Wave reworking of abandoned deltas

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Received 5 October 2013; revised 23 October 2013; accepted 25 October 2013; published 19 November 2013.

[1] River deltas and individual delta lobes frequently face reduction of sediment supply, either from the geologic process of river avulsion or, more recently, due to human activities such as river damming. Using a process-based shoreline evolution model, we investigate wave reworking of delta shorelines after fluvial input elimination. Model results suggest that littoral sediment transport can result in four characteristic modes of delta abandonment, ranging from diffusional smoothing of the delta (or delta lobe) to the development of recurved spits. A straightforward analysis of delta shape and wave characteristics provides a framework for predicting the mode of delta abandonment. The observed morphologies of historically abandoned delta lobes, including those of the Nile, Ebro, and Rhone rivers, fit within this framework. Our results provide quantitative insight into the potential evolution of active delta environments in light of future extreme reduction of fluvial sediment input. **Citation:** Nienhuis, J. H., A. D. Ashton, P. C. Roos, S. J. M. H. Hulscher, and L. Giosan (2013), Wave reworking of abandoned deltas, *Geophys. Res. Lett.*, *40*, 5899–5903, doi:10.1002/2013GL058231.

1. Introduction

[2] River deltas are dynamic and complex depositional landforms, shaped by the competition between marine and fluvial processes [*Wright and Coleman*, 1973]. Fluvial sediment delivery to deltas or individual delta lobes varies over time, with the potential for elimination or drastic reduction of fluvial sediment by (i) delta channel avulsion, which causes sediment to be routed through a new channel [*Roberts*, 1997], (ii) redistribution of discharge among distributaries [*Giosan et al.*, 2006], or, over the last decades, (iii) river damming and water use [*Milliman et al.*, 2008]. The reduction in sediment supply often tips the balance between marine and fluvial processes, as reworking by waves changes the abandoned delta's morphology (Figure 1). Despite the importance of marine reworking [*Roberts*, 1997] in the preservation of deltaic stratigraphy [*Geleynse et al.*, 2011], there have been few quantitative studies of reworking after abandonment [e.g., *Hillen et al.*, 2009]. Here we apply a process-based model of plan-view shoreline evolution to characterize the long-term (centennial to millennial) plan-view response of a delta to wave reworking after elimination of fluvial sediment load. We then investigate how wave characteristics combined with the morphology of the delta plain created during growth affect the morphologic style of post-abandonment reworking, using both modeled and natural examples.

Additional supporting information may be found in the online version of this article.

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0094-8276/13/10.1002/2013GL058231

2. Background: Marine Reworking of Deltas

[3] The balance between incoming wave energy, tides, and river discharge operates as a first-order morphologic control on delta shape [*Galloway*, 1975; *Wright and Coleman*, 1973]. Wave influence sculpts characteristic plan-view landforms and morphologies indicative of marine reworking, including beach ridges and recurved spits; these features may be coeval with delta formation or develop after abandonment. Waves also suppress mouth bar formation [*Geleynse et al.*, 2011; *Nardin and Fagherazzi*, 2012; *Wright*, 1977], thereby limiting the amount of distributary channels on the delta plain [*Bhattacharya and Giosan*, 2003; *Jerolmack and Swenson*, 2007]. Obliquely approaching waves can deflect the river mouth itself [*Bhattacharya and Giosan*, 2003; *Nardin and Fagherazzi*, 2012].

[4] Over decadal to millennial time scales, river avulsions [*Jerolmack and Mohrig*, 2007] and discharge redistribution [*Giosan et al.*, 2005] can result in drastic reduction of sediment delivery to the coast. River damming presents a new mechanism for severe decline or even elimination of fluvial sediment discharge for the entire delta system [*Syvitski et al.*, 2009]. Sediment discharge reduction initiates a "destructive" period of the so-called "Delta Cycle" [*Roberts*, 1997], where subsidence and marine reworking control the morphology of the abandoned coast (Figure 1). Although this cycle is typically applied to river-dominated deltas, reworking of abandoned wave-dominated deltas similarly reorients the coast, resulting in truncated beach ridges and other features generally indicative of changes in driving forces [*Curray et al.*, 1969; *Giosan et al.*, 2006].

