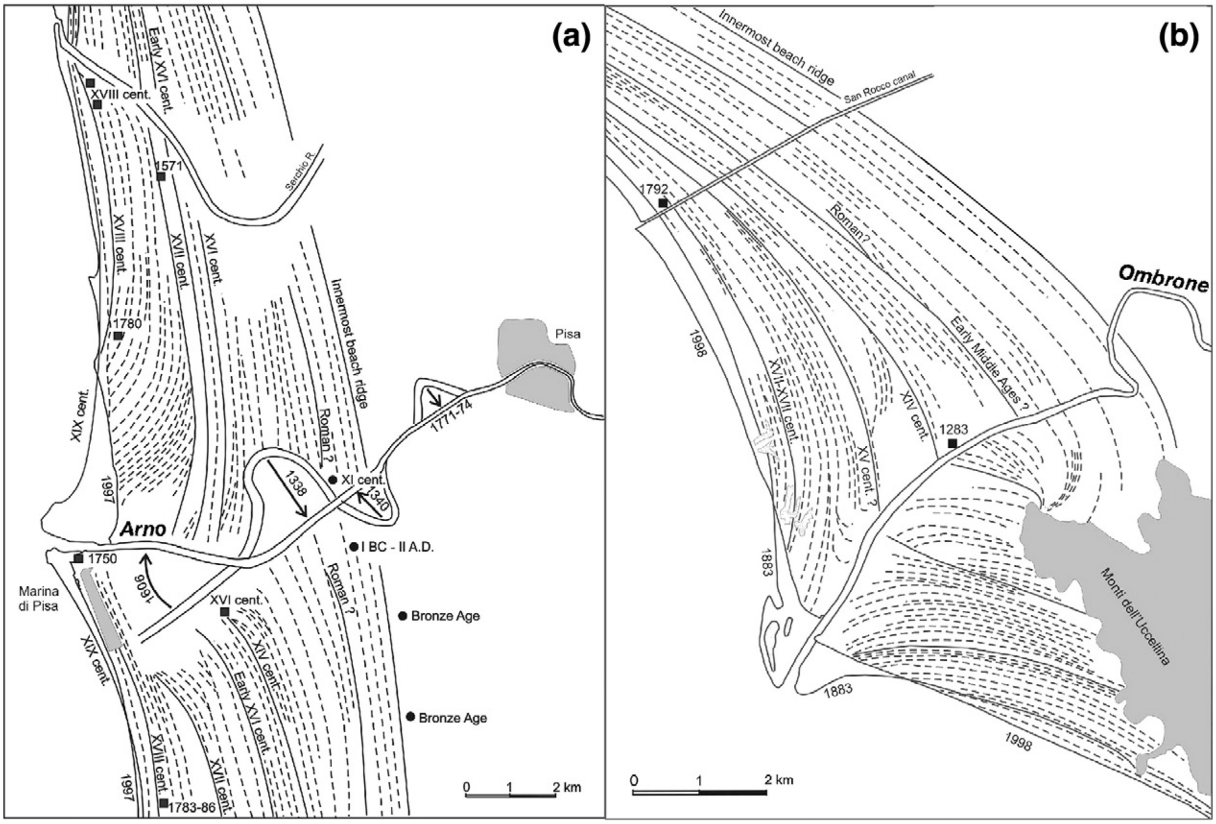
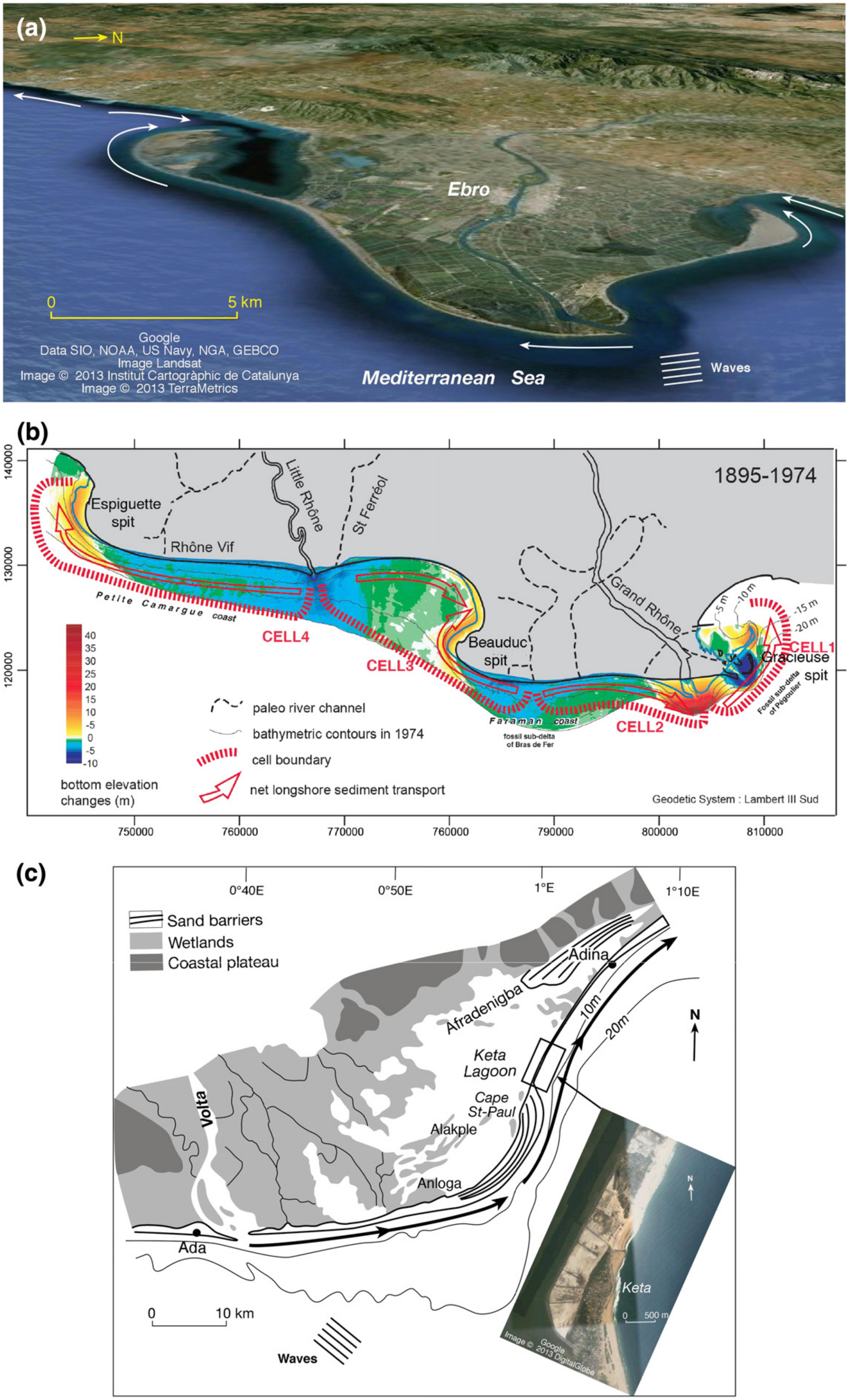


Fig. 10. Beach-ridge patterns displayed by the Arno (a) and Ombrone (b) river deltas, two small, sand-rich deltas in the Mediterranean. From Pranzini, 2007).

eroding coasts. These mechanisms can produce abundant sediment for wave-driven delta progradation. Delta shoreline progradation may commonly occur as successive beach ridges, sometimes capped by dunes where aeolian activity is significant. Deltaic beach-ridge plains are sometimes organized in various sets that commonly reflect abundant sand (and less commonly gravel) supply, but also delta shoreline truncation and reworking, when such a sand supply diminishes or is rerouted in another deltaic channel, as in the Godavari (Nageswara Rao et al., 2012), the Danube (Vespremeanu-Stroe and Preoteasa, in press) and Ombrone and Arno (Pranzini, 2001, 2007) deltas (Figs. 9, 10). Such patterns illustrate the response of wave gradients and longshore currents to changing deltaic shoreline configurations, sediment loads, channel switches, incident wave angles, and possibly deepwater wave directional changes. River deltas with abundant sand supply may, in fact, exhibit delta plains dominated by beach ridges, as in the cases of the Arno and Ombrone (Fig. 10). Delta plains may, therefore, span a wide range of progradational types in terms of beach-ridge sets, from tightly packed sets, to episodic beach ridges and cheniers in more mud-dominated settings, probably most typical of the larger deltas, especially in Asia. Variations in the abundance of beach ridges may also occur over time, as in the cases of the Rhône (Vella et al., 2005), the Mekong (Tamura et al., 2012a), and the Godavari (Nageswara Rao et al., 2012). Beach-ridge patterns have been used by Pranzini (2007) to reconstruct variations in processes of wave reworking and deposition during the growth of the Arno delta.

Spits are extremely common features of wave-influenced deltas. They are, however, very diverse in morphology and genesis. Most small spits, such as the numerous spits of the Moa delta (Fig. 5b) are more or less rapidly changing and ephemeral features subject to strong wave influence. Larger spits reflect various shades of longer-term morphodynamic adjustments between river influence, bedload supply, shoreface gradient, and longshore drift. Infilling lagoons behind perennial spits may commonly sequester alongshore drifting sand or gravel supplied by washover events or through breaches across spits. Fine examples of well-documented spits are provided by the Ebro, the Rhône and Volta deltas (Fig. 11). Sabatier et al. (2009) have suggested a lag between Rhône delta lobe and spit development. Sediments are initially trapped in the lobe off the mouth, leading to a pronounced delta mouth protuberance, and are then reworked by waves to form spits when the mouth location shifts and the lobe is abandoned. This is in agreement with the modelling observations by Nienhuis et al. (2013), according to which well formed, spatially extensive recurved spits

Fig. 11. Three examples of river deltas characterised by prominent spits: (a) divergent drift associated with spits growing from the mouth of the Ebro follows a pattern of progradation wherein delta growth has occurred to face the dominant wave direction. The two flanking spits end in embayments characterised by counter-transport as a result of high wave angles, a process that contributes to sand sequestering within the confines of the delta; (b) the three major spits and multicellular drift structure of the Rhône delta shoreline: La Gracieuse spit (western, downdrift end of cell 4), Beaduc spit (western, downdrift end of cell 3) and Espiguette spit (eastern, downdrift end of cell 1). Modified after Sabatier and Suanez (2003) and Sabatier and Anthony (in press). Drift cells 2, 3 and 4 are sourced by the reworking of two abandoned delta lobes, but Espiguette spit, a relatively rectilinear feature, appears to be mainly sourced by sand reworked from the mouth bar that forms a permanent feature off the engineered mouth of the Rhône (Fig. 8) and transported eastward by longshore currents. The abandoned protuberant lobe sources of both La Gracieuse and Beauduc spits, associated with former strongly protruding river mouths, have set the template for spit plan-shape morphology characterised by recurves towards embayments that act as sand traps through wave refraction and counter-transport; (c) morphology of the Volta River delta and shoreface, showing the prograded river-mouth spit between Anloga and Keta. The spit shows massive distal progradation in a swash-aligned sand-sequestering context that initiated a wave of important erosion of the narrower sand barrier linking the Volta delta to the Adina barrier system. Spit progradation has diminished considerably in response to a decreasing fluvial sand supply, but, correlatively, the welding of the distal tip of the spit in the 1990s to the narrow Keta barrier (Google image inset) has led to a reduction in erosion of the latter barrier, the southern part of which has been further consolidated by engineering works. Remnants of highly degraded beach ridges belonging to the pre-spit delta shoreline occur at Alakple, within Keta Lagoon.


(a)
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Mediterranean Sea
Waves
(b)
1895-1974
Espiguette spit
Rhône Vif
Little Rhône
St Ferréol
Grand Rhône
Petite Camargue coast
CELL4
CELL3
CELL2
CELL1
Beauduc spit
Gracieuse spit
Faraman coast
fossil sub-delta of Bras de Fer
Fossil sub-delta of Pégoulier
-5 m
-10 m
-15 m
-20 m
paleo river channel
bathymetric contours in 1974
cell boundary
net longshore sediment transport
bottom elevation changes (m)
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Sand barriers
Wetlands
Coastal plateau
Adina
Afradenigba
Keta Lagoon
Cape St-Paul
Alakple
Anloga
Volta
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10m
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0
10 km
Waves
Keta
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500 m
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Image © 2013 DigitalGlobe

(which they considered as generally diagnostic of wave reworking of sediment promontories) likely arise from abrupt lobe abandonment after a previous stage of intense progradation.

