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Wave-angle control of delta evolution

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[1] Wave-influenced deltas, with large-scale arcuate shapes and demarcated beach ridge complexes, often display an asymmetrical form about their river channel. Here, we use a numerical model to demonstrate that the angles from which waves approach a delta can have a first-order influence upon its plan-view morphologic evolution and sedimentary architecture. 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. Oblique wave approach (and a consequent net alongshore sediment transport) can lead to the development of morphologic asymmetry about the river in a delta's plan-view form. This plan-form asymmetry can include the development of discrete breaks in shoreline orientation and the appearance of self-organized features arising from shoreline instability along the downdrift delta flank, such as spits and migrating shoreline sand waves—features observed on natural deltas. Somewhat surprisingly, waves approaching preferentially from one direction tend to increase sediment deposition updrift of the river. This 'morphodynamic groin effect' occurs when the delta's plan-form aspect ratio is sufficiently large such that the orientation of the shoreline on the downdrift flank is rotated past the angle of maximum alongshore sediment transport, resulting in preferential redirection of fluvial sediment updrift of the river mouth. **Citation:** Ashton, A. D., and L. Giosan (2011), Wave-angle control of delta evolution, *Geophys. Res. Lett.*, *38*, L13405, doi:10.1029/2011GL047630.

1. Introduction

[2] River deltas, shaped by the interplay between their feeding rivers and reworking by tides and waves [*Galloway*, 1975; *Wright and Coleman*, 1973; *Edmonds and Slingerland*, 2010], store integrated records of environmental changes, both natural and anthropogenic, and have provided vital functions to human societies since prehistory [*Day et al.*, 2007; *Stanley and Warne*, 1997; *Syvitski et al.*, 2009]. The mark of ocean waves on the depositional pattern of river deltas is clearly apparent in their plan-view morphologies, which include large-scale arcuate or cuspate shapes, beach ridge complexes, and extensive barrier systems (Figure 1). These diagnostic landforms, which can preserve the history of climate change and land use over a large span of temporal scales [*Giosan et al.*, 2006; *Stanley and Warne*, 1997], reflect the reworking and alongshore transport of coarse-grained sediment by waves and associated littoral processes. Due to sediment compaction, floodplain engineering, rising global sea level, and especially dwindling sediment discharge from river damming [*Syvitski et al.*, 2009], waves are increasing their influence along most deltaic coasts—a phenomenon expected to continue over the coming century until reservoirs fill with sediment.

[3] River delta morphology has been considered to reflect a balance between the rate and type of fluvial input of sediment to the coast and the rate of sediment removal (both offshore and alongshore) by waves and tides [*Galloway*, 1975; *Wright and Coleman*, 1973]. The relative strength of waves has often been used to understand the degree of reworking of deltaic coasts [*Swenson et al.*, 2005; *Wright and Coleman*, 1973]. Similarly, the direction of waves approaching the coast has been identified as a primary cause for the emergence of basic patterns in the morphology and sedimentary architecture of wave-influenced deltas [*Bhattacharya and Giosan*, 2003]; quantitative studies, however, have yet to account for wave approach angle. Here, we present numerical modeling results demonstrating that wave approach angle can play a first-order role in the plan-form morphologic evolution of river deltas, affecting delta lobe width, progradation rate, morphology, and sedimentary architecture.

2. Background

[4] Current understanding of the plan-form evolution of wave-influenced deltas relies upon the one-contour-line modeling approach, which assumes that coarse-grained sediment remains close to shore as part of the wave-affected shoreface. The resulting diffusion equation for plan-view shoreline shape evolution [*Pelnard-Consideré*, 1956] can be solved analytically [*Larson et al.*, 1987], resulting in a symmetric solution about the riverine sediment source. *Grijm* [1960, 1964] investigated the effect of varying wave angle on delta shape, findings expanded upon by *Bakker and Edelman* [1965], who note the possibility of a downdrift shoreline instability and the formation of spits if waves approach from sufficiently oblique angles. *Komar* [1973, 1977] presents numerical modeling of wave-influenced deltas using waves approaching at a fixed and low angle, resulting in generally symmetrical cuspate shapes, similar to those predicted by the simple diffusion equation. A more recent model of delta formation by *Seybold et al.* [2007] contains formulations emulating the effects of both fluvial and marine processes, with the latter parameterized as a diffusional smoothing of bathymetry which acts symmetrically and independently of wave approach angle.