3. Background: Modeling Coastline Evolution

[5] Alongshore transport of littoral sediment by breaking waves is an efficacious sediment transport mechanism. The alongshore flux of sediment depends on the angle between wave crests (at the toe of the shoreface) and the shoreline, and displays a maximum at approximately 45° (Figure 2) [*Ashton et al.*, 2001]. Waves from beyond the maximizing angle drive an antidiffusional shoreline instability, with increasing instability for more oblique waves (Figure 2) [*Ashton and Murray*, 2006a]. Just as every set of wave conditions drives a given quantity of sediment alongshore, each set of wave conditions contributes to the stability of the

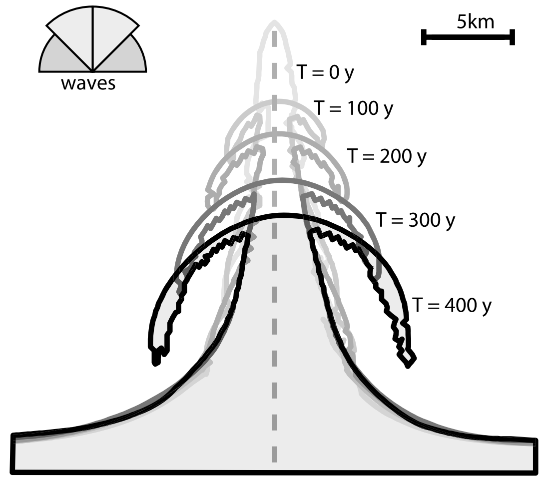

Figure 1. Demonstration of the destructive stage of the "delta cycle" [*Roberts*, 1997] using an example model run. Reworking by littoral sediment transport of a delta that is river-dominated during growth results in two distinct recurved spits. Successive shorelines are shown at 100-year intervals, from grey to black. Simulations use a symmetric wave climate (inset rose represents the angular distribution of wave energy, of which the darker portions are unstable, high-angle waves).

coastline, either diffusively (<45°) or antidiffusively (>45°) [*Ashton and Murray*, 2006b]. The net littoral transport Q_s (kgs^{-1}, positive to the right, looking offshore) and the net diffusivity Γ (a dimensionless number varying between −1 and 1) can be computed by summing over a long-term series of waves (a "wave climate"). For a given shoreline, the value of Γ is the relative rate at which plan-view shoreline perturbations will decay (stable shoreline, $\Gamma > 0$) or amplify (unstable shoreline, $\Gamma < 0$). Unstable shorelines tend to develop capes, flying spits, and alongshore sand waves [*Ashton et al.*, 2001; *Falqués and Calvete*, 2005].

[6] Plan-view delta evolution has been previously modeled both analytically [*Larson et al.*, 1987] and numerically [*Komar*, 1973] for the case of a river with constant sediment input and exclusively low-angle waves, i.e., waves approaching relatively straight to the shoreline. More recent investigations by *Ashton and Giosan* [2011] emphasize the role of wave angle climate on delta morphologies during growth. If there is asymmetry in the wave climate, downdrift shorelines will experience higher-angle waves, with an increased probability of downdrift spit formation and shoreline instability. These results can explain certain features observed on asymmetric wave-influenced deltas [*Bhattacharya and Giosan*, 2003], such as shore-parallel barriers or spits. However, none of the simulations by *Ashton and Giosan* [2011] shows the formation of distinct recurved spits, observed, for example, on the Ebro and Krishna Deltas [*Canicio and Ibanez*, 1999; *Rao et al.*, 2006].

4. Methods: Coastline Evolution Model

[7] We study the effect of fluvial sediment elimination on delta morphology using an exploratory [*Murray*, 2007] process-based one-contour-line model of shoreline evolution (for a full description, see *Ashton and Murray* [2006a]). In short, the plan-view coastal zone is discretized into square (200 m) cells whose geometry defines the shoreline. Littoral transport, Q_s, is calculated with the CERC (Coastal Engineering Research Center) formula using breaking wave angle and height [*Komar*, 1971, 1973], assuming refraction over shore-parallel shoreface contours (Figure 2). To simulate long-term fluvial sediment influx, we add sediment to the model coastline at a predefined alongshore position ("river mouth") at a constant rate (Q_r). There are no feedbacks between waves and Q_r, and littoral sediment is allowed to bypass the river mouth moving alongshore.