It is not clear why spits, rather than strandplains with more or less closely spaced beach ridges form on the flanks of: (1) some delta distributary mouths or (2) abandoned lobes. In the case of still active distributary mouths, this is likely to be a sediment supply criterion, with successive mouth-flanking strand-plain deltas sourced by significant sand or gravel supply, as suggested earlier, and mouth-flanking infilling embayment systems bound by large spits associated with deltas with a lesser sediment supply. Flanking spits are also likely associated with either entrenched single-mouthed (or non-bifurcating mouths) delta systems characterised by periodic extreme liquid and solid discharges rather than regular but lower discharges over time, or with avulsions that generate a new mouth that captures much of the discharge, resulting in a strong fluvial jet, the effect of which is maximal during extreme discharge spates. The Ebro delta spits (Fig. 11a) are probably a reflection of the former case, the development of this delta having been particularly accelerated by major but pulsed sediment supply during the Little Ice Age (LIA) (Guillén and Palanques, 1997). The latter case is probably illustrated by the western flank of the present Sinu delta lobe, created following avulsion between 1938 and 1945 (Suarez, 2004). Apart from a possible bedload supply criterion, many large lobate spits bounding wide lagoons subject to infill probably express the influence of a strongly protruding river-mouth or pronounced abandoned lobe on longshore drift and consequently on the net plan-view shape of deltas. In the case of active distributary mouths, the proximal zone of these flanking spit shorelines is commonly adjacent to the river mouth, the strong protrusion of which, relative to the re-entrant shoreline, results in distal spit sectors that end in downdrift embayments that may act as salient traps, in the sense of Davies (1980).

The second case corresponds to the spit type recognised by Sabatier et al. (2009) and Nienhuis et al. (2013) which occurs downdrift of protruding abandoned delta lobes. The inception and development of the Rhône spits (Fig. 11b) have been controlled by morphodynamic adjustments between avulsion and mouth dynamics, the reworking of prominent lobes following abandonment, and longshore currents generated by waves from the south and southeast (Sabatier and Suanez, 2003; Sabatier et al., 2006; Sabatier and Anthony, in press). Waves refract over the shoreface formed by abandoned lobes, resulting in four drift cells that are bracketed by counter-transport at the margins of the delta, thus resulting in net sequestering of sand (Fig. 11b) to the detriment of adjacent shorelines which may erode, as in the case of the western, low-lying narrow barrier coast of the Gulf of Lions west of the Rhône delta. The central part of the delta corresponding to the pronounced abandoned lobe of the Bras de Fer branch has, thus, served, and still does, as a central sediment source.

Spit plan shape can be very variable, ranging from rectilinear to concave or convex, or combinations thereof, with active or inactive distal elongation, and variable alongshore progradation rates. This variability probably hinges on delicate balances among wave approach angles, sediment supply, alongshore wave transport gradients, shoreface gradients, and overall delta shoreline orientation. Where wave angles at the mouth are low, as in the case of the Ebro delta (Fig. 11a), divergent longshore transport from the mouth sand source zone results in two flanking spits. High wave angles and unidirectional regional longshore transport at the pronounced river-mouth protrusion shoreline commonly lead to a single downdrift spit as in the cases of the Sacalin barrier spit of the Sfantu Gheorghe lobe, and the Damietta lobe of the Nile. In many cases, because of the initially pronounced mouth or lobe bulge, spits recurve in response to increasingly higher wave angles towards the embayed downdrift shorelines where their extension may be suppressed by counter-transport, thus contributing to sand sequestering within the system (Fig. 11). Spit growth may be characterised by seaward progradation in lieu of elongation as in the case of the Volta delta spit (Fig. 11c), but very often there is a continuous interaction between cross-shore and longshore sediment transport (Dan et al., 2011). Overwash can also be manifest where no progradation occurs and where accretion of low-lying sectors has not been enhanced by aeolian dune growth. In both cases of progradation or overwash, bedload is kept within the confines of the delta, in addition to the counter-transport effect in the downdrift embayment.

Although in being a skewed delta the Volta differs from the other spit-flanked examples mentioned in this section, it provides yet another shade of spit development associated with deltaic sand sequestering in a context of strong longshore transport (Fig. 11c). The inception of this distinct spit in lieu of a former distally shore-attached beach-ridge barrier-lagoon system (Anthony and Blivi, 1999), remnants of which subsist in the infilling lagoon between Alakple and Anloga (Fig. 11c), is tentatively interpreted as the result of a change in river-mouth position (Anthony, in press). The amount of sand captured annually through spit accretion has been estimated, for the period 1968 to 1996, at about 750,000 m^3 a year (Anthony and Blivi, 1999). Accretion of the Volta spit occurs through adjunction of successive beach ridges, rather than through spit elongation. This net progradation in the area of Cape St. Paul has forced further wave refraction, amplifying cell segmentation, and resulting in the instauration of a swash alignment associated with further sequestering of sand by the spit. Longshore transport requirements downdrift of the spit have been satisfied by substantial barrier retreat and shoreface erosion in the Keta area (Fig. 11c). The situation may have been aggravated in recent years following the construction of the Akosombo Dam in the 1960s. A recent feature of this spit growth is that the formerly highly eroded proximal zone of the transport acceleration zone, or drift ‘pulse’ in the area of Keta (inset in Fig. 11c), is now being protected by this spit. Anthony and Blivi (1999) considered that this probably heralded a shift towards a less swash-aligned distal spit zone, and predicted eastward ‘leakage’ of some of the Volta sand, rather than quasi-total sequestering, thus alleviating erosion further downdrift. Recent satellite images indeed show that the distal tip of the spit has now welded to the shoreline, thus resulting in the reconversion of spit to attached barrier, a process probably consolidated by engineering works in this sector (Fig. 11c).

Where parts of a delta plain become abandoned, by channel switching, for instance, enhanced wave reworking can result in destruction as the delta shoreline in such areas becomes deprived of fresh sediment. Erosion and marine flooding of the delta plain are two common outcomes of abandonment, resulting in coastline retreat, as sediment is dispersed alongshore or offshore (Anthony, 2014). In deltas with a large amount of fine-grained sediment, muddy progradation may be punctuated by coarser-grained cheniers, as in the Huanghe (Yellow River) (Saito et al., 2000), and Amazon deltas (Anthony et al., 2014a), or even by beach-ridge formation as in the Kuakata Peninsula of the huge, tide-dominated Ganges–Brahmaputra delta (Allison et al., 2003). In contexts of delta retreat, surface winnowing of the mud commonly results in a thin sand cover derived from eroded channels and river-mouth bars that may then be built up into barrier deposits by waves. These may form isolated cheniers or a series of retreating barrier islands, such as the Chandeleur Islands east of the present Mississippi, behind which fine sediment may temporarily accumulate to be subsequently reworked as the barriers migrate landward. The barrier islands may end up being submerged to form shoals such as Ship Shoal in the Mississippi delta (Stone et al., 2004). Abandoned delta lobes on the shoreface can also generate changing patterns of wave refraction and directional approach to the shore that can affect delta shoreline patterns.

5. Waves and the plan shape of river deltas

The plan shape of river deltas is determined by long-term morphodynamic adjustments involving balances and feedbacks that lead to self-organized delta growth. The foregoing sections have shown that waves can play a fundamental role in these processes. These go well beyond those simply related to shaping of the shoreline,

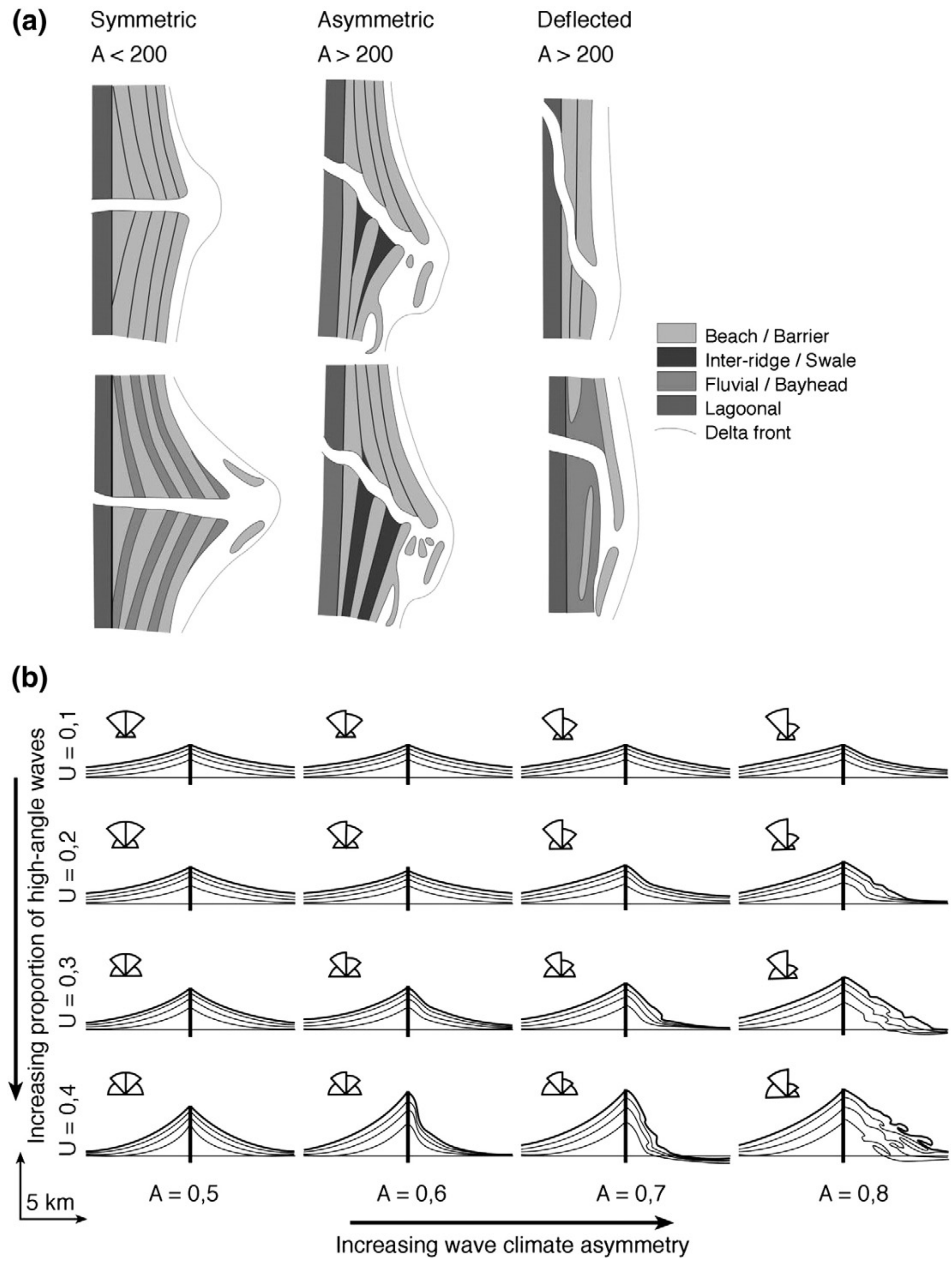

Fig. 12. Delta plan-form shoreline asymmetry based on longshore drift and river discharge (a) and on the influence of high-angle waves (b). The asymmetry index, *A*, is defined as the ratio of the net longshore transport rate at the mouth (in m^3/yr) to river discharge (in 10^6 m^3/month). From Bhattacharya and Giosan (2003), modified by Giosan (2007). The plan-view time series of simulated delta shorelines in the vicinity of a wave-dominated river mouth for different wave angles is shown with insets of area-normalized wave energy rose-type plots. The simulation is based on shorelines plotted at intervals of 65.4 model years, with a final shoreline at 327 model years. From Ashton and Giosan (2011). (a) with permission from Wiley; (b) with permission from the American Geophysical Union.

as discussed later in Section 7. This section proposes a closer scrutiny of the relationship between delta plan shoreline shape and waves. Bhattacharya and Giosan (2003) examined this relationship in terms of an asymmetry index, *A*, defined as the ratio of the net longshore transport rate at the mouth (in m^3/yr) to river liquid discharge (in 10^6 m^3/month), that attempts to express the importance of longshore drift relative to fluvial processes in determining delta plan shape. The model, which integrates delta facies, is based on several modern examples. Deltas with an *A* index below 200 are characterised by symmetry associated with little or no deflection of the river mouth resulting from longshore drift, whereas deltas with a higher index are asymmetric with their river mouths being more or less deflected by longshore drift, maximal deflection resulting in the most nearly rectilinear shoreline (Fig. 12a). From numerical modelling, Ashton and Giosan (2011) concluded that the angles from which waves approach a delta have a first-order influence on its plan-view morphologic imprint and sedimentary architecture (Fig. 12b). These authors have suggested that the directional spread of incoming waves plays a dominant role over fluvial sediment discharge in controlling the width of an active delta lobe, which in turn affects the characteristic rates of delta progradation. This results in the asymmetrical form about their river channel commonly displayed by many deltas. This plan-form asymmetry can include the development of discrete breaks in shoreline orientation and the formation of self-organized features resulting from shoreline instability along the downdrift delta flank, such as spits and migrating shoreline sand waves. The authors noted that somewhat surprisingly, waves approaching preferentially from one direction tend to increase sediment deposition updrift of the river. They termed this a 'morphodynamic groyne' effect and showed that it occurs when the delta's plan-form aspect ratio (ratio of cross-shore to alongshore delta length measured at the delta apex) is sufficiently large such that the orientation of the shoreline on the downdrift flank is rotated past the angle of maximum alongshore sediment transport (~45°), resulting in preferential redirection of fluvial sediment updrift towards the river mouth.