[5] Recent research has expanded on the importance of the direction of wave approach on shoreline evolution, demonstrating that the wave angle (between wave crests and

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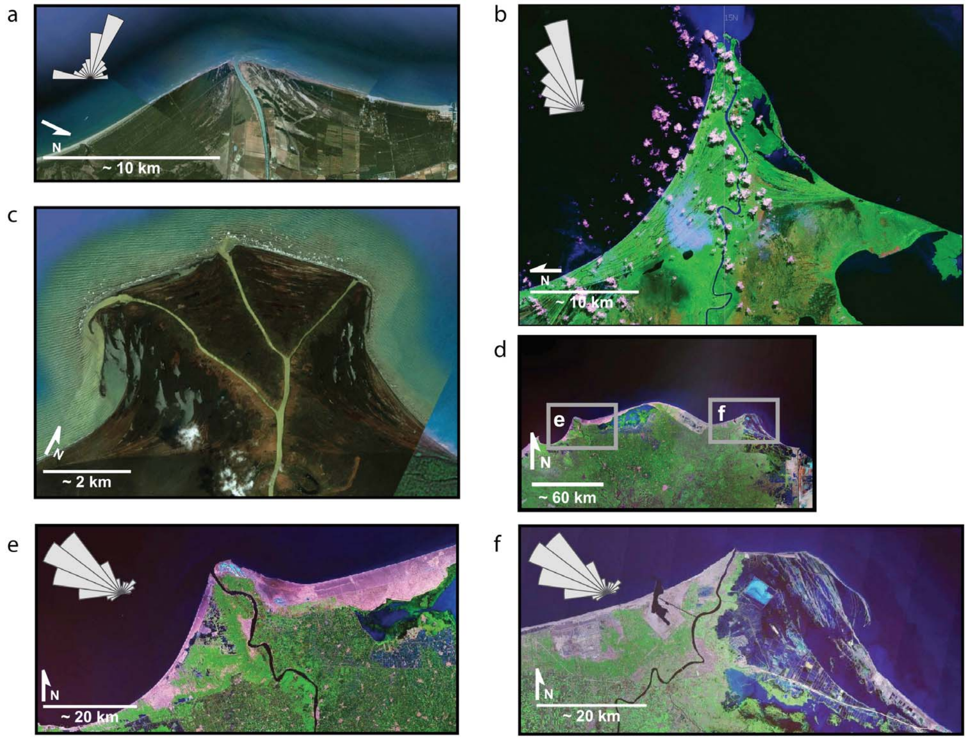

Figure 1. Satellite imagery of wave-influenced deltas. (a) Ombrone delta, Italy, (b) Coco River delta, Honduras/Costa Rica, (c) Tinajones lobe of the Sinu River delta, Colombia, and the (d) Nile Delta with (e) Rosetta and (f) Damietta lobes. Included are insets of binned rose-type plot of area-normalized wave contributions to alongshore sediment transport. See auxiliary material for data sources.

the shoreline) before local refraction, and not the breaking angle, is morphologically important and has a maximum at approximately 45° (Figure 2a). As a consequence, the correct formulation for shoreline evolution includes a diffusivity that changes magnitude and sign as wave angle changes [*Ashton and Murray*, 2006a, 2006b; *Ashton et al.*, 2001; *Falqués*, 2003]. This shoreline diffusivity is positive when wave angles are smaller than the maximum in alongshore sediment transport (tending to smooth the coast) and negative for larger angles (meaning a straight shoreline configuration would be unstable) (Figure 2a). Numerical simulations demonstrate that coasts affected by predominantly anti-diffusive, high-angle waves can self-organize, developing landforms including alongshore sandwaves, cuspate caped coasts, and series of flying spits [*Ashton and Murray*, 2006a; *Ashton et al.*, 2001].

