From fluvial supply to delta deposits

Simulating sediment delivery, transport and deposition

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Helena van der Vegt | 2018 |

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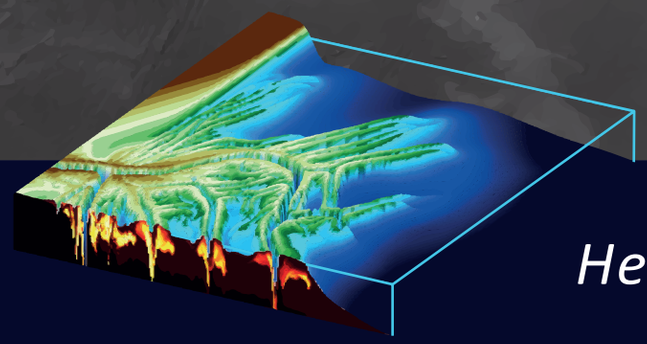

TU Delft

Helena van der Vegt

FROM FLUVIAL SUPPLY TO DELTA DEPOSITS

SIMULATING SEDIMENT DELIVERY, TRANSPORT AND DEPOSITION

From fluvial supply to delta deposits Simulating sediment delivery, transport and deposition

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus Prof.dr.ir. T.H.J.J. van der Hagen;
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op
donderdag 3 mei 2018 om 15:00 uur

door

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CONTENTS

SUMMARY

Geological reservoir models, created based on sparse core and seismic data, inform hydrocarbon production, geothermal applications and aquafer management. Important factors contributing to reservoir quality in these applications include the heterogeneities within and connectivity between the relevant geo-bodies constituting the reservoir. The transport and preservation of sediment at the time of deposition impacts these factors. Therefore, a better understanding of sediment delivery, transport and deposition can be used to better quantify reservoir properties. This same computational methodology can also be applied test hypotheses concerning the depositional processes responsible for preservation of ancient deposits. Constraining such hypotheses improves our understanding of the paleo-sediment dynamics and the accuracy of future geological models.

In this work, the computational study will be confined to studying the interaction between fluvial sediment supply and the 3D evolution of the preserved deposits in deltaic environments. Traditionally, delta deposition has been classified by hydrodynamics (waves, tides, fluvial discharge), sediment properties (grain size, cohesivity) and basin geometry (slope, lateral confinement). These parameters control deposition through their influence on sediment transport within the deltaic domain. Therefore, a detailed study was undertaken on the effect of sediment transport mechanism on depositional patterns in deltaic environments (chapter 2). Once the influence of sediment transport on deposition is better understood, the investigation turns to the autogenic organisation of different sediment classes within the receiving basin (chapters 3 and 4).

In chapters 2, 3 and 4, all boundary conditions are considered constant in time. These boundary conditions are e.g. river discharge, wave height, tides etc. Such constant forcing is clearly a simplification of natural systems. But is this simplification acceptable and if so under which conditions? Chapter 5 starts to investigate the effect of variation in forcing parameters on delta deposits. Simulating the variation in forcing parameters necessitates the consideration of temporal and geometric scales of interest. The spacial scale of the analyses must not be too coarse to record the effects of the imposed temporal variation in forcing parameter.

Quantitative, comparative studies of the delta deposits requires the development of a framework for analysis of the depositional patterns. This raises the question: “Based on which metrics can we compare different deltas?” Deltas are not static. Boundary conditions influencing deposition and erosion change over time scales ranging from seconds to geological times. So when is the best time to take the snapshot of the natural system? We compare channel dynamics, architectural element geometry, as well as the sediment composition. By analysing many simulations, spanning the evolution of the simulated deposition, delta progradation was investigated in detail. Knowledge gained through this study necessitated a refinement of the definition of the architectural

elements. It is expected that this refinement will continue throughout future studies. It is then also expected that a refinement of the analysis will continue as the field of computational process-sedimentology evolves. This dissertation presents a robust framework for defining architectural elements and their properties, which can serve as the base for future developments.

Three main conclusions can be drawn from the research presented in this dissertation. The first conclusion is that the sediment mixture within a single type of architectural element does not have to have the same composition as the overall sediment supply. As an example of this we show how mouth bar deposits are likely to favour fine to medium sand, even though the sediment supply to the delta may comprise a more complex composition. This is important for understanding the depositional systems in which ancient sediment, preserved in the rock record, was deposited.

Secondly, the concept of accommodation-to-supply ratio, often used to describe large scale depositional behaviour in paralic systems is challenged, at least in as far as it may represent an over-simplification at a hydrodynamic scale. Within a prograding delta, sediment partitioning takes place between different delta sub-environments. We show that the preserved organisation of sediment within the sub-environments is controlled in the following ways:

(1) Basin geometry determines the shape of the overall accommodation space

(2) Hydrodynamic processes partitions this accommodation space into sub-environments. These processes determines which grain size classes are able to reach the sub-environment as well as which grain size classes are retained by the sub-environment and which will be eroded and moved further off-shore.

(3) Sediment supply composition determines which grain size classes are available to deposition at each sub-environment. An over- or under-supply of individual grain size classes can contribute to the sediment grain size heterogeneity of the final deposits.

The third conclusion is that the importance of variation of forcing conditions over time is dependent on the scale of interest of the specific study. When considering deposits on a large spacial or time scale, it may not add value to refine the resolution of variations of forcing parameters.

A number of topics related to this methodology warrants further investigation. Some remaining questions relate to heterogeneity in the sedimentary features. In particular the effects of waves, and the refinement of sediment grain size classes or refinement of the spacial or temporal scale at which the simulations are considered. In addition, we recommend the investigation of a number of Delft3D capabilities which are not addressed in this study. In particular salinity, flocculation, 3D resolution of the hydrodynamics, subsidence and compaction are promising avenues for further study. Broader topics which required to further advance the methodology include:

(1) Improving automated definition of facies

(2) Applying results to inform statistical studies

(3) Quantitative validation against field data

(4) Scaling-up of results on temporal and spacial scale.

It is my aim for this work to facilitate the evolution of the methodology beyond the simulation of single, prograding deltas, far from the shelf edge. Exactly how this should be achieved remains open for discussion within the wider research community. My future outlook is that that this methodology finds its place within the context of source-to-sink systems and continue to facilitate collaboration between researchers from various sub-disciplines related to earth sciences.

SAMEVATTING

Geologische reservoir modellen zijn vaak gebaseerd op geringe hoeveelheid gegevens uit seismiek en boorkernen. Deze informatie vormt de basis voor de planning van olie en gas productie, geothermie en grondwater management. De kwaliteit van reservoirgesteente voor deze doeleinden is in grote mate bepaald door de eigenschappen, de variabiliteit (interne heterogeniteit) en de connectiviteit van de geologische eenheden waaruit deze reservoirs bestaan. Bovengenoemde factoren zijn primair beïnvloed door sediment transport en mate van behoud. Een verbeterd begrip van de aanvoer, transport en afzetting van sediment kan gebruikt worden om de verdeling van eigenschappen binnen het reservoir beter te kunnen kwantificeren. Door het gebruik van computersimulaties kunnen de sediment transport en preservatie processen toegepast worden om verschillende hypotheses met betrekking tot afzettingen uit het geologische verleden te toetsten. De verkregen kennis over de significantie van verschillende sedimentaire processen verbetert ons begrip van de palaeo-sedimentaire dynamiek en de nauwkeurigheid van toekomstige geologische modellen.

In dit werk is de interactie tussen fluviatiele en 3D evolutie van de gepreserveerde afzettingen in delta milieus gesimuleerd en geanalyseerd. Traditioneel gezien is de delta classificatie gebaseerd op basis van hydrodynamica (golf, getijde, rivier debiet), sediment eigenschappen (korrelgrootte, mate van cohesie) en bekken geometrie (helling, geografische inperking). Deze parameters beïnvloeden de afzetting van sediment door hun invloed op sediment transport binnen de delta. Daarom is er een gedetailleerde studie gedaan naar de afzettingen patronen in delta's (hoofdstuk 2). De verkregen kennis over de invloed van sediment transport is vervolgens toegepast om de organisatie van de verschillende sediment klassen binnen het bekken te analyseren (hoofdstukken 3 en 4).

In hoofdstuk 2, 3 en 4 zijn de grenswaarden als constant gesteld. Deze opgelegde grenswaarden zijn bijvoorbeeld rivier afvoer, golfhoogte, getijde, etc. De aanname van de constante controlerende grenswaarden is een simplificatie van natuurlijke systemen. Het is de vraag of deze aanname wel aanvaardbaar is, en zo ja, onder welke condities? In Hoofdstuk 5 wordt een begin gemaakt aan het in kaart brengen van de effecten ten gevolge van het variëren van de controlerende grenswaarden op delta afzettingen. Bij het ontwerpen van simulaties met variërende grenswaarden is de instelling van dimensie in tijd en geometrie van belang. De ruimtelijke schaal van de analyse moet niet te grof zijn, zodat het effect van de opgelegde variaties in de parameter tijd kunnen worden waargenomen.

Om een kwantitatieve, vergelijkende studie van delta afzettingen mogelijk te maken is de ontwikkeling van een kader voor de analyse van afzetting patronen nodig. Dit riep de vraag op: "Welke metingen kunnen we het best gebruiken om verschillende delta's met elkaar te vergelijken?" Delta's zijn immers niet statisch en deze grenswaarden beïnvloeden de afzetting en erosie van sedimenten van seconden tot geologische tijdseenheden. Maar

op welk tijdstip nemen we de meting van het natuurlijk systeem? Om dit te onderzoeken worden geul dynamica, architecturale elementen, en korrelgrootte van de sedimenten met elkaar vergeleken. Door middel van vele analyses van de hele evolutie van de gesimuleerde delta's, is de delta progradatie nader onderzocht. Deze studie leert ons dat de definities voor de architecturale elementen aangescherpt moeten worden. Het is dan ook de verwachting dat dit soort aanpassingen zullen doorgaan als het onderzoeksveld van computationeel-proces-sedimentologie zich verder ontwikkelt. Dit proefschrift presenteert een robuust kader voor de definitie van architecturale elementen en hun eigenschappen wat als fundament kan dienen voor dit toekomstig werk.

Uit dit proefschrift kunnen drie voornaamste conclusies worden getrokken. De eerste conclusie is dat de geschatte sediment samenstelling binnen een architecturaal element niet overeenkomt met de samenstelling van sediment aanvoer van het gehele systeem. Onderzoek van de mondingsbanken laten zien dat deze voornamelijk middel zand korrelgrootte bevat, hoewel de delta als geheel een meer gevarieerde sediment aanvoer heeft. Dit is een belangrijk gegeven voor de gedetailleerde interpretatie van afzettingen in het geologische archief.

