Littoral steering of deltaic channels

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Abstract

The typically single-threaded channels on wave-influenced deltas show striking differences in their orientations, with some channels oriented into the incoming waves (e.g., Ombrone, Krishna), and others oriented away from the waves (e.g., Godavari, Sao Francisco). Understanding the controls on channel orientation is important as the channel location greatly influences deltaic morphology and sedimentology, both subaerially and subaqueously. Here, we explore channel orientation and consequent feedbacks with local shoreline dynamics using a plan-form numerical model of delta evolution. The model treats fluvial sediment delivery to a wave-dominated coast in two ways: 1) channels are assumed to prograde in a direction perpendicular to the local shoreline orientation and 2) a controlled fraction of littoral sediment transport can bypass the river mouth. Model results suggest that channels migrate downdrift when there is a significant net littoral transport and alongshore transport bypassing of the river mouth is limited. In contrast, river channels tend to orient themselves into the waves when fluvial sediment flux is relatively large, causing the shoreline of the downdrift delta flank to attain the orientation of maximum potential sediment transport for the incoming wave climate. Using model results, we develop a framework to estimate channel orientations for wave-influenced deltas that shows good agreement with natural examples. An increase in fluvial sediment input can cause a channel to reorient itself into incoming waves, behavior observed, for example, in the Ombrone delta in Italy. Our results can inform paleoclimate studies by linking channel orientation to fluvial sediment flux and wave energy. In particular, our approach provides a means to quantify past wave directions, which are notoriously difficult to constrain.

1 Introduction

Major channels of wave-influenced deltas tend to be straight, or gently curving, rather than meandering, with orientations that can diverge from the upland river course. It has been hypothesized that a delta's channel orientation arises from the interaction between fluvial channel-building processes and littoral sediment transport at the shoreline (Bhattacharya and Giosan, 2003; Pranzini, 2001). However, the controls on channel orientation are not straightforward as, on some deltas, channels turn into the waves, whereas, on other deltas, channels migrate away from the waves (Fig. 1). The presence of the channel itself affects coastal processes, as river mouths can limit bypassing of littoral sediment (Nienhuis et al., 2016). As such, a mechanistic understanding of the basic controls on channel orientation has been previously lacking. To investigate the mechanisms and controls that set the channel orientations on wave-influenced deltas, we have conducted experiments using an exploratory model of plan-view delta evolution. In these experiments, we allow local shoreline dynamics to determine the channel orientation, while also controlling the quantity of littoral sediment that can bypass the river channel. We compare these model experiments to natural examples in a mechanistic framework, which not only allows us to predict the channel orientation for modern deltas, but also, as the channel orientation of wave-influenced deltas is preserved in the morphology of deltas and eventually stored in the stratigraphic record, has the potential to inform us about past and present fluvial and alongshore sediment transport fluxes.

2 Background

2.1 Asymmetric Wave-influenced Deltas

In the absence of waves, river deltas often develop intricate networks of distributary channels resulting from mouth-bar formation and channel avulsions (Geleynse et al., 2011; Wright, 1977). However, waves inhibit mouth bar formation and move sediment alongshore, and as such can suppress the emergence of small-scale distributaries, generally leading to the growth of a single major channel (Wright and Coleman, 1973) and a cuspate delta shape (Grijm, 1960).

Alongshore transport of fluvial sediment is the primary mechanism shaping wave-influenced deltas (Bakker and Edelman, 1964; Tanner, 1958). Waves breaking at an angle to the coastline drive a flux of sediment alongshore (Komar, 1971); this flux is maximized for incoming waves with an offshore direction of about 45 degrees (Fig. 2, see also Ashton and Murray, 2006a, 2006b). Alongshore sediment transport also defines when a delta adopts a cuspate, wave-dominated morphology. If the fluvial sediment supply is less than the maximum potential alongshore sediment transport (the maxima in Fig. 2a), both flanks of a delta can be oriented such that the fluvial supply of coarse-grained shore-compatible sediment is transported away from the river mouth by alongshore sediment transport (Nienhuis et al., 2015).

Because of the angle dependence of alongshore sediment transport (Fig. 2a), oblique waves can generate a net alongshore drift that can result in delta plan-view asymmetry, particularly if fluvial sediment input is relatively large (Ashton and Giosan, 2011; Bhattacharya and Giosan, 2003). In asymmetric deltas, accumulating sediments come not only from the "dipfeeding" river but also from updrift sources via the wave-driven "strike-feeding" littoral region (Ashton and Giosan, 2011; Dominguez, 1996; Giosan, 1998).

To characterize the morphologic and sedimentological asymmetry of deltas, Bhattacharya and Giosan (2003) proposed an asymmetry index, A: net alongshore sediment transport at the river mouth (in m^3yr^{-1}) divided by river water discharge (in 10^6 m^3month^{-1}). For low values of A (<200), deltas tend to be symmetric, and both delta flanks have similar morphologies. For large values of A (>200), deltas are asymmetric and the updrift flank is sourced from the littoral system whereas the downdrift flank is composed of fluvial sediments. For example, in its later history the Sao Francisco delta built beach plains on its north (updrift) side, whereas fluvial fine-grained sediments fed the downdrift and accumulated, interspersed with beach ridges, on the south side flank (Fig. 1b, Dominguez, 1996). Depending on the balance between fluvial and marine controls, delta or delta lobe asymmetry can change during growth (Bhattacharya and Giosan, 2003; cf., Rossetti et al., 2015). A quantitative framework of deltaic channel orientation has therefore the potential to strengthen interpretations of the sedimentary architecture of deltas.

2.2 Channels on Deltas

Deltaic distributary channels are generally devoid of meanders that are common on many alluvial channels farther upstream (Jerolmack and Mohrig, 2007). The absence of meanders is a direct result of the lack of lateral channel migration (Hudson and Kesel, 2000; Kolb, 1963). Lamb et al. (2012) postulated that backwater dynamics create an efficient fluvial sediment transport regime through the lower reaches of a deltaic channel, limiting point bar formation and meander initiation on the delta plain. In the absence of post-depositional lateral migration mechanisms, deltaic channel patterns must therefore be the result of depositional history at the delta coastline (e.g., Bates, 1953).

However, controls on the channel orientation of wave-influenced deltas are not straightforward; channels can be directed either along with or against the direction of net littoral drift. For example, the Ombrone delta (Fig. 1a) is oriented into the direction of wave approach. Other deltaic channels (e.g. Nile, Sao Francisco) have migrated away from the waves (Fig. 1b, 1c), or display no dominant direction (Fig. 1d).

Investigating the orientation of small streams along the coast, Gulliver (1896) noted that stream deflections follow nearshore currents, which Zenkovich (1967) attributed to breaking-wave-driven alongshore sediment transport. Pranzini (2001) demonstrated how the channels of the Ombrone and the Arno delta have changed their orientation over time, suggesting that the channels rotated into the direction of net alongshore drift during a period of increased sediment load associated with land use changes. He noted that delta progradation into a more pointy cuspate shape increased the wave energy per meter of coast on the updrift flank but decreased wave energy on the downdrift flank. In this model, wave energy imbalance can increase sediment transport away from the river mouth along the updrift flank, reorienting the channel into the direction of wave approach (Pranzini, 2001).

Although the coupling between alongshore sediment transport and channel orientation appears to be intuitive, there have been no studies to date that offer a predictive characterization of channel orientation, or studies that have shown how the continuum of delta morphologies could lead to a continuum of channel orientations.

2.3 Alongshore Sediment Bypassing the River Mouth

A river mouth can act as a 'hydraulic groin' along a sandy coastline and partially or entirely block alongshore transport, trapping sediments updrift and limiting supply to downdrift beaches (Zenkovich, 1967). Littoral sediment that is blocked by the river mouth can form river mouth spits and initiate river mouth migration (Dominguez, 1996; Zenkovich, 1967). Aibulatov and Shadrin (1961) used tracers to study littoral sediment bypassing the river mouth and found transport pathways around the river mouth bar. Another study, by Balouin et al. (2006), found that sediment can also be bypassed through the channel to the downdrift beach. Investigating controls on bypassing, Kirk (1991) observed that river mouths tend to low bypassing rates at moderate discharge conditions and high bypassing rates for low discharge conditions. This tendency for increased discharge to lead to decreased bypassing has also been demonstrated using numerical modeling experiments (Nienhuis et al., 2016). A dependence on discharge would give alongshore sediment bypassing a strongly seasonal character (Cooper, 1994).

Sediment bypassing occurs on longer timescales at distributary mouths of large wave-dominated deltas (Bhattacharya and Giosan, 2003). Subaqueous shoals that develop during floods can lead to a feedback between the trapping of fluvial sediment near the river mouth and the blocking and redistribution of littoral sediments that further expands the subaqueous delta (Giosan et al., 2005). Eventual emergence, elongation, and amalgamation of river mouth islands transforming into spits that then attach to the delta coast represents a long-term bypassing mechanism with timescales of multiple centuries. On the Danube delta, bypassing is intertwined with the simultaneous dynamics of littoral transport along the wave-dominated coastline (Giosan, 2007; Giosan et al., 2013). Bypassing and other river mouth processes could affect the delta channel orientation by controlling the partitioning of fluvial and littoral sediments between both delta flanks.