[8] Each model day, a wave direction is picked from a probability distribution defined by two variables: asymmetry (A), the fraction of waves coming from the left, and the proportion of unstable, high-angle waves (U), where larger U results in decreased overall diffusivity (see supporting information Table S2 for model run parameters).

5. Results: Modes of Delta Reworking

[9] We model delta formation over 500 years, then eliminate the fluvial sediment supply while keeping wave conditions constant. During growth, feedback between alongshore sediment transport, shoreline orientation, and sediment input control the delta's planform shape. Larger sediment delivery rates, greater wave asymmetry, and higher-angle waves result in more steeply pointed delta shapes [*Ashton and Giosan*, 2011]. The delta shape during growth is important as it sets a template for post-abandonment wave reworking.

[10] We identify four distinct modes of delta abandonment by their dominant morphologic expression (Figure 3) (i) smooth diffusive shoreline, (ii) discontinuous shoreline, (iii) growing spit, and (iv) decaying shoreline sand waves. Shoreline instability and therefore more complex responses are favored on the downdrift delta coast [*Ashton and Giosan*, 2011]; here we identify abandonment modes based on this downdrift behavior. Note, however, complex behavior is also possible

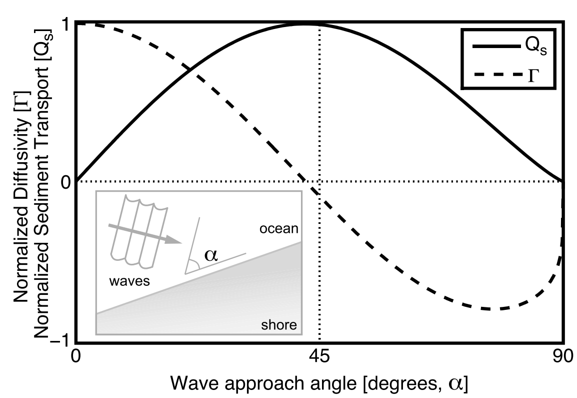

Figure 2. Plot of normalized wave-sustained littoral sediment transport (Q_s, solid line) and normalized diffusivity (Γ, dashed line) versus deepwater wave approach angle, α, defined at the toe of the shoreface. Following *Ashton and Murray* [2006b], littoral transport is described by the CERC formula: $Q_s = K_2 H_0^{\frac{12}{5}} T^{\frac{1}{5}} \cos^{\frac{6}{5}}(\alpha)\sin(\alpha)$, where K_2 is an empirical constant (m s^{-2}), relating wave energy to sediment volume; H_0 and T are, respectively, the significant deepwater wave height and period. Normalized diffusivity (in this case, for waves approaching from a single angle) is described by $\Gamma = \cos^{\frac{1}{5}}(\alpha)\left[\cos^2(\alpha) - \left(\frac{6}{5}\right)\sin^2(\alpha)\right]$. Inset depicts the wave approach angle definition.