De tweede conclusie is dat het gebruik van de accommodatie-aanvoer ratio ter verklaring van grootschalige kust tot marine afzettingen in twijfel moet worden getrokken omdat dit op hydrodynamisch vlak tot een te vereenvoudigd beeld leidt. Dit blijkt uit het feit dat in de uitbouwende delta, sortering van sedimenten tussen de verschillende delta sub-milieus plaats vindt. Wij laten zien dat het preserveren van sediment binnen de sub-milieus op de volgende manier beïnvloed wordt:

(1) Bekken geometrie beïnvloedt de accommodatie.

(2) Hydrodynamische processen verdelen deze accommodatie voor de sub-milieus. Deze processen beheren welke korrelgroottes de sub-milieus bereiken, of ze opgeslagen blijven, en of ze later geërodeerd en verder zeewaarts getransporteerd worden.

(3) De compositie van de sediment toevoer bepaalt de korrelgrootteverdeling beschikbaar voor transport en uiteindelijk voor afzetting in de sub-milieus. Een overvloed of schaarste van bepaalde korrelgroottes kan de heterogeniteit van de afzettingen beïnvloeden.

De derde conclusie omvat het belang van de variatie van externe invloeden. Het effect van externe invloeden hangt af van de omvang en tijdsparameters van de specifieke studie. Bij het onderzoek op een grote geografische- of tijdsschaal kan het zijn dat het detail in de externe invloeden geen significante toegevoegde waarde oplevert.

Een aantal onderwerpen zijn aandachtspunten voor vervolgonderzoek. Er blijven nog vragen over de heterogeniteit binnen sedimentaire afzetting. Dit geldt vooral voor de invloed van golfwerking, de verfijning in de korrelgrootte klassen en van de tijd- en ruimtelijke schaal van de simulaties. Ook zijn een aantal mogelijkheden binnen Delft3D

niet in dit onderzoek toegepast. Saliniteit, flocculatie, 3D hydrodynamica, verzakking en inklinking zijn veelbelovende onderwerpen voor vervolg onderzoek.

Verder is breder onderzoek mogelijk die de methodologie verder kan ontwikkelen:

(1) Verbetering in de automatisch detecteren van afzettingen

(2) De resultaten gebruiken voor verdere statistische analyses

(3) Kwantitatieve toetsing met veldgegevens

(4) Opschaling van de resultaten op tijd en ruimteschaal

Het is mijn doel dat dit werk de evolutie van deze methode tot voorbij de simulatie van één enkele prograderende delta zal faciliteren. Hoe dit precies bereikt gaat worden is nog open voor een bredere wetenschappelijke discussie. Mijn blik op de toekomst is dat deze methodologie verder wordt uitgebreid naar complexe bron-tot-bekken reconstructies. En dat deze methodologie samenwerking tussen onderzoekers tussen verschillende velden in de toekomst zal blijven bevorderen.

CHAPTER 1: INTRODUCTION

1.1 THE ROADMAP

1.1.1 MOTIVATION

Geological reservoir models are used to inform hydrocarbon production, geothermal applications and aquifer management. They are created based on sparse core and seismic data. Important factors determining reservoir quality are the heterogeneities within and connectivity of the relevant geo-bodies constituting the reservoir. To predict these properties, subsurface data is complemented with data from comparable sedimentary systems (analogues). Extensively studied ancient deposits or modern systems typically serve as analogues. The properties extrapolated from these analogues include channel distributions, channel geometries or net-to-gross ratios. To produce 3D geological models, all the available measurements and analogue data are combined and stochastic techniques are used to interpolate between available measurements. Due to the large financial investments involved in obtaining direct data of the subsurface, there is a strong demand for improved understanding of sediment distribution and properties, e.g. by using predictive geological models.

The 3D organisation of sediment in the subsurface is controlled by the sediment provenance, its transport along the sedimentary system as well as the diagenetic and mechanical processes acting on the preserved sediments post-deposition. This work focusses on transport and preservation of sediment, which occurs along the entire sedimentary system, from high mountain regions to deep ocean environments (Figure 1).

To understand the preservation of sediment across sedimentary systems requires a detailed understanding of the processes influencing its deposition, erosion and transport. The study of these preserved sediments and their relevant depositional processes is often referred to as process sedimentology. More specifically, process sedimentology has been defined as “a sub-discipline of physical sedimentology, concerned with the detailed bed-by-bed description of siliciclastic sedimentary rocks for establishing the link between the deposit and the physics of the depositional process. It is the foundation for reconstructing ancient depositional environments” (Shanmugam, 2006). This definition implies a cross-disciplinary field combining geology, geomorphology, experimental work, and physics.

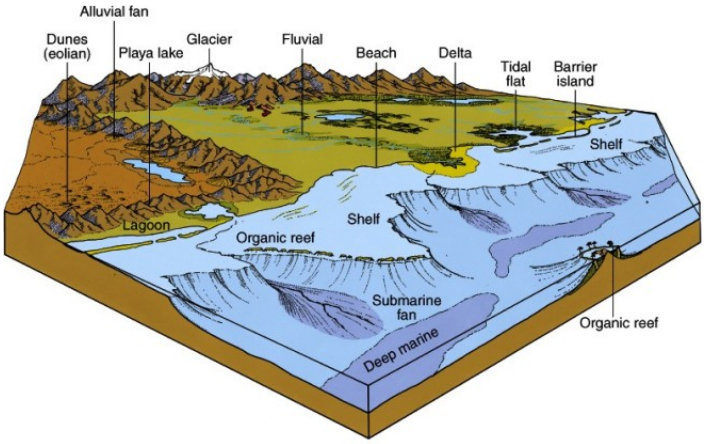


Figure 1: Illustration of the major environments within the sedimentary system (Christiansen, 1995).

Process-sedimentological descriptions of physical processes can furthermore be generalised into mathematical formulations (systems of equations). When specific, carefully selected boundary conditions are assigned to these equations, the resultant numerical solution predicts the behaviour of the system. However, the solution of such complex models requires millions of computations, necessitating the application of advanced computing methods. Gigabytes to terabytes of data can be generated in this way, which have to be stored and analysed using techniques from the field of data science. Such studies therefore exist on the interface between geology, geomorphology, experimental work, physics, mathematics, computer science and statistics. This numerical approach can be described as "computational process sedimentology", and is the approach followed in this dissertation. This methodology allows for repeatability and control to isolate and study the effect of individual variables, while producing detailed datasets for analysis.

Computational process sedimentology facilitates a better understanding between sediment distribution in the subsurface and the physical conditions influencing their deposition. The link between preserved deposits and depositional processes means that sediments preserved in in the rock record may hold clues to the climatic conditions under which they were deposited. Process sedimentology can therefore improve our understanding of the paleo-sediment dynamics based on the preserved rock record. This knowledge improves our ability to predict changes under future climatic disturbances and accelerated climatic change. The computational methodology allows the testing of hypotheses regarding the depositional processes responsible for preservation of a specific ancient deposit. In this way, computational process sedimentological techniques allow a unique glimpse into both the past and the future evolution of our planet's surface.

1.1.2 BACKGROUND

In order to investigate the evolution of deposits over time, the transport and preservation of sediment needs to be understood. There are various scales at which to consider sediment erosion, transport and deposition along the sedimentary system. The spatial scale of a study is determined by the scale of heterogeneity relevant to the research question. In geological studies, spatial and time scales are often related, as illustrated in Figure 2. Questions which require the reconstruction of the entire sedimentary system are usually less detailed spatially. In such cases a long time scale needs to be considered to allow sediment to traverse the entire system. In contrast, questions concerning localised heterogeneities in deposits can focus on a subset of the sedimentary system, e.g. a single depositional environment. Confining the available resources to a smaller scale of study allows investigations at more detailed spatial and temporal intervals. In this work we confine our study to scales from meters to tens of kilometres and depositional times of days to millennia.

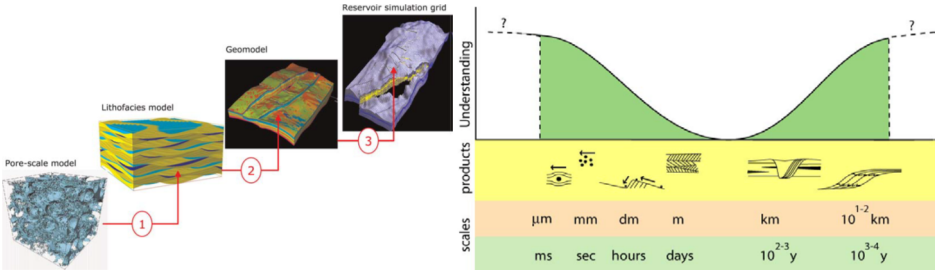


Figure 2: Representations of scales in geological studies. (a) Example of geologically based reservoir simulation models at four scales (Ringrose et al., 2008), from pore networks (50 mm cube) to lamina sets (0.05 m x 0.3 m x 0.3 m) to facies architecture (80 m x 1 km x 3 km) to reservoir simulation (dimensions 200 m x 3 km x 5 km). (b) Schematic diagram showing knowledge gap at the boundary between in situ measurements and stratigraphic data (Storms et al., 2007).

While the underlying physics which control deposition does not change along the sedimentary system, the relative importance of the different processes varies between different depositional environments. For example, when studying the production and storage of sediment in continental settings, it may be imperative to consider temperature and precipitation, while further along the fluvial system temperature may no longer play a significant role. The large scale evolution of eolian dunes, on the other hand, may be very dependent on wind directions with precipitation having playing a smaller role. From a computational perspective, modelling turbidic flows in the deep marine may warrant resolving the hydrodynamics into three dimensions while depth averaged velocities could be sufficient in shallower water.