2.4 Modeling Wave-influenced Deltas

The plan-view dynamics of wave-influenced deltas has been modeled analytically (Bakker and Edelman, 1964; Grijm, 1960; Larson et al., 1987) and numerically (Ashton and Giosan, 2011; Komar, 1973; Nienhuis et al., 2013). These previous models have assumed a fixed channel orientation, typically perpendicular to the regional shoreline trend with sediment deposition modeled as a point source at the river mouth. In the model of Larson et al. (1987), alongshore sediment transport is linearly related to the wave approach angle (small angle approximation of the CERC equation, Fig. 2a), which reduces coastal evolution to a classic diffusion problem with no morphologic differences between the updrift and downdrift delta flank. Accounting for non-linearity but not for wave refraction, Bakker and Edelman (1964) demonstrate how oblique wave incidence can result in a morphologic groin effect: preferential growth of the updrift delta flank when shoreline instability, and an associated decrease in alongshore sediment transport, occurs along the downdrift flank.

More recently, Ashton and Giosan (2011) studied the effect of a distribution of wave angles on wave-influenced deltas in the Coastline Evolution Model (CEM, Ashton and Murray, 2006a). The model results, which account for non-linearity and wave refraction, suggest that the morphologic groin effect occurs due to a decrease in wave height along the downdrift coast, even when waves break at relatively small angles. Furthermore, Ashton and Giosan (2011) suggest that the spread of incoming wave directions acts as an important control on the delta plan-view shape and progradation rate. Further analytical exploration by Nienhuis et al. (2015) suggest that the distribution of incoming waves can even control whether a delta will attain a wave-dominated or river-dominated morphology. Using CEM, Ashton et al. (2013) modeled two channels that randomly rotate laterally. By coupling channel length via channel slope to the fluvial sediment flux partitioning, their study showed that feedbacks tend to equilibrate channel lengths and result in more regularly cuspate delta shapes even with multiple active distributaries. All of these previous model applications treated the river mouth solely as an additional sediment source—littoral sediment was freely able to bypass the river mouth.

Here, we expand upon previous studies by incorporating two aspects of wave-dominated deltas that have not yet been accounted for: (1) the potential for feedbacks at the shoreline to reorient the channel course, and (2) the ability of the river mouth to block bypassing of some of the alongshore sediment transport flux. We use an exploratory modeling approach (Murray, 2003) to analyze and quantify the potential effect of wave climate, fluvial sediment load, and alongshore sediment bypassing on channel orientation.

3 Methods

3.1 Coastline Evolution Model

To investigate the controls on channel orientation, we modified the existing plan-view model of shoreline dynamics CEM (see Ashton and Murray, 2006a). CEM assumes a constant shoreface cross-sectional profile such that the divergence of littoral fluxes along the coast corresponds directly to advance or retreat of the shoreline position (Ashton and Murray, 2006a; Ashton et al., 2001). Assuming refraction over shore-parallel shoreface contours, the wave energy and wave direction then drive a sediment flux alongshore (Q_s), calculated with the CERC formula for littoral transport (Fig. 2a, Komar, 1971). The plan-view domain is divided into cells (cell size is 40 m) that are filled (land), empty (sea) or partially filled (shoreline). The percentage filled in each cell sets the cross-shore location of the shoreline within the cell and is used to calculate the shoreline orientation with respect to neighboring cells (Fig. 3a, Ashton and Murray, 2006a).

Every time step (one day), the model picks a deep-water wave direction from a probability distribution function representing the directional wave climate. We define the directional spectrum of incoming waves using two parameters: the fraction of waves coming from the left looking offshore (wave asymmetry, A), and the fraction of waves coming approaching from high angles ($|\phi_0 - \theta| > 45$, H, see Fig. 2b). In our model experiments, we have varied the wave asymmetry A between 0.5 and 0.8, the high-angle proportion H between 0.1 and 0.3, and the wave height between 0.8 and 1.2 meters. We use a constant wave period of 5 seconds.

3.2 Fluvial Sediment Flux and Dynamic Channel Orientation

To represent a fluvial sediment source in the CEM, one cell along the shoreline is defined as the river mouth cell (using a method described below) and includes a fluvial sediment flux (Q_r) in addition to the littoral sediment flux. We assume that fine-grained fluvial sediment is transported offshore by wave suspension and that the coarse-grained sediment directly amalgamates to the shoreface (Ashton and Giosan, 2011). The fluvial sediment flux (Q_r) should therefore be interpreted as the coarse-grained or sand load fraction of the total fluvial sediment flux. By using periodic boundary conditions, the model assumes that deltas grow out along an infinitely long sandy coastline with a continuous supply of sediment from the updrift delta coast.

Ashton and Giosan (2011) and Ashton et al. (2013) modified the CEM such that straight channels grew from a nodal point upstream on the delta plain, either in a predefined or randomly selected direction. Channel direction was therefore independent of local shoreline conditions. Here, we have modified CEM such that the channel no longer grows in a predefined direction, instead allowing feedbacks between the shoreline and fluvial sediment delivery to the coast to redirect the channel. To allow these feedbacks, we apply a phenomenological rule, a type of ansatz, such that the river grows perpendicularly to the local shoreline orientation set by the channel's two neighboring cells (Fig 3b).

This shore-perpendicular approach is the adoption of the idea that river mouth morphology acts as the primary control on river mouth hydrodynamics and the resulting sedimentation and erosion patterns (Roelvink et al., 1998): if sediment is primarily deposited on one end of the channel, this would likely redirect the flow such that the resulting deposition would become more perpendicular to the local topography contours. Although there is an *ad hoc* element to this river steering rule, analysis of several deltas worldwide shows that the channel trajectory is often perpendicular to the local (~100 m) shoreline orientation, typically varying by only a few degrees (Supplemental Materials Table 1). Our model results therefore act in part as a test of this shore-perpendicular growth rule, which, in keeping with our exploratory modeling approach, allows us to examine feedbacks between shoreline orientation and channel direction.

Sensitivity tests show that the channel path is not sensitive to grid resolutions between 20 m and 100 m.

3.3 Channel Bypassing

The other modification to CEM is a limit to the amount of littoral sediment flux that is allowed to bypass the river mouth. If there is a sediment flux from a neighboring cell into the river mouth cell, only a fraction of this alongshore sediment flux, β (the bypassing fraction), is allowed to move into the river mouth cell (Fig. 3b). When $\beta = 0$, the river mouth acts as a perfect groin and blocks all the updrift sediment. For $\beta = 1$, as in the original model of Ashton and Giosan (2011), all sediment is freely able to bypass the river mouth, and sediment transport across the river mouth is only based on the local shoreline orientation. The bypassing fraction applies to each wave condition, and therefore the river can block sediment transport across the mouth cell from both the left and right neighbors.

Note that we do not model river mouth processes directly, rather we assume an average sediment bypassing fraction and investigate its effects on delta dynamics. Even though the assumption of a constant bypassing fraction is a simplification of the natural bypassing process, our approach allows for straightforward understanding of the end member cases $\beta = 0$ and $\beta = 1$, and is in keeping with our exploratory modeling approach. We ran model experiments for fluvial sediment fluxes between 10 kgs^{-1} and 80 kgs^{-1} and for β of 0, 0.5, and 1.

4 Results

4.1 Styles of Channel Orientation

We have modeled delta formation under different scenarios by varying fluvial sediment supply (Q_r), wave energy, angular wave distribution, and alongshore sediment bypassing (β) to investigate morphologic control on deltaic channel orientation. After ~10 model years under constant forcing (Q_r, β, and wave climate), modeled deltas reach a dynamic steady state at the river mouth, with intermittent variability in river channel orientation arising from the stochastic wave angle selection. At this steady state, deltas continue to grow with constant (or near constant) shoreline orientation and channel orientation (Fig. 4).

We observe three styles of delta growth based upon channel orientation: (i) *symmetric growth*, (ii) *downdrift migration*, and (iii) *updrift migration* (Fig. 4). As expected, symmetrical wave climates build symmetric deltas because there is no net alongshore sediment flux across the river mouth and the shoreline angles on both flanks remain identical. However, symmetric growth also occurs for asymmetrical wave climates for low Q_r and full bypassing (Fig. 4). In this case, shoreline reorientation is limited such that the small angle approximation of the alongshore sediment transport function is appropriate; alongshore transport remains linearly related to the shoreline angle (Fig. 2a) and the shoreline orientations close to the river mouth remain symmetric. If river mouth bypassing is limited and Q_r is low, the channel migrates downdrift. However, for higher Q_r, channels migrate updrift into the direction of dominant wave approach, an effect that is accentuated by low alongshore sediment bypassing (Fig. 4).

4.2 Framework for Analyzing Wave-influenced Deltas

To understand the controls on channel orientation, we next sought to identify the sediment transport fluxes driving morphologic change. Three key sediment fluxes affect the morphology of the modeled wave-influenced deltas. Q_r is the fluvial sediment flux that is retained nearshore and therefore contributes to the cuspate shape of the delta. $Q_{s,regional}$ is the regional, "strike-feeding" (Dominguez, 1996) net alongshore sediment flux (kgs^{-1}). This regional flux is driven by asymmetry in the wave climate and is therefore independent of the river's influence on the delta shoreline. The alongshore sediment transport tends towards $Q_{s,regional}$ far away from both the left and right delta flanks (Fig. 5a, d). The third important sediment flux, set by the wave climate, is the maximum potential gross alongshore sediment flux $Q_{s,max}$, the sum of the maxima in sediment transport on the updrift, $Q_{s,u,max}$, and downdrift, $Q_{s,d,max}$, flanks for a given wave climate. Along each flank, the maximum potential flux occurs when waves approach the shoreline at approximately 45^o (Fig. 2a), but can occur at other orientations for a distribution of wave approach angles (Nienhuis et al., 2015).

For a set of environmental conditions (model inputs or for a natural delta setting), these three fluxes Q_r, $Q_{s,regional}$, and $Q_{s,max}$ can be known *a priori* and can therefore be used in a predictive framework to understand consequent delta dynamics. Following Nienhuis et al. (2015), we define the *River Dominance Ratio*:

$$R = \frac{Q_r}{Q_{s,\max}}, \quad (1)$$

which measures how wave-influenced a river delta is. If $R > 1$, fluvial sediment supply (Q_r) is larger than what waves can maximally transport away along the left and right delta flank, which should tend towards a river-dominated delta morphology.