The utility of the *A* index (Bhattacharya and Giosan, 2003) is hampered for several reasons. Large deltas such as the Nile, Mekong, Niger, Goadavari and Po commonly exhibit large delta fan width, such that delta dynamics are conditioned more by the interplay of aggradation, progradation and channel switching, modulated by subsidence and relative sea-level, rather than by eventual skewing of the delta mouths by wave processes. All of these processes are modulated by river sediment supply, which is not considered in this index. Marriner et al. (2012a, 2013) have highlighted, for instance, the complexity of the millennial-scale evolution of the Nile delta under the constraints of human activities and climate pacing of sediment supply. Waves may, however, play a determining role in shaping delta lobes through the building of wave-formed deposits and redistribution of sediment via longshore drift cells between distributary mouths as well as in river-mouth bar and channel morphodynamics (Section 3 and processes such as avulsion (Section 7)). Multi-mouth deltas are discussed in the next section. The transition is abrupt between symmetric ($A < 200$) and asymmetric delta ($A > 200$). It is also not clear whether the *A* index is robust enough to withstand the test of numerous deltas. Longshore transport data along the Sao Francisco delta coast (Bittencourt et al. (2005) cast against the liquid discharge of this river (Bittencourt et al., 2007) yield, for instance, an *A* index of only 48 for this delta, considered as asymmetric by Bhattacharya and Giosan (2003). For many deltas, basic data on waves and liquid discharge from which an *A* index can be determined are also simply not available, without even considering the unreliability of current paradigms of measurement of longshore drift volumes (Cooper and Pilkey, 2004). Although net regional drift may be unidirectional for much of the year on many coasts (note that reversals generated by regional changes in wave climate are frequent and can be multi-annual, most clearly manifested by beach rotation, Anthony, 2009), transport directions in the vicinity of deltas may become bi-directional and divergent as long-term delta growth and protrusion progressively affect wave incidence (e.g., Pranzini, 2001). Determining the drift pattern on some cuspate or lobate deltas can, therefore, be tricky. Long-term wave climate data incorporating wave incidence at the delta shoreface are indispensable for determining net longshore transport directions. In default of such data, these directions are sometimes determined from beach-ridge patterns on delta flanks, and this can be misleading. A fine example is given by some of the river deltas in Brazil. Martin et al. (1985, 1987) and Dominguez (1996) argued from sand grain shape and grain 'maturity' characteristics that the strand plains on the updrift flanks of the Doce, Jequitinhonha, Paraibo do Sul and Sao Francisco deltas were constructed from sand derived from the nearshore shelf within an unidirectional longshore transport system, whereas sediment supplied by the rivers served in downdrift delta flank construction. More recently, Dominguez (2004) mapped the Doce and Jequitinhonha deltas with divergent longshore transport from the mouth, thus suggesting that the updrift flanks of these deltas may also be supplied by sand from these rivers. Murillo et al. (2009) have similarly suggested from geophysical and sedimentary analyses of shoreface sediments off the Paraibo do Sul that this deltaic system is characterised by bi-directional, divergent transport sourced by fluvial sand dispersed offshore. By adopting an approach based on delta morphometry and wave climate, the model of Ashton and Giosan (2011) presents an interesting contribution to the analysis of delta morphological variability, but it ignores the important aspect of fluvial sediment supply and tends to downplay the capacity of the river mouth in organizing sediment fluxes as shown in Section 3.

Based on the foregoing review and analysis, Fig. 13 proposes schematic large-scale delta plan-shape configurations hinged on the relationship between river influence and longshore drift for single-mouth deltas or individual delta lobes. Although the process interactions at the mouth (Fig. 6) embedded in the continuum shown in this figure are the same for deltas having multiple active distributary mouths (Section 6) and evolving in wave-influenced settings, their propensity to develop a multiple sediment cell system tends to limit them to the left-hand side of the diagram. The same also largely applies to deltas with divergent transport at the mouth that have, through morphodynamic adjustments over time, developed facing the dominant waves. The trajectory shown in this figure presupposes that river influence is more susceptible to lasting fluctuations than wave climate (see also Section 8) and this has important implications for future scenarii of delta sustainability. Deltas that are morphometrically relatively symmetrical and subject to bi-directional drift, such as the Ebro (Jimenez et al., 1997), the Ombrone and the Arno (Aminti and Pranzini, 1990; Pranzini, 2001), and the main Pila lobe of the Po (Simeoni and Corbau, 2009) constitute, theoretically, the ideal cases of river delta sediment supply to adjacent shorelines (Fig. 4b2), although sand supply from the nearshore zone can also supplement fluvial supply as has been suggested for the Ebro (Jimenez et al., 1997). Divergence leads to redistribution of mouth deposits on both flanks of the delta. Other examples of this potential relationship between longshore drift and the delta mouth are the Rosetta lobe of the Nile (El Banna and Frihy, 2009), the Shkumbini in Albania (Ciavola et al., 1999), the Tiber and Volturno in Italy (Pranzini (2001). Pranzini (2001) has suggested that the trend towards delta symmetry is a product of delta growth despite an initial dominant regional transport direction. The terminal courses of the rivers forming the Arno and Ombrone deltas face the dominant waves, a configuration induced by rapid delta progradation as a consequence of increased river sediment input due to widespread catchment deforestation in Tuscany from the Early Middle Ages to the eighteenth century (Pranzini, 2001). The rivers maintained their directions as a result of higher accretion rates on the less exposed downdrift sides of the deltas. On the more exposed updrift sides, delta growth caused the shoreline to gradually rotate so that it directly faced the waves approaching the coast (Fig. 14). Here, due to lower refraction, wave energy per unit of shoreline increased whilst the shoreline accretion rate decreased. This rotation of the shoreline induced longshore inversion on the updrift side, whereas present-day erosion of the cuspate mouth under an increasingly deficient sediment supply is restoring the original transport direction.

Interestingly, all of the aforementioned deltas are, with the exception of the Rosetta lobe, on the northern Mediterranean seaboard, and have developed under a particular set of conditions that include (Anthony et al., 2014b): (1) pulses of large sediment supply mediated by human activities over the last two thousand years and by LIA changes from the sixteenth to the nineteenth centuries that favoured rapid delta formation and changes in delta morphodynamics, (2) a commonly single parent channel through which this sediment is routed, (3) relatively fetch-limited conditions and a large directional apportionment of the wave energy, potentially limiting wave removal of fluvial sediment, but with one dominant wave window, (4) high winter river discharges that also coincide with the most energetic waves, potentially favouring the rapid growth of cuspate-type deltas facing the energetic wave window and subject to divergent transport from the mouth.

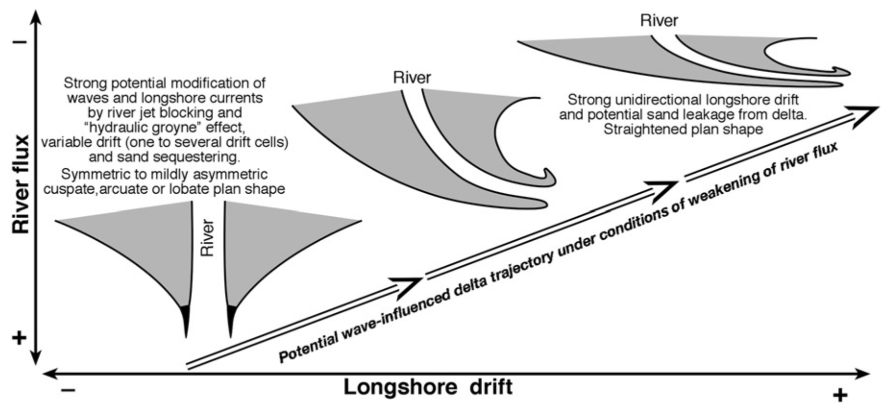

Fig. 13. Schematic continuum of delta morphology ranging from symmetric to strongly longshore deflected, as a function of river influence relative to longshore drift. Deltas with multiple active mouths are likely to occupy the left side of the diagram. A potential net long-term trajectory of delta evolution is also proposed as river influence becomes weakened by a variety of natural (changes in catchment climate and vegetation linked to the LIA, for instance, avulsion) and human-induced changes (catchment land-use and reforestation, catchment engineering, dams). For symmetric deltas on the left side of the diagram subject to divergent drift, the trajectory may dominantly involve simple recession through redistribution of delta lobe sediments towards the flanks, leading eventually to delta shoreline straightening.

Regional unidirectional drift is probably the most common drift configuration on the world's coasts. For delta symmetry to prevail, strong river flow needs to act as an efficient hydraulic groyne on bedload transport, an effect that presupposes that abundant sand-sized or coarser-grained sediment is supplied from one (the updrift) end by wave-induced longshore transport, and intercepted by the fluvial jet exiting through the river mouth. The stronger the groyne effect and larger the sediment supplied alongshore from updrift the larger the deltaic growth likely to result from this interception, except where through-transport occurs when river discharge is low. With time, an increasingly prominent delta lobe growing relatively perpendicularly to the general coastal trend would tend to reduce the net sediment transport towards the mouth as the waves assume a more normal approach direction (Bhattacharya and Giosan, 2003; Ashton and Giosan, 2011). This type of delta configuration is probably rare. Possible examples of such deltas are the Sao Francisco in Brazil and the Moa in West Africa (Fig. 5). Sand deposited on the updrift flank of the Sao Franciso as strand plains (or transgressive sand dunes as seen in Fig. 5a) could be derived from nearshore sources as Dominguez (1996) has suggested. The Gulf of Guinea coast of West Africa with its well-defined swell wave regime from a narrow south to southwest window is particularly rich in such strand plains built from fluvial sand reworked from the inner nearshore zone and redistributed by longshore transport (Anthony, 1995).

More commonly, under conditions of regional unidirectional transport, mutual adjustments between the river flow and wave approach angle can result in variably skewed river mouths and delta lobes (asymmetric deltas) that highlight a more or less strong influence of longshore drift relative to river influence (Fig. 13). The sediment transported along the flank updrift of the mouth may be derived from erosion of deltaic strand-plain deposits as in the case of the Sfantu Gheorghe lobe (Fig. 9b) of the Danube (Giosan, 2007; Vespremeanu-Stroe and Preoteasa, in press), or from abandoned delta lobes, as in the Rhône (Fig. 11b) (Sabatier and Suanez, 2003; Sabatier et al., 2006; Sabatier and Anthony, in press). Connected sediment cells along deltaic coasts subject to strong longshore transport are likely where several active or abandoned lobes coexist. Apart from the Danube and the Rhône, the Nile delta with its active (Rosetta and Damietta) and abandoned (Burullus) lobes provides fine examples of such connected cells (El Banna and Frihy, 2009). A fine example of a skewed river delta is that of the Volta, the lobe of which has been diverted eastwards over a distance of about 30 km by sustained longshore transport generated by constant southwesterly swell waves from the Atlantic (Fig. 11c). Other examples are the Mahanadi in India and the Magdalena on the Carribean coast of Colombia.

Deflected deltas are associated with strong sustained unidirectional longshore transport. The Senegal delta is often cited as the archetype of

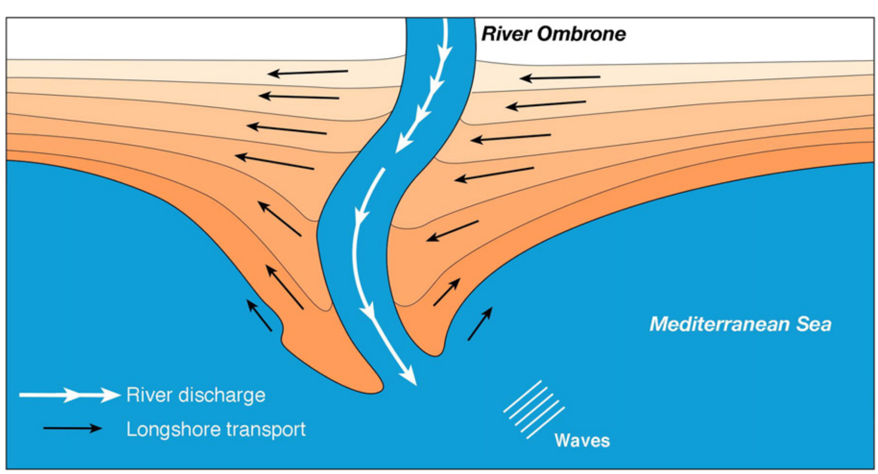

Fig. 14. Schematic illustration showing the shift from regional unidirectional longshore drift, in the early phases of formation of some deltas, to divergent drift from the mouth, based on the example of the Ombrone river delta in the Mediterranean, but several other deltas in the Mediterranean appeared to have developed in the same way. This growth mode has involved gradual rotation of the updrift flank in a way as to generate the drift divergence from the mouth.
Modified after Pranzini (2001).

this configuration (Fig. 2). This delta, terminus of a large catchment of about 400,000 km^2, developed, however, as Bhattacharya and Giosan (2003) noted, essentially as an infilling bayhead delta behind the protection of elongate spits constructed by strong longshore drift (Michel, 1980). Gac et al. (1982) conducted a historical analysis of the mobility of the Langue de Barbarie, the current spit barring the Senegal, and of the corresponding locations of breaches across the spit, and showed that the farthest downdrift river outlet position, which corresponded to the maximal distal spit extension, did not exceed 30 km. A drift volume that decreases from north to south along the spit from 0.70 to 0.60×10^6 m^3 has been calculated by SOGREAH (1994), the gradient attributed to progressively more significant aeolian dune abstraction of sand between the relatively urbanised sector of the historical city of St. Louis, where dunes have been fixed by vegetation, notably plantations of Filao (*Casuarina equisetifolia*), and the relatively poorly vegetated distal zone. Mild opposite transport towards the north occurs during the short summer period when waves from the southwest dominate. Further elongation of the spit beyond 30 km was no doubt constrained by the decreased sand availability due to the transport gradient and seasonal counter-transport, and by outlet discharge maintained by drainage of an aggraded lower delta plain as a result of efficient trapping of fluvial sediment behind the spit (Anthony, in press). This last effect reflects morphodynamic feedback between the wave-formed spit and delta aggradation. A consequence of such aggradation is an increasing propensity for fluvial flooding of settlements such as Saint Louis.

