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Controls on the apex location of large deltas

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The majority of sediment transport to the world's oceans is routed via large deltas. We examine controls on delta apex location using a database of 84 of the world's largest deltas. Of the dataset, 94% of apices are controlled by either bedrock valleys (80%) or Pleistocene alluvial valleys (14%), suggesting that the principal control on modern apex development is valley exit and/or bedslope-mediated avulsion and not hydrodynamic backwater length. Valley exit control on large delta apex location may have been as important in the rock record as it is today, and should be considered as a key control on delta development.

Supplementary material: Tabulated data on backwater length and apex type for studied deltas available at https://doi.org/10.6084/m9.figshare.c.3469770

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Deltas form an important component of many sedimentary basin-fill successions and are sensitive recorders of the interplay between eustatic, climatic and tectonic processes. They contain up to 30% of all global hydrocarbon reserves and are important aquifers for 25% of the human population (Tyler & Finley 1991; Giosan & Bhattacharya 2005; Syvitski & Saito 2007). Predicting the controls on sandstone body distribution within deltaic deposits is important. Early studies of deltas focused on the relationship between the fluvial system and the dominant basinal process, with classifications based on tide, wave or fluvial dominance (Wright & Coleman 1972; Galloway 1975). More recent work has focused on the upstream part of the delta, which has highlighted the importance of quantitatively defining the morphodynamics of channel networks and how scaling relationships can be applied to predict river channel avulsion location and length (e.g. Jerolmack & Swenson 2007; Chatanantavet *et al.* 2012).

Of particular importance is the recognition that delta lobe-scale avulsion of fluvial channels (and thus the apex of predominantly fluvial-dominated deltas) occurs at a characteristic upstream distance from the shoreline that scales roughly to the backwater length, the upstream distance over which river hydraulics are affected by the process regime in the receiving basin (e.g. Chow 1959; Paola & Mohrig 1996; Jerolmack & Swenson 2007; Chatanantavet *et al.* 2012). The identification of this scaling relationship has important implications for predicting sandstone body development in the subaerial part of modern and ancient deltas. For example, in the Mississippi River, *c.* 75% of the suspended sand fraction is lost 100 km downstream of the apex (Allison *et al.* 2012) and predictable changes in channel belt migration rates and width/thickness ratios occur over this distance (Blum *et al.* 2013; Fig. 1). If these relationships hold for all deltas, then identification of the nodal avulsion point should help in predicting reservoir and aquifer distribution as well as in constraining palaeogeographical reconstructions. To assess the controls on apex location we have determined apex type for the world's largest deltas. Results show that apex locations of most large modern deltas occur at the end of bedrock valleys. In addition, we analyse backwater length for a number of large deltas and discuss the role of backwater length in influencing apex development.

Method. We analysed all the large deltas on Earth (Fig. 2) to determine apex type and estimate backwater length (L_b where possible). A large delta is defined as an alluvial protrusion seaward of the coeval shoreline and having a >30 km apex to shoreline length measured along the centre line of the river and reported as river kilometres. In addition to coastal deltas we also recognize valley-confined subaerial deltas where sediment accumulation is confined to a bedrock valley and has >30 km apex–shoreline length (Fig. 1). Apex type was established for 84 deltas from digital elevation models (DEMs) derived from the Shuttle Radar Topography Mission (SRTM) data and published geological and topographical maps. The vertical accuracy in the SRTM data at 3 arc second or 90 m grid cell resolution is ±16 m at the 90% confidence level for low-gradient surfaces such as delta tops (Karwel & Ewiak 2008) and is <3.5 m total or absolute error relative to other measured elevation surfaces. In detail, the pixel-to-pixel variability is much smaller (see Jarvis *et al.* 2004) such that most of this error is in estimation of peak and ridge heights in a drainage. For deltas internally contained in these basins the DEM error is probably a maximum of *c.* 1 m.

The backwater length (L_b) is defined as h_f/S, where h_f is flow depth (typically bankfull channel depth) and S is channel slope (Paola & Mohrig 1996). We estimated L_b for 13 deltas for which the rivers are primarily single thread, avulsion dominated, low gradient (<1.678E – 04) and with limited wave and tidal reworking. Channel bankfull slope was measured from DEMs between the bankfull elevation at the apex and the shoreline of each delta and cross-checked with the literature to ensure consistency. Channel length (the apex–shoreline distance) is measured in river kilometres. Channel depth was taken from published information and for most examples included an average depth over the apex–shoreline length. Where this was not available, reliable depth measurements for portions of the river close to the apex were used.