We also define a second non-dimensional number comparing the regional alongshore sediment flux (driven by the wave climate asymmetry) to the fluvial sediment flux. The *Sediment Source Ratio*:

$$S = \frac{Q_{s,regional}}{Q_r}, \tag{2}$$

defines the relative littoral flux asymmetry of a delta. For $S = 0$, the wave climate is symmetrical and there is no net regional alongshore sediment transport. For $S > 1$, the long term, net alongshore transport of sediment to the delta from the updrift coastline exceeds the fluvial sediment supply, independent of river mouth dynamics.

4.3 Littoral Transport along Wave-influenced Deltas

Because our modeled deltas reach a dynamic equilibrium configuration, associated alongshore sediment transport fluxes correspondingly reach a long-term steady state that can help explain the mechanisms controlling channel orientation. We calculate the net littoral flux by summing the alongshore sediment transport contributions for a given shoreline orientation across the entire wave climate, taking into account shadowing of waves by other portions of the coast (Fig. 3a).

Approaching the river mouth from updrift (the left side for our model experiments), the alongshore sediment transport decreases, and can even reverse direction (Fig. 5d). Alongshore sediment transport increases linearly near the river mouth—a constant divergence of flux corresponds to a constant shoreline accretion rate, demonstrating that the modeled deltas are growing at a steady state.

At the river mouth, the delta shoreline abruptly reorients to accommodate the fluvial sediment flux, Q_r (Fig. 5d). We define $Q_{s,u}$ and $Q_{s,d}$ as the alongshore sediment transport immediately updrift and downdrift of the river mouth, respectively, and the maximum potential alongshore sediment transport along the flanks as $Q_{s,u} = Q_{s,u,max}$ and $Q_{s,d} = Q_{s,d,max}$. Note that if sediment is transported along the updrift flank towards the river mouth, $Q_{s,u}$ is positive, whereas a negative $Q_{s,u}$ indicates a reversal in the transport direction driven by delta growth.

4.4 Controls on channel orientation

We now apply this framework based upon alongshore and fluvial fluxes to better understand the mechanisms behind the observed model behaviors. This allows us to develop quantitative metrics that can predict the degree of downdrift or updrift migration depending on quantities determined by the delta environment: the offshore wave climate ($Q_{s,regional}$, $Q_{s,max}$), the fluvial sediment flux (Q_r), and the fraction of river mouth bypassing (β). As these quantities are exogenous, we can then apply our framework to both modeled and natural examples.

4.4.1 Symmetric Growth

For small symmetric deltas with non-migrating channels, shoreline reorientation is symmetrical on both flanks, leading to $Q_{s,u} = Q_{s,regional} - ½\, Q_r$, and $Q_{s,d} = Q_{s,regional} + ½\, Q_r$ (Fig.

5d, Case A). The reorientation of the coastline remains symmetric (or nearly so) as long as alongshore sediment transport along the downdrift flank of the delta ($Q_{s,d}$) is less than the maximum potential alongshore sediment transport along the downdrift flank ($Q_{s,d,max}$) (Fig. 5e, Case A).

4.4.2 Downdrift Migration

Downdrift migration occurs when river mouth bypassing is limited ($\beta < 1$) (Fig. 6) and fluvial sediment supply is low such that alongshore sediment transport on the updrift flank is oriented towards the river mouth ($Q_{s,u} > 0$, Fig. 5d). When downdrift migration occurs, the downdrift shoreline is oriented at a higher angle than the updrift shoreline, typically at or close to the angle of maximum transport (indicated by the magnitude of the transport flux, Fig. 5e). Interestingly, bypassing does not appear to affect the shoreline angle updrift of the river mouth: $Q_{s,u}$ is the same for no bypassing and bypassing scenarios at identical Q_r (Fig. 5e).

To formulate an *a priori*, necessary condition for downdrift migration, we cast $Q_{s,u}$ into sediment fluxes set by the delta environment. Because bypassing does not appear to affect the updrift shoreline orientation, we can write $Q_{s,u} = Q_{s,regional} - ½Q_r$. The channel will migrate downdrift if $Q_{s,u} > 0$, or, substituting into (2), if the *Sediment Source Ratio* $S > ½$ assuming no bypassing ($\beta = 0$) (Fig. 6). When some bypassing occurs ($\beta > 0$), the transition and degree of downdrift migration is controlled by a combination of the *Sediment Source Ratio* S and the bypassing fraction β (Fig. 6). Recognizing that the volume of updrift sediment blocked by the river mouth scales with the relative alongshore sediment flux (S) that cannot bypass the channel

(1-β), the ability of the deltaic channel to migrate downdrift can be described by the *Downdrift Migration Index D*:

$$D = (1-\beta)\cdot S\,. \qquad (3)$$

For D = 0, there is either a symmetric wave climate ($Q_{s,regional}$ = 0) or β =1, and the channel will not migrate downdrift. D demonstrates that, as expected, some of the alongshore sediment transport needs to be blocked by the river mouth to cause downdrift migration (see also Fig. 6). For increasing values of D, the channel should be increasingly oriented downdrift away from the direction of wave approach.

4.4.3 Updrift migration

Similarly, we can investigate what flux combinations lead to updrift migration. For small cuspate deltas that do not significantly reorient their shorelines, the channel does not migrate because the shoreline orientation is symmetrical updrift and downdrift of the river mouth. This symmetry is disturbed if, because of large fluvial sediment supply (high Q_r) or a very asymmetric wave climate ($Q_{s,regional}$ approaching $Q_{s,d,max}$), the downdrift coastline would need to transport more than what it can maximally accommodate through shoreline reorientation (i.e., if $Q_{s,regional} + \frac{1}{2}Q_r > Q_{s,d,max}$). In this case, the additional fluvial sediment flux will have to be moved away from the channel along the updrift coast, accommodated through reorientation of the updrift flank's shoreline. Asymmetry in the shoreline angles around the river mouth associated with this reorientation causes updrift migration of the channel, regardless of the direction of sediment transport updrift of the channel ($Q_{s,u}$ positive or negative). However, in most of our model simulations, the large fluvial sediment supply that caused reorientation of the updrift delta flank resulted in reversal in the direction of updrift sediment transport (Fig. 5e).

Cast into alongshore sediment transport fluxes, the channel will migrate updrift when the alongshore sediment transport that would need to be conveyed by the downdrift flank ($\frac{1}{2}Q_r$ + $\beta \cdot Q_{s,regional}$) in a symmetrical configuration is larger than the maximum potential sediment transport ($Q_{s,d,max}$):

$$\tfrac{1}{2}Q_r + \beta \cdot Q_{s,regional} > Q_{s,d,\max}\,, \tag{4}$$

or, rearranging using $Q_{s,d,max} = \frac{1}{2} Q_{s,max}$,

$$1 + 2\beta \cdot \frac{Q_{s,regional}}{Q_r} > \frac{Q_{s,\max}}{Q_r}\,, \tag{5}$$

and rewriting in terms of the *River Dominance Ratio R* and the *Sediment Source Ratio S*, we define the *Updrift Migration Index U*:

$$U = R(1 + 2 \cdot \beta S)\,. \tag{6}$$

where channels migrate updrift if $U > 1$. For $U < 1$, fluvial sediment supply is insufficient to force updrift migration, and the channel will either be symmetric or migrate downdrift. If no alongshore sediment is able to bypass ($\beta = 0$), the channel should switch from downdrift to updrift migration when $R = 1$. If alongshore sediment can bypass the mouth ($\beta > 0$), updrift migration can occur for lower fluvial sediment supply rates, as bypassed sediment from the updrift coastline brings the downdrift flank closer to $Q_{s,d,max}$.

Note that even though the transition from downdrift to updrift migration is dependent on alongshore sediment bypassing, the channel orientation of an updrift-migrating channel becomes less dependent on bypassing for increasing fluvial sediment supply. For high fluvial sediment supply $S << R$, such that $U \approx R$ (eq. 6) and U then becomes independent of β. This is intuitive because for high fluvial sediment supply, net littoral transport along the updrift flank is directed away from the river mouth ($Q_{s,l} < 0$) such that littoral sediment is rarely transported across the river mouth and therefore bypassing is unimportant

4.4.5 Updrift and downdrift migration in model results

Investigating channel orientation across a wide variety of fluvial sediment supply conditions, wave heights, angular distributions of incoming wave energy, and alongshore sediment bypassing fractions, we find that the *Updrift Migration Index U* (eq. 6) and the *Downdrift Migration Index D* (eq. 3) effectively explain the variety in modeled channel orientations (Fig. 7a). Channel orientations in the space defined by U and D vary smoothly; channels migrate downdrift for large values of D and updrift for large U. Updrift channel orientations increase for more asymmetric wave climates. This occurs in part because if the wave climate is symmetrical ($S = 0$), there is no “updrift” or “downdrift”, and the channel will not migrate even if $U > 1$.

4.5 Comparison to natural examples

We use our model simulations to derive a predictive framework of channel orientation, fitting a smooth contour mapping onto our model-derived results to link U and D to a channel orientation (Fig. 7b). R and S (and therefore U and D for an assumed alongshore sediment bypassing fraction) can be determined *a priori*, allowing us to test this channel orientation framework for natural deltas. We calculate R and S for 10 natural deltas (or delta lobes) using NOAA WaveWatch III data (Chawla et al., 2013) and published fluvial sediment fluxes (see Supplemental Table 1). We measured the regional shoreline orientation by connecting the updrift and downdrift coast at the locations closest to the river mouth where their orientations align.