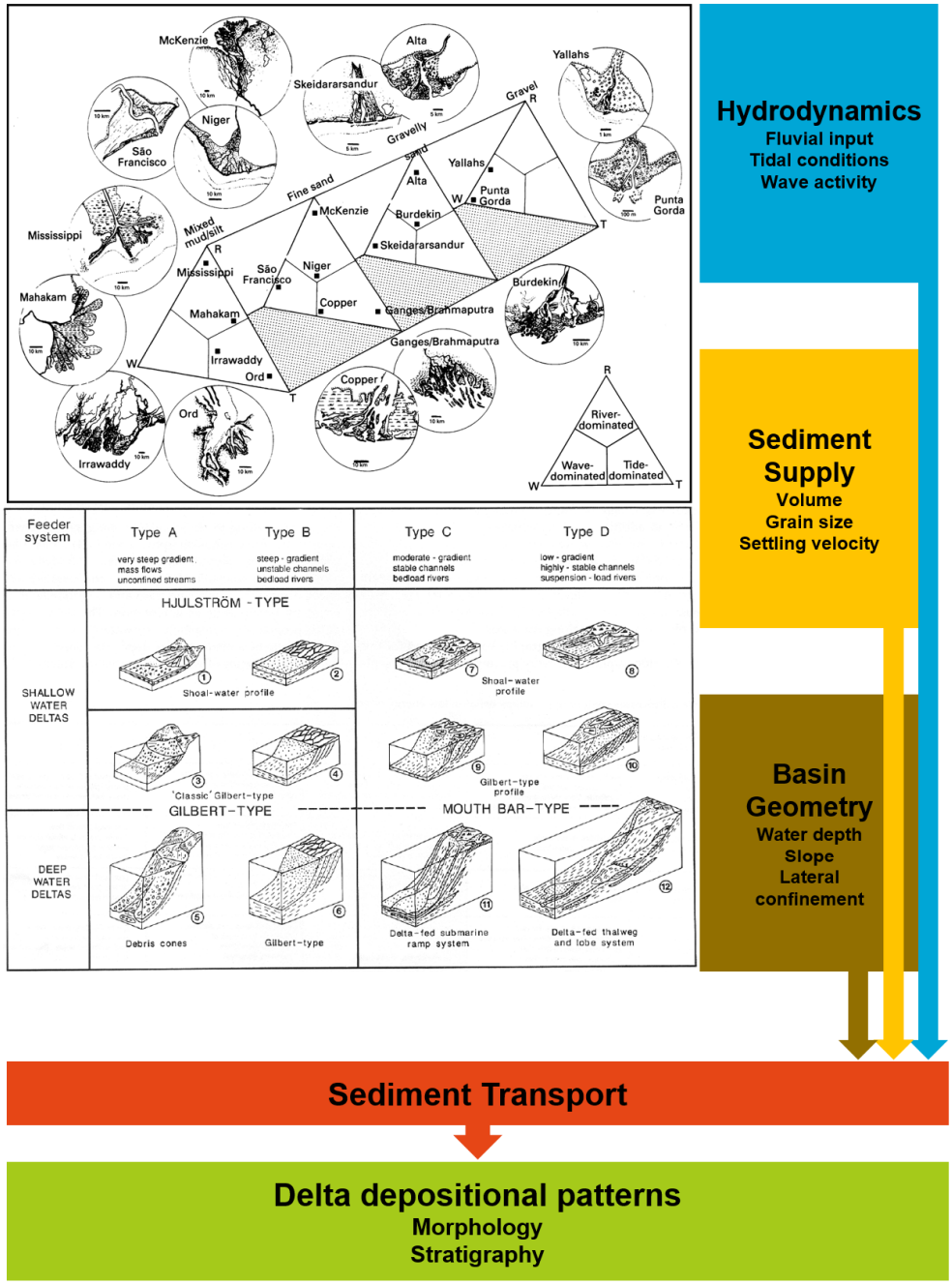


Figure 3: Preserved morphology and stratigraphy in deltaic environments is controlled by variations in sediment transport. Sediment transport in turn is determined by the local interactions between hydrodynamics (Galloway, 1975), sediment supply (Orton and Reading, 1993) and basin geometry (Postma, 1990).

This dissertation is aimed at understanding deposition in the fluvio-deltaic domain. Historically, deltas are described according to many factors, including river-wave-tidal power balance (Galloway, 1975), grain size supplied to the delta (Orton and Reading, 1993) and basin geometry (Postma, 1990). Traditional classifications of modern deltas often focus on the morphological expression of deltaic deposits rather than their preserved stratigraphy. Recent years have seen an increasing drive towards combined analysis of both the morphology and the related stratigraphy in deltaic systems (Ainsworth et al., 2011; Howell et al., 2008; Korus and Fielding, 2015).

From a computational process sedimentology perspective, a combination of hydrodynamics, sediment supply and basin geometry determines the transport direction of sediment locally across the delta (Figure 3). Understanding how these factors influence the transport of sediment across the delta is key to understanding the preservation of delta morphology and stratigraphy. While basin geometry, tidal condition and wave effects certainly have important impact on depositional patterns, fluvial supply of sediment is the necessary condition for the formation of a delta. Therefore, fluvial supply is the natural starting point when studying delta deposits and will be the focus of this research.

Problem statement: What is the relationship between fluvial sediment supply and the 3D evolution of the preserved deposits in deltaic environments?

1.2 THE ROUTE

A number of questions arise from this problem statement. How can the 3D evolution of preserved deposits be quantified and compared between systems? What aspects of fluvial supply should be studied? In order to address the problem statement, focussed research questions were identified to be addressed in subsequent chapters.

1.2.1 RESEARCH QUESTION 1: BASED ON WHICH METRICS CAN WE COMPARE DIFFERENT DELTAS?

Deltas are not static. Boundary conditions influencing deposition and erosion change over time scales ranging from seconds to geological times. So when is the best time to take the snapshot of the natural system? Can delta deposition ever be considered complete?

While these may be interesting questions for discussion, quantitative metrics are required to compare different deltas. For our purposes, these metrics should be applicable to both simulated delta deposits as well as to natural systems (modern deltas or ancient systems). Defining metrics which describe modern deltas and ancient deposits is an evolving field (Bhattacharya and Giosan, 2003; Edmonds et al., 2011; Howell et al., 2008; Korus and Fielding, 2015; Nanson et al., 2013; Syvitski and Saito, 2007). However much work is still needed to consolidate and adapt these metrics to be relevant for simulated output, modern systems as well as ancient deposits. Such metrics would allow more objective

validation of simulation results and, therefore, the iterative improvement of the relevant models. They would also allow us to better constrain the effects of the vast number of controlling parameters affecting delta deposition.

Once we are able to compare simulated and/or natural deltas, it is important to develop a firm grasp of the most important controls on delta deposition. The following chapters consider the effect of sediment transport (Chapter 2), sediment grain size (Chapter 3 and 4) and time-varying discharge (Chapter 5) on depositional patterns. Each of these investigations required the addition of new metrics (Research question 1) to describe the resultant deposition. The work presented in this dissertation provides a framework within which further comparative analyses can be undertaken, as well as a proof of concept for its application on specific delta simulations.

1.2.2 RESEARCH QUESTION 2: HOW DOES SEDIMENT TRANSPORT INFLUENCE PRESERVED DEPOSITS?

Sediment transport controls the dispersal of supplied sediment across the deltaic environment. The influence of hydrodynamics, sediment supply, and basin geometry can be described by their influence on sediment transport behaviour. As such, the physical properties of the supplied sediment cannot be viewed separately from their effect on sediment transport. For example, both cohesive sediment and sediment with low particle density will be transported over relatively long distances before settling. A detailed study of sediment transport mechanisms and the resulting autogenic organisation within the basin was undertaken. The effect of sediment transport mechanism (bed load or suspended load) is compared to the effect of different proportions of cohesive material in the sediment supply, to isolate the effect of sediment transport from that of the sediment's physical properties. Numerical simulation is an ideal methodology for this kind of study, as it allows the isolation and study of individual variables which may be more difficult to isolate in natural systems or physical experiments. This research question is addressed in chapter 2.

1.2.3 RESEARCH QUESTION 3: HOW DOES SEDIMENT SUPPLY COMPOSITION TRANSLATE INTO DEPOSITED COMPOSITION ACROSS THE DELTA?

Are all sediment types delivered to the delta preserved in the same proportions as they are supplied? In order to answer this question a range of sediment supply compositions were supplied to a basin to build 4 different deltas. After allowing the deltas to develop and mature, a comparative study was undertaken to compare the differential deposition of the sediment types in the preserved deposits. The results are discussed in the context of accommodation-to-supply ratios, and highlight the importance of considering the interaction between all three factors (hydrodynamics, sediment supply and basin geometry) when predicting delta stratigraphy. This research question is addressed in chapter 3 and 4.

1.2.4 RESEARCH QUESTION 4: TO WHAT EXTENT IS HETEROGENEITY IN PRESERVED DEPOSITS CONTROLLED BY TIME-VARYING DISCHARGE?

Up to now, simulation of deltas up to millennial time scales have typically considered constant fluvial and marine conditions over time, but this is far from the case in natural systems. The question arises to what extent the heterogeneities observed in deposits from natural systems originate from the autogenic organisation of the system and what extent they are caused by fluctuation in the allogenic controls. In order to study this question, simulations with different time-varying discharges were created. Each simulation has variations in fluvial discharges at a different time-scale, from seasonal fluctuations to long term increase or decrease in discharge, representing climate shifts. The resultant heterogeneity in the deposits are discussed in chapter 5.

1.2.5 APPROACH

Processes controlling deposition in fluvially-dominated deltas were simulated in modelling software Delft3D (Lesser et al., 2004). The software is open source and currently has a user base of more than 15000 active users. This allows for transparency, continuous improvements of the software as well as a large audience who can benefit from the results of a research study. Simulations are based on sediment transported by a fluid, where the deposited sediment can subsequently be preserved or eroded at a later stage in the simulation.

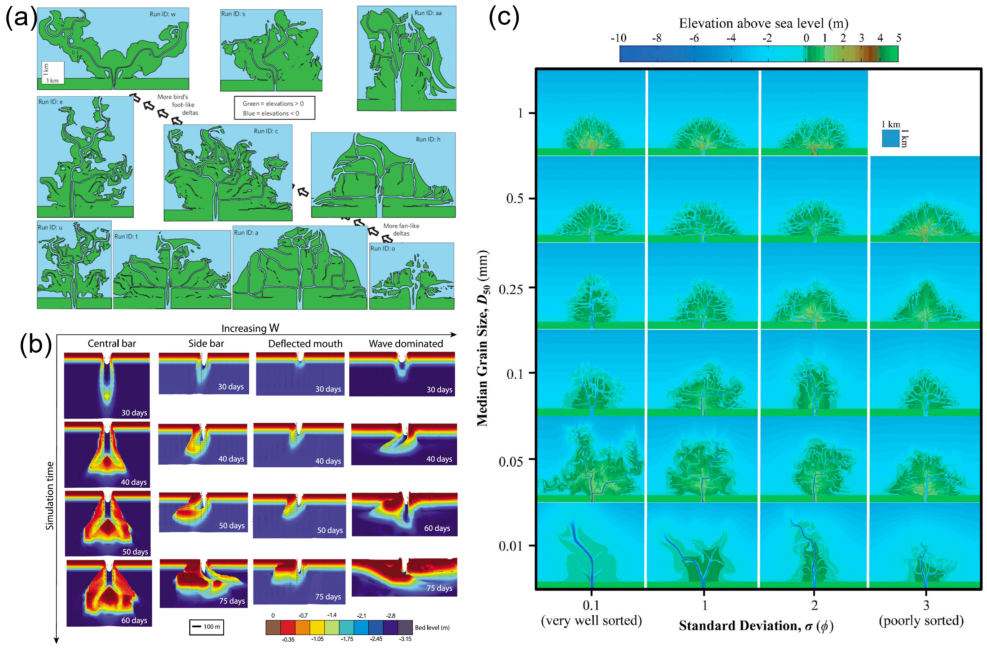


Figure 4: Delta morphology created in Delft3D by (a) (Edmonds and Slingerland, 2009) (b) (Nardin and Fagherazzi, 2012) (c) (Caldwell and Edmonds, 2014)

Delft3D has been used for numerous morphological studies of deltas over the last 10 years (e.g. Figure 4). The research group at TU Delft has additionally been coupling this morphological development to the resultant stratigraphy (Figure 5). However, thus far the study of stratigraphy in Delft3D has focussed on describing the depositional features qualitatively. This dissertation builds on previous research by developing and employing quantitative analyses to allow comparative study of the effects of individual processes and controls on delta morphology and stratigraphy.