Bayhead deltas with still infilling lagoons behind beach-ridge barriers are a common feature of the West African coast (Fig. 15a). Several examples of deltas that considerably prograded in protected bedrock embayments, under conditions of human-induced strong sediment supply, to become increasingly shaped by waves, have also been described from the Mediterranean. These include the Büyük Menderes (Brückner et al., 2002), the Acheloos (Vött et al., 2007) and the Argens (Bony et al., 2011). The Vistula delta in Poland is a similar prograding delta (Koszka-Maron, 2009) with a mild cuspate protrusion flanked by wave-straightened shorelines in a large embayment. In some cases of wave influence involving very strong unidirectional longshore transport, delta development can indeed be stalted, as fluvial bedload is integrally transported downdrift of the river mouth. There are numerous examples of straightened river mouths on the world's coast exhibiting no characteristic delta bulge, a fine example being that of the Mono River in Benin, West Africa (Fig. 15b). Despite almost complete infill of its lower valley, the mouth of the Mono, which supplies about 100,000 m^3/yr of sand to the Bight of Benin coast, cannot prograde to form a deltaic lobe or bulge because the sand is swept alongshore to the east by very strong wave-induced longshore drift (Laïbi et al., 2014). Some of the 'river-dominated' estuaries described by Cooper (2001) from the strongly wave-influenced South African coast also probably belong to this category.

Although spits, discussed in the previous section, can be robust long-term features of river deltas that reflect various shades of the influence

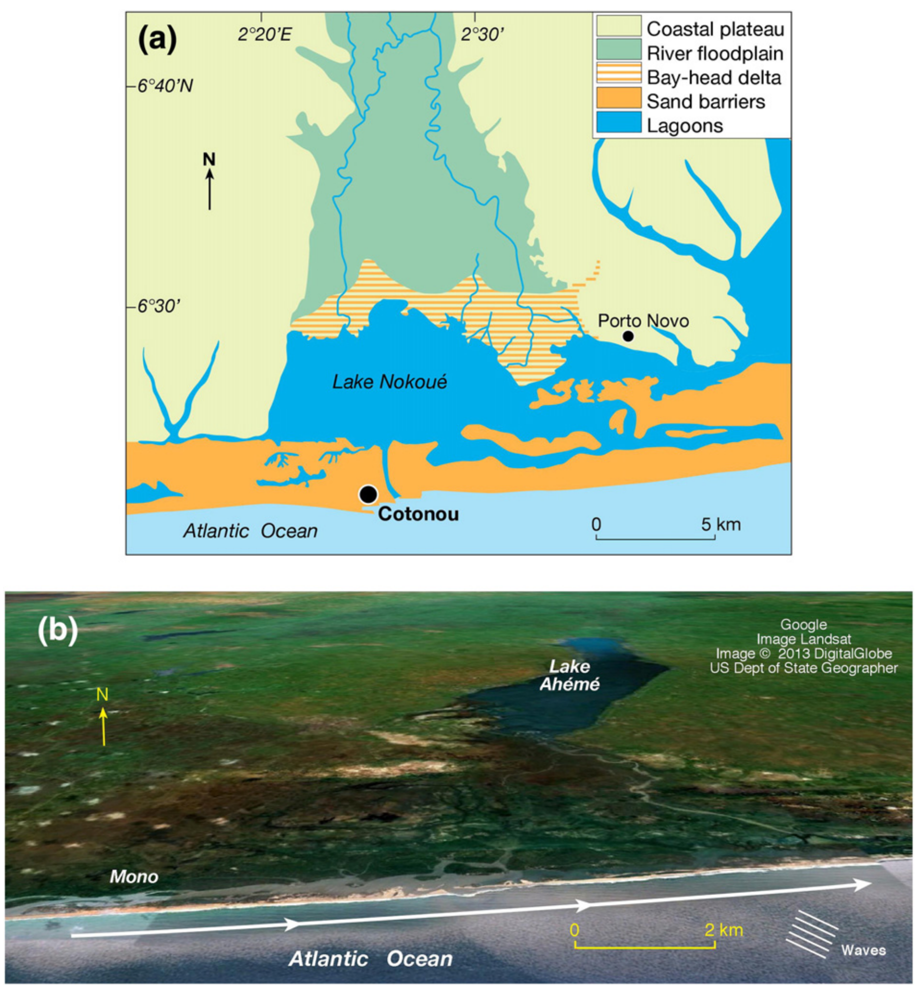

Fig. 15. Strong longshore drift and the bayhead delta of the Ouémé river (a), and stalted Mono river delta (b), both in Benin, West Africa. The bayhead delta of the Ouémé, which drains a relatively important catchment of nearly 50,000 km^2, continues to prograde in the lagoonal shelter of a beach-ridge barrier several kilometres wide that has enclosed Lake Nokoué. This part of the West African coast is characterised by strong unidirectional (eastward) longshore transport that prevents the strongly deflected Mono delta, located about 70 km updrift of the Ouémé, from forming a distinct shoreline bulge.

of strong longshore drift, a distinction needs to be made between these forms and delta-mouth deflection, which may or may not be present, depending on the strength of the river mouth. Although flanked by two large spits, the mouth of the Grand Rhône shows hardly any deflection (Fig. 11b). This channel 'entrenchment' has been enhanced by engineering aimed at ensuring that almost all of the river's present discharge is conveyed by this channel.

6. Waves and deltas with multiple active distributary mouths

There are several deltas in settings with significant wave influence that are characterised by several active distributary mouths. These reflect large-scale long-term apportionment of river liquid and solid discharge. These multiple active mouths, commonly characteristic of large deltas, multiply the river-mouth effect on waves and longshore transport. Pronounced longshore variability in wave-induced sediment transport may ensue, resulting in multiple drift cells that assure the retention of sediments within the confines of these deltas. Even though a predominant direction of longshore transport may prevail, the morphodynamic feedback effects between river (supplemented by tides) and wave influence involved in generating a multiple cell system contribute to the sequestering of sand and coarser-grained sediments, which may be then accommodated by successive beach-ridge progradation, obviating eventual problems of river-mouth instability that may be generated by excessive bedload accumulation at the mouth (Section 7). The Mekong (Fig. 6b) and the Niger deltas (Fig. 16) illustrate these effects. Other examples are the San Juan, Sinu, Mira and Patìa river deltas in South America (Restrepo and Lopez, 2008), and the Zambezi in East Africa. The beach ridge sets of the Mekong delta are strictly limited to the multiple river-mouths sector, thus suggesting a strong propensity for sand sequestering along the 250 km-long mouths sector of the 650 km-long delta shoreline (Fig. 6b). Beach-ridge progradation shows, however, an asymmetric pattern caused by the southwestward longshore sediment transport generated by the winter monsoon waves (Tamura et al., 2012b), which are dominant in terms of energy, although the five or so active river mouths themselves are not skewed. River-mouth bars play an important role in the formation and dynamics of these mouths (Tamura et al., 2012b), as shown earlier in Section 3, but field observations suggest that there is no systematic through-transport of sand across the mouths which are characterised by high river discharge during the summer monsoon when wave energy is low and longshore transport is towards the northeast, but by low river discharge and significant tidal pumping during the high wave-energy season (Wolanski et al., 1996), during which the salt intrusion may transport bedload upchannel. These mouths are therefore separated by prograding

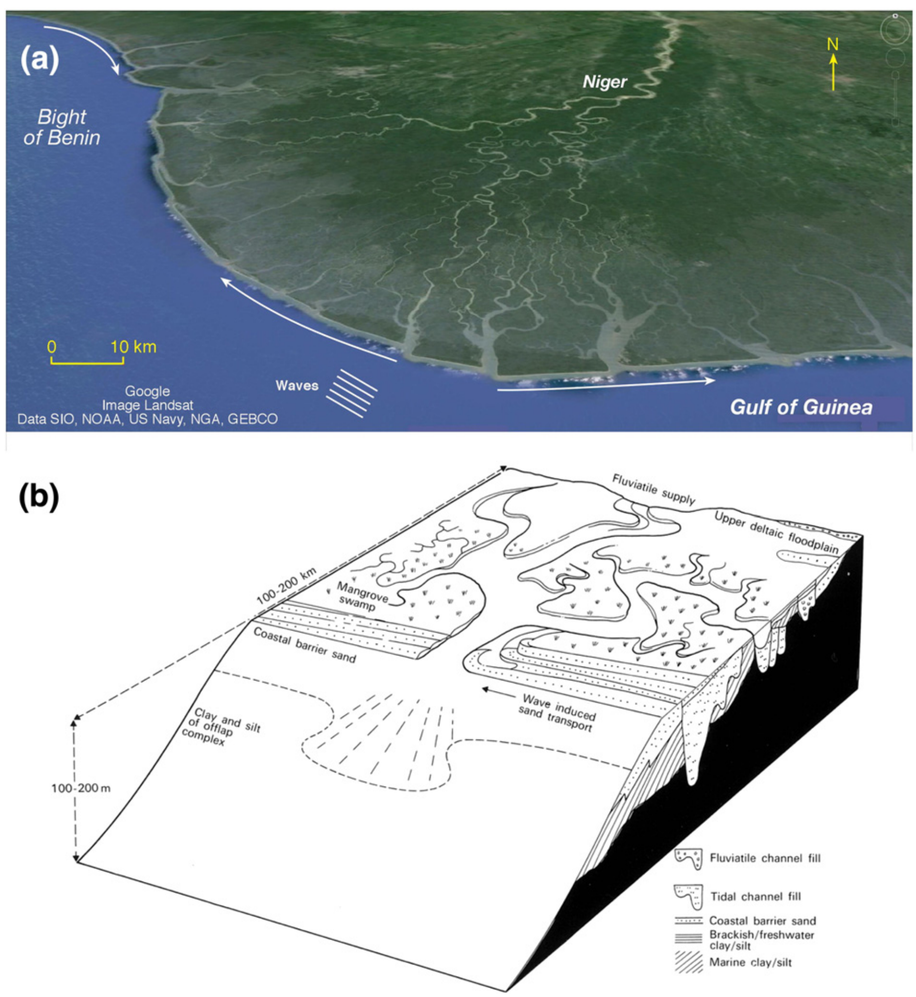

Fig. 16. The Niger delta lobe (a) and flanking beach-ridge and distributary mouth system (b). The delta shows a wave-modelled lobate shoreline and comprises about 11 active distributary mouths that channel both river discharge and tidal flow across a dissected prograding sand barrier system associated with a multiple, sand-sequestering drift cell structure under conditions of regional bi-directional divergent longshore transport. Sand is further supplied to the western margin of the delta shoreline by regional eastward transport from the Bight of Benin. 'Inlet migration' attributed to longshore drift by Oomkens (1974) in his model of the delta-plain barrier system (b) does not, in fact, prevail. The potential for the strong longshore transport to generate downdrift distributary mouth migration is limited by combined river and tidal flux (mesotidal tidal range) through the distributary mouths (possible wave-blocking and hydraulic groyne effects). Choking of the river mouths by sand and eventual consequent channel switching or avulsion are prevented by the incorporation of this bedload into the prograding beach-ridge barriers. (b) modified after Oomkens (1974), with permission from Wiley.

sandy shorelines characterised by discrete longshore sediment cells. Accretion of beaches dominantly occurs at the southwest approaches to the mouths through mouth-bar reworking and is a precursor to beach-ridge formation, but pronounced wave refraction occurs locally at the northwest approaches to these mouths, resulting in a characteristic arcuate beach-ridge pattern between these mouths that further contributes to the strong cell structure.