Unfortunately, long-term bypassing rates are unknown for most natural case samples, partially because direct measurements of such rates are difficult to measure. This limitation does not apply to deltas with nearly (but not completely) symmetric wave climates ($S \rightarrow 0$ but $S > 0$) with large U (Rosetta, Nile) where the channel orientation is mostly independent of the bypassing fraction (Fig. 7b).

However, for asymmetric wave climates and an unknown bypassing fraction, there is only a limited space within Fig 7B that the delta can plot (shown by the dashed lines for the Danube and the Sao Francisco), such that our predictive framework can be used to determine if a delta's channel orientation suggests significant bypassing. Starting with an initial assumption of no bypassing ($\beta = 0$), the tendency for deltaic channels to either grow into (blue shades) or away from (red shades) the dominant wave direction coincides with the predictive framework for all cases except for the Danube and the Sao Francisco (Fig. 7b). This provides a general prediction that bypassing is low for most of the cases with large S. The general agreement between our prediction and the test cases suggests that wave climate asymmetry and fluvial sediment supply are primary controls on channel orientation for these deltas, and that the modeled dynamics in our exploratory coastline model are appropriate for the representation of large-scale delta morphology.

Assuming $\beta = 0$ overestimated the downdrift orientation of the channels for the St. George lobe of the Danube and the Sao Francisco, suggesting that bypassing is likely significant for these deltas. For these two cases, we can apply our predictive framework to infer the fraction of alongshore sediment bypassing. In the space defined by U and D, the bypassing fraction β follows a linear trajectory from $U = R$ and $D = S$ (for $\beta = 0$) to $U = R \cdot (1+2S)$ and $D = 0$ (for $\beta = 1$). We can follow the trajectory for increasing bypassing to match an observed channel orientation with an unknown bypassing fraction (dashed lines in Fig. 7b).

The St. George lobe of the Danube delta shows a symmetrically growing channel (Fig. 1d). For $\beta = 0$, the framework predicts a downdrift deflection of about 10°. Following the trajectory for increasing β (dashed line in Fig. 7b), we find that an efficient bypassing regime (β approaching 1) compares best to the observed channel orientation. Although quantitative measurements have yet to be performed for alongshore sediment bypassing around the Danube, the possibility of an efficient bypassing regime has been suggested by Giosan (2007) based upon the existence of a large subaqueous platform in front of the river mouth promoting wave breaking and alongshore sediment bypassing.

The Sao Francisco River delta channel is also reoriented downdrift to a smaller extent (15°) than what the $\beta = 0$ scenario would predict (35°, Fig. 7b). Using our predictive framework, we find our model simulations at $U = 2/3$ and $D = 4/10$ generate channel orientations of 15° (Fig.

7b). For the Sao Francisco, with a *Sediment Source Ratio* $S = 1$, and the *River Dominance Ratio* $R = 0.3$ (Supplemental Table 1, Dominguez, 1996), this leads to a predicted long-term bypassing fraction of $\beta = 0.6$.

Using predicted bypassing fractions, we can also estimate the relative proportion of coarse-grained sediment from the updrift littoral system versus fluvially sourced sediment in the downdrift delta flank. For the Sao Francisco, with $\beta = 0.6$ and $S = 1$, and using $Q_{s,u} = Q_{s,regional} - \frac{1}{2}Q_r$, we estimate that $\beta \cdot Q_{s,u} = \frac{6}{10}(Q_{s,regional} - \frac{1}{2}Q_r) = \frac{3}{10} Q_r$ of the downdrift flux is littoral material sourced from the updrift flank. Compared to 1 Q_r that is sourced from the river, we estimate that $\frac{10}{13}$ of the downdrift coarse-grained flux should be fluvially derived. This dominance of fluvially derived sediment on the downdrift flank qualitatively agrees with analyses of the Sao Francisco beach median grain size that indicate that the downdrift flank is composed of less mature (fluvially derived) sands of about 0.23 mm whereas the updrift flank is composed of 0.125 mm sands (Barbosa and Dominguez, 2004).

4.6 Change in sediment supply

Our modeling results suggest that deltas experiencing changes in wave climate or fluvial sediment supply should see a corresponding shift in their channel orientation at the coastline. Such changes have also been observed on natural deltas. For example, noting the channel orientation of the Arno and Ombrone deltas in Italy, Pranzini (2001) suggested that a change from downdrift to updrift migration occurred as a response to land-use changes that increased the fluvial sediment flux.

To investigate the response of the channel orientation of a wave-influenced delta to changes in the fluvial sediment supply, we ran a modeling scenario resembling the case of the Ombrone delta. In this simulation, we first grow a delta with a low fluvial sediment supply and no alongshore sediment bypassing ($\beta = 0$) such that a downdrift migrating channel develops. Then, we increase the fluvial sediment supply under a constant wave climate. We find that for an increase in sediment supply, the channel orientation rapidly adjusts from downdrift to updrift migration (Fig. 8). The steady-state channel orientations for both the low flux and high flux periods agree with the predictive framework (markers on Fig. 7b).

To investigate if a fluvial sediment supply decrease has a similar effect on channel orientation, we extend the previously described scenario and now decrease fluvial sediment supply back to 40 kgs^{-1} (Fig. 8b). Interestingly, because the decrease initiated partial abandonment and retreat of the river mouth, we find a significant delay before the channel again attains its original orientation (Fig. 8c). Even though the channel still supplies fluvial sediment to the coast, the river mouth temporarily erodes and ceases to prograde for an extended period. Focused erosion around the river mouth occurs because the flanks of the delta are oriented to transport more littoral sediment to the distal flanks than they now receive from the river mouth. This negative (local) sediment budget results in a pulse of coastline retreat diffusing outwards away from the river mouth even as the distal portions of the delta continue to grow, with potentially important consequences not only for interpretations of modern deltaic change but also the stratigraphic record of delta growth (Madof et al., 2016).

5 Discussion

5.1 Implications for delta predictions and paleo-environmental reconstructions

Model explorations performed here show how deltaic channel orientation can respond to long-term environmental conditions via feedbacks with wave-driven alongshore sediment transport (Fig. 5). For known directional wave climate, fluvial sediment supply, and alongshore sediment bypassing we can calculate U and D (eq. 3 and 6), which determine the resulting steady-state channel orientation in accordance with our model simulations and natural examples (Fig. 7b).

Following the same approach, our framework (Fig. 7b) also offers new possibilities for paleo-environmental reconstructions. From an observed channel orientation and an alongshore sediment bypassing fraction (inferred for instance from the channel size, see Nienhuis et al., 2016), we can determine both the *River Dominance Ratio R* and the *Sediment Source Ratio S*. R offers insight into the gross morphology of the river delta (Nienhuis et al., 2015), and S can be used to characterize the delta's sedimentological asymmetry (Dominguez, 1996; Giosan, 1998). Additionally, the product of R and S (equal to $Q_{s,regional}/Q_{s,max}$), which can be determined from just the channel orientation, provides a novel measure of wave climate directionality. For $R \cdot S = 0$, where the framework suggests a delta channel perpendicular to the regional coastline, the wave climate is predicted to be fully symmetrical (equal contributions of wave energy from the left and right regional coastline). At the other extreme, if $R \cdot S = ½$ ($Q_{s,regional} = ½\ Q_{s,max} = Q_{s,r,max}$), the wave climate is fully asymmetrical. Note that this is not a measure of local wave climate asymmetry at a single alongshore location, but rather of the deep-water wave climate, referenced from the regional coastline and independent of delta dynamics. Examples of natural systems that lend themselves to such a reconstruction are the Arno and the Ombrone deltas in Italy (Pranzini, 2001), the Jequitinhonha, the Sao Francisco, and the Doce deltas in Brazil (Rossetti et al., 2015), and the Cretaceous San Miguel Formation (Bhattacharya and Giosan, 2003).

5.2 Effect of fluvial water discharge

Our model explorations of wave-influenced deltas suggest that, in all cases, the channel orientation of wave-influenced deltas should generally become increasingly updrift for increasing fluvial sediment supply (Fig. 4). High fluvial water discharge, on the other hand, is associated with low alongshore sediment bypassing (Kirk, 1991; Nienhuis et al., 2016), which for low fluvial sediment supply should result in downdrift migrating channels. Combined, the influence of fluvial sediment supply and fluvial discharge on channel orientations suggest that fluvial sediment concentration (fluvial coarse-grained sediment supply divided by discharge) may play an important role in controlling delta morphology. Deltas fed by a channel with low fluvial sediment concentration should tend to migrate downdrift, as the relatively high discharge will limit bypassing. In contrast, deltas fed with a high fluvial sediment concentration, with a relatively large fluvial sediment supply, should tend to migrate updrift.

5.3 Channel orientation for low fluvial sediment supply

For low fluvial sediment flux or high wave energy, river mouths are not able to reorient the coastline (Nienhuis et al., 2015). These small channels, however, are often ‘deflected’ (Bhattacharya and Giosan, 2003) and show downdrift migration along an otherwise straight coastline. River mouth processes likely dictate at this scale, such that the dynamics that set channel orientation are not determined by fluvial sediment supply, but rather by alongshore sediment bypassing (Kirk, 1991; Nienhuis et al., 2016). When downdrift migration occurs without the net progradation typical of river deltas, channel orientation is generally variable, as spit breaching will reset the channel orientation on decadal timescales (Zenkovich, 1967). Because our model sets the channel direction by the local shoreline orientation, downdrift migration in our study requires coastline reorientation. The smallest-scale downdrift migrating channel our model can resolve therefore must extend on the order of a few river mouth widths offshore (e.g., Fig. 1c).