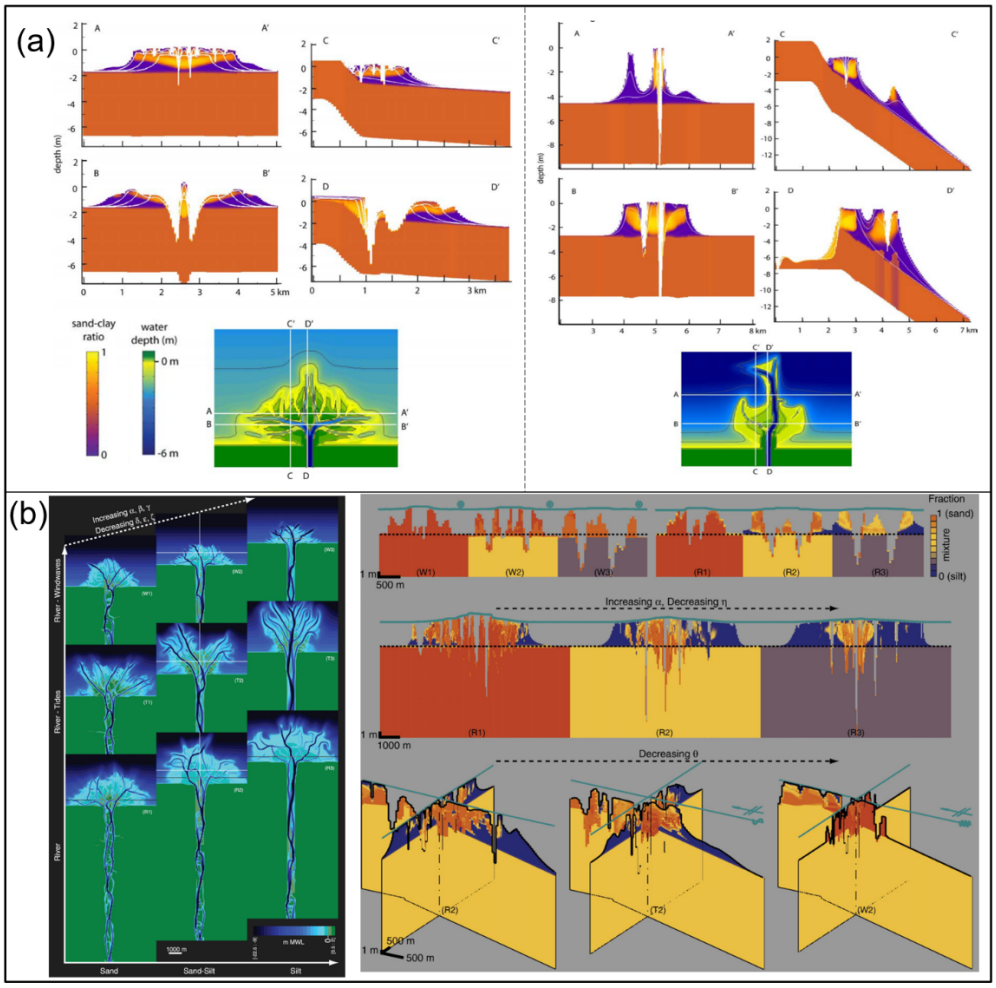


Figure 5: Delta morphology and stratigraphy (a) (Storms et al., 2007) (b) (Geleynse et al., 2011)

1.3 THE JOURNEY - POSTCARDS FROM THE ROAD

1.3.1 THE (SEDIMENT) JOURNEY IS JUST AS IMPORTANT AS THE DESTINATION (CHAPTER 2)

Understanding the processes and conditions at the time of deposition is key to the development of robust geological models representing heterogeneous delta morphology and stratigraphy. In this sense the preserved deposits can be seen as the sediment "destination" while sediment transport can be viewed as the sediment's "journey". This chapter shows how the mechanism of sediment transport (that is, the proportion of the sediment transported as bed load vs. suspended load) impacts delta kinematics, 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 process-based simulations in Delft3D.

1.3.2 BREAKING DELTAS DOWN INTO ARCHITECTURAL ELEMENTS (CHAPTER 3)

Industry professionals and scientists who work in subsurface applications are faced with the challenge of predicting sediments in the subsurface in 3D from limited, discrete datasets. The key to accurate prediction is understanding the processes governing their deposition. In this chapter delta sediment is divided into architectural elements, followed by a detailed study of the sediment grain size composition of the mouth bars. Fluvial catchments deliver a range of sediment grain sizes to coastal delta environments. However, the grain size distribution preserved in the mouth bar deposits are notably different from that supplied. This could explain the bias towards sandy (medium to very fine sand) deltas which dominate literature on ancient deltaic deposits. This grain size alteration is not addressed in many source to sink studies, which are largely volume-based. Therefore, interpretations of palaeo-conditions based on preserved deltaic deposits could lead to wrong assumptions about source and/or sink conditions. The findings highlights the importance of including the prodelta in description and study of ancient system to better understand its sediment supply composition at the time of deposition.

1.3.3 BUILDING DELTAS UP FROM SUB-ENVIRONMENTS (CHAPTER 4)

This chapter reports on the autogenic organisation of sediment within a delta, specifically looking at the interdependence between different sub-environments. Deposition in deltaic systems is controlled by a delicate balance between sediment supply volume and accommodation. Delta deposits are known for their heterogeneity, which is determined by the localised balance between depositional and erosional processes. The accommodation and supply balances are analysed for three delta sub-environments individually. The chapter shows why supply and accommodation volumes should not only be studied on a delta-wide scale. Due to the reworking processes acting in different regions within the delta, a strong relationship exists between the sediment grain sizes

supplied to the delta and sediment available to fill each sub-environment's accommodation. E.g. a grain size profile consisting of fine sediment, supplied to a delta with strong wave reworking will have a large supply of sediment to fill the prodelta, but less sediment to deposit to fill the delta front and delta top accommodation. It is therefore entirely possible for one sub-environment to be supply-limited while another can be accommodation-limited at the same time.

1.3.4 THE DEVIL IS IN THE SCALE OF DETAIL REQUIRED TO DESCRIBE HETEROGENEOUS DEPOSITS (CHAPTER 5)

Sediments deposited in deltaic environments can serve as hydrocarbon or geothermal reservoirs or aquifers, but the inherent depositional heterogeneity of these deposits can significantly influence the quality of these reservoirs. Numerical simulations were conducted to understand the effect of time-varying fluvial discharge on sedimentary heterogeneities in deltaic depositional environments. The results show how the scale at which to consider discharge variation in simulations of prograding deltas, is dependent on the spatial scale at which heterogeneity is being considered.

CHAPTER 2: THE (SEDIMENT) JOURNEY IS JUST AS IMPORTANT AS THE DESTINATION

This is based on the publication “van der Vegt, H., Storms, J.E.A., et al., 2016. Can bed load transport drive varying depositional behaviour in river delta environments? Sedimentary Geology, 345.”

The research presented here followed a detailed review of all the sediment transport formulations available in Delft3D. This review highlighted the importance of the mechanism of sediment transport (bed load or suspended load) on the depositional patterns within the delta. The mechanism of sediment transport is closely related to, but not equivalent to, the effect of cohesion of the sediment supply. Past studies on the effect of cohesion on delta morphology, did not consider the effect this has on the mechanism of sediment transport explicitly. The aim of this study was to decouple these two factors to investigate their individual and combined effects on delta depositional patterns. Before undertaking this study, tens of models were simulated to select the most appropriate transport formula for simulation of deltaic deposition. The Engelund-Hansen formula was selected to conduct this detailed investigation on the effect of bed load on delta deposition.

2.1 INTRODUCTION

Past studies have shown that the balance between cohesive and non-cohesive sediment can have significant effects on deltaic morphology (Edmonds and Slingerland, 2009; Geleynse et al., 2011; Hoyal and Sheets, 2009; Peakall et al., 2007). Deltaic stratigraphy, in turn, can be viewed as a record of the evolving morphological changes. We examine the effect of both sediment transport mechanism and cohesive content on depositional geometries in fluvial dominated deltas. We propose that the mechanism of sediment transport (that is what proportion of the sediment supply transported as bed load vs. suspended load) impacts depositional behaviour to at least the same extent as sediment properties such as cohesivity.

The heterogeneous nature of river delta morphology and stratigraphy complicates the development of geological models. 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 (Hoyal and Sheets, 2009; Orton and Reading, 1993). Comparatively less attention has been given to the effects sediment transport mechanisms have on deltaic morphology and stratigraphy (Ahmed et al., 2014).

Sediment transport ultimately regulates where and how sediment is deposited, based on local hydrodynamic conditions and sediment properties. Sediment transport in a delta 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. Existing work primarily considers fluvial systems with limited work having been conducted at coastlines (Van Rijn, 2007). In experimental settings there are various challenges associated with the scaling of sediment transport (Paola et al., 2009).

Due to this limited data availability, bed load is typically estimated or calculated based on the suspended load measurements (e.g. 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 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. compiled in their review. It shows that as little as 1% and or as much as 50% of the total sediment load can be transported as bed load. For ephemeral rivers, however, this is often even higher, up to 100% (Karimaee Tabarestani and Zarrati, 2015; Turowski et al., 2010).

Various factors have been hypothesised to influence the balance between suspended load and bed load transport in fluvial systems. Locally this is determined by particle size, weight, shape and the hydraulic conditions, while on a larger scale influencing factors may include catchment geology, climate and relief (Karimaee Tabarestani and Zarrati, 2015; Kleinhans and Grasmeijer, 2006; Laronne and Reid, 1993; Turowski et al., 2010; Van Rijn, 2007). 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 (Ashworth and Lewin, 2012; Kleinhans, 2010; Turowski et al., 2010). The significance of sediment transport mechanism as a control on deltaic depositional patterns is yet to be established. Considering the challenges associated with obtaining field data for bed load transport, it is imperative to better understand the implications of these processes on delta morphology and stratigraphy prior to undertaking field studies.