The Niger delta exhibits a relatively smooth lobate plan shape (Fig. 16), and covers a large area of 19,135 km^2 (Coleman and Huh, 2004). The lobate shape of the delta reflects alongshore wave energy gradients, with a major divergence in longshore transport, at the centre of the delta shoreline, to the northwest and the east (Allen, 1965). The delta comprises about eleven active river mouths as well as a high distributary density averaging 0.48 km of stream length per 500 km^2 (Coleman and Huh (2004), one of the highest of the 40 deltas inventoried by these authors. Oomkens (1974) drew a parallel between these beach-ridge barriers and the distributary mouths with barrier-island and inlet systems that suggests downdrift mouth migration under strong longshore transport (Fig. 16). A scrutiny of present satellite imagery and aerial photographs published by Allen (1965) and Usoro (1985), and the more recent work by Kuenzer et al. (2014) suggest, however, that this migration mode is not valid. Deflection of the river mouths downdrift by longshore currents is very limited (Fig. 16). The multiplicity of these mouths and the individual hydraulic groyne effect each exerts tend to favour the development of individual sand barriers with beach-ridge sets with mild downdrift spit recurves associated with limited updrift erosion of barriers on the other downdrift side of each mouth (Allen, 1965; Usoro, 1985; Kuenzer et al., 2014). These barriers act as depocentres for fluvial sand as well as sand probably derived from the nearshore shelf, especially in the western confines of the delta away from the main delta bulge which also constitutes a sink zone for sand transported by the strong longshore transport prevailing on the Bight of Benin coast (Anthony, in press). Progradation of the barriers is recorded by the numerous beach-ridge sets, but wave reworking of these sets is also manifest (Allen, 1965), possibly reflecting pulses of lower sand availability relative to the wave regime. Coleman and Huh (2004) noted that the subaerial delta is nearly eight times larger than the subaqueous delta, and attributed this to the relatively high nearshore wave action and the presence of the strong longshore currents. The abundance of sand supplied from the widespread outcrops of sandstone and granite of the Niger river catchment may also explain the large size of the subaerial delta. In essence, barrier progradation, limited to the seaward fringes of the delta (there are no older barriers visible within the delta-plain) has considerably favoured back-barrier aggradation which involves the extensive development of tidal flats and freshwater marshes.

Unlike the relative stability in location evinced by the multiple mouths of the Mekong and the Niger deltas, the San Juan delta in Colombia is characterised by marked variability in the delta shoreline (Restrepo et al., 2002) within an overall frame of sand sequestering. The rapid changes in delta shoreline morphology reflect the effects of a singular combination of extreme regional climatic, tectonic, and oceanographic conditions and the absence of human-induced impact in the San Juan drainage basin (Restrepo et al., 2002). In contrast, the Mangoky river delta, further discussed in Section 7, shows similar rapid shoreline changes but these appear to have been generated by the impact of land-use changes on sediment supply.

7. Waves and the instability of delta distributary channels: implications for overall delta development

Mouth-bar deposition at the shoreline is a process that can lead to the creation of new distributary channels through bifurcations (Edmonds et al., 2009; Jerolmack, 2009). This process has been reported from the Mekong by Tamura et al. (2012b). These authors showed that the delta plain propagated laterally during the late Holocene, evolving from bars that resulted in asymmetric river-mouth bifurcations, the asymmetry caused by the net southwestward longshore sediment transport. Bars were successively formed on the wider side of the bifurcated river mouths, and subsequently accreted seaward, forming beach ridge barriers that fostered the development of shore-perpendicular elongate delta plains.

Jerolmack and Swenson (2007) derived scaling relationships for mouth-bar deposition at the shoreline and subsequent channel bifurcation, and for avulsion. They showed that mouth-bar distributary lengths scale with the width of the parent channel, whereas avulsive distributary lengths scale with the backwater length, intermediate channel lengths being relatively rare. The backwater length is the length of the channel from the mouth to an upstream extent that is affected by both river discharge and water surface elevation at the river mouth. The water surface elevation at the river mouth can be affected, in turn, by tidal variation, storm surges, sea level and river plume dynamics. Large floods push the upstream boundary of backwater towards the shoreline, and this affects patterns of sediment convergence that control erosion and deposition (Lamb et al., 2012). By suppressing mouth-bar development, wave processes at the mouth control the network topology, preferentially eliminating smaller-scale distributaries (Jerolmack and Swenson, 2007).

The role of waves in the suppression of river-mouth bar development can be closely tied to longshore transport since the latter provides a mechanism for evacuation of bedload from river mouths (mouth bars) that may become choked, thus affecting both the width of the parent channel and backwater length. Where bedload is sequestered between multiple river mouths, choking of the river mouths is obviated by progradation assured by successive beach ridges (Mekong, Niger) and/or by aeolian dunes where wind action is important (Nile delta). Where bedload accumulation becomes not only too large to be evacuated by longshore transport but also engenders significant local wave energy losses, this can induce a positive feedback effect that leads to increasing sediment concentration in the mouth and subsequently up the channel. Such feedback is likely to end in avulsion, as the channel becomes sediment-choked (Edmonds et al., 2009; Jerolmack, 2009). Past patterns of lobe development, followed by avulsion and new distributary formation in the Rhône river delta, have been shown to have been controlled by episodes, during the LIA, of strong sediment-charged river floods that brought down large amounts of bedload to the river mouth that could not be eliminated by longshore transport (Provansal et al., 2015). Pulses of delta lobe switching caused by similar LIA fluctuations in discharge have also been reported for the Po delta (Correggiari et al., 2005; Simeoni and Corbau, 2009). Fig. 17 shows a modern example of a delta with similar changes in a wave-influenced setting associated with an extremely high solid-discharge river. Affected by catchment land-use changes involving vegetation stripping, the Mangoky river delta in Madagascar shows several avulsion channels and has been reported as being characterised since 1951, on the basis of cartographic and satellite imagery, by unstable channels dominated by switching and a general southward shift of the mouths under conditions of a high supply of sediment dominated by fine sand (Rakotomavo and Fromard, 2010), notwithstanding regional northward longshore transport.

In an interesting effort at probing delta shoreline evolution involving relationships between waves and river mouths, Ashton et al. (2013) used a plan-view shoreline evolution model combining wave-driven alongshore sediment transport and fluvial influence based on addition of sediment along the coastline. Their simulations revealed that sediment discharge variability can have a significant effect on delta morphology if fluvial delivery of sediment temporarily exceeds the capacity for alongshore sediment transport to remove sediment from regions proximal to the river mouth. They also showed that in a delta system with multiple active distributary channels, changes to the coastline affect the apportionment of discharge flowing out of coeval distributaries through a two-way feedback. According to their model

Fig. 17. The Mangoky river delta in Madagascar. The Mangoky drains a sand-rich semi-arid catchment subject to sporadic sediment-laden high liquid discharges that have contributed to avulsions and southward distributary migrations since 1951. The updrift flank of the delta is probably further sourced by exogenous sand that contributes to excess mouth accumulation and delta distributary instability. The delta displays numerous spits oriented with the regional longshore transport system to the north but counter-transport locally prevails with smaller spits oriented southward in response to wave diffraction.

simulations, wherever distributary length affects sediment discharge, the dynamics of one distributary can control the sediment discharge of another. In such wave-influenced deltas exhibiting strong channel feedbacks, delta lobes may prograde faster where such feedback exists than those without feedback. This can, in turn, have a feedback effect on sediment redistribution by longshore transport.

8. Waves and delta morphological trajectories under decreasing river loads, subsidence, and rising sea level

The question of the vulnerability of deltas resulting from various human activities, from sinking, and in the face of sea-level rise associated with climate change has been abundantly addressed in the literature (e.g., Ericson et al., 2006; Syvitski et al., 2009; Evans, 2012; Foufoula-Georgiou, 2013; Anthony, 2014; Ibáñez et al., 2014). There is a plethora of human activities that affect river catchments down to the deltas themselves, thus impacting on the capacity of the latter to maintain morphosedimentary equilibrium. Chief among these human interventions are flow regulation by dams and sediment entrapment by reservoirs, resulting in strong reductions in both river liquid and solid discharges (Syvitski et al., 2005; Milliman and Farnsworth, 2011) that are crucial to the morphodynamics of deltas in wave-influenced settings. Dams are, however, relatively recent in the history of deltas, unlike other human alterations of landscapes that have been ongoing since the advent and expansion of agriculture and catchment engineering. Many deltas have been formed or have grown considerably in the wake of human interventions that liberated large amounts of sediments in the catchments, especially in Europe, with many iconic examples in the Mediterranean (Anthony et al., 2014b) such as the Ebro, Ombrone, Po, Rhône and Tiber (Guillén and Palanques, 1997; Pranzini, 2001; Correggiari et al., 2005; Sabatier et al., 2009; Simeoni and Corbau, 2009; Bellotti et al., 2011; Maselli and Trincardi, 2013; Provansal et al., in pressa). By reducing river liquid discharge, sediment supply and the potential for river-mouth bar formation and accretion of the delta lobe, human activities favour the sinking of deltas (Syvitski et al., 2009), and invariably also enhance the potential influence of waves in washover processes and in dispersing deltaic sand and fine-grained sediment. Many of the world's deltas in wave-influenced settings have been affected by reductions in liquid and solid discharges, including most of the deltas shown in Fig. 3. It is perhaps interesting to recall here the old classification proposed by Fisher et al. (1969) which insisted on the destructive role of waves in delta dynamics by distinguishing between 'highly constructional' river deltas in settings of strong fluvial influence and weak wave and current activity, and 'highly destructional' deltas which occur where wave reworking removes a significant part of the fluvial load.

The reworking of abandoned delta lobes by waves has been evoked in preceding sections. Apart from such cases of wholesale lobe abandonment and ensuing reworking, two potential directions of delta morphological change associated with wave reworking following the weakening of river influence may be invoked. Symmetric deltas facing the dominant waves may retreat whilst keeping their plan shape, although over time positive feedback effects may lead to a dominant transport direction. This type of situation is typical of the eroding Rosetta lobe of the Nile (Hereher, 2011) and the Ombrone (Pranzini, 2001). Variations in longshore sediment transport rate associated with the retreat of the Ombrone delta (Figs. 9b, 13) have been numerically modelled by Aminti and Pranzini (1990). They showed an almost symmetrical sediment distribution in 1883, with a drift divergence involving approximately 200,000 m^3/yr of sand moving in opposite directions on either side of the delta. Results for 1977 yielded 150,000 m^3/yr of sand moving northward of the river mouth and only 65,000 m^3/yr southward.

The other direction may be represented by the continuum shown in Fig. 13, from symmetric deltas to skewed or asymmetric and finally deflected or straightened deltas as net river strength decreases over the long term whereas the wave climate is likely to become more energetic in response to climate change and greater storminess. These situations are illustrated by two examples. Bittencourt et al. (2007) have documented significant erosion of the downdrift flank of the Sao Francisco delta (Fig. 5a) sourced by fluvial sand following reductions in river discharge and sediment loads that have resulted from several dams, especially after 1994. They predicted chronic shoreline erosion downdrift of the mouth and a progressive deflection of the mouth in the downdrift direction. This should lead to a progressively more skewed or asymmetric delta bulge increasingly sourced by updrift sand supply by the regional longshore transport with the concomitant decrease in fluvial sand supply. Prior to dam construction, the sediment supply of the Moulouya River in the semi-arid setting of western Morocco was significant enough to have led to the progradation of a small asymmetric delta of about 30 km^2 skewed eastwards by longshore drift (Snoussi et al., 2002). Since the construction of a major dam on the river, the fluvial sediment input has been reduced by 93%, leading to the straightening of the shoreline and narrowing of the mouth (Snoussi et al., 2002). This situation has resulted in the gradual destruction of the small Moulouya delta, with the reworked delta sediments evacuated eastwards by longshore drift.

These shoreline changes may be recorded in delta plan shape through truncated beach-ridge patterns, as in the Danube (Fig. 9b), and Ombrone and Arno deltas (Fig. 10). In deltas where narrow barriers or spits impound lagoons, these changes may involve transgressive barrier or spit migration implying extensive overwash and/or chenier formation over muddy back-barrier substrates. Barrier overwash is a common manifestation of delta erosion in wave-influenced settings, such as in the cases of the Krishna and Godavari (Nageswara Rao et al., 2010) and the Patìa deltas (Restrepo and Kettner, 2012).

Although delta stratigraphic and morphodynamic scenarii would basically predict delta shoreline retreat where sediment supply is insufficient to fill the accommodation space created by sea-level rise, Ibáñez et al. (2014) have argued that 'river-dominated' deltas, especially common in microtidal settings such as the Mediterranean (where most deltas are, in fact, strongly wave-influenced) and the Gulf of Mexico, can cope with sea-level rise (SLR) through three self-reinforcing mechanisms as the SLR rates increase, and argued that these mechanisms would tend to enhance the efficiency of the deltaic sedimentary trap. These are: (a) an increase in the frequency of delta lobe switching with accelerated SLR leading to the formation of new lobes in shallow areas; (b) an increase in the frequency and magnitude of flood events in the delta plain as a consequence of increased crevassing through the river natural levees, leading to enhanced sediment deposition; and (c) an increase in the frequency and magnitude of overwash events in the delta fringe enhancing the ability of sandy (or gravelly) beaches to adapt to SLR. Barrier overwash can thus also be important in the storage of sand and gravel in delta systems, especially when aggradation needs to balance sea-level rise (Ibáñez et al. 2014) and sinking. Ibáñez et al. (2014) further suggested that vertical aggradation (what they referred to as "rising grounds") more so than "rising dikes", or a combination of both, may be needed in many cases, such rising grounds being achieved through rational forms of sediment husbandry, such as in the Ebro delta, where the natural fluvial sediment supply has been drastically reduced by human activities.