5.4 Coarse-grained assumption

We assume that fluvially derived fine-grained sediment does not significantly contribute to the processes controlling subaerial plan-view delta shape. Even though this is generally a reasonable assumption for deltas primarily shaped by alongshore sediment transport (Limber et al., 2008), river mouths on asymmetric deltas can act as traps of fine-grained material on the downdrift flank, resulting in series of shoreface sands separated by finer grained deposits (Bhattacharya and Giosan, 2003). Further research is needed to investigate how much fine-grained sediment contributes to the overall mass balance (and shoreline orientations) of wave-influenced deltas.

5.5 Shoreline-parallel bathymetry contours

CEM assumes that waves refract across shoreline-parallel contours and that alongshore sediment flux divergence is linearly related to shoreline change (Ashton and Murray, 2006a). With this assumption, the model collapses vertical delta dynamics down to a single contour line. A drawback is that the parallel contour line assumption neglects the sometimes complex bathymetry that characterizes many wave-influenced deltas. In particular, deltas that develop in an asymmetric wave climate often show large subaqueous platforms downdrift that reduce the local downdrift wave energy (Correggiari et al., 2005; Giosan, 2007; Giosan et al., 2005), and therefore violate the one-contour-line assumption (Falqués and Calvete, 2005). However, as our analysis suggests that the channel orientation is controlled by the updrift flank sediment flux partitioning, delta mouth dynamics may be relatively independent of the downdrift delta flank unless there is significant coastline reorientation.

6 Conclusion

In this study we have investigated how feedbacks between the directional wave climate, fluvial sediment supply, and alongshore sediment bypassing can determine the channel orientation of wave-influenced deltas. Modeling results enabled us to formulate key criteria for updrift and downdrift channel migration. In particular, we found that limiting alongshore sediment bypassing of river mouths should tend to drive downdrift channel migration. On the other hand, deltaic channels are expected to migrate updrift when the magnitude of the fluvial sediment supply causes the downdrift flank to reach the angle of maximum alongshore transport, a phenomenon that can occur both with and without alongshore sediment bypassing. Translating modeling results into a predictive framework shows good agreement with natural examples, providing an approach to estimate the long-term alongshore sediment bypassing of river mouths. Additionally, we find that the deltaic channel orientation can respond dynamically to fluvial sediment supply changes, highlighting the potential of plan-view delta geometry to backtrack climate and land-use changes.

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8 References

Aibulatov, N.A., Shadrin, I.F., 1961. Some data on the long-shore drift of sand near natural obstacles. Tr. Inst. Okeanol. Akad. Nauk. SSSR 53.

Ashton, A.D., Giosan, L., 2011. Wave-angle control of delta evolution. Geophys. Res. Lett. 38, L13405. doi:10.1029/2011GL047630

Ashton, A.D., Hutton, E.W.H.H., Kettner, A.J., Xing, F., Kallumadikal, J., Nienhuis, J.H., Giosan, L., 2013. Progress in coupling models of coastline and fluvial dynamics. Comput. Geosci. 53, 21–29. doi:10.1016/j.cageo.2012.04.004

Ashton, A.D., Murray, A.B., 2006a. High-angle wave instability and emergent shoreline shapes: 1. Modeling of sand waves, flying spits, and capes. J. Geophys. Res. 111, F04011. doi:10.1029/2005JF000422

Ashton, A.D., Murray, A.B., 2006b. High-angle wave instability and emergent shoreline shapes: 2. Wave climate analysis and comparisons to nature. J. Geophys. Res. 111, F04012. doi:10.1029/2005JF000423

Ashton, A.D., Murray, A.B., Arnoult, O., 2001. Formation of coastline features by large-scale instabilities induced by high-angle waves. Nature 414, 296–300. doi:10.1038/35104541

Bakker, W.T.J.N.P., Edelman, T., 1964. The Coastline of River-deltas, in: Edge, B. (Ed.), Proc. of the 9th Conf. on Coastal Engineering. ASCE, Lisbon, pp. 199–218. doi:10.9753/icce.v9.%25p

Balouin, Y., Ciavola, P., Michel, D., 2006. Support of Subtidal Tracer Studies to Quantify the Complex Morphodynamics of a River Outlet: the Bevano, NE Italy. J. Coast. Res. 1, 602–606.

Barbosa, L.M., Dominguez, J.M.L., 2004. Coastal dune fields at the São Francisco River strandplain, northeastern Brazil: morphology and environmental controls. Earth Surf. Process. Landforms 29, 443–456. doi:10.1002/esp.1040

Bates, C.C., 1953. Rational theory of delta formation. Am. Assoc. Pet. Geol. Bull. 37, 2119–2162.

Bhattacharya, J.P., Giosan, L., 2003. Wave-influenced deltas: geomorphological implications for facies reconstuction. Sedimentology 50, 187–210. doi:10.1046/j.1365-3091.2003.00545.x

Chawla, A., Spindler, D.M., Tolman, H.L., 2013. Validation of a thirty year wave hindcast using the Climate Forecast System Reanalysis winds. Ocean Model. 70, 189–206. doi:10.1016/j.ocemod.2012.07.005

Cooper, J.A.G., 1994. Sedimentary processes in the river-dominated Mvoti estuary, South Africa. Geomorphology 9, 271–300. doi:10.1016/0169-555X(94)90050-7

Correggiari, A., Cattaneo, A., Trincardi, F., 2005. The modern Po Delta system: Lobe switching and asymmetric prodelta growth. Mar. Geol. 222, 49–74. doi:10.1016/j.margeo.2005.06.039

Dominguez, J.M.L., 1996. The Sao Francisco strandplain: a paradigm for wave-dominated deltas? Geol. Soc. London, Spec. Publ. 117, 217–231. doi:10.1144/GSL.SP.1996.117.01.13

Falqués, A., Calvete, D., 2005. Large-scale dynamics of sandy coastlines: Diffusivity and instability. J. Geophys. Res. 110, C03007. doi:10.1029/2004JC002587

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 modelling. Earth Planet. Sci. Lett. 302, 217–226. doi:10.1016/j.epsl.2010.12.013

Giosan, L., 2007. Morphodynamic Feedbacks on Deltaic Coasts: Lessons from the Wave-Dominated Danube Delta. Coast. Sediments ’07. doi:10.1061/40926(239)63

Giosan, L., 1998. Long term sediment dynamics of Danube delta coast, in: Dronkers, J., Scheffers, M. (Eds.), Physics of Estuaries and Coastal Seas. Balkema, Rotterdam, pp. 365–376.

Giosan, L., Constantinescu, S., Filip, F., Deng, B., 2013. Maintenance of large deltas through channelization: Nature vs. humans in the Danube delta. Anthropocene 1, 35–45. doi:10.1016/j.ancene.2013.09.001

Giosan, L., Donnelly, J.P., Vespremeanu, E., Bhattacharya, J.P., Olariu, C., Buonaiuto, F.S., 2005. River delta morphodynamics: examples from the Danube delta, River Deltas: Concepts, Models and Examples. SEPM (Society for Sedimentary Geology). doi:10.2110/pec.05.83

Grijm, W., 1960. Theoretical forms of shorelines, in: Edge, B. (Ed.), 7th Conference on Coastal Engineering. ASCE, Lisbon, pp. 197–202. doi:10.9753/icce.v7.11

Gulliver, F.P., 1896. Cuspate forelands. Bull. Geol. Soc. Am. 7, 399–422.

Hudson, P.F., Kesel, R.H., 2000. Channel migration and meander-bend curvature in the lower Mississippi River prior to major human modification. Geology 28, 531. doi:10.1130/0091-7613(2000)28<531:CMAMCI>2.0.CO;2

Jerolmack, D.J., Mohrig, D., 2007. Conditions for branching in depositional rivers. Geology 35, 463. doi:10.1130/G23308A.1

Kirk, R.M., 1991. River-beach interaction on mixed sand and gravel coasts: a geomorphic model for water resource planning. Appl. Geogr. 11, 267–287. doi:10.1016/0143-6228(91)90018-5

Kolb, C.R., 1963. Sediments Forming the Bed and Banks of the Lower Mississippi River and their Effect on River Migration. Sedimentology 2, 227–234. doi:10.1111/j.1365-3091.1963.tb01216.x

Komar, P.D., 1973. Computer models of delta growth due to sediment input from rivers and longshore transport. Bull. Geol. Soc. Am. 84, 2217–2226. doi:10.1130/0016-7606(1973)84<2217:CMODGD>2.0.CO;2

Komar, P.D., 1971. Mechanics of Sand Transport on Beaches. J. Geophys. Res. 76, 713–721. doi:10.1029/Jc076i003p00713

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. J. Geophys. Res. Earth Surf. 117, 1–15. doi:10.1029/2011JF002079

Larson, M., Hanson, H., Kraus, N.C., 1987. Analytical solutions of the one-line model of shoreline change. US Army Waterw. Exp. Stn., Vicksburg.