Employing Delft3D (e.g. Lesser et al. 2004) to generate process-based models, we assess the effect of the sediment transport mechanism and sediment composition on deltaic

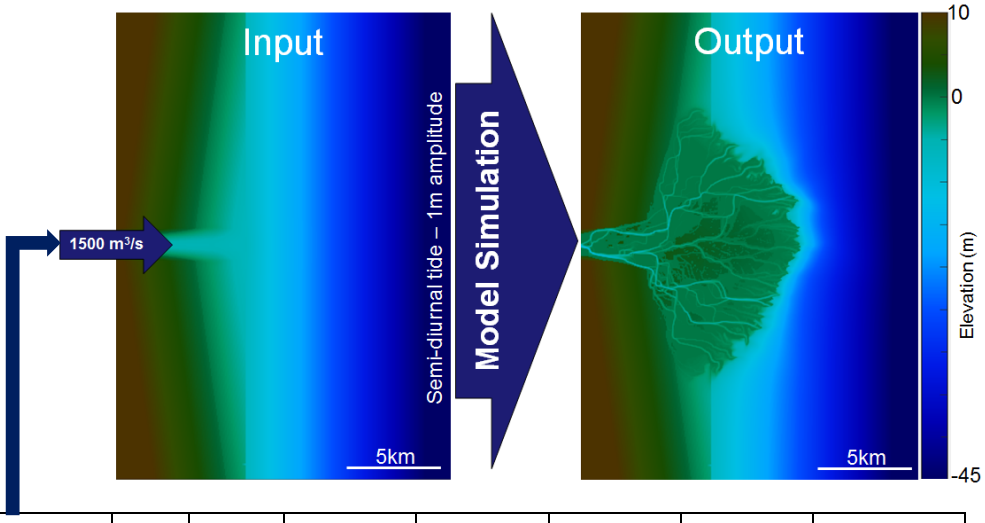
morphology and stratigraphy. As predictions made with process-based models are consistent and they allow careful control of boundary conditions, the quantitative output can be compared and specific processes or mechanisms can be isolated. Following this approach we explore three metrics: (1) channel geometry and channel dynamics, (2) locations of sediment deposition, reworking (in these examples mainly reworking by channel erosion) and preservation (3) large scale delta geometry. We also discuss the relationship 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.

2.2 EXPERIMENTAL DESIGN

We created an ensemble of 15 numerical models using process-based modelling software Delft3D (Lesser et al., 2004). Models were calculated using Delft3D (Version 4168) with parallel processing on a single, Linux operating, 16-core node. In past studies, Delft3D has been extensively applied to study the effects of hydrodynamic forcing and sediment properties on river delta morphodynamics (e.g. Geleynse et al. 2011; Geleynse et al. 2012; Geleynse et al. 2010; Caldwell & Edmonds 2014; Edmonds & Slingerland 2009). Our numerical experiments investigate the implications of mechanism of sediment transport on depositional behaviour in a river delta.

2.2.1 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 (Geleynse et al. 2011). One change is that the 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. The initial channel width is 1000m and with constant discharge of 1500m^3/s. This discharge should be considered as a continuous bankfull flood stage. A tide with amplitude of 1m was added to introduce some dynamics into an otherwise very steady system. The effect of salinity profiles was not considered.



Sediment Class	Median grain size (μm)	Settling Velocity (mm/s)	Critical bed shear stress for dep. (N/m^2)	Critical bed shear stress for erosion (N/m^2)	Reference density for hindered settling	Specific density (kg/m^3)	Dry bed density (kg/m^3)
Sand1	200	-	-	-	1600	2650	1600
Sand2	100	-	-	-	1600	2650	1600
Cohesive1	-	0.86	1000	0.3	1600	2650	500
Cohesive2	-	0.25	1000	0.5	1600	2650	500

Figure 6: Bathymetry and boundary conditions for all models in the simulation ensemble and sample output for model 2.3. The input boundary conditions include discharge and sediment input at the fluvial boundary and a semi-diurnal tide at the distal basin boundary.

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 $0.2kg/m^3$ 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 the 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 millenial timescale. Simulation output was recorded at the end of each of the 366 hydrodynamic days.

2.2.2 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 in suspension, 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 (Caldwell and Edmonds, 2014; Edmonds and Slingerland, 2009; Van Rijn, 1993) or the Engelund-Hansen transport formulation (Engelund and Hansen, 1967; Geleynse et al., 2011, 2010) 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 Figure 6. Each class is simplified to a single D50 value, or in the case of cohesiv material to a settling velocity and critical shear stress for erosion. The properties for the individual sediment classes as well as the total sediment supply concentration are the same in all simulations

The models parameter space explores the role of sediment transport and sediment composition on delta development. The effect of bulk composition is explored by varying the cohesive versus the non-cohesive sediment fraction. The effect of sediment transport mechanism is explored by varying the relative proportions of bed load versus suspended load transport. The translation of this parameter space into the model input is provided in Figure 7. Models that have high suspended load transport are grouped as SL-models while models with high bed load transport are grouped as BL-models. Cohesive models then follow with the CS abbreviation and non-cohesive models with the NS abbreviation. The 15 simulations were categorised into four quadrants based on their mechanism of sediment transport and cohesiveness: SL-CS, BL-CS, SL-NS, and BL-NS. These abbreviations will be referred to when comparing depositional trends relating to these differences in cohesivity and sediment transport.

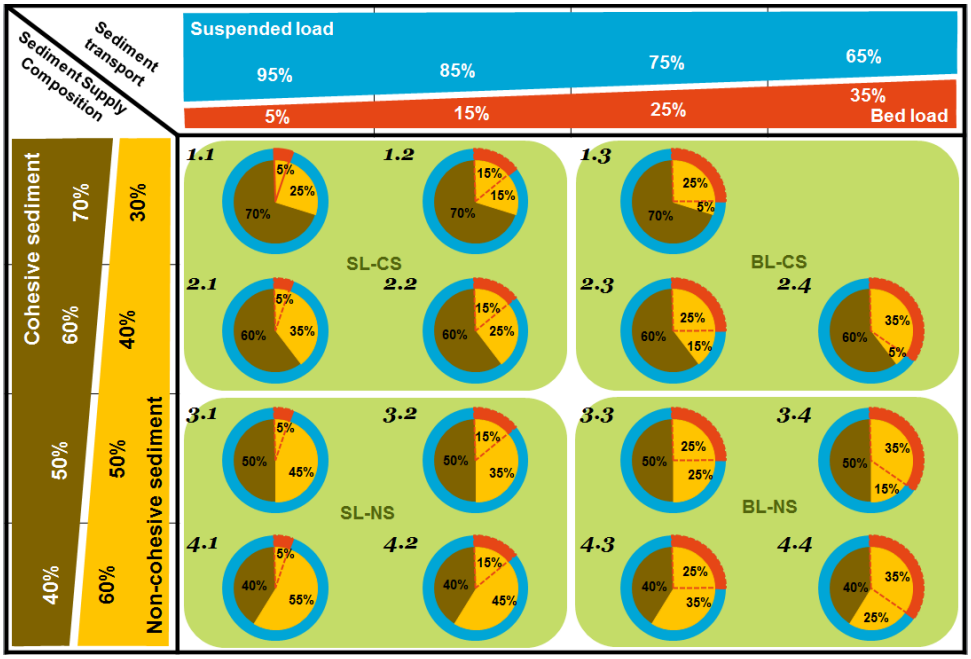


Figure 7: Variation in boundary conditions for the models used in this study. Sediment transported as bed load (orange) increases from left to right at the expense of suspended load (blue). The proportion of non-cohesive sediment supply (yellow) increased downwards at the expense of cohesive sediment (brown). Total load concentration is constant at 0.2 kg/m3 across all models. Model 1.4 does not exist as it is not possible to define 35% bed load when only 30% sediment is classified as non-cohesive. Models are grouped into 4 quadrants depending on their proportions of bed load transport (BL) vs. suspended load (SL) and proportion of cohesive sediment (CS) vs. non-cohesive (NS).

2.2.3 ANALYSIS AND PROCESSING

A delta is an evolving landform with morphology and stratigraphy changing over time. To account for the evolution of the depositional behaviour, the analyses were performed per output time interval. Output files contain a record of the bathymetry and the hydrodynamic conditions prevailing at each output time step. This provides insight into the morphology and stratigraphy as the delta evolves, as well as the processes controlling its evolution.

The first set of analyses pertain to the morphology and kinematics of the channel network. The channels constitute a distributed sediment supply network across the delta top and delta front. In addition to acting as a sediment source, the active channels are also the main erosive features responsible for reworking of sediment.

We defined the active channel network to consist of locations with high sediment transport values together with large flow velocity or erosion. Active channel network locations must have a water depth greater than 0.5m. Owing to the element size of 50m x 50m horizontally, a water depth of less than 0.5m would imply a width-to-depth ratio of

more than 100. This value falls well outside of the definition of a channel, filtering out sheet flow at the current grid resolution (Gibling, 2006; Hajek and Wolinsky, 2012). Channel depth has implications for the reworking of the underlying sediment. The average channel depth w.r.t. the surrounding delta plain/delta top was also calculated for each model at every time interval.

The channel network does not occupy the same locations over time. As channels prograde into the basin, individual channels can migrate laterally, avulse or become abandoned. All of these processes lead to new areas of the delta top becoming incorporated into the active channel network while other areas no longer form part of this network. We calculated the proportion of the active channel network which overlaps with part of the active channel network of the previous output time interval as an indication of channel network mobility. The the scale of lateral reworking of sediments as well as the distribution of sediment deposition across the delta network (Jerolmack and Mohrig, 2007).

Understanding where sediment was deposited and where it was subsequently reworked provides insight into the preserved stratigraphy of the delta top, delta front and prodelta. Deposited sediment was divided into four architectural elements based on location and depositional process. These consist of the following categories (Figure 8):

1. Channel deposits: consist of accretion deposits as channels migrate or aggrade as well as channel fill following an avulsion. This was defined as any sediment deposited at active channel locations, or at a location which was part of the active channel network until the elevation at that position equals the average elevation of surrounding delta top.

2. Overbank deposits: Consists of sediment deposited on the delta top outside of the active channel network.

3. Delta front deposits: Consists of mouth bar sediments deposited at the mouth of the active channels as well as lobate geometries lower down the delta front. These deposits were defined as locations were more than 0.15m of sediment was deposited in one output time interval. This thickness definition is based on inspection of the results as well as the vertical resolution of the grid.

4. Prodelta deposits: Consists of all other deposits.

For the purpose of analysis it is necessary to define a definite boundary between delta front and prodelta deposits, however it is important to recognise that in natural systems this transitions is more gradual.

In addition to calculating the architectural units deposited we are especially interested in the reworking and preservation of these units. They acts as drivers for the final geometry of the delta deposits. Large scale geometric trends were calculated as a function of distance from the delta apex. For this purpose, radially averaged topographies were constructed as shown in Figure 9. The model results were mapped to polar coordinates with origin located at the delta apex. This allows each location to be described by distance

from apex and angle from the coastline. The boundaries on either side of the apex were respectively defined at 10° and 170° to account for the initial trumpet shaped bathymetry. Active channel elements were not included such that the remainder of the bathymetry constitute the delta top, delta front and prodelta. The elevation was averaged across all angles from 20° to 160° and plotted as a function of distance from apex. For each model 366 topographic profiles were constructed, representing the 366 output time intervals. For each profile the location of the brink point (separating the delta top and delta front) and delta toe (separating the delta front and pro delta) were identified.