3. Numerical Model

[6] The numerical model used herein [*Ashton and Murray*, 2006a; *Ashton et al.*, 2001] follows the principles of other one-contour-line numerical models by evolving the shoreline shape based upon gradients in alongshore sediment transport. The coast is defined along a 2-D grid of partially filled 'cells' comprising the shoreline location. As deep-water waves with a given height and angle approach the shore, they refract over assumed shore-parallel contours until they break (due to depth limitation); sediment transport is computed using the common CERC formula for alongshore sediment transport [*Komar*, 1971] (see

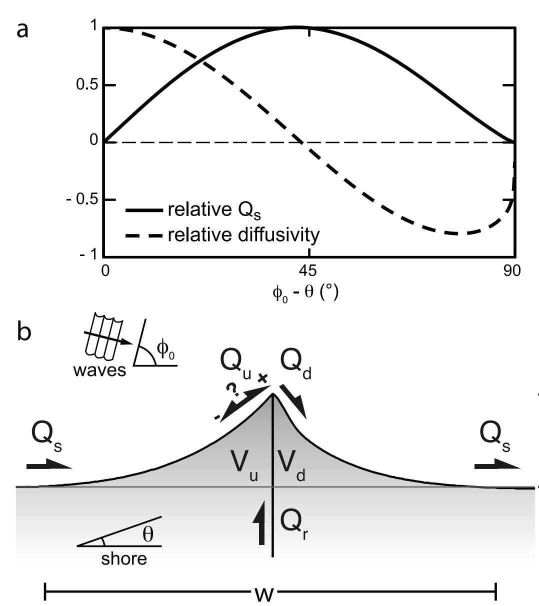

Figure 2. Illustrations of relationships affecting shoreline evolution, showing (a) the deep-water angle dependence of alongshore sediment transport and shoreline diffusivity and (b) elements for determining mass balance relationships along a wave-influenced delta, including the alongshore fluxes immediately updrift and downdrift of the river mouth (Q_u and Q_d, respectively).

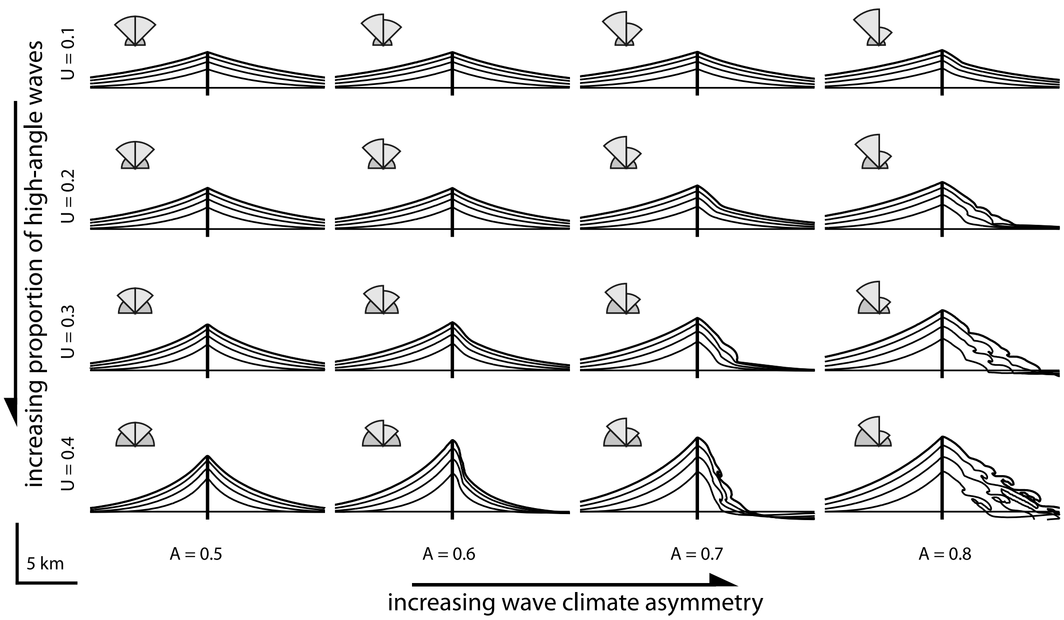

Figure 3. Plan-view time series of simulated delta shorelines for different wave angle climates, zooming on the domain proximal to the river (with insets of area-normalized wave energy rose-type plots). Shorelines plotted at intervals of 65.4 model years, with final shoreline at 327 model years. In all simulations, the other wave characteristics (height 1 m, period 6 s), offshore geometries (shoreface slope 0.01; shelf slope 0.001; shoreface depth 10 m) and river bedload input (92 kg/s) are held constant—the changes in morphology are attributable to solely to differences in wave approach angle. See auxiliary material for Animations S1 and S2.

auxiliary material).[1] The shoreline evolves according to gradients in sediment transport and the conservation of cross-shore mass.