Limber, P.W., Patsch, K.B., Griggs, G.B., 2008. Coastal Sediment Budgets and the Littoral Cutoff Diameter: A Grain Size Threshold for Quantifying Active Sediment Inputs. J. Coast. Res. 2, 122–133. doi:10.2112/06-0675.1

Madof, A.S., Harris, A.D., Connell, S.D., 2016. Nearshore along-strike variability: Is the concept of the systems tract unhinged? Geology 44, 315–318. doi:10.1130/G37613.1

Murray, A.B., 2003. Contrasting the goals, strategies and predictions associated with simplified numerical models and detailed simulations, in: Wilcock, P.R., Iverson, R.M. (Eds.), Prediction in Geomorphology. American Geophysical Union, Washington DC, USA, pp. 151–165. doi:10.1029/135GM11

Nienhuis, J.H., Ashton, A.D., Giosan, L., 2015. What makes a delta wave-dominated? Geology 43, 511–514. doi:10.1130/G36518.1

Nienhuis, J.H., Ashton, A.D., Nardin, W., Fagherazzi, S., Giosan, L., 2016. Alongshore sediment bypassing as a control on river mouth morphodynamics. J. Geophys. Res. Earth Surf. 121. doi:10.1002/2015JF003780

Nienhuis, J.H., Ashton, A.D., Roos, P.C., Hulscher, S.J.M.H., Giosan, L., 2013. Wave reworking of abandoned deltas. Geophys. Res. Lett. 40, 5899–5903. doi:10.1002/2013GL058231

Pranzini, E., 2001. Updrift river mouth migration on cuspate deltas: two examples from the coast of Tuscany (Italy). Geomorphology 38, 125–132. doi:10.1016/S0169-555x(00)00076-3

Roelvink, J.A., Boutmy, A., Stam, J., 1998. A simple method to predict long-term morphological changes, in: Edge, B.L. (Ed.), Coastal Engineering 1998. ASCE, Copenhagen, Denmark, pp. 3224–3237.

Rossetti, D. de F., Polizel, S.P., Cohen, M.C.L., Pessenda, L.C.R., 2015. Late Pleistocene–Holocene evolution of the Doce River delta, southeastern Brazil: Implications for the understanding of wave-influenced deltas. Mar. Geol. 367, 171–190. doi:10.1016/j.margeo.2015.05.012

Tanner, W.F., 1958. The equilibrium beach. Trans. Am. Geophys. Union 39, 889. doi:10.1029/TR039i005p00889

Wright, L.D., 1977. Sediment Transport and Deposition at River Mouths - Synthesis. Geol. Soc. Am. Bull. 88, 857–868. doi:10.1130/0016-7606(1977)88<857

Wright, L.D., Coleman, J.M., 1973. Variations in morphology of major river deltas as functions on ocean wave and river discharge regimes. Am. Assoc. Pet. Geol. Bull. 57, 370–398.

Zenkovich, V.P., 1967. Processes of Coastal Development, 1st ed. Oliver & Boyd, Edinburgh.

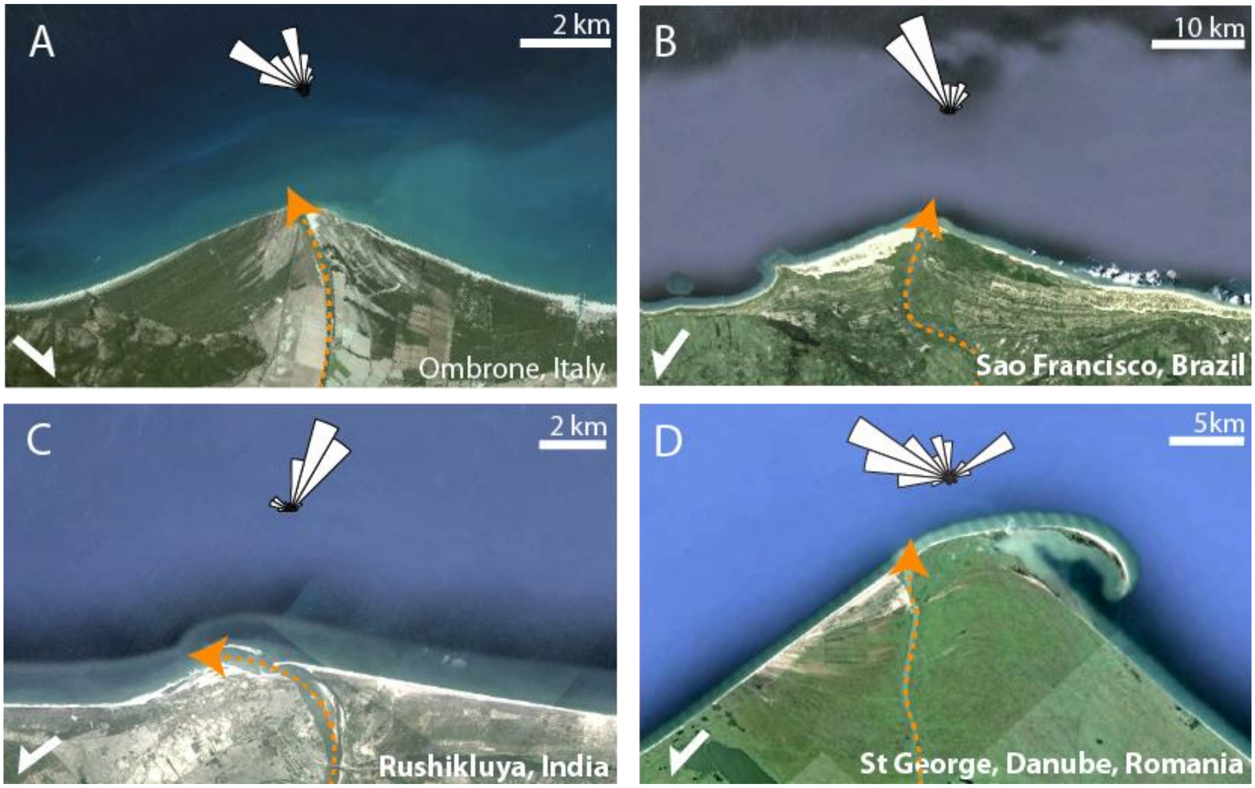

Figure 1. Examples of wave-influenced deltas with differing channel orientations in relation to the wave direction. (**A**) Ombrone, Italy, (**B**) Sao Francisco, Brazil, (**C**) Rushikulya, India and (**D**) Danube, Romania. The orange arrows indicate the active channels on these deltas. Wave roses show the angular distribution of wave energy, wave data from NOAA WaveWatch III® (Chawla et al., 2013). Images © Google Earth.

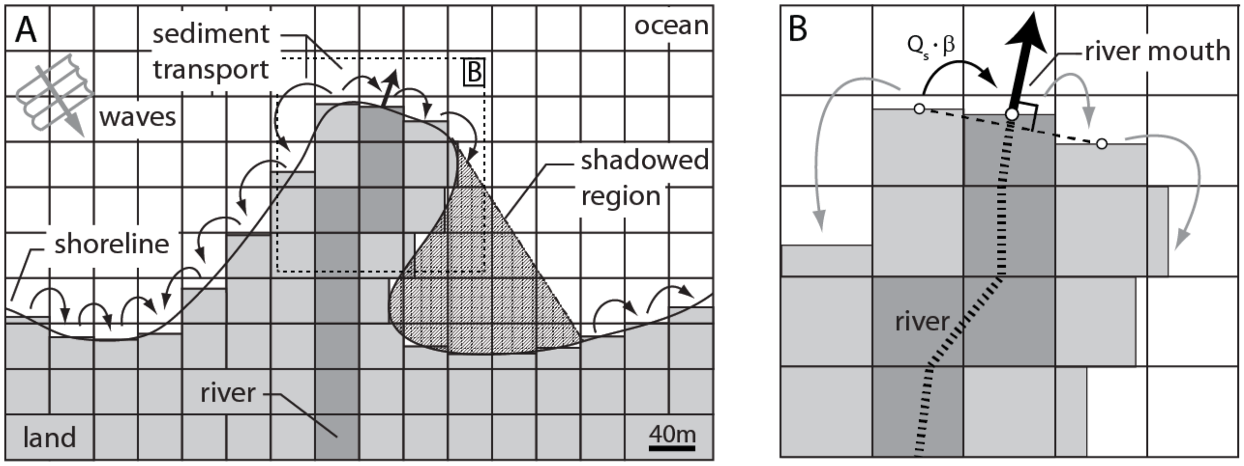

Figure 2. (**A**) Alongshore sediment flux Q_s as a function of the deep-water wave approach angle, normalized to $Q_{s,d,max}$. (**B**) Definition of the deep-water wave approach angle and the local shoreline orientation.

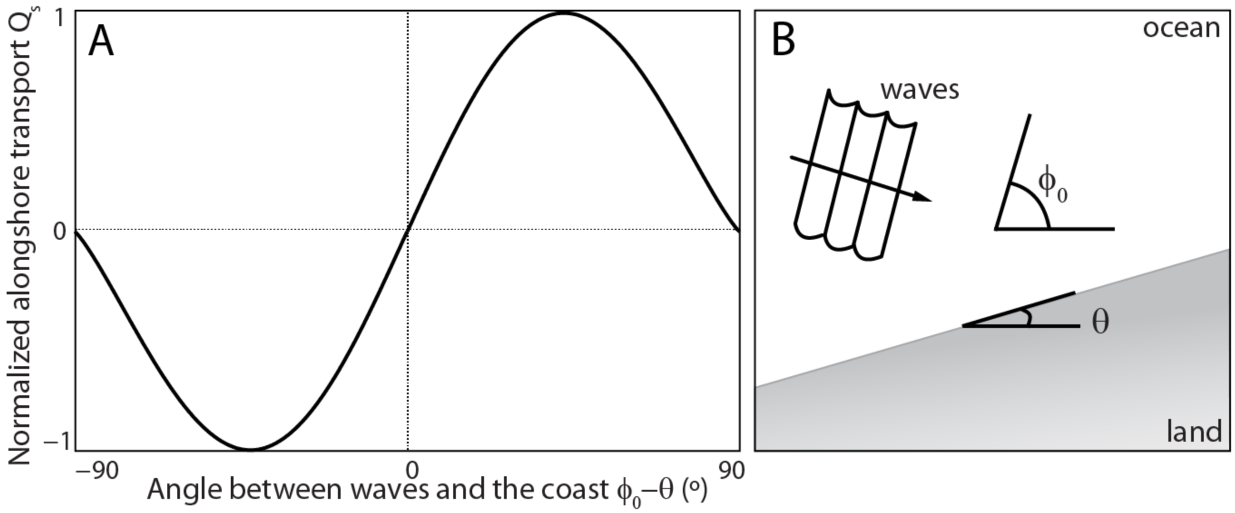

Figure 3. (**A**) Model domain schematic of CEM. The dashed box is enlarged in panel B. (**B**) Schematic depiction of the two modifications to CEM: the ability of the channel to reorient itself to be perpendicular to the local shoreline orientation and the restriction in alongshore sediment flux allowed to bypass the river mouth cell by a fraction β.