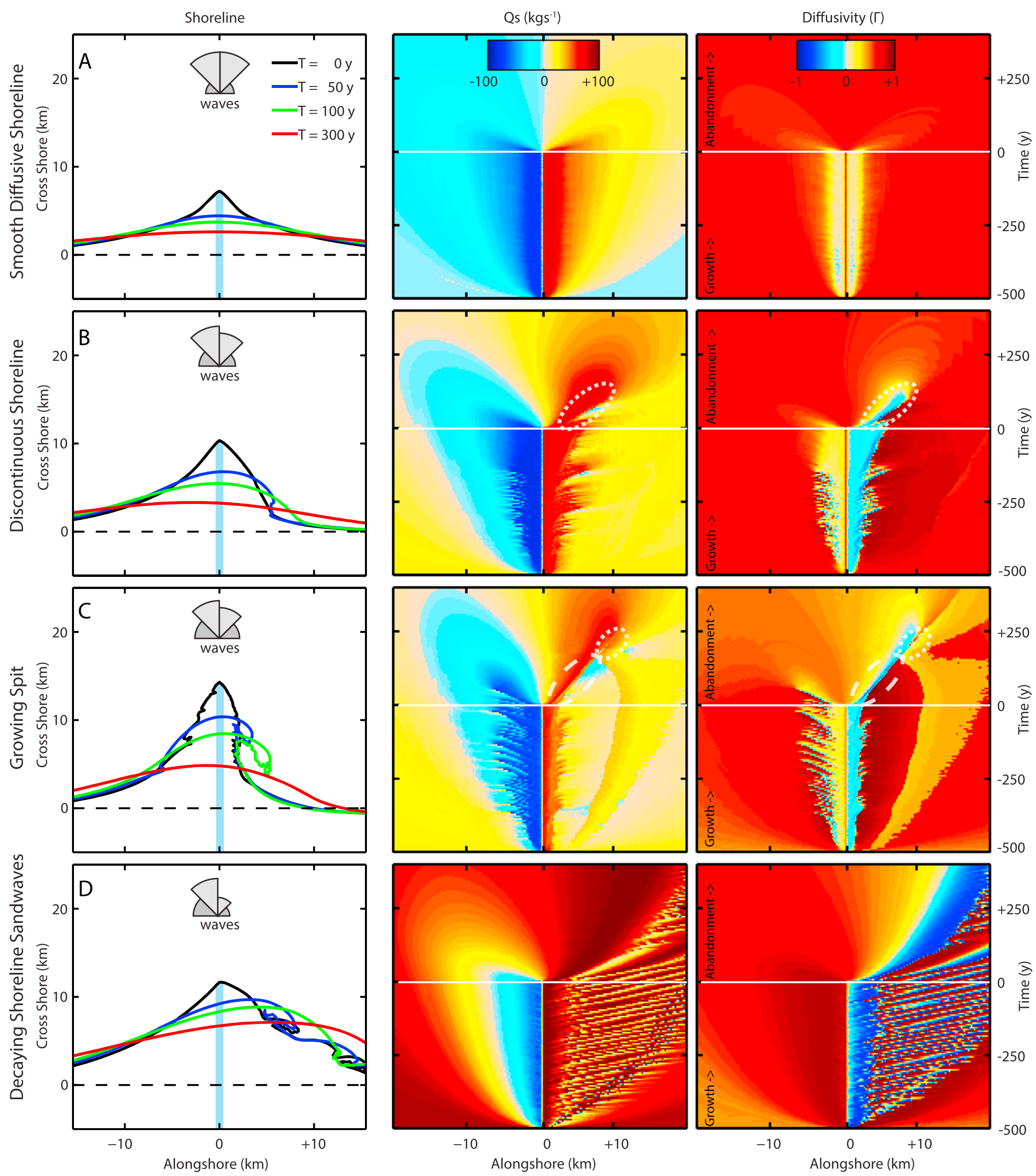

Figure 3. (a–d) Sample model results of the four identified delta abandonment modes, plotting shoreline configuration (left column) at abandonment ($T = 0$ y) and afterward. Inset roses display the angular distribution of incoming wave energy. Plotted time stacks show net alongshore sediment transport (Q_s) (middle column, sediment transport is positive to the right) and normalized shoreline diffusivity (Γ) (right column). Note that wave height (1 m), wave period (5 s), and fluvial bedload flux ($Q_r = 200$ kg s^{-1}) are left unchanged among these runs—these different behaviors are solely due to differences in the angular distribution of waves. Dashed and dotted ellipses indicate regions discussed in the text.

on the updrift coasts or along both coasts if the wave climate is symmetric (Figure 1) or nearly so.

[11] The smooth diffusive shoreline mode occurs when the pre-abandonment delta has a cuspate shape, and both the updrift and downdrift shorelines are stable (Figure 3a). The abandoned delta maintains its general shape, which is diffused by alongshore transport gradients, with erosion around the river mouth and deposition on the updrift and downdrift flanks. This is the expected response given by the traditional diffusion equation for shoreline evolution [*Larson et al.*, 1987].