Data analysis. Four apex types have been identified (Fig. 3): (1) bedrock valley, where the apex is located at the mouth of a bedrock valley; (2) valley-confined, where the apex and delta are located within a bedrock valley; (3) Pleistocene valley, where the apex occurs at the mouth of or partly within a valley cut into Pleistocene alluvium; (4) alluvial plain, where the apex occurs on an alluvial plain and no valley is present. Valleys were identified based on the presence of a marked break in slope between the valley and fluvial channel. Of the 84 deltas, bedrock valleys account for 59 apices, bedrock valley-confined eight, Pleistocene valleys 12 and alluvial deltas five.

In the 13 examples where L_b could be calculated confidently, a wide range in values of between 25 and 1950 km is present (Fig. 4). The ratio between L_b and the apex–shoreline distance (ASD) is a useful way to quantify this variation. Two examples (Nile and

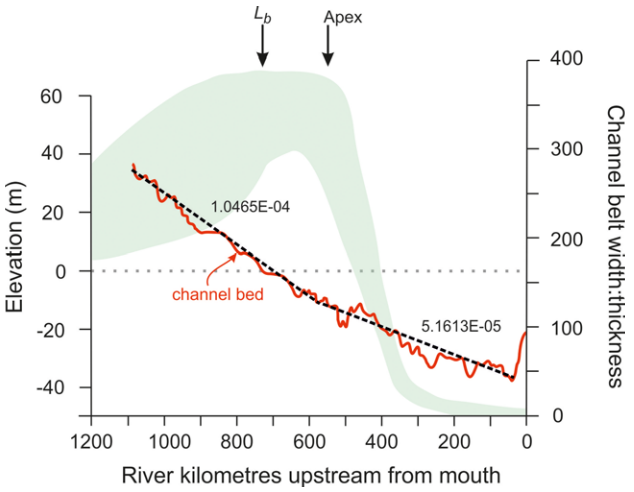

Fig. 1. Plot of channel bed elevation (red line) with best-fit gradient (black dashed line) and channel width–thickness ratios (green zone) for the Mississippi River delta. The gradient decreases by about 50% downstream of the apex. L_b marks the location of the hydrodynamic backwater length (modified after Blum *et al.* 2013).

Orinoco) have a ratio of between unity and 1.25, indicating that the L_b and apex location are effectively coincident. The Niger, Brahmaputra and Zambezi have L_b values that occur downstream of the apex (0.79, 0.63 and 0.5 respectively), whereas the Huanghe has a particularly short backwater length of 0.03 of ASD. The remaining nine deltas show a wide range in ratios from 1.56 to 5.63. Three deltas (Mississippi, Rhône and Paraná) have values between 1.56 and 1.67, indicating that the L_b extends approximately half the length of the ASD upstream of the apex. The Song Hong and Mekong have L_b to ASD ratios of 2.5, with a ratio of 3.33 for the Changjiang and 5.63 for the Amazon.

Discussion. Our data indicate that the apex location of >90% of modern deltas is fixed by the position of a feeder valley cut through either bedrock or Pleistocene strata, with many of the Pleistocene valleys representing an extension of older bedrock valleys (e.g. Volga, Fig. 3). This suggests that the nodal avulsion point of large deltas is controlled by processes operative at the valley mouth. In a recent study of the Huanghe, Ganti *et al.* (2014) identified two avulsion styles: bedslope-mediated avulsion, which occurs where the river exits the valley, and hydrodynamic backwater driven avulsion located on the delta plain 500 km downstream of the apex. Bedslope-mediated avulsion occurs at the valley mouth owing to reduction in the slope of the surface water and channel bed, resulting in decreased sediment transport capacity, aggradation and avulsion (Parker *et al.* 1998; Slingerland & Smith 2004). It is associated with a marked slope break where the river exits the valley (Ganti *et al.* 2014), such as the 50% decrease in gradient that occurs downstream of the Mississippi apex (Fig. 1). We suggest that an additional control on apex development occurs at the valley mouth, termed valley exit avulsion. At the valley mouth channels are free to migrate laterally outside the confines of the valley, resulting in a decrease in channel bed and surface water slope, decreased sediment transport capacity and increased aggradation and avulsion. We suggest that the majority of large delta apices occur as a result of valley exit and bedslope-mediated avulsion at the valley–delta plain transition.