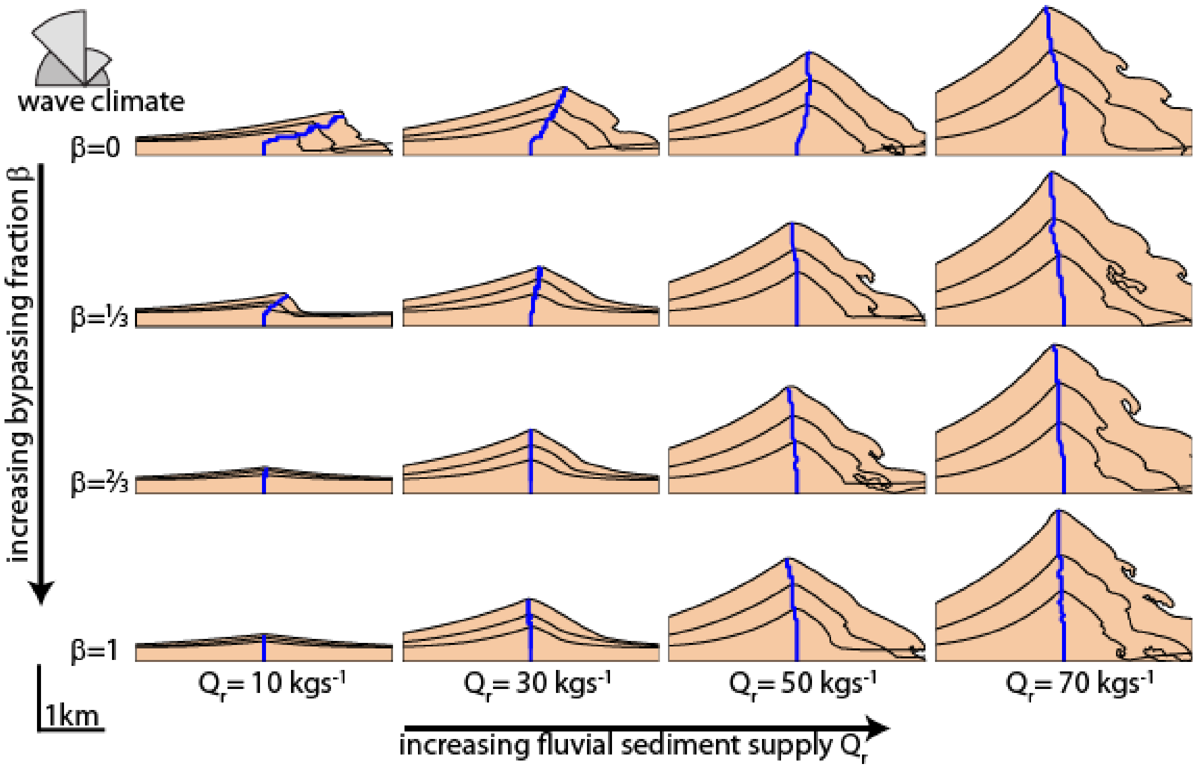

Figure 4. Examples of modeled wave-influenced deltas for different fluvial sediment supply rates and different bypassing fractions, β. The black lines indicate the shoreline position every 20 model years. All results here have the same wave climate, with 1 m waves, A= 0.8, and H = 0.3, as represented by rose of the angular distribution of incoming wave energy.

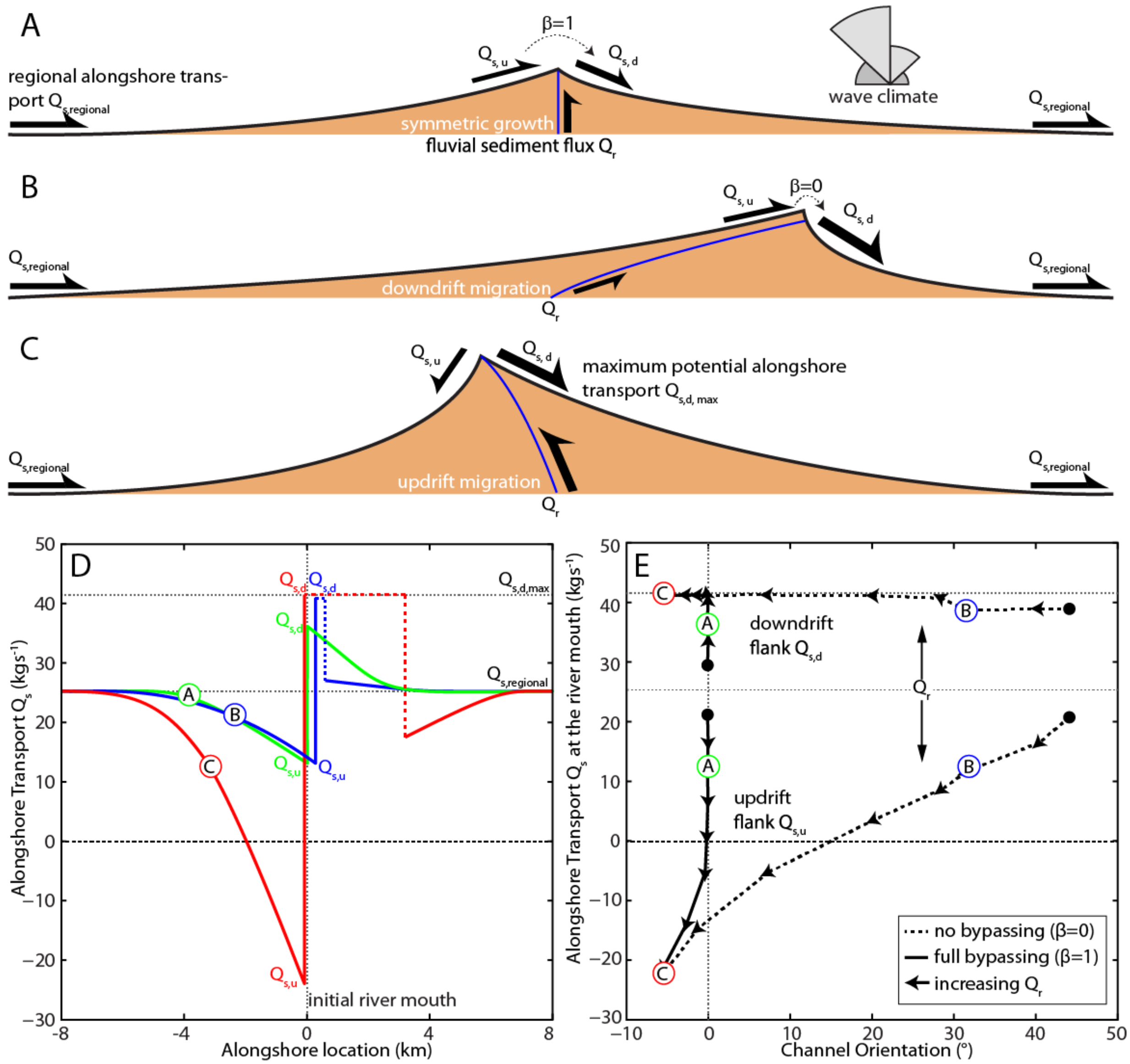

Figure 5. Flux definitions for three schematized model experiments showing (**A**) symmetric growth (R = 0.3, S = 0.9, β = 1), (**B**) downdrift migration (R = 0.3, S = 0.9, β = 0), and (**C**) updrift migration (R = 1.1, S = 0.3, β = 0). Arrows scale with the magnitude and direction of the littoral and fluvial sediment flux. The wave rose represents the area-weighted angular distribution of incoming wave energy. A = 0.8, H = 0.1. (**D**) Long-term average alongshore

sediment fluxes of three model runs schematized in panels A, B and C. Dashed portions of the lines represent when the deltaic shoreline has reached $Q_{s,r,max}$. The increase in alongshore sediment transport rate Q_s when moving across the river mouth equals the fluvial sediment flux Q_r. (**E**) Average alongshore sediment fluxes to the left and right of the river mouth ($Q_{s,l}$ and $Q_{s,r}$, the peaks in panel D) plotted against the channel orientation for modeled deltas with differing fluvial sediment fluxes ranging from 10 kgs^{-1} to 80 kgs^{-1}, with arrows, plotted for different model runs, pointing in the direction of increasing fluvial sediment flux.