In the case of the first two mechanisms, processes acting at the mouth and involving wave-mouth bar interactions and longshore drift, as well as the influence of the marine environment on backwater dynamics, can be influential, as shown in the previous sections. Given the significant morphodynamic feedback loops that characterize deltas, changing sea level will affect the balance between aggradation and progradation as well as the processes involved in delta distributary channel development, as Jerolmack (2009) has shown in his conceptual model of channel adjustments to sea-level rise. Under steady sea-level rise, increasing delta size and water depth lead to a reduced rate of progradation, whereas aggradation driven by this sea-level rise becomes important. Channel aggradation can result in avulsions and in the creation of new channels, whereas older channels are reworked by waves (Jerolmack, 2009). Such aggradation may be enhanced by greater salt-wedge intrusion into river mouths following weaker river discharges, as in the case of the highly human-altered Ebro (Guillén and Palanques, 1992). Ultimately, channel switches, of primary importance in delta development, may be an efficient mechanism of bedload sequestering within wave-influenced deltaic systems under conditions of sea-level rise. The creation of new lobes and wave reworking of abandoned lobes under such circumstances may be expected to generate marked gradients in longshore drift along delta shorelines that may also contribute to net overall sand sequestering, as suggested by the reworking of the abandoned lobes of the Rhône (Fig. 11b).

The foregoing considerations require, however, that the ongoing rise in sea level is more or less matched by fluvial sediment supply or by managed sediment husbandry. Although many deltas are products in part or in whole of human transformations of river catchments, the switch towards significant reductions in fluvial sediment supply reaching the coast today (Milliman and Farnsworth, 2011) may mean that this balance is not likely to be achieved, thus probably heralding an important swing towards the demise of many of the world's deltas. Using a process-based shoreline evolution model, Nienhuis et al. (2013) proposed four characteristic modes of wave reworking of abandoned delta shorelines involving longshore transport following the elimination of fluvial input. These range from diffusional smoothing of the delta (or delta lobe), under conditions of low to normal wave incidence, to the development of recurved spits and final delta shoreline smoothing under conditions of a dominant oblique wave approach liable to generate asymmetry (Fig. 18). Mode 1 of abandoned lobe reworking corresponds to the evolution direction mentioned above (quasi-symmetric delta retreat but possibly evolving to asymmetric with time, as in the case of the Ombrone), whereas the other three can probably be encompassed by the direction of change in the continuum in Fig. 13 associated with asymmetry. Nienhuis et al. (2013) found that the two characteristics of the delta at abandonment that best predict post-abandonment evolution are the plan-view aspect ratio and the shoreline range over which longshore transport is diffused on the downdrift flank. Their model results and their comparison with natural examples also suggest that delta shoreline geometry and wave climate at the time of abandonment can be good parameters for predicting the abandonment mode. These results are of interest in the future management of increasingly vulnerable deltas.

9. Summary and conclusion

Although waves are an important control on delta development, much still remains to be studied on how they interact with rivers to shape deltas. To probe the relationship between waves and deltas, the literature has commonly revolved around the same few better-known examples, the large majority of deltas not even having been inventoried, although earth observation tools and satellite imagery should be a way forward (Syvitski et al., 2012). The combination of wave climate data and delta morphometric parameters (e.g., Ashton and Giosan, 2011; Nienhuis et al., 2013) is also yielding interesting results. Given the extremely difficult environment of encounter between the river mouth and waves, improved numerical modelling, especially based on better calibration of wave parameters under such encounter, offers scope for further progress, notably in understanding the mechanisms of mouth-bar formation and reworking.

The smaller the delta, the stronger the influence of waves on overall delta evolution is likely to be, whereas large deltas evolve under the more complex interplay of sediment supply, aggradation, progradation, channel switching, and subsidence, with waves assuming importance in the destruction phase where fresh sediment supplies fail or lobes abandoned. In this review, a broad range of deltas has been used to show the diversity and the complexity of the relationship between waves and river deltas. Deltas show a continuum in plan shape morphology and morphodynamics from symmetric to skewed or asymmetric and finally deflected or straightened deltas as a function of the relationship between river strength and waves and wave-generated longshore drift. Deltas can show long-term switches within this continuum more commonly as a function of changes in river strength rather than changes in wave climate, the former being more susceptible to lasting fluctuations, especially given the tendency for many deltas to have undergone more or less significant changes in liquid and solid discharge related to human activities. The balancing of a weak river effect by strong longshore transport can lead to strongly longshore-skewed deltas or even prevent delta development. Even where wave influence is strong, however, large-scale delta morphodynamic adjustments can significantly influence the longshore transport cell structure through a number of feedback mechanisms. This occurs notably through the hydraulic groyne and blocking effects of river discharge (sometimes aided by tidal flow) on waves and wave-generated longshore currents, especially in the case of symmetrical deltas. Numerical modelling efforts on these aspects are still hampered by scale constraints and the difficulty of replicating the complex interactive processes prevailing where flow from the river mouth encounters waves and longshore transport.

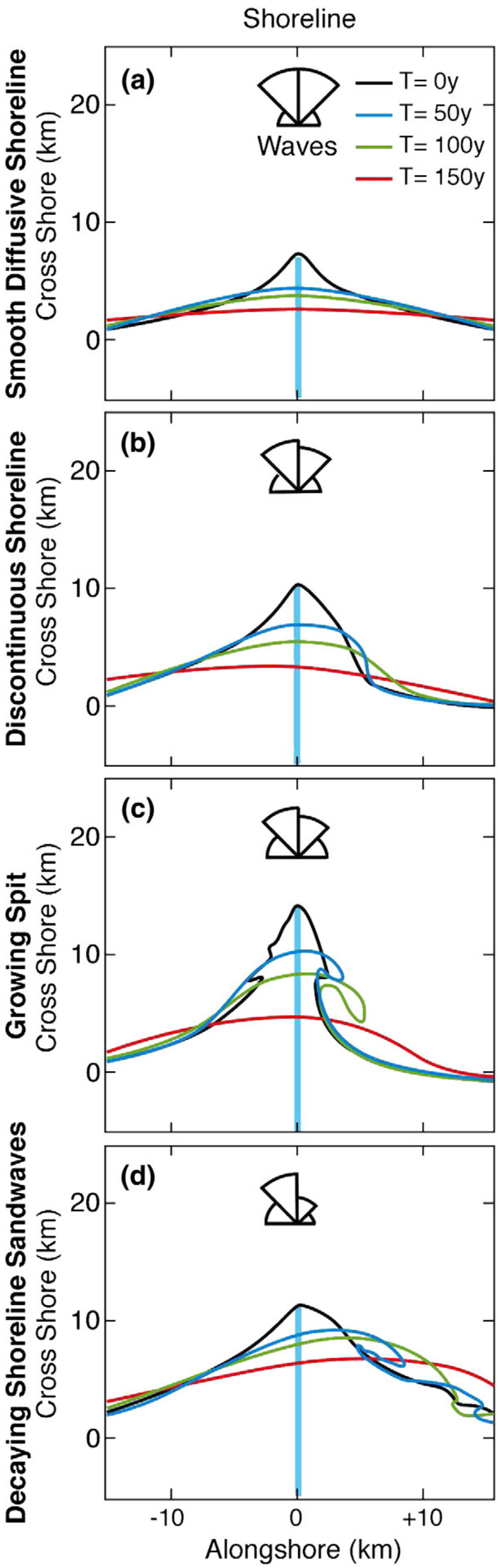

Fig. 18. Numerical model results of shoreline configurations of four identified delta abandonment modes, from abandonment (T = 0 y) and afterward. Inset roses display the angular distribution of incoming wave energy.
From Nienhuis et al. (2013).

Strong river influence can play an important role in delta shoreline and plan shape morphodynamic adjustments through both mouth bar deposits and the distance at which these form relative to the delta shoreline. These factors can generate a self-reinforcing process of mouth progradation by assuring conservation of a large share of the bedload in the vicinity of the mouth. The mouth protuberance generated by progradation forms the template for the regional shoreline pattern to which waves and longshore gradients adjust. Where several distributary mouths occur, multiplying the river-mouth effect, pronounced longshore variability in wave-induced bedload transport may ensue, resulting in multiple drift cells that assure sediment retention within deltas. Transport may be either divergent from the mouth, this being the classic case of fluvial bedload supply to adjacent coasts connected via longshore drift cells, or may involve unidirectional drift wherein the symmetry of the delta is enhanced by a strong river hydraulic groyne effect on bedload transport from the updrift flank, although such symmetry under regional unidirectional drift is deemed to be rare. Regional unidirectional drift is more likely to generate asymmetric deltas and highlights the significance of updrift bedload supply in the growth of some deltas in wave-influenced settings. Such sediment may be derived from abandoned delta lobes or from older relict nearshore deposits.

Under conditions of unchanging river liquid and solid discharge, progradation of a deltaic lobe occurs whilst longshore transport contributes to updrift and downdrift delta growth by reworking mouth bar deposits emplaced during strong river flow. This reworking contributes to the preclusion of a bedload-choked mouth that may end in promoting delta distributary avulsion. Where avulsion processes occur, however, they result in bedload redistribution alongshore through the wave recycling of abandoned deltaic lobes or mouths. The weakening of river liquid and solid discharges resulting from human activities will invariably lead to enhanced wave reworking of deltas and bedload redistribution by longshore transport. This may involve generalised retreat in deltas subject to divergent drift that feed non-deltaic downdrift coasts, whereas others subject to unidirectional drift may become increasingly skewed in the dominant regional transport direction. In the latter, the updrift flank may still continue to be sourced by older lobes or 'exogenous' sediment supplies assured by longshore transport.

Although sea-level rise is considered as a mechanism by which delta reworking by waves is enhanced, modes of delta development involving notably increased aggradation in lieu of progradation, channel switching and avulsion, washover processes, and chenier development, may contribute to delta survival through sediment sequestering, including via longshore redistribution within the deltaic shoreline system. This might require, however, that rivers still continue to supply sediment to balance some of the accommodation space created by sea-level rise and sinking, or that forms of management and sediment husbandry in deltas serve to palliate insufficiencies in river sediment supply. Many deltas are products in part or in whole of human transformations of river catchments, essentially through enhanced sediment supply, as shown by the history of many Mediterranean deltas, for instance. The massive swing towards significant reductions in fluvial sediment supply reaching many wave-influenced deltas today may signify their demise in the coming decades.

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References

Alexander, C.S., 1969. Beach ridges in northeastern Tanzania. Geographical Review 59, 104–122.

Allen, J.R.L., 1965. Coastal geomorphology of eastern Nigeria: beach-ridge barrier islands and vegetated tidal flats. Geologie en Mijnbouw 44, 1–21.

Allison, M.A., Khan, S.R., Goodbred Jr., S.L., Kuehl, S.A., 2003. Stratigraphic evolution of the late Holocene Ganges–Brahmaputra lower delta plain. Sedimentary Geology 155, 317–342.

Aminti, P., Pranzini, E., 1990. Variations in longshore sediment transport rates as a consequence of beach erosion in a cuspate delta. EUROCOAST 1990. Institut Méditerranéen de Technologie, Marseille, pp. 130–134.

Anthony, E.J., 1995. Beach-ridge progradation in response to sediment supply: examples from West Africa. Marine Geology 129, 175–186.

Anthony, E.J., 2009. Shore processes and their palaeoenvironmental applications. Developments in Marine Geology vol. 4. Elsevier Science, Amsterdam (519 pp.).

Anthony, E.J., 2014. Deltas. In: Masselink, G., Gehrels, R. (Eds.), Coastal Environments and Global Change. John Wiley & Sons Ltd, pp. 299–337.

Anthony, E.J., 2015. Patterns of sand spit development and their management implications on deltaic, drift-aligned coasts: the cases of the Senegal and Volta River delta spits, West Africa. In: Randazzo, G., Jackson, D.W.T., Cooper, J.A.G. (Eds.), Sand and Gravel Spits. Coastal Research Library Series. Springer (in press).

Anthony, E.J., Blivi, A.B., 1999. Morphosedimentary evolution of a delta-sourced, drift-aligned sand barrier-lagoon complex, western Bight of Benin. Marine Geology 158, 161–176.

Anthony, E.J., Gardel, A., Gratiot, N., 2014a. Fluvial sediment supply, mud banks, cheniers and the morphodynamics of the coast of South America between the Amazon and Orinoco river mouths. In: Martini, I.P., Wanless, H.R. (Eds.), Sedimentary Coastal Zones from High to Low Latitudes: Similarities and Differences. Geological Society, London, Special Publications 388, pp. 533–560.

Anthony, E.J., Marriner, N., Morhange, C., 2014b. Human influence and the changing geomorphology of Mediterranean deltas and coasts over the last 6000 years: from progradation to destruction phase? Earth-Science Reviews 139, 336–361.

Ashton, A.D., Giosan, L., 2011. Wave-angle control of delta evolution. Geophysical Research Letters 38, L13405. http://dx.doi.org/10.1029/2011GL047630.

