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Can bed load transport drive varying depositional behaviour in river delta environments?

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Understanding the processes and conditions at the time of deposition is key to the development of robust geological models which adequately approximate the heterogeneous delta morphology and stratigraphy they represent. We show how the mechanism of sediment transport (the proportion of the sediment supply transported as bed load vs. suspended load) impacts channel kinematics, delta morphology and stratigraphy, to at least the same extent as the proportion of cohesive sediment supply. This finding is derived from 15 synthetic delta analogues generated by processes-based simulations in Delft3D. The model parameter space varies sediment transport mechanism against proportions of cohesive sediment whilst keeping the total sediment mass input constant. Proximal morphology and kinematics previously associated with sediment cohesivity are also produced by decreasing the proportion of bed load sediment transport. However, distal depositional patterns are different for changes in sediment transport and sediment load cohesivity. Changes in sediment transport mechanisms are also shown to impact clinoform geometry as well as the spatiotemporal scale of autogenic reorganisation through channel avulsions. We conclude that improving insight into the ratio of bed load to suspended load is crucial to predicting the geometric evolution of a delta.

1. Introduction

Understanding deposition in deltaic environments is not only important to predict the effect of anthropogenic changes in these densely populated areas (Syvitski and Saito, 2007), but also forms the basis of geological models of ancient deltaic deposits. The heterogeneous nature of river delta morphology and stratigraphy complicates the development of geological models (Howell et al., 2008). To simplify this process, a number of classification schemes have been developed based on modern deltaic systems. Initially, classification only characterised deltas by the hydrodynamic forces acting on the system (e.g., fluvial input, tidal conditions, wave activity) (Galloway, 1975). Subsequently it was shown that the physical properties of the supplied sediment (e.g., cohesivity, grain size) can be equally important (Orton and Reading, 1993; Hoyal and Sheets, 2009). Past studies have shown that the balance between cohesive and non-cohesive sediments can have significant effects on deltaic morphology (Peakall et al., 2007; Edmonds and Slingerland, 2009; Hoyal and Sheets, 2009; Geleynse et al., 2011).

Comparatively less attention has been given to the effects that sediment transport mechanisms have on deltaic morphology and stratigraphy. Deltaic stratigraphy can be viewed as a record of the sediments preserved by this evolving morphology. Sediment transport ultimately regulates where and how sediment is deposited, based on local hydrodynamic conditions and sediment properties. Sediment transport to and within a delta environment can be simplified to two mechanisms: bed load and suspended load. In deltaic systems, the majority of sediment supply is typically cohesive and transported in suspension, forming the bulk of the suspended load. A smaller proportion of sediment consists of non-cohesive material (sands) transported partially in suspension and partially through creep and saltation, constituting the bed load.

Field measurements of the suspended load (the cohesive and non-cohesive sediment transported in suspension) is relatively simple and can even be partially automated. Bed load measurements are more expensive and labour intensive to obtain (Turowski et al., 2010), especially in coastal settings. River deltas are formed at the interface between the fluvial and the coastal domain and are therefore both influenced by fluvial processes as well as marine reworking. Existing work primarily considers fluvial systems with some work having been conducted at coastlines (van Rijn, 2007). In experimental settings of such systems,

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there are various challenges associated with the scaling of sediment transport (Paola et al., 2009).

Due to the limited data availability, bed load is typically estimated or calculated based on the suspended load measurements (e.g., Syvitski and Saito, 2007; Kleinhans et al., 2012). Turowski et al. (2010) conducted an extensive review of reported values for bed load, but found that often no reference is made to original data. They traced the source of most data back to a data table in a report from the 1950's (Maddock and Borland, 1950) which claimed to "give data on estimates of the unmeasured bed load of streams based on the Bureau of Reclamation experience". Available measurements are mainly for fluvial systems, which Turowski et al. (2010) compiled in their review. It shows that between 1% and 50% of the total sediment load can be transported as bed load. For ephemeral rivers, however, the percentage can be even higher, up to 100% (Turowski et al., 2010; Karimaee Tabarestani and Zarrati, 2015).

Various factors have been hypothesised to influence the balance between suspended load and bed load transport in fluvial systems. Locally this balance is determined by particle size, weight, shape and hydraulic conditions, while on a larger scale influencing factors may include catchment geology, climate and relief (Laronne and Reid, 1993; Kleinhans and Grasmeijer, 2006; van Rijn, 2007; Turowski et al., 2010; Karimaee Tabarestani and Zarrati, 2015). Turowski et al. (2010) conclude that there is not yet sufficient data available to isolate the effect of different parameters on the partitioning between sediment transported as bed load and suspended load.