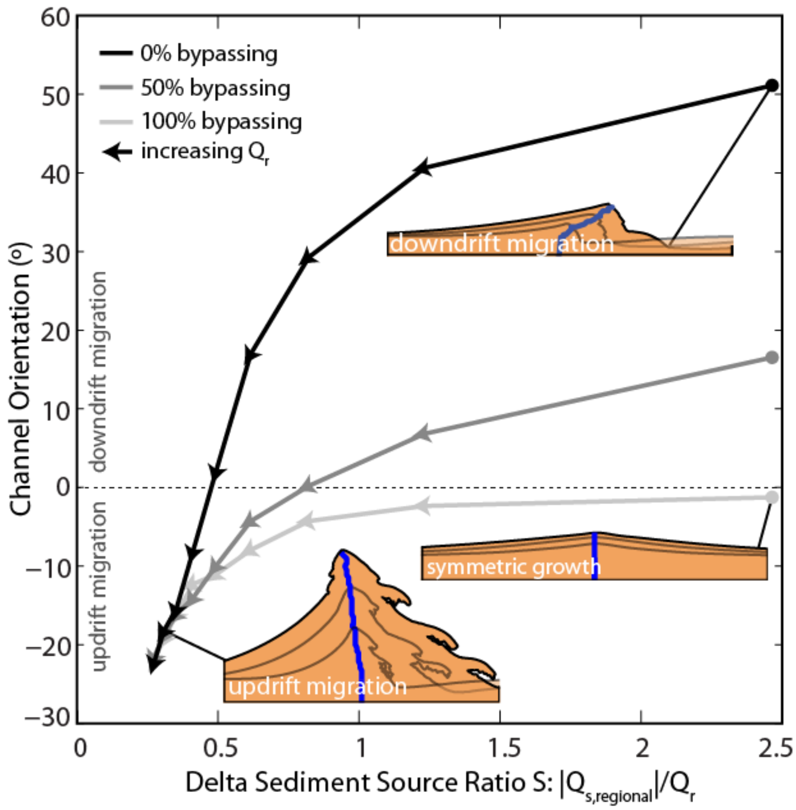

Figure 6. Channel orientation for different values of the *Sediment Source Ratio S* for varying bypassing rates and fluvial sediment supply Q_r (10 to 80 kgs^{-1}) for the same wave climate (A = 0.8, H = 0.1). Arrows point in the direction of increasing Q_r. Three model runs provide examples of delta morphology for different channel orientations.

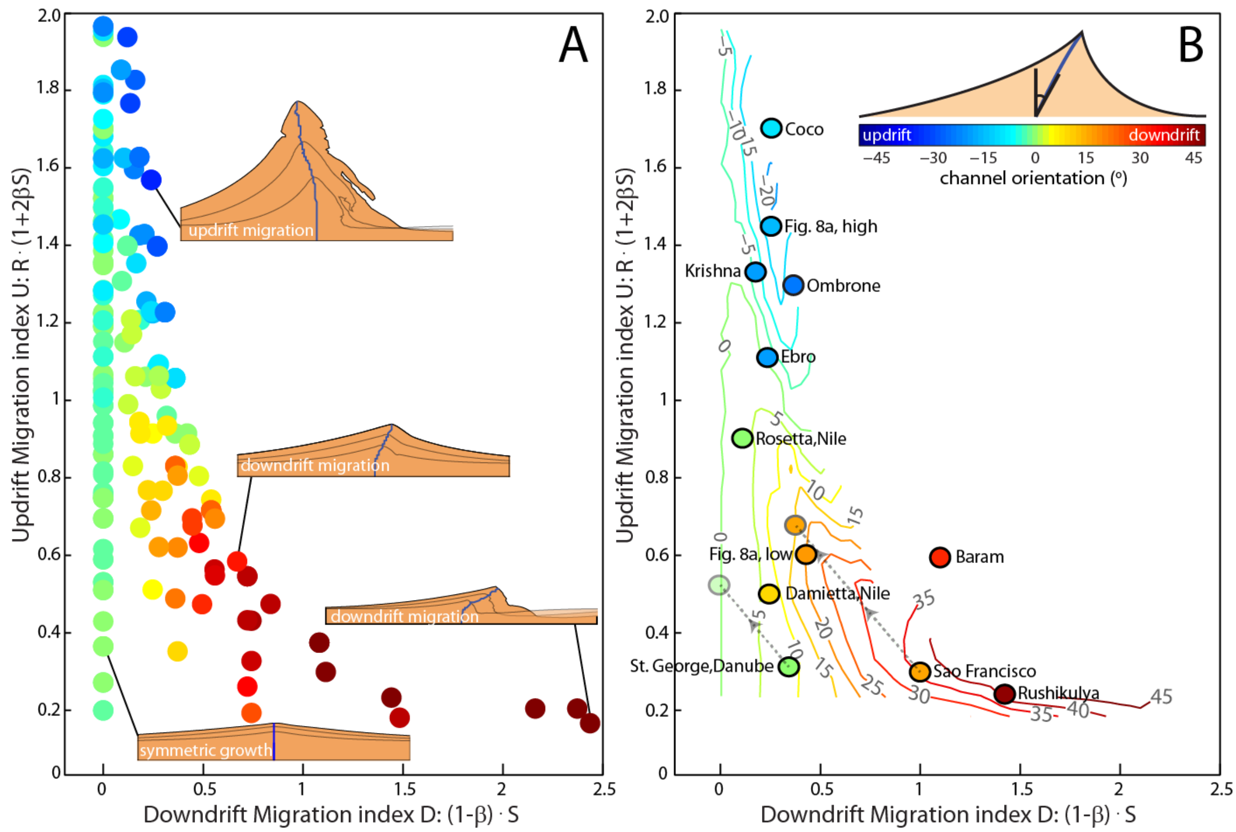

Figure 7. (**A**) Channel orientation of modeled deltas (color-coded, inset in panel B shows angle definition, positive in the direction of regional littoral drift.) for different values of *D* and *U*. Four model runs provide examples of delta morphology for different channel orientations. (**B**) Predictive framework of the channel orientation of wave-influenced deltas, plotted as contours of the channel orientation (in degrees) in the space defined by *D* and *U*. Markers are natural examples of wave-influenced deltas, plotted assuming $\beta = 0$. The dashed lines show the trajectory of the Sao Francisco and the Danube delta for increasing bypassing up to the inferred bypassing fraction. Two markers show the low and high flux channel orientation of the experiment of Fig. 8a.

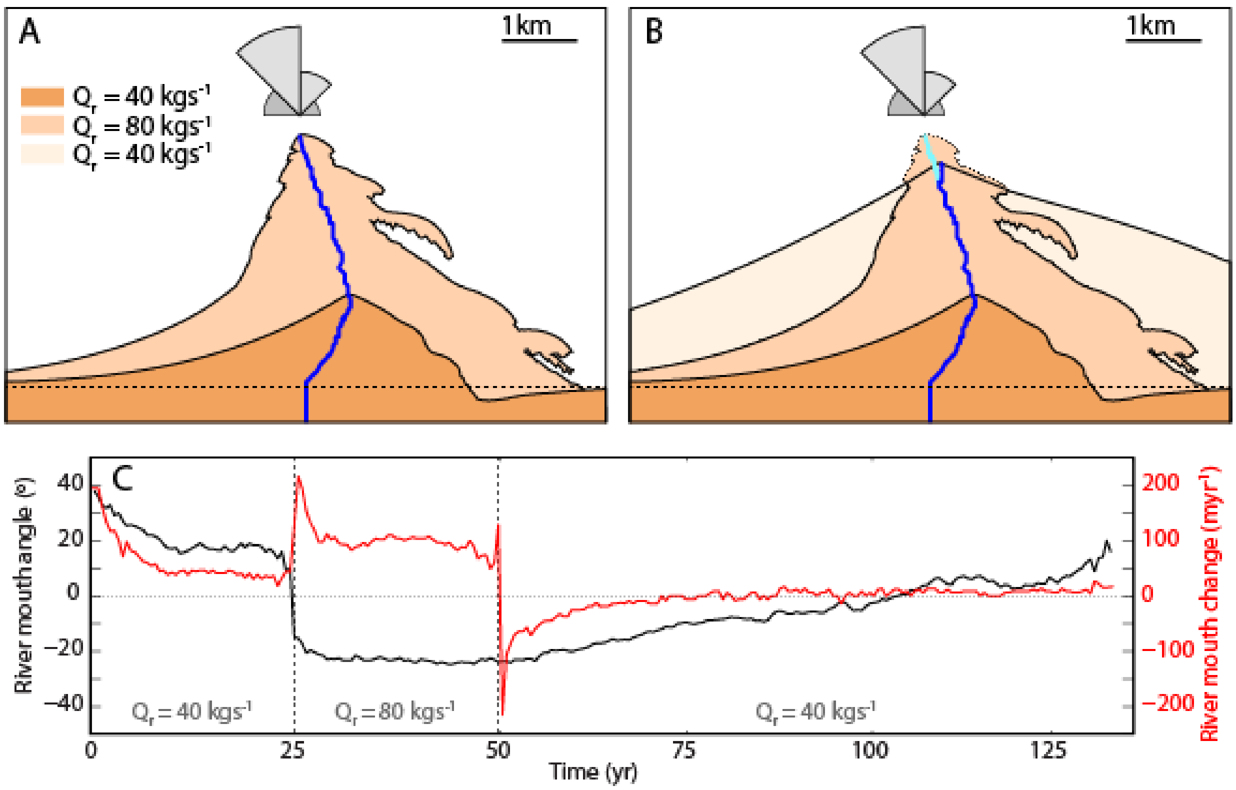

Figure 8. (**A**) Channel orientation response to an increase in fluvial sediment supply (40 kgs^{-1} to 80 kgs^{-1}), changing the *Sediment Source Ratio S* from 0.6 to 0.3, and increasing the *River Dominance Ratio R* from 0.6 to 1.2. (**B**) Channel orientation response to a subsequent decrease in fluvial sediment supply (80 kgs^{-1} to 40 kgs^{-1}). Initially the river mouth retreats (light shaded blue channel) before progradation can set a new orientation (dark shaded blue channel). Inset shows distribution of incoming wave energy. Dotted lines indicate the initial coastline. (**C**) River mouth angle (black) and river mouth progradation rate (red) of the delta in panels A and B. Vertical dotted lines indicate time of fluvial sediment supply change.