[7] Fluvial sediment delivery is treated in a simplified manner—sediment is added to the shoreline at a constant rate at a fixed alongshore location, representing the net riverine flux (primarily bedload) that remains within the shoreface, Q_r (deposited volume in m^3/s). This assumes that wave suspension causes finer-grained sediment to be transported offshore, and that the compatible coarse sediment amalgamates to the shoreface directly at (or close to) the river mouth. We also assume that the river debouches along an already sandy coast; if there is a net littoral drift, sediment is supplied at the updrift boundary. Furthermore, there are no assumed impediments to breaking-wave-driven alongshore sediment transport by the river, allowing sediment to bypass the river mouth. This simplified treatment of the fluvial domain obviously neglects the importance of river mouth bar formation and avulsion that are integral in delta evolution [*Edmonds and Slingerland*, 2010; *Giosan et al.*, 2005; *Jerolmack and Swenson*, 2007]. However, our objective is to focus on the large-scale dynamics of the system, with a specific focus on how waves apportion sediment delivered from a river.

[8] Each model day, the approaching wave angle is selected randomly from a probability distribution function controlled by two variables that affect the most relevant wave climate characteristics: the proportion of high-angle waves (U) and the net asymmetry (A). The wave climate asymmetry, A, would be associated with a net direction of alongshore sediment transport. For $A = 1.0$, waves approach only from the left, looking offshore; waves approach equally from both sides for $A = 0.5$ (see insets in Figure 3). U represents the fraction of waves that approach from unstable, 'high' angles (>45°). As U increases, the net shoreline diffusivity decreases.

[9] Note that the results presented here have $U < 0.5$ – all climates have a net diffusivity; our focus is on the interplay between fluvial sediment delivery and waves that generally would be expected to smooth a coastline, as opposed to previous model applications that studied the self-organization of a shoreline subjected to net unstable waves [*Ashton and Murray*, 2006a]. The temporal and spatial scales of the presented results are specific to values of the input wave energy and delta geometry, these prototype results can be rigorously rescaled in space and time for different wave conditions and geometries [*Ashton and Murray*, 2006b].

4. Characteristic Delta Morphologies

[10] Deltas develop markedly different morphologies as wave angle characteristics are varied (Figure 3). For a symmetric wave climate (with little to no net alongshore transport, $A \sim 0.5$) and relatively small fluvial input, simulations develop classic cuspate delta shapes, similar to those previously modeled [*Komar*, 1973] or found through the analytical solution of the diffusion equation [*Larson et al.*, 1987]. As the proportion of unstable waves (U) increases, a delta will project further offshore, attaining a more pronounced cuspate shape. Although slight wave climate asymmetry has little effect on delta morphology, as A increases,

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL047630.