To determine if there are alternative controls on delta apex location, we examine the importance of hydrodynamic backwater length in controlling avulsion node location. Recent work has highlighted that the apices of some large river deltas (e.g. Nile, Rhine–Meuse, Orinoco, Magdelena, Danube, Mississippi, Amazon and Paraná) scale to their L_b (Chatanantavet *et al.* 2012; Blum *et al.* 2013). In the 13 deltas for which L_b was calculated, we recorded similar values for the Nile, Mississippi, Orinoco and Paraná and significantly different values for the Amazon (see the supplementary material for details). In addition, our calculations show a wide range of values for the L_b:ASD ratio that indicate that no relationship is present between delta apex location and the hydrodynamic backwater length in the Changjiang, Song Hong, Mekong, Brahmaputra, Zambezi and Huanghe rivers. A further important point is that the apices of all the rivers studied by Chatanantavet *et al.* (2012) are located at the end of bedrock or Pleistocene valleys (e.g. Nile, Orinoco, Magdalena, Danube and Mississippi, Figs 2 and 3) or occur within a valley (Amazon and Paraná, Fig. 3). This suggests that the nodes for the backwater length-scale avulsion and valley exit or bedslope-mediated avulsion for the Nile, Mississippi, Orinoco and Paraná are close to coincident, but differ significantly for the other studied rivers. It should also be noted that a scaling relationship between the hydrodynamic backwater length and the delta apex avulsion node is applicable to only a subset of deltas, specifically single-thread rivers on avulsion-dominated fluvial deltas (Jerolmack & Swenson 2007). It cannot be applied to bifurcation-dominated fluvial deltas, deltas that are strongly modified by wave or tidal processes, or those with steep gradients such as fan deltas (Jerolmack & Swenson 2007; Jerolmack 2009).

An important distinction between valley exit or bedslope-mediated and backwater-driven avulsion is that avulsion nodes influenced by backwater hydrodynamics migrate as the delta progrades whereas the valley exit or bedslope-mediated avulsion node will remain fixed to the mouth of the valley (e.g. Ganti *et al.* 2014). This has implications for developing predictive tools for distributary channel development in ancient outcrop and subsurface

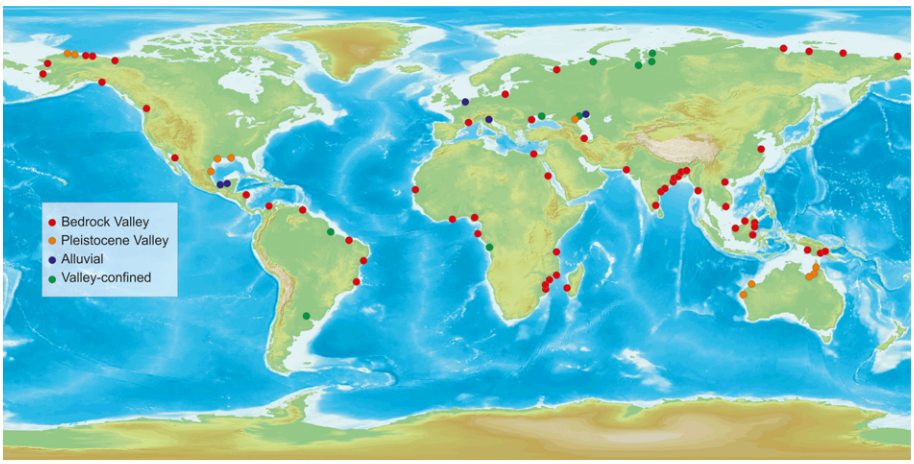

Fig. 2. The global distribution of studied deltas and their apex type.