Ashton, A.D., Hutton, E.W.H., Kettner, A.J., Xing, F., Kallumadikal, J., Nienhuis, J., Giosan, L., 2013. Progress in coupling models of coastline and fluvial dynamics. Computers & Geosciences 53, 21–29.

Bellotti, P., Calderoni, G., Di Rita, F., D'Orefice, M., D'Amico, C., Esu, D., Preite, Magri D., Martinez, M., Tortora, P., Valeri, P., 2011. The Tiber river delta plain (central Italy): coastal evolution and implications for the ancient Ostia Roman settlement. The Holocene. 21 pp. 1105–1116.

Bhattacharya, J.P., 2006. Deltas. In: Posamentier, H.W., Walker, R.G. (Eds.), Facies Models Revisited. SEPM, Tulsa, pp. 237–292.

Bhattacharya, J.P., Giosan, L., 2003. Wave-influenced deltas: geomorphological implications for facies reconstruction. Sedimentology 50, 187–210.

Bittencourt, A.C.S.P., Dominguez, J.M.L., Martin, L., SILVA, I.R., 2005. Longshore transport on the northeastern Brazilian coast and implications to the location of large-scale accumulative and erosive zones: an overview. Marine Geology 219, 219–234.

Bittencourt, A.C.S.P., Dominguez, J.M.L., Fontes, L.C.S., Sousa, D.L., Silva, I.R., Da Silva, F.R., 2007. Wave refraction, river damming, and episodes of severe shoreline erosion: the São Francisco River mouth, Northeastern Brazil. Journal of Coastal Research 23, 930–938.

Bony, G., Morhange, C., Bruneton, H., Carbonel, P., Gébara, C., 2011. Silting-up of the Frejus ancient harbour (Forum Julii, France) during the past 2000 years: a two-phase model of palaeoenvironmental change. Comptes Rendus Geoscience 343, 701–715.

Booij, N., Ris, R.C., Holthuijsen, L.H., 1999. A third-generation wave model for coastal regions; 1. Model description and validation. Journal of Geophysical Research 104 (C4), 7649–7666.

Boyd, R., Dalrymple, R.W., Zaitlin, B.A., 1992. Classification of clastic coastal depositional environments. Sedimentary Geology 80, 139–150.

Brückner, H., Müllenhoff, M., Handl, M., van der Borg, K., 2002. Holocene landscape evolution of the Büyük Menderes alluvial plain in the environs of Myous and Priene (Western Anatolia Turkey). Zeitschrift für Geomorphologie, Supplement Band 127, 47–65.

Canestrelli, A., Nardin, W., Edmonds, D., Fagherazzi, S., Slingerland, R., 2014. Importance of frictional effects and jet instability on the morphodynamics of river mouth bars and levees. Journal of Geophysical Research, Oceans 119, 509–522.

Ciavola, P., Mantovani, F., Simeoni, U., Tessari, U., 1999. Relation between river dynamics and coastal changes in Albania: an assessment integrating satellite imagery with historical data. International Journal of Remote Sensing 20, 561–584.

Coleman, J.M., 1981. Deltas — processes of deposition and models for exploration. Burgess Publishing Company, Minneapolis (124 pp.).

Coleman, J.M., Huh, O.K., 2004. Major deltas of the world: a perspective from space. Coastal Studies Institute. Louisiana State University, Baton Rouge, LA, USA (www.geol.lsu.edu/WDD/PUBLICATIONS/C&Hnasa04/C&Hfinal04.htm).

Cooper, J.A.G., 2001. Geomorphic variability among microtidal estuaries from the wave-dominated Soth African coast. Geomorphology 40, 99–122.

Cooper, J.A.G., Pilkey, O.H., 2004. Longshore drift: trapped in an expected universe. Journal of Sedimentary Research 74, 599–606.

Correggiari, A., Catanneo, A., Trincardi, F., 2005. The modern Po delta system: Lobe switching and asymmetric delta growth. Marine Geology 222–223, 49–74.

Curray, J.R., Emmel, F.J., Crampton, P.J.S., 1969. Holocene history of a strand plain, lagoonal coast, Nayarit, Mexico. In: Castañares, A.A., Phleger, F.B. (Eds.), Coastal Lagoons, a Symposium. University Nacional Autonoma Mexico–UNESCO, Mexico, pp. 63–100.

Dan, S., Stive, M.J.F., Walstra, D.J.R., Panin, N., 2009. Wave climate, coastal sediment budget and shoreline changes for the Danube Delta. Marine Geology 262, 39–49.

Dan, S., Walstra, D.J.R., Stive, M.J.F., Panin, N., 2011. Processes controlling the development of a river mouth spit. Marine Geology 280, 116–129.

Davies, J.L., 1980. Geographical variation in coastal development. 2nd ed. Longman, London (212 pp.).

Dodet, G., 2013. Morphodynamic modeling of a wave-dominated tidal inlet: the Albufeira Lagoon. (Thèse de Doctorat), Université de la Rochelle (181 pp.).

Dodet, G., Bertin, X., Bruneau, N., Fortunato, A.B., Nahon, A., Roland, A., 2013. Wave–current interactions in a wave-dominated tidal inlet. Journal of Geophysical Research, Oceans 118, 1587–1605.

Dolgopolova, E.N., Mikhailova, M.V., 2008. Mathematical modeling of the formation and progradation of a river mouth bar into a sea: case study of Danube delta branches. Water Resources 35, 287–296.

Dominguez, J.M.L., 1996. The São Francisco strandplain: a paradigm for wave-dominated deltas? In: De Baptist, M., Jacobs, P. (Eds.), Geology of Siliciclastic Shelf Seas. Geological Society of London, Special Publication 117, pp. 217–231

Dominguez, J.M.L., 2004. The coastal zone of Brazil: an overview. Journal of Coastal Research Special Issue 39, 16–20.

Edmonds, D.A., Slingerland, R.L., 2007. Mechanics of river mouth bar formation: implications for the morphodynamics of delta distributary networks. Journal of Geophysical Research 112, F02034.

Edmonds, D.A., Hoyal, D.C.J.D., Sheets, B.A., Slingerland, R.L., 2009. Predicting delta avulsions: implications for coastal wetland restoration. Geology 37, 759–762.

El Banna, M., Frihy, O.E., 2009. Human-induced changes in the geomorphology of the northeastern coast of the Nile delta, Egypt. Geomorphology 107, 72–78.

Ericson, J.P., Vörösmarty, C.J., Dingman, S.L., Ward, L.G., Meybeck, M., 2006. Effective sea-level rise and deltas: causes of change and human dimension implications. Global and Planetary Change 50, 63–82.

Evans, G., 2012. Deltas: the fertile dustbins of the world. Proceedings of the Geologists' Association. 123, pp. 397–418.

Fisher, W.L., Brown, L.F., Scott, A.J., McGowen, J.H., 1969. Delta systems in the exploration for oil and gas. Transactions of the Gulf Coast Association of Geological Societies. 17 pp. 105–125.

Foufoula-Georgiou, E., 2013. A vision for a coordinated effort on delta sustainability, 2013. In: Young, G., Perillo, G.M. (Eds.), Deltas: Landforms, Ecosystems and Human Activities. vol. 358. Book Series: IAHS Publication, Gothenburg, pp. 3–11.

Fox, J.M., Hill, P.S., Milligan, T.G., Ogston, A.S., Boldrin, A., 2004. Floc fraction in the waters of the Po River prodelta. Continental Shelf Research 24, 1699–1715.

Gac, J.Y., Kane, A., Monteillet, J., 1982. Migrations de l'embouchure du fleuve Sénégal depuis 1850. Cahiers ORSTOMsérie Géologie 12 pp. 73–76.

Galloway, W.E., 1975. Process framework for describing themorphologic and stratigraphic evolution of delta depositional systems. In: Broussard, M.L (Ed.), Deltas: Models for Exploration. Houston Geological Society, Houston, pp. 87–98.

Geleynse, N., Storms, J.E.A., Walstra, D.J.R., Jagers, H.R.A., Wang, Z.B., Stive, M.J.F., 2011. Controls on river delta formation; insights from numerical modeling. Earth and Planetary Science Letters 302, 217–226.

Giosan, L., 2007. Morphodynamic feedbacks on deltaic coasts: lessons from the wave-dominated Danube delta. Coastal Sediments 2007, 828–841.

Giosan, L., Donnelly, J.P., Vespremeanu, E., Bhattacharya, J.P., Olariu, C., Buonaiuto, F.S., 2005. River delta morphodynamics: examples from the Danube delta. In: Giosan, L., Bhattacharya, J.P. (Eds.), River Deltas — Concepts, Models and Examples. SEPM Special Publication 83, pp. 393–411.

Giosan, L., Coolen, M., Kaplan, J.O., Constantinescu, S., Florin, F., Filipova-Marinova, M., Kettner, A.J., Thom, N., 2012. Early anthropogenic transformation of the Danube — Black Sea system. Scientific Reports 2 (http://dx.doi.org/10.1038/srep00582).

Guillén, J., Palanques, A., 1992. Sediment dynamics and hydrodynamics in the lower course of a river highly regulated by dams — the Ebro River. Sedimentology 39, 567–579.

Guillén, J., Palanques, A., 1997. A historical perspective of the morphological evolution in the lower Ebro river. Environmental Geology 30, 174–180.

Hereher, M., 2011. Mapping coastal erosion at the Nile Delta western promontory using 440 Landsat imagery. Environmental Earth Sciences 64, 1117–1125.

Hori, K., Saito, Y., 2008. Classification, architecture and evolution of large river deltas. In: Gupta, A. (Ed.), Large Rivers: Geomorphology and Management. John Wiley and Sons, pp. 214–231.

Ibáñez, C., Day, J.W., Reyes, E., 2014. The response of deltas to sea-level rise: natural mechanisms and management options to adapt to high-end scenarios. Ecological Engineering 65, 122–130.

Jerolmack, D.J., 2009. Conceptual framework for assessing the response of delta channel networks to Holocene sea level rise. Quaternary Science Reviews 28, 1786–1800.

Jerolmack, D.J., Swenson, J.B., 2007. Scaling relationships and evolution of distributary networks on wave-influenced deltas. Geophysical Research Letters 34, L23402. http://dx.doi.org/10.1029/2007GL031823.

Jimenez, J.A., Sanchez-Archilla, A., Valdemoro, H.I., Garcia, V., Nieto, F., 1997. Processes reshaping the Ebro delta. Marine Geology 144, 59–79.

Komar, P.D., 1973. Computer models of delta growth due to sediment input from rivers and longshore transport. Geological Society of America Bulletin 84, 2217–2226.

Koszka-Maron, D., 2009. Facies model of the contemporary delta lobe of the Vistula River. Oceanological and Hydrobiological Studies 38, 57–68.

Kuenzer, C., van Beijma, S., Gessner, U., Dech, S., 2014. Land surface dynamics and environmental challenges of the Niger Delta, Africa: remote sensing-based analyses spanning three decades. Applied Geography 53, 354–368.

Laïbi, R.A., Anthony, E.J., Almar, N., Castelle, B., Sénéchal, Kestenare, E., 2014. Longshore drift cell development on the human-impacted Bight of Benin sand barrier coast, West Africa. Journal of Coastal Research, Special Issue 70, 78–83.

Lamb, M.P., Nittrouer, J.A., Mohrig, D., Shaw, J., 2012. Backwater and river plume controls on scour upstream of river mouths: implications for fluvio-deltaic morphodynamics. Journal of Geophysical Research 117, F01002. http://dx.doi.org/10.1029/2011JF002079.

Larson, M., Kraus, N.C., 2000. Enhancements of the numerical model of the longshore current NMLONG to include interaction between currents and waves (NMLong-CW). Coastal Engineering Technical Note CETN-IV-25. U.S. Army Engineer Research and Development Center, Vicksburg, MS (http://chl.wes.army.mil/library/publications/cetn/).

Leonardi, N., Canestrelli, A., Sun, T., Fagherazzi, S., 2013. Effect of tides on mouth bar morphology and hydrodynamics. Journal of Geophysical Research Oceans 4169–4183.

Maillet, G.M., Vella, C., Berné, S., Friend, P.L., Amos, C.L., Fleury, T.J., Normand, A., 2006. Morphological changes and sedimentary processes induced by the December 2003 flood event at the present mouth of the Grand Rhône River (southern France). Marine Geology 234, 159–177.

Marriner, N., Flaux, C., Kaniewski, D., Morhange, C., Leduc, G., Moron, V., Chen, Z., Gasse, F., Empereur, J.-Y., Stanley, J.-D., 2012a. ITCZ and ENSO-like pacing of Nile delta hydrogeomorphology during the Holocene. Quaternary Science Reviews 45, 73–84.

Marriner, N., Flaux, C., Morhange, C., Kaniewski, D., 2012b. The Nile delta's sinking past: quantifiable links with Holocene compaction and climate-driven changes in sediment supply? Geology 40, 1083–1086.

Marriner, N., Flaux, C., Morhange, C., Stanley, J.-D., 2013. Tracking Nile Delta vulnerability to Holocene change. PloS One 8, e69195.