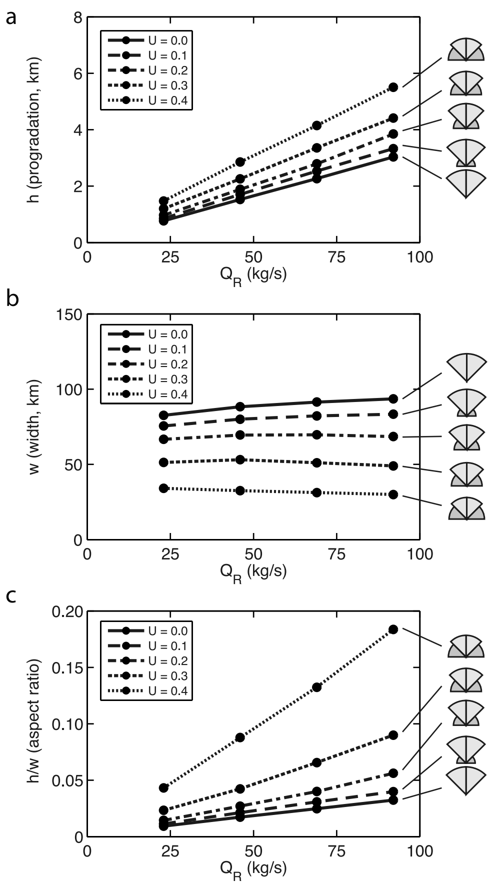

Figure 4. Growth characteristics of simulated deltas affected by a symmetrical wave climate for different values of fluvial sediment input, Q_R, and directional spread of incoming waves, U, after 327 simulated years, showing: (a) delta mouth progradation, h, (b) plan-view delta width, w, (defined as the full width using a threshold criteria where the shoreline is one cell width landward of the initial coast) and (c) aspect ratio (h/w). Insets of area-normalized rose-type plots of wave energy are included for each case.

so does the tendency for the downdrift coast to experience high-angle waves. Greater asymmetry can cause a discontinuity in shoreline orientation and encourages the formation of landforms associated with shoreline instabilities on the downdrift flank, including migrating alongshore sandwaves and offshore extending spits. The propensity towards asymmetric development of the delta and emergence of downdrift shoreline instability with associated rhythmic landforms is amplified for larger values of A, U, and Q_s (Figure 3).

5. Delta Morphodynamics

[11] Wave climate characteristics not only affect delta morphologies (Figure 3), they also control morphodynamic evolution through the rates and shape of delta progradation. As an illustration, with a symmetric wave climate (which forms simple 'cuspate' delta morphologies), an increase in U augments the rate of delta progradation, an effect that can be of similar magnitude to a doubling of sediment input rate (Figure 4). Correspondingly, the width of a lobe is largely unaffected by the sediment input rate, but is sensitive to the wave climate characteristics. Taken together, the aspect ratio of the delta's planform shape is affected by both the sediment input and wave climate characteristics (Figure 4c). This implies that wave angle climate plays an important role in the process of river avulsion (the punctuated realignment of the river channel and abandonment of an active lobe) because the characteristic temporal scales of delta lobe avulsion depend on both the rate of progradation and the lobe width [*Jerolmack and Swenson*, 2007; *Swenson*, 2005].

6. Sediment Partitioning

[12] As modeled deltas evolve, the partitioning of alongshore sediment transport on either side of the mouth (Q_u and Q_d, Figure 2b) rapidly reaches a steady state (with slight fluctuations due to the stochastic driving forces). Note that Q_u can be directed either towards or away from the river mouth depending on the angle between this section of coast and the wave angle climate. (Accordingly, future reference to the terms 'updrift' and 'downdrift' are relative to the regional sediment transport direction, not necessarily the direction of fluxes at the river mouth.) A simple mass-balance approach (Figure 2b, see auxiliary material) reveals important aspects of the asymmetric sediment partitioning (Figure 5). In contrast with previous inferences [*Wright and Coleman*, 1973], in simulations with asymmetric wave approach angles, sediment is preferentially deposited on the updrift flank of the river (Figure 5a). This tendency becomes increasingly manifest as both the wave climate asymmetry and the rate of fluvial input increase. At low fluvial inputs, the downdrift shoreline orients itself such that both the river flux and sediment from updrift, which bypasses the mouth, are transported to the downdrift flank, where they are deposited (Figure 5b); in this case, fluvially derived sediment does not significantly contribute to the updrift deposits (Figure 5c). When this preferential downdrift deposition of fluvial sediment is greatest (high A and low Q_R,), deposition rates tend to be symmetric with both flanks growing at the same rate (Figures 5a and 5b).

[13] In contrast, when the updrift delta flank grows faster than the downdrift flank (high A, high Q_R), not only are downdrift deposits expected to consist almost entirely of fluvial sediments, but a significant fraction of the sediment delivered by the river at the mouth is redirected towards the updrift flank as well (Figures 5c and 5d). This tendency to redirect sediment upstream can be demonstrated by comparison to a hypothetical case where a volumetric symmetry condition is imposed (see auxiliary material); the asymmetrical deposition manifests as a significant reduction in the tendency for sediment to bypass the river mouth (Figure 5b).