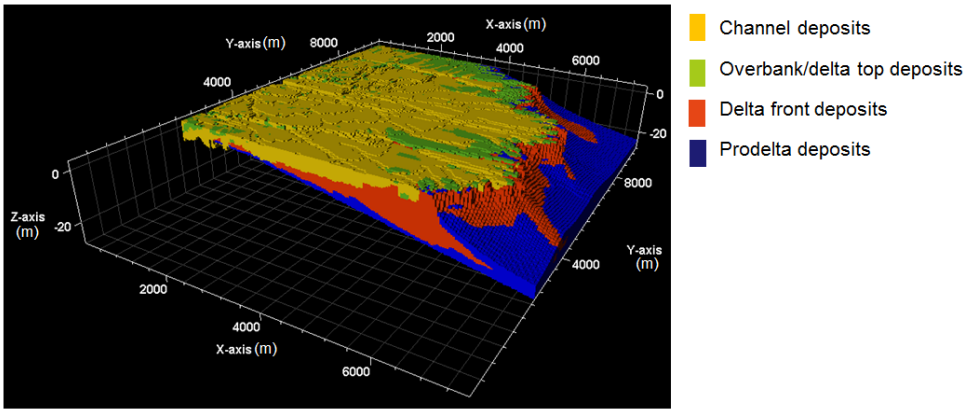


Figure 8: Distribution of preserved architectural elements at the end of simulation for Model 2.3

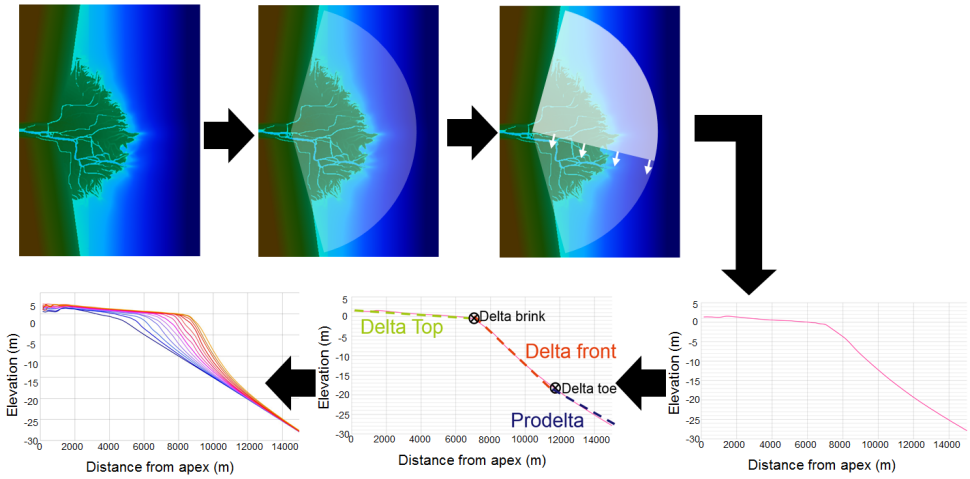


Figure 9: Construction of the averaged topographic profiles. Elevation of the non-channel bathymetry points averaged radially around the delta apex, plotted as a function of distance from apex.

2.3 RESULTS

The ensemble of numerical simulations allow us to study and compare the evolving geometry (morphologic and stratigraphic) and kinematics of the deltas within our parameter space. Figure 10 displays a plan view of the bathymetry at the end of each of the 15 simulations. Bathymetry has been corrected for local water level, which can be higher proximally due to the backwater effect. But, in order to evaluate the depositional behaviour of an evolving landform, we need to compare analyses which account for change in behaviour over time.

The analysis starts with channel morphology and kinematics. The active channel network acts as a distributed sediment source across the delta top and as such drives the location of sediment deposition. Additionally the active channel network occupies different locations over time, eroding lateral and underlying sediment. Hereby channel kinematics determine the locations where sediment is reworked. We subtract the volume of sediment which is reworked after its initial deposition, obtaining the volume of preserved deposits. Deposited sediments are classified by architectural elements to describe where sediment is deposited. Large scale delta geometry is in turn a product of the preserved architectural elements.

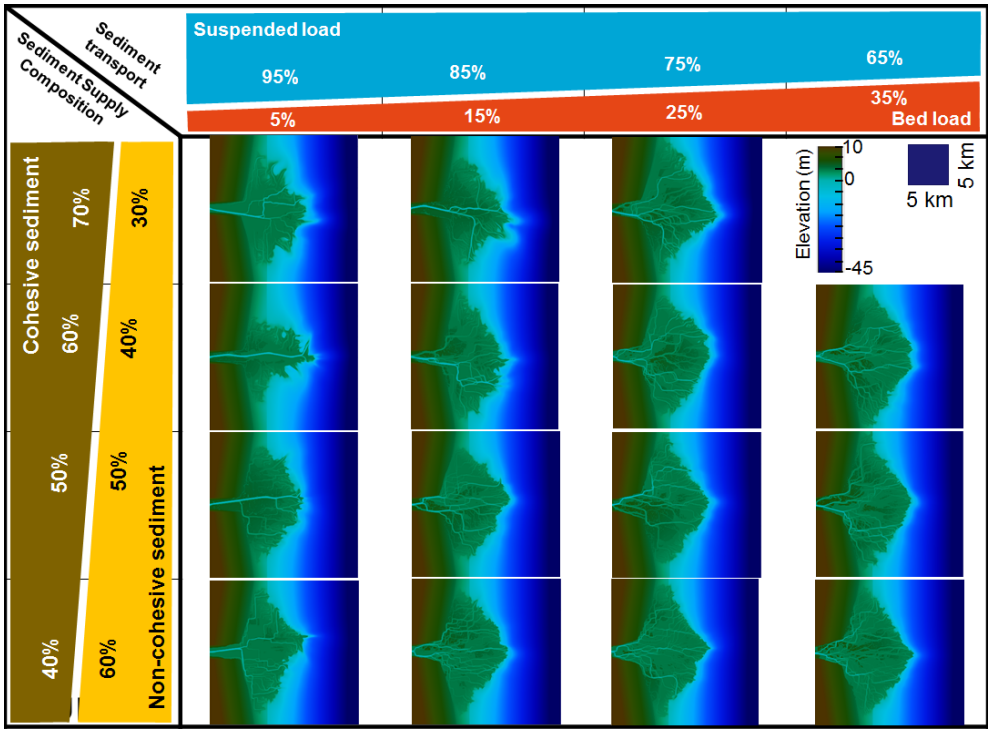


Figure 10: Bathymetry of model ensemble at the end of the simulation. Elevation values were normalised for difference in water level.

2.3.1 CHANNEL MORPHOLOGY AND KINEMATICS

In this section we focus on channel properties (morphology and kinematics) which drive sediment deposition and reworking. The channel depth relative to the surrounding delta top elevation was determined for each model in the ensemble. The mean depth (spatially and temporally) was then calculated for each model (Figure 11). Channel depth decreases both with less cohesive sediment supply and less suspended load. This means SL-CS model typically have deeper channels than BL-NS models.

Mean values of channel overlap were calculated (Figure 11) as a proxy for channel mobility. Channel mobility is greater in BL-NS models while channel networks in SL-CS models tend to occupy the same locations for longer periods of time.

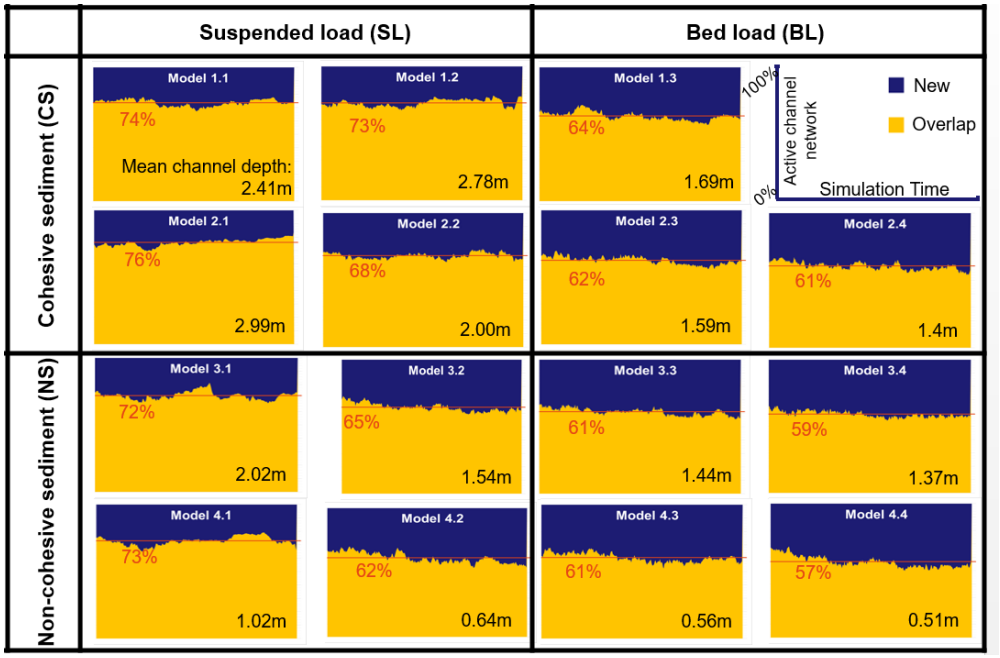


Figure 11: Channel network area showing the percentage of the active channel network area overlapping with the active channel network of the previous time interval. Mean channel depth (m) with respect to the adjacent delta top/flood plain is displayed in the bottom right corner. The mean is calculated spatially and over time.

2.3.2 SEDIMENT REWORKING AND PRESERVATION

During the simulation sediment is deposited in varying quantities across the model domain. At the same time, previously deposited sediment is eroded (reworked) by the evolving channel network. Subtracting the reworked sediment from the total deposited sediment provides the net volume of sediment deposited. This volume of net deposition is reasonably constant for each output time interval. It is important to note that eroded (reworked) sediment can again be deposited in one of the following time intervals and

ultimately preserved. The volume of overall preserved deposits increases over time as the delta progrades and can be calculated as the cumulative net deposition.

The volume of reworked sediment varies significantly between simulations (Figure 12). The model where deposited sediment undergoes the most reworking (model 4.4) shows more than 5 times as much reworking than the model experiencing the least reworking (model 1.1). In contrast the volume of preserved deposits is relatively constant between simulations. The model preserving the largest volume of sediment (model 1.3) preserves 1.4 times as much sediment as the model preserving the least (model 4.1).