Even with this limited data availability, previous studies of river morphologies have identified the proportion of sediment supply transported as bed load as an important control on sediment depositional patterns (Kleinhans, 2010; Turowski et al., 2010; Ashworth and Lewin, 2012). Considering the challenges associated with gathering field data of bed load transport, it is imperative to better understand the implications of these processes on delta morphology and stratigraphy prior to undertaking field studies. In addition, field studies are limited by the availability of appropriate data or field sites and often cannot span the entire parameter space of interest. Comparing different natural systems involves variations in many parameters at the same time. Conducting a modelling study allows the detailed investigation of individual processes and in so doing extend and supplement experimental and field-based studies.

In this study we examine the effect of both sediment transport mechanism and cohesive sediment content on depositional geometries in fluvial dominated deltas. We propose that the mechanism of sediment transport (i.e., what proportion of the sediment supply is transported as bed load vs. suspended load) impacts depositional behaviour to at least the same extent as sediment properties, such as cohesivity.

In this study we use process-based simulations to assess the effects of sediment transport mechanism compared to sediment composition on deltaic morphology and stratigraphy. As predictions made with process-based models are consistent, and they allow careful control of boundary conditions, the quantitative output can be compared, and specific processes or mechanisms can be isolated. Following this approach we explore three metrics: (1) channel geometry and channel dynamics, (2) locations of sediment deposition, reworking and preservation, and (3) large scale delta geometry. We also discuss the relationships between these quantitative measures. The metrics developed here can be applied to other fluvio-deltaic model ensembles to study the implications of a range of boundary conditions on delta morphology and stratigraphy.

2. Experimental design

We created an ensemble of 15 numerical models using the open source process-based modelling software Delft3D (Lesser et al., 2004). Models were calculated using Delft3D Flow (Version 4168) with parallel processing on a single, Linux operating, 16-core node. For detailed descriptions of the governing equations representing each of the processes as well as the finite difference solution methodology the reader is referred to the Delft3D-Flow documentation which is freely available online. In past studies, Delft3D has been extensively applied to study the effects of hydrodynamic forcing and sediment properties on river delta morphodynamics (e.g., Edmonds and Slingerland, 2009; Geleynse et al., 2010, 2011, 2012; Caldwell and Edmonds, 2014). Our numerical experiments investigate the implications of mechanism of sediment transport on depositional behaviour in a river delta.

2.1. Bathymetry, hydrodynamic forcing and sediment properties

Parameters described in this section were applied to all 15 experiments. The starting bathymetry is similar to that described in previous studies, consisting of a channel delivering water and sediment into a sloped basin already filled with fresh water (Geleynse et al., 2011). One change is that our channel is partially formed by two floodplains sloping toward the basin and channel. This forms a trumpet-shaped channel debouching into the basin, representative of a river mouth towards the end of a rising sea-level cycle. However, sea level was kept constant during the model runs. The initial channel width is 1000 m and with constant discharge of 1500 $m^3\ s^{-1}$. This discharge should be considered as a continuous bankfull flood stage. A tide with amplitude of 1 m was added to introduce dynamics into an otherwise very steady system. The effect of flocculation was not considered in this study.

The total sediment supply was estimated based on average suspended load measurements in modern delta systems of a similar scale (Milliman and Farnsworth, 2011). This resulted in a total load concentration of 0.2 kg m^{-3} being applied across the models. The sediment transport calculations do not take migrating bedforms into account, although a Manning roughness coefficient of 0.02 implicitly accounts for the impact of smaller scale bedforms on hydrodynamics.

Calculations span a full hydrodynamic year, but include a morphological scaling factor (MORFAC) of 60 (Ranasinghe et al., 2011). Combining this with continuous bankfull discharge results in deposition equivalent to delta evolution on a millennial timescale. Simulation output was recorded at the end of each of the 366 hydrodynamic days.

2.2. Cohesivity vs. sediment transport

The majority of sediment supplied to deltaic environments consists of a cohesive silt and clay mixture. These sediment types are typically transported as part of the suspended load. Suspended load in Delft3D is calculated by solving a depth-averaged (2DH) advection–diffusion (mass-balance) equation for the suspended sediment (Galappatti, 1983). The remainder of the sediment is non-cohesive (sands and gravels) and is transported partially in suspension, adding to the suspended load, and partially through saltation and creep, constituting the bed load.

Previous simulations of delta formation in Delft3D have used the default Van Rijn (1993) transport formulation (van Rijn, 1993; Edmonds and Slingerland, 2009; Caldwell and Edmonds, 2014) or the Engelund-Hansen transport formulation (Engelund and Hansen, 1967; Geleynse et al., 2010, 2011; Guo et al., 2015) to determine sediment transport of non-cohesive sediment (sands). The Engelund-Hansen formulation reflects total transport. However, its implementation allows for the partitioning of sands into a suspended load and a bed load fraction, for which the transport is calculated separately.

For our simulations, we selected and implemented the Engelund-Hansen transport model after a series of sensitivity studies with the available sediment transport formulas in Delft3D. The total fluvial sediment input of 0.2 kg m^{-3} is made up of four sediment classes, as defined in Fig. 1. The properties for the individual sediment classes as well as the total sediment supply concentration are the same in all simulations.