[14] The asymmetric sediment partitioning, which we term a 'morphodynamic groin effect', occurs when waves approach dominantly from one direction and a delta reaches a significant aspect ratio such that the downdrift coastline rotates past the maximizing angle for alongshore sediment transport (coincident with the development of shoreline instability, Figure 2a). When the shoreline is past the maximum angle, as the aspect ratio of the delta increases, the downdrift flux decreases, and a smaller proportion of sedi-

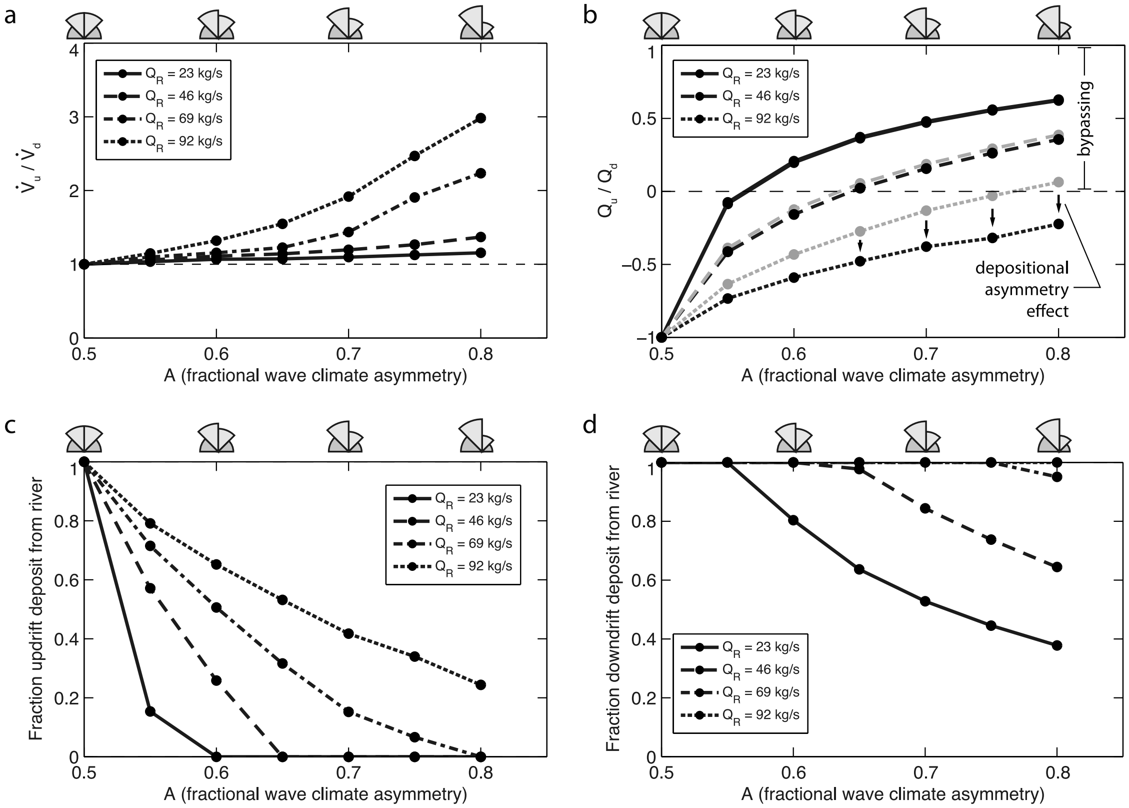

Figure 5. Sediment partitioning for simulations with $U = 0.3$ for varying wave climate asymmetry, A, and fluvial sediment delivery rate, Q_R: (a) ratio of updrift mass accumulation rate ($\dot{V}_u$) versus downdrift rate ($\dot{V}_d$), (b) ratio of updrift alongshore flux (Q_u) to downdrift flux (Q_d) on either side of the river mouth, where the grey lines represent this ratio if the updrift and downdrift growth rates were equal (i.e., $\dot{V}_u = \dot{V}_d$), (c) fraction of updrift delta flank sediment deposition sourced from the river, and (d) fraction of downdrift sediment deposition sourced from the river.