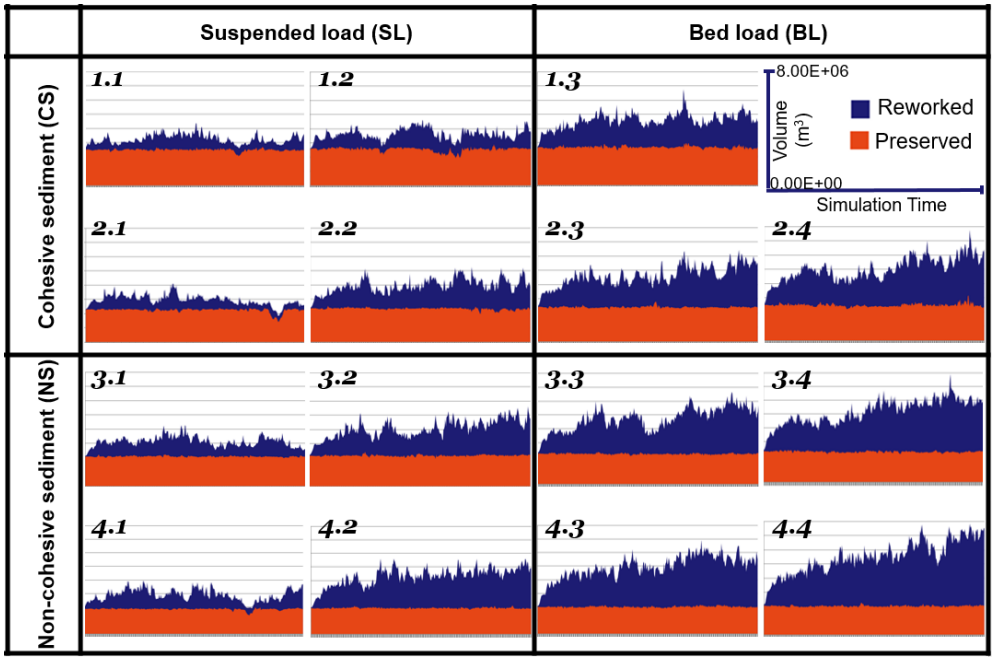


Figure 12: Total deposition over time for all 15 models. The net volume of sediment deposited in each time interval (blue plus orange area) over the entire model domain normalised for the maximum deposition in single time interval. The blue area represents the volume which is eroded (reworked) and the orange area the net volume of sediment which is deposited as the delta progrades.

Sediment deposited in BL-models are much more likely to undergo reworking than in SL-models (Figure 12, blue area). To a lesser extent, sediments deposited in NS-models undergo slightly more reworking compared to those deposited in CS-models. Therefore, either more bed load transport or more non-cohesive sediment leads to a greater volume of sediment reworked in the simulated deltas. As the delta evolves, the volume of reworked sediment per output time interval increases and the differences between the models also become even more pronounced.

The total deposited sediment was classified into four architectural elements: channel deposit, overbank deposit, delta front deposit and prodelta deposit. The reworked and preserved sediment can therefore also be classified into these architectural elements.

Sediment reworking occurred mainly in delta top deposits (channel- and overbank deposits) and to a smaller extent in the delta front deposits (Figure 13). Only in shallower, proximal regions, where a thinner layer of delta top and delta front sediments were deposited, did sediment erosion reach older prodelta or substrate deposits. Sediment eroded from the substrate contributed less than 0.2% of the total sediment supplied to the systems and was not included in the analyses. SL-CS models show smaller proportions of delta top reworking compared to BL-NS models, but larger proportion of delta front and prodelta reworking. As the delta top grows over time, a larger volume of channel and overbank deposits undergo reworking within each time interval (Figure 13). This trend is stronger in BL-NS models where it is barely visible in SL-CS models. Delta front and prodelta deposits undergo a more uniform volume of reworking over time.

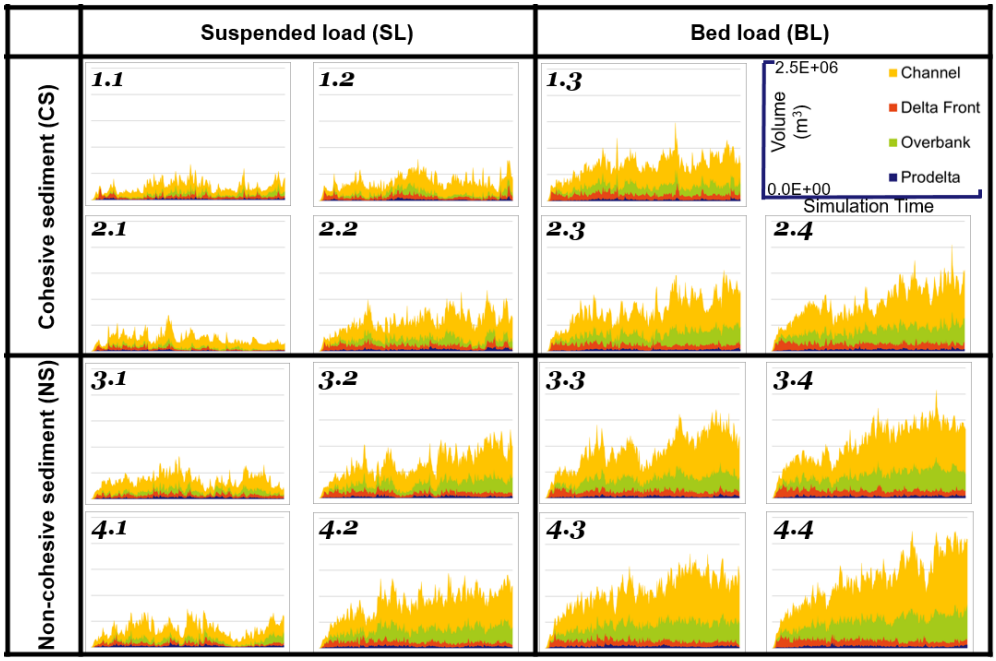


Figure 13: Composition of the reworked sediment by architectural unit

The proportion of the preserved architectural units reaches a steady state and therefore each delta can be characterised by a unique ratio of preserved architectural elements, which differ between simulations (Figure 14). To compare the values of architectural units across models these values are normalised for the total deposition in model 1.1.

The proportion of channel deposits which are preserved is largest in BL-NS models and smallest in SL-CS models. Conversely, preserved volume of prodelta deposits is largest in SL-CS models and smallest in BL-NS-models. Overbank deposits account for only a small volume of the preserved deposits and variation between models is negligible.

In all analyses presented thus far, SL- to BL models show similar trends to CS- to NS-models. However, for delta front deposit preservation (which includes mouth bars) the

opposite trend is observed between SL- to BL-models compared to CS- to NS-models. The volume of delta front deposits is smaller in SL-models than in BL-models. However larger volumes of delta front deposit is preserved in CS-models than NS-models.

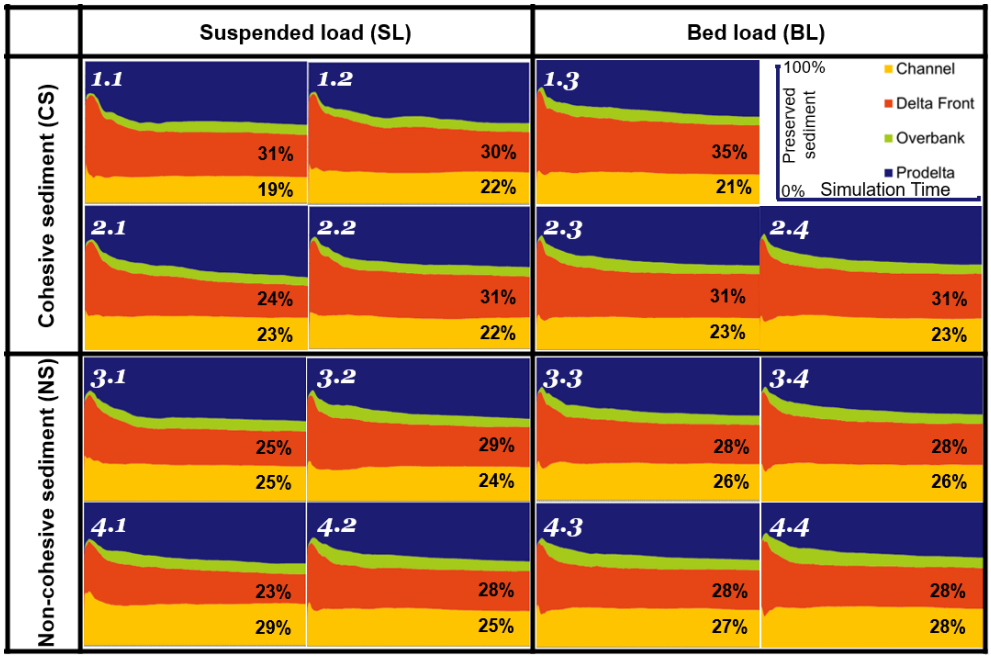


Figure 14: Evolution of total preserved deposit throughout the simulation, by architectural elements. The average proportions of channel reaches a stead state early on in the simulation.

2.3.3 EVOLUTION OF DELTA GEOMETRY

The topographic profile of a delta changes as it progrades (Figure 15).While BL-NS models show progradation and aggradation, SL-CS models are only progradational.

The brink point displacement is a proxy for delta top progradation and is much larger in BL-NS models than SL-CS models. Conversely the delta toe displacement is a proxy for delta progradation and is larger in SL-CS models than in BL-NS models. Therefore, while SL-CS models undergo more delta progradation into the basin, the BL-NS undergo more delta top progradation (Figure 15).

When considering the two end members, the smallest median displacement of the brink point (model 1.1) is only 50% of that of the largest (model 4.4). The smallest median displacement of the delta toe (model 4.4) is only 68% of that of the largest (model 1.1).

Brink point displacement in BL-NS models is relatively constant over time while in SL-CS models brink point exhibits episodic displacement followed by times of relatively little displacement (Figure 15). However, the delta toe is displaced smoothly over time for all models.

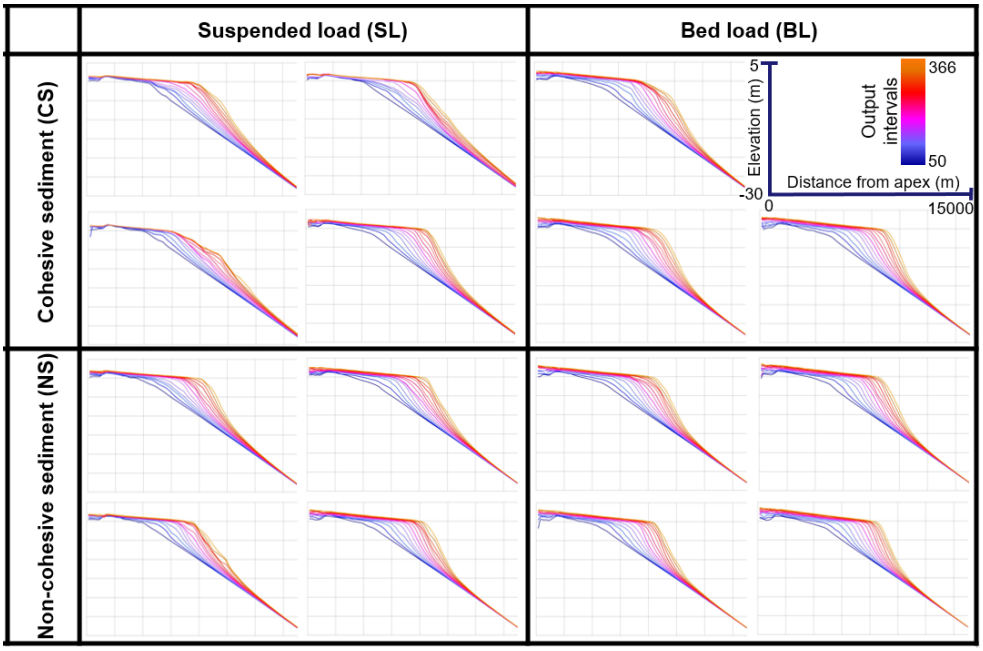


Figure 15: Evolution of averaged topographic profile of each model over time. 14 of the 366 topographic profiles spanning the evolution of each simulated delta are displayed. Blue shows the oldest profile and orange the youngest.