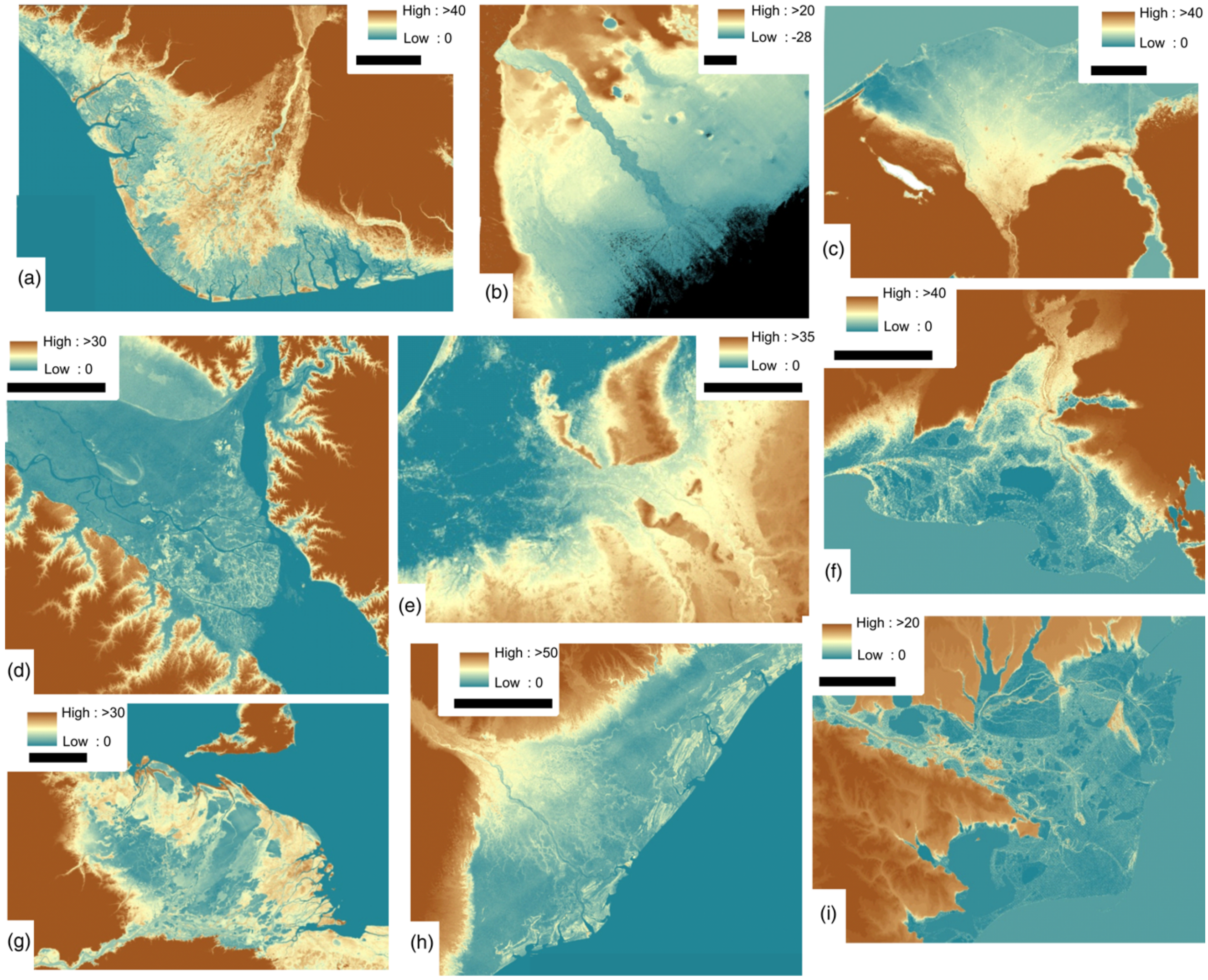

Fig. 3. Digital elevation models showing apex type examples: (**a**) bedrock valley (Niger); (**b**) Pleistocene valley (Volga); (**c**) bedrock valley (Nile); (**d**) bedrock valley-confined (Paraná); (**e**) alluvial (Rhine; note extension from bedrock valley); (**f**) bedrock valley (Rhône); (**g**) bedrock valley (Orinoco); (**h**) bedrock valley (Zambezi); (**i**) bedrock-valley (Danube). Black scale bar represents 50 km in all images, except (**f**) and (**i**), where bar represents 25 km. We use the DEMs to display characteristics of deltas as these typically show more detail than imagery as they are not obscured by atmospheric haze.