ment flux delivered by the river is able to pass downdrift. Consequently, the delta progrades faster as this river sediment remains proximal to the river mouth. Further morphodynamic adjustments tend to send more fluvial sediment towards the updrift flank (or reduce the amount of sediment bypassing the mouth, Figure 5b). This effect manifests for large Q_R and A wave climate asymmetry. The pronounced preferential updrift mass gain (up to 3:1, Figure 5b) requires only subtle changes in relative fluxes on either side of the river mouth (Figure 5b). Over time, the preferential partitioning of sand to the updrift flank of the delta can lead to enhanced complexity in facies and stratigraphic architecture of wave-dominated deltas [e.g., *Bhattacharya and Giosan*, 2003].

[15] Littoral sediment could reasonably be expected to become trapped on the updrift side of a delta as a river extends offshore, a phenomenon similar to the sand trapping by shore-perpendicular engineering structures such as groines or jetties. However, we do not observe such a classic groin-type effect. Preferential updrift sediment trapping is minimal or non-existent for low Q_R and small plan-form aspect ratio (Figure 5a)—the river does not block sediment transport in this case. Illustratively, when depositional asymmetry (and therefore the morphologic groin effect) is strongest, the sediment preferentially deposited updrift originates from the river (observe the trend in Figure 5c with increasing Q_r), opposite of the trapping behavior expected for a simple groin.

7. Comparison to Natural Deltas

[16] The general phenomena revealed by our model results can be observed on many natural deltas, such as the Nile, the Danube, the Rhone, or the Po deltas [*Bhattacharya and Giosan*, 2003]. For example, the symmetrical evolution of cuspate deltas, as exhibited by the Ombrone River delta in Italy (Figure 1a) [*Pranzini*, 2001], has long been considered typical. The Tinajones lobe of the Sinu River delta in Colombia, formed after a breach between 1938 and 1945 [*Suarez*, 2004], demonstrates both symmetric evolution of the central branch and asymmetric development on the flanks, which both exhibit downdrift extending spits (Figure 1c). Both the observed symmetric and asymmetric development of the Tinajones is to be expected for waves approaching from the north (as would expected as local geography blocks waves from other directions). The Coco Delta, on the Costa Rica/Honduras border (Figure 1b), displays several characteristics observed in simulations: a pronounced asymmetry, a break in shoreline angle on the downdrift coast, and an enlarged updrift flank.

[17] The Nile River delta provides an excellent test of the influence of wave angle asymmetry in lobe development

(see Animations S1 and S2 of the auxiliary material). Both active lobes of the Nile delta, the Damietta in the east and the Rosetta in the west, experience similar wave climates; however, the Rosetta branch is oriented into incoming waves, whereas the Damietta Lobe is more obliquely aligned to them (Figures 1d and 1e). Accordingly, the Rosetta lobe displays a symmetric plan-view form whereas the Damietta lobe is asymmetric, with more apparent sandy deposition on the updrift flank and spits irregularly extending downdrift.

8. Conclusions

[18] As a result of the angle dependence of alongshore sediment transport and the presence of a maximizing angle for this transport, the angle distribution of approaching waves plays an important role in the evolution of wave-influenced deltas. Increasing the spread of approaching wave angles results in narrower delta lobes that prograde at faster rates. Waves approaching dominantly from one direction can lead to the asymmetric evolution of a delta, where sediment is preferentially deposited on the updrift flank, with the possible formation of off-shore extending spits and alongshore sand waves. The autogenic nature of the downdrift shoreline undulations is important to consider when unraveling the driving forces that may be responsible for their resulting deposits, as they provide another example where invariable driving forces can result in episodic and irregular depositional patterns [*Jerolmack and Paola*, 2007]. In general, the asymmetrical delta evolution and the morphologic groin effect predicted here arises due to morphodynamic feedbacks between the river and the wave climate, requiring not only a net direction of alongshore sediment transport, but also sufficient fluvial input to deform the plan-view shoreline shape such that the downdrift coast rotates past the angle of maximum alongshore sediment transport.

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