Martin, L., Suguio, K., Flexor, J.M., Tessler, M., Eichler, B.B., 1985. Roundness in Holocene sands of the Paraibo do Sul coastal plain, Rio de Janeiro, Brazil. Journal of Coastal Research 1, 343–351.

Martin, L., Suguio, K., Flexor, J.M., Dominguez, J.M.L., Bittencourt, A.C.S.P., 1987. Quaternary evolution of the central part of the Brazilian coast: The role of relative sea-level variation and of shoreline drift. Quaternary coastal geology of West Africa and South America. UNESCO Reports in Marine Science 43, 97–145.

Maselli, V., Trincardi, F., 2013. Man made deltas. Scientific Reports 3, 1926. http://dx.doi.org/10.1038/srep01926.

Michel, P., 1980. The southwestern Sahara margin: sediments and climate change during the recent Quaternary. Palaeoecology of Africa and the Surrounding Islands 12, 297–306.

Milliman, J.D., Farnsworth, K.L., 2011. River discharge to the coastal ocean. Cambridge University Press, Cambridge.

Morales, J.A., 1997. Evolution and facies architecture of the mesotidal Guadiana River delta (SW Spain–Portugal). Marine Geology 138, 127–148.

Murillo, V.C., Silva, C.G., Fernandez, G.B., 2009. Nearshore sediments and coastal evolution of Paraibo do Sul delta, Rio de Janeiro, Brazil. Journal of Coastal Research Special Issue 56, 650–654.

Nageswara Rao, K., Subraelu, P., Naga Kumar, K.C.V., Demudu, G., Hema Malini, B., Rajawat, A.S., Ajai, 2010. Impacts of sediment retention by dams on delta shoreline recession: evidences from the Krishna and Godavari deltas, India. Earth Surface Processes and Landforms 35, 817–827.
Nardin, W., Fagherazzi, S., 2012. The effect of wind waves on the development of river mouth bars. Geophysical Research Letters 39, L12607. http://dx.doi.org/10.1029/2012GL051788.

Nageswara Rao, K., Saito, Y., Nagakumar, K.Ch.V., Demudu, G., Basavaiah, N., Rajawat, A.S., Tokanai, F., Kato, K., Nakashima, R., 2012. Holocene environmental changes of the Godavari Delta, east coast of India, inferred from sediment core analyses and AMS 14C dating. Geomorphology 175–176, 163–175.

Nardin, W., Fagherazzi, S., 2012. The effect of wind waves on the development of river mouth bars. Geophysical Research Letters 39, L12607. http://dx.doi.org/10.1029/2012GL051788.

Nardin, W., Mariotti, G., Edmonds, D.A., Guercio, R., Fagherazzi, S., 2013. Growth of river mouth bars in sheltered bays in the presence of frontal waves. Journal of Geophysical Research, Earth Surface 118, 1–15.

Nienhuis, J.H., Ashton, A.D., Roos, P.C., Hulscher, S.J.M.H., Giosan, L., 2013. Wave reworking of abandoned deltas. Geophysical Research Letters 40, 5899–5903.

Oomkens, E., 1974. Lithofacies relations in the Late Quaternary Niger Delta complex. Sedimentology 21, 195–222.

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

Pranzini, E., 2007. Airborne LIDAR survey applied to the analysis of the historical evolution of the Arno River delta (Italy). Journal of Coastal Research Special Issue 50, 400–409.

Provansal, M., Dufour, S., Sabatier, F., Anthony, E.J., Raccasi, G., Robresco, S., 2014. The geomorphic evolution and sediment balance of the lower Rhône River (southern France) over the last 130 years: hydropower dams versus other control factors. Geomorphology 209, 27–41.

Provansal, M., Pichard, G., Anthony, E.J., 2015. Geomorphic changes in the Rhône delta during the LIA: input from the analysis of ancient maps. In: Robin, M, Maanan, M (Eds.), Coastal Sediment Fluxes. Coastal Research Library, pp. 47–72.

Rakotomavo, A., Fromard, F., 2010. Dynamics of mangrove forests in the Mangoky River delta, Madagascar, under the influence of natural and human factors. Forest Ecology and Management 259, 1161–1169.

Restrepo, J.D., Kettner, A., 2012. Human induced discharge diversion in a tropical delta and its environmental implications: the Patía River, Colombia. Journal of Hydrology 424–425, 124–142.

Restrepo, J.D., Lopez, S.A., 2008. Morphodynamics of the Pacific and Caribbean deltas of Colombia, South America. Journal of South American Earth Sciences 25, 1–21.

Restrepo, J.D., Kjerfve, B., Correa, I.D., Gonzalez, J., 2002. Morphodynamics of a high discharge tropical delta, San Juan River, Pacific coast of Colombia. Marine Geology 192, 355–381.

Ris, R.C., Holthuijsen, L.H., 1996. Spectral modelling of current induced wave-blocking. Proceedings of the 25th Conference on Coastal Engineering. American Society of Civil Engineers, Reston, Virginia, pp. 1247–1254 (Orlando, Florida).

Roberts, H.H., 1997. Dynamic changes of the Holocene Mississippi River delta plain: the delta cycle. Journal of Coastal Research 13, 605–627.

Rodriguez, A.B., Hamilton, M.D., Anderson, J.B., 2000. Facies and evolution of the modern Brazos Delta, Texas; wave versus flood influence. Journal of Sedimentary Research 70, 283–295.

Sabatier, F., Suanez, S., 2003. Evolution of the Rhône delta coast since the end of the 19th century. Géomorphologie: Relief, Processus, Environnement. 47 pp. 283–300.

Sabatier, F., Maillet, G., Fleury, J., Provansal, M., Antonelli, C., Suanez, S., Vella, C., 2006. Sediment budget of the Rhône delta shoreface since the middle of the 19th century. Marine Geology 234, 143–157.

Sabatier, F., Samat, O., Ullmann, A., Suanez, S., 2009. Connecting large-scale coastal behaviour with coastal management of the Rhône delta. Geomorphology 107, 79–89.

Sabatier, F., Anthony, E.J., 2015. The sand spits of the Rhône River delta: formation, dynamics, sediment budgets and management. In: Randazzo, G., Jackson, D.W.T., Cooper, J.A.G. (Eds.), Sand and Gravel Spits. Coastal Research Library Series. Springer (in press).

Saito, Y., Wei, H.L., Zhou, Y.Q., Nishimura, A., Sato, Y., Yokota, S., 2000. Delta progradation and chenier formation in the Huanghe (Yellow River) Delta, China. Journal of Asian Earth Sciences 18, 489–497.

Simeoni, U., Corbau, C., 2009. A review of the Delta Po evolution (Italy) related to climatic changes and human impacts. Geomorphology 107, 64–71.

Snoussi, M., Haïda, S., Imassi, S., 2002. Effects of the construction of dams on the water and sediment fluxes of the Moulouya and the Sebou Rivers, Morocco. Regional Environmental Change 3, 5–12.

SOGREAH, 1994. Etudes de faisabilité et d'avant projet sommaire de l'émissaire delta. Rapport final (70 pp.).

Stone, G.W., Pepper, D.A., Jingping, X., Zhang, X., 2004. Ship Shoal as a prospective borrow site for barrier island restoration, coastal south-central Louisiana, USA: numerical wave modeling and field measurements of hydrodynamics and sediment transport. Journal of Coastal Research 20, 70–88.

Suarez, B.E.S., 2004. The Sinu river delta on the northwestern Caribbean coast of Colombia: bay infilling associated with delta development. Journal of South American Earth Science 16, 623–631.

Syvitski, J.P.M., Saito, Y., 2007. Morphodynamics of deltas under the influence of humans. Global and Planetary Change 57, 261–282.

Syvitski, J.P.M., Vörösmarty, C.J., Kettner, A.J., Green, P., 2005. Impact of humans on the flux of terrestrial sediment to the global coastal ocean. Science 308, 376–380.

Syvitski, J.P.M., Kettner, A.J., Overeem, I., Hutton, E.W.H., Hannon, M.T., Brakenridge, G.R., Day, J., Vörösmarty, C.J., Saito, Y., Giosan, L., Nicholls, R.J., 2009. Sinking deltas due to human activities. Nature Geoscience 2, 681–689.

Syvitski, J.P.M., Overeem, I., Brakenbridge, G.R., Hamon, M., 2012. Floods, floodplains, delta plains — a satellite imaging approach. Sedimentary Geology 267–268, 1–14.

Ta, T.K.O., Nguyen, V.L., Tateishi, M., Kobayashi, I., Tanabe, S., Saito, Y., 2002. Holocene delta evolution and sediment discharge of the Mekong River, southern Vietnam. Quaternary Science Reviews 21, 1807–1819.

Tamura, T., Saito, Y., Bateman, M.D., Nguyen, V.L., Ta, T.K.O., Matsumoto, D., 2012a. Luminescence dating of beach ridges for characterizing multi-decadal to centennial deltaic shoreline changes during Late Holocene, Mekong River delta. Marine Geology 326–328, 140–153.

Tamura, T., Saito, Y., Nguyen, V.L., Ta, T.K.O., Bateman, M.D., Matsumoto, D., Yamashita, S., 2012b. Origin and evolution of interdistributary delta plains; insights from Mekong River delta. Geology 40, 303–306.

Tatui, F., Vespremeanu-Stroe, A., Rusessink, B.G., 2011. Intra-site differences in nearshore bar behavior on a nontidal beach (Sulina — Sf. Gheorghe, Danube Delta coast). Journal of Coastal Research Special Issue 64, 840–844.

Todd, T.W., 1968. Dynamic diversion: influence of longshore current–tidal flow interaction on chenier and barrier island plains. Journal of Sedimentary Petrology 38, 734–746.

Traini, C., Schrottke, K., Stattegger, K., Dominguez, J.M.L., Guimarães, J.K., Vital, H., d'Avila Beserra, D., da Silva, A.G.Q., 2012. Morphology of subaqueous dunes at the mouth of the dammed River Saõ Francisco (Brazil). Journal of Coastal Research 28, 1580–1590.

Uehara, K., Sojisuporn, P., Saito, Y., Jarupongsakul, T., 2010. Erosion and accretion processes in a muddy dissipative coast, the Chao Phraya Riverdelta, Thailand. Earth Surface Processes and Landforms 35, 1701–1711.

Usoro, E.J., 1985. Nigeria. In: Bird, E.C.F., Schwartz, M.L. (Eds.), The World's Coastline. Van Nostrand Reinhold Co., New York, pp. 607–619.

van Maren, D.S., 2005. Barrier formation on an actively prograding delta system: the Red River Delta, Vietnam. Marine Geology 224, 123–143.

van Maren, D.S., 2007. Water and sediment dynamics in the Red River mouth and adjacent coastal zone. Journal of Asian Earth Sciences 29, 508–522.

Vassas, C., Sabatier, F., Vella, C., 2007. Résultats préliminaires sur le taux de transport à l'embouchure du Grand Rhône (SE de la France). La Houille Blanche 4, 35–40.

Vella, C., Fleury, T.J., Raccasi, G., Provansal, M., Sabatier, F., Bourcier, M., 2005. Evolution of the Rhône delta plain in the Holocene. Marine Geology 222–223, 235–265.

Vespremeanu-Stroe, A., Preoteasa, L., 2015. Morphology and the cyclic evolution of Danube delta spits. In: Randazzo, G., Jackson, D.W.T., Cooper, J.A.G. (Eds.), Sand and Gravel Spits. Coastal Research Library Series. Springer (in press).

Vött, A., Schriever, A., Handl, M., Brückner, H., 2007. Holocene palaeogeographies of the central Acheloos River delta (NW Greece) in the vicinity of the ancient seaport Oiniadai. Geodinamica Acta 20, 241–256.

Westhuysen, A., 2012. Spectral modeling of wave dissipation on negative current gradients. Coastal Engineering 68, 17–30.

Wolanski, E., Huan, N.N., Dao, L.T., Nhan, N.H., Thuy, N.N., 1996. Fine sediment dynamics in the Mekong River estuary, Vietnam. Estuarine, Coastal and Shelf Sciencen 43, 565–582.

Woodroffe, C.D., Saito, Y., 2011. River-dominated coasts. In: Wolanski, E., McLusky, D.S. (Eds.), vol. 3. Academic Press, Waltham, UK, pp. 117–135.

Wright, L.D., 1977. Sediment transport and deposition at river mouths: a synthesis. Geological Society of America Bulletin 88, 857–868.

Wright, L.D., 1995. Morphodynamics of inner continental shelves. CRC Press, Boca Raton (241 pp.).

Wright, L.D., Coleman, J.M., 1972. River delta morphology: wave climate and the role of the subaqueous profile. Science 176, 282–284.

Wright, L.D., Coleman, J.M., 1973. Variations in morphology of major river deltas as functions of ocean wave and river discharge regimes. American Association of Petroleum Geologists 57, 370–398.

Wright, L.D., Coleman, J.M., Erickson, M.W., 1974. Analysis of major river systems and their deltas: morphologic and process comparisons. Technical Report 156, Coastal Studies Institute. Louisiana State University (125 pp.).