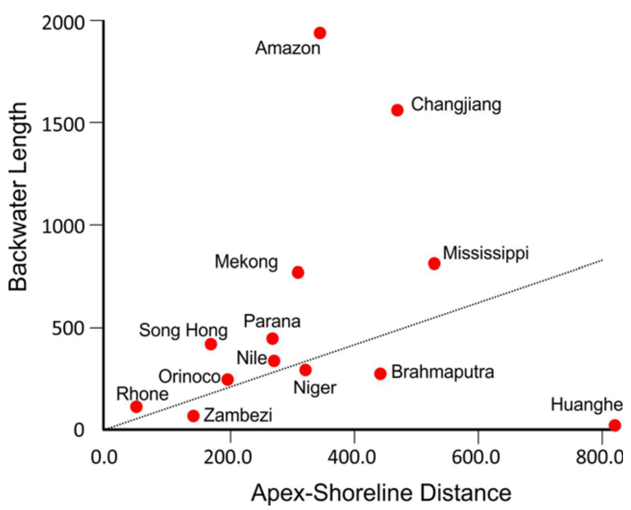

Fig. 4. Graph illustrating the relationship between hydrodynamic backwater length and apex–shoreline distance (ASD). Dotted line shows where deltas should plot if there was a one-to-one relationship between ASD and L_b.

datasets. For example, it has been noted that changes in sediment deposition, channel belt migration rate and width/thickness ratios occur in fluvial-dominated deltas at predictable distances downstream of the apex (e.g. Blum *et al.* 2013). If the avulsion node is fixed at the valley mouth, then there will be no significant change in the location of sediment accumulation and channel properties; however, if the avulsion node is driven by backwater length, then the node and associated facies and channel belt properties will migrate downstream through time as the delta progrades, as illustrated by Ganti *et al.* (2014) for the Huanghe. Consequently, to develop predictive facies models for ancient deltas and to generate accurate palaeogeographical reconstructions, it is important to determine what the principal control on the avulsion node was. Given that the vast majority of large delta apices occur at significant slope breaks, we suggest that valley exit or bedload-mediated avulsion was the primary control on apex development.

We recognize that the deltas studied here are still responding to changes in Pleistocene sea-level, and it is possible that the valley control on apex development identified here may not be as important in the rock record. It is interesting to note that some deltas have a backwater reach that does not extend upstream as far as the apex (e.g. Niger, Brahmaputra, Zambezi), yet the apex is still located at the mouth of bedrock valleys, suggesting that the break in slope is still the main control on delta development. In addition, for rivers with large backwater lengths such as the Amazon, Changjiang and Mekong, the delta will need to extend hundreds of kilometres seaward of the valley mouth before the backwater reach extends outside the valley. In some cases this may not be possible, as any prograding delta will intersect the shelf-slope break (200 – 300 km) before the backwater reach exits the valley, such that the main control on apex location will be the mouth of the bedrock valley.

Conclusions

Analysis of 84 of the world's largest modern deltas indicates that the apices of 94% of the deltas are located at the mouth of bedrock or Pleistocene alluvial valleys. This suggests that the principal control on apex development is valley exit or bedslope-mediated avulsion, where decreased sediment transport capacity associated with a reduction in the surface water and channel bed slope results in aggradation and avulsion. The role of hydrodynamic backwater length in controlling apex development was considered using a dataset generated from 13 rivers and through comparison with published examples. Five rivers show a broad scaling relationship between backwater length and delta apex location. However, in all these examples, the apices lie at the mouth of bedrock or Pleistocene valleys, suggesting a coincidence between valley exit or bedslope and backwater length avulsion nodes. The other eight examples show no relationship to backwater length and have apices at the mouth of or within bedrock valleys. Models that predict sediment distribution and channel properties downstream of the apex of single-thread, avulsion-dominated river deltas will need to determine if the apex was fixed (valley controlled) or mobile (related to backwater length). As the majority of modern large deltas apices occur at the foot of valleys we suggest that fixed, valley exit or bedslope-mediated systems are the most important at the present day and may have been equally important in the rock record.

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