[12] Alternatively, abandonment can spur the growth of shoreline features if, during delta growth, the shoreline passed the orientation for which maximum transport occurs. A discontinuous shoreline mode (Figure 3b) arises when the shoreline is marginally unstable, with Γ below, but close to 0. After abandonment, removal of the riverine sediment source results in rapid rearrangement of the delta tip while sediment flux remains positive (i.e., $Q_s > 0$ along the entire downdrift coast) (Figure 3b, dotted ellipse). The mouth "collapse" propagates as a downdrift-migrating erosion/accretion couplet (Figure 3b, inside the dotted ellipse), much like the expected downdrift migration of the upcoast inflection points for the case of a single growing flying spit [*Ashton and Murray*, 2006a]. This shoreline discontinuity, where Γ becomes negative, migrates away from the river mouth, initially preserving the downdrift-skewed form of the delta. The discontinuity eventually dissipates as the shoreline flattens.

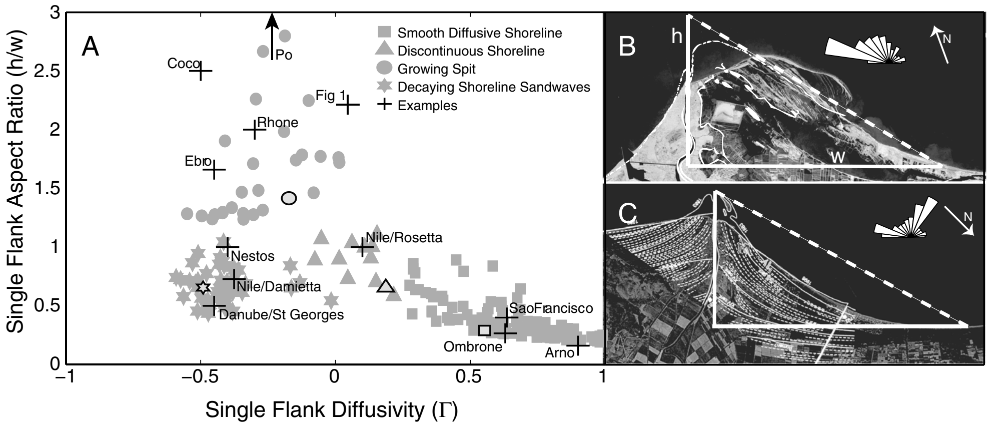

Figure 4. (a) Abandonment modes plotted in terms of pre-abandonment aspect ratio (h/w) versus normalized diffusivity of the delta flank (for model parameters, see Table S2). The markers with solid outlines show examples from Figure 3. The aspect ratio of the Po Delta (di Goro Lobe) is 6. (b) The Rosetta lobe of the Nile Delta, Egypt and (c) the Ombrone Delta, Italy, demonstrating the calculation method for aspect ratio and wave climate characteristics. Images copyright NASA, overlays from *Pranzini* [2001] and *Stanley and Warne* [1998].

[13] A delta extending further offshore (i.e., with a larger offshore to alongshore aspect ratio), either due to a relatively large fluvial sediment input or small effective shoreline diffusivity during growth, exhibits a different abandonment mode marked by the development of a recurved spit. In contrast with the shoreline discontinuity case, delta tip collapse creates a zero flux location ($Q_s = 0$) which persists as the delta decays (Figure 3c, dashed ellipse). The zero flux point then translates downdrift with a plan-view trajectory gentler than that of the shoreline angle itself, forming a spit. Eventually, the spit reconnects with the shoreline and dissipates, at this point behaving analogously to the shoreline discontinuity mode with $Q_s > 0$ and $\Gamma < 0$ (Figure 3c, dotted ellipse).

[14] Finally, strongly asymmetric wave climates result in highly unstable downdrift coasts, triggering the formation of shoreline sand waves before abandonment (Figure 3d). During growth, increased sediment transport downdrift from the river mouth decreases the overall plan-view extent (for the same fluvial input). In this case, post-abandonment behavior is complex, with formation of a spit that collapses near the river mouth and continued formation of shoreline sand waves as the delta is reworked. As wave conditions favor downdrift instability, the subtle shoreline discontinuity persists longer than in the other modes.

6. Results: Controls on Abandonment Mode

[15] To better understand the controls on deltas after abandonment, we ran simulations for a range of fluvial and marine conditions (162 runs, see supporting information for parameter ranges) and characterized the abandonment mode based on the plan-view morphology. After investigating a wide array of parameters, including fluvial discharge rate and wave height, we found two characteristics of the delta at abandonment that best predict post-abandonment evolution: plan-view aspect ratio and the diffusivity for the flank-averaged coastal orientation (Figure 4a). These two quantities are emergent properties of delta evolution that arise during growth and can be measured from delta geometry (using either the shoreline or beach ridges) and modern driving forces (with knowledge of the directional wave climate). Our approach therefore does not require quantification of fluvial sediment discharge, which is notoriously difficult to measure [*Turowski et al*., 2010].

[16] Interestingly, the spit mode occurs almost exclusively when the aspect ratio of the coast is greater than one (i.e., the coast is beyond 45°; Figure 4a). This suggests that when well-formed, spatially extensive recurved spits (which are generally diagnostic of wave reworking of sediment promontories) are found on a delta plain, they likely arose from abrupt abandonment after a previous stage of intense progradation. Note that our investigations here studied complete elimination of fluvial sediment supply on deltas in a low-tide environment; less drastic sediment reductions make shoreline reorientation more gradual, decreasing the possibility of recurved spit growth. Overall, our results also emphasize the ephemeral nature of promontories to wave attack.

[17] For natural examples, we determine pre-abandonment geometry from satellite images and wave climate characteristics from wave hindcast data (see Table S1) (Figures 4b and 4c). Lobes of the Ebro, Po, and Rhone deltas experienced drastic reductions of sediment supply due to river avulsion (Ebro, Rhone) or geoengineering (Po) [*Canicio and Ibanez*, 1999; *Sabatier et al*., 2006; *Simeoni et al*., 2007; *Vella et al*., 2005], with subsequent spit development (La Banya Spit on the Ebro, the Goro Spit on the Po, and the Beaudoc spit on the Rhone). The observed spit formation after avulsion is consistent with their location in our parameter space (Figure 4a). Significant reductions of fluvial input due to human impact in their drainage basins have affected the Ombrone [*Innocenti and Pranzini*, 1993] and Arno [*Pranzini*, 2001] deltas, as well as the two modern lobes of the Nile [*Stanley and Warne*, 1998]. Whereas the Ombrone and Arno Deltas, with their diffusive wave climates and subtle shape [*Bellotti et al*., 2004], exhibit a diffusive shoreline mode (Figure 4c), the Rosetta lobe of the Nile delta, with the formation of undulating spits extending downdrift as the delta recedes, demonstrates behavior spanning the spit and alongshore sand wave modes (Figure 4b). In other cases where deltas or delta lobes are not yet abandoned per se (Nestos, Coco, Danube, and Sao Francisco), the parameter space suggests possible future delta abandonment styles if fluvial supply were to (or were to continue to) decrease dramatically (Figure 4a).

7. Conclusions

[18] We identify four distinct modes of marine working of delta planforms after abrupt reduction of sediment supply, providing, for the first time, a quantitative framework to understand the morphologic evolution of an abandoned wave-influenced delta. Model results and comparison with natural examples show that delta shoreline geometry and wave climate at the time of abandonment can be a good predictor of the abandonment mode. Overall, development of alongshore-extending spits tends to occur on abandoned deltas with initially high ratios of offshore versus alongshore extent—i.e., sharply protruding spits tend to form when a delta is close to fluvial dominance before sediment supply is eliminated.

[19] Understanding the controls upon the style of delta reworking is important for interpreting immediate and long-term paleo-environmental conditions that may be recorded in delta plain geometries [e.g., *Giosan et al.*, 2006]. Not only may this knowledge help guide interpretation of the rock record, but the more immediate application pertains to interpretation of the geometries of Holocene delta forms, for instance, providing insight into the mechanistic origin of features such as recurved spits found on some deltas. Looking toward the future, as sediment supply to deltas continues to wane due to human influence, understanding the likely style and form of wave reworking will play an important role in management of deltaic coastlines.

[20] **Acknowledgments.** This research was supported by NSF grant EAR-0952146. We wish to thank Ad van der Spek for feedback and two anonymous reviewers of this submittal.

[21] The Editor thanks Irina Overeem and an anonymous reviewer for their assistance in evaluating this paper.

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