2.4 DISCUSSION

We developed and employed a set of general metrics to compare deposits from an ensemble of synthetic deltas. These metrics fall into three categories:

1. Channel morphology and kinematics,

2. Sediment reworking and preservation,

3. Large scale delta geometry.

Depositional responses are interdependent, as the evolving system strives to reach optimal hydraulic efficiency. In these prograding systems the driving force behind the evolution is the fluvial input, supplied to the delta through the channel network. The evolution of the channel network is therefore key in describing the depositional behaviour of the system.

We have identified gradual differences in the geometric depositional patterns from bed load (BL) systems and suspended load (SL) systems. Although BL-models exhibit many of the same characteristics as NS-models, we have demonstrated that these characteristics can also originate from the preferential mechanism of sediment transport alone.

2.4.1 SUSPENDED LOAD SYSTEMS

The degree of channel network overlap from one output time interval to the next is a proxy for channel mobility, reflecting both avulsion and lateral migration of channels. Low channel mobility, such as that seen in SL-models, has previously been associated with cohesive sediment (Edmonds & Slingerland 2009; Geleynse et al. 2011; Edmonds et al. 2011; Hoyal & Sheets 2009).

The suspended sediment (cohesive plus suspended non-cohesive sediment) in the SL-models can readily bypass the channel network, decreasing vertical aggradation within the channels. Channels therefore erode deeper into the underlying delta deposits than in BL-models. Active channels occupy the same location for a long time, producing localised delta front deposits (mouth bar) sediments over- and through which the channel progrades into the basin. This leads to rugose delta brink contours (Figure 10) and more interdistributaraty bays developing. After an avulsion does occur in these systems it leaves a deep abandoned channel feature in the delta top which is initially unfilled but no longer forms part of the active channel network. Together with the rugose delta brink development, this contributes to a larger variability in delta top geometry in SL-models.

The low channel mobility not only affects delta top geometry, but also implies that channels rework a limited area of the delta top. The delta top deposits override the older delta front deposits and even older prodelta deposits. Since SL-models produced deep channels, channel erosion can reach down to underlying delta front and prodelta deposits more readily. The extent to which the underlying deposits are reworked also depends on the thickness of the delta top deposits. The low mobility of the channel network causes the elongated, prograding channels to transport sediment deeper into the basin. More sediment is transported to the delta front and prodelta rather than being distributed on the delta top. Therefore the delta top does not aggrade, but instead the entire delta progrades further into the basin at the expense of delta top aggradation. The reworking of these vertically stacked architectural elements, over a limited horizontal area, could produce heterogeneous delta facies, disconnected by the deep channel features.

Channel network behaviour in SL-models is similar to that found in CS-models. However, the preservation of delta front deposits is distinctly different between SL-models and CS-models. While more cohesive material causes more delta front deposition, more suspended load causes less sediment to be deposited in the delta front.

The cohesive sediment fractions have a smaller grainsize than the non-cohesive sediment fractions. Therefore the mean grain size of the sediment supply decreases with increasing cohesivity in this model ensemble. The combined mean grain size of the sediment supply is smaller in CS-models than in in NS-models, increasing the distance sediment is transported before being deposited. Therefore, more sediment bypasses the delta top in CS-models, depositing in delta front and prodelta instead. Similar response to grain size has been recorded in the literature (Caldwell & Edmonds 2014).

In this paper, we have kept the overall mean sediment grain size of the sediment supply constant while increasing the suspended sediment transport. This means that grain size

cannot be the cause of the difference in channel network behaviour between SL- and BL-models. As suspended sediment transport increases, there is a gradual change in sediment dispersal from the deposition predominantly at the delta top to deposition at the delta front and prodelta. The delta front in SL-models consists of a thin, elongated sediment bed which gradually blends into the prodelta distally. In addition, low channel mobility leads to localised sediment supply to the delta front rather than being spread in a smooth arc around the delta apex. Once deposited, the delta front is soon partially reworked by the prograding, low mobility channel from which it was initially deposited. This, together with the deeper channels in SL-models reaching down to rework older delta front deposit, causes a high ratio of delta front reworking compared to the delta top reworking and lower proportions of delta front deposit being preserved in SL-models.

2.4.2 BED LOAD SYSTEMS

BL-models exhibit highly mobile channel networks with frequent avulsions. The high bed load transport constrains sediment to the channel network both during transport and deposition. This causes vertical aggradation, increasing the rate of avulsion. Overloading of bed sediment has previously also been linked to vertical channel aggradation followed by avulsion (e.g. Kleinhans et al. 2012).

The shallow channels contribute to less variability in delta top geometry. The highly mobile channel network also distributes sediment smoothly across the entire delta front and delta top leading to a smooth delta brink contour, with an absence of distributary bays. Repeated reworking by the channel network further smooths delta top geometry.

Together with the smooth, reworked delta top, the vertical aggradation in the channel network causes the entire delta top to aggrade over time. This is most pronounced at proximal locations, which have undergone aggradation and reworking for a longer period than the distal locations. The rise in proximal flood plain elevation also causes a rise in water level. This creates additional accommodatio in the inter-distributary/bay areas, which further channel avulsions can occupy. It is not possible to isolate whether the depositional trends drive the channel dynamics or whether the channel dynamics drive the depositional trends. Most likely this mechanism represents a feedback in delta top aggradation in high bed load systems.

Additionally, the high channel mobility causes a large area of the delta top to be reworked by the channels. The shallow channels do not frequently erode into the underlying delta front and or prodelta deposits. Therefore reworking is mainly constrained to the channel and overbank deposits which constitute the delta top.

While channel dynamics and proximal floodplain aggradation occur in both BL- and NS models, trends in delta front deposits differ. Higher bed load transport (BL-models) causes more delta front deposit while higher non-cohesive sediment supply (NS-models) causes less. As discussed, the differences in delta front deposits between cohesive to non-cohesive deltas may similarly be driven by grain size variation.

In BL-models however, any transported bed load not deposited in active channel network is transported towards the channel mouth where it is deposited as mouth bar or delta front deposits. When the downstream distance along the channel becomes too large for sediment to be transported to the channel mouth, vertical channel aggradation increases that eventually leads to avulsion (Kleinhans et al., 2012). This increases the proportion of sediment deposited close to the channel network (channel and proximal delta front deposit) at the expense of prodelta and overbank deposit. The shallower, aggradational channels are also less likely to rework delta front deposits at the channel mouth or reach down to it as the channels traverse the delta top. Therefore BL-models preserve a larger quantity of especially upper delta front deposits.

2.4.3 FROM SYNTHETIC ANALOGUES TO NATURAL SYSTEMS

The model results are presented as synthetic analogues to analyse the effect of sediment transport on the general depositional behaviour in natural systems. This requires consideration of the differences between the synthetic analogues and natural systems.

We investigate variation in the mechanism of sediment transport (suspended- vs. bed load) independently from variation in sediment cohesivity. However in natural deltaic systems these two aspects are related. Bed load transport in deltaic systems is still poorly understood and it has been suggested that it should not be calculated as a function of suspended load but as a separate entity (Kazemi et al. 2012).

One process which has been linked to the proportion of bed load transport in fluvial systems is flooding (Karimaee Tabarestani & Zarrati 2015). Our simulations impose constant discharge which limits the amount of channel over-spilling and may underestimate overbank deposition. Due to the link between floods and higher proportions of bed load transport, an underestimation of overbank deposits is likely more relevant for systems with high bed load transport (BL-models). At the same time, we do not model low stage discharge, which would be dominated mainly by suspended load. During these low discharges, overbank deposits are unlikely to be generated and the models could therefore also overestimate overbank deposition.

In natural systems the relationship between suspended load and bed load is not constant (Chatanantavet et al. 2012; Karimaee Tabarestani & Zarrati 2015; Laronne & Reid 1993). E.g. during peak flow events bed load transport may constitute a much higher proportion of the total load (Turowski et. al. 2010). Lamb et al. (2012) suggest that flooding can increase erosion in the backwater region. We assume a constant flooding stage, which lacks the base flow discharge. Future work could investigate the effect which varying flow between flooding and base discharge has on the balance between aggradation and erosion of the flood plain and subaqueous delta top. This is addressed in chapter 5.

The set of metrics presented here allow objective comparison of the evolution of deltaic deposits in four dimensions. Currently the data resolution required for these analyses is primarily available from synthetic deltas generated by process-based modelling. However, the same analyses could be applied to a wider array of data sources.

2.5 CONCLUSION

We showed that when cohesivity remains constant, morphology previously associated with sediment cohesivity could also be produced by increasing the proportion of suspended load sediment transport. Increases in suspended load sediment transport is linked to decreased channel network mobility and increased channel depth. This decreases delta top reworking and the delta progrades further into the basin.

Morphology commonly associated with non-cohesive sediment can also be reproduced by increasing bed load sediment transport proportions. Increases in bed load sediment transport is linked to increased channel network mobility and decreased channel depth. This increases delta top reworking and proximal delta aggradation.

We developed a set of metrics that allow objective comparison of the evolution of deltaic deposits in four dimensions. These metrics were applied to better understand the interactions between morphology and kinematics and delta stratigraphy.

Channel kinematics is a response to the mechanism of sediment transport and supply composition. We found channel kinematics to be a key factor in predicting the evolution of delta morphology and the preservation of delta top deposits (channel and overbank deposition). Delta front and prodelta beds are more continuous and less likely to be intersected by erosive channel features. The preservation of the architectural elements and their distribution within the delta deposits determines the resultant delta stratigraphy.

In contrast to kinematics-driven behaviour, delta front preservation with greater bed load transport did not correspond to the preservation corresponding to greater non-cohesive sediment supply. This indicates that delta front preservation has to have additional influencing factors outside of the channel network evolution. In simulations with large proportions of non-cohesive sediment, less delta front sediment is preserved than in their cohesive counterparts. We concluded this is caused by larger mean grain size of the sediment supply in these models. However, increasing bed load transport was shown to also increase delta front preservation in the simulations. We concluded that this is due to increased confinement of sediment to the channel network which increases the deposition at the channel mouth.

Mechanism of sediment transport was shown to have at least as big an impact on delta kinematics, morphology and stratigraphy as sediment cohesivity. Kinematics and delta top morphology are comparable for suspended load systems and cohesive systems. However larger scale geometries differ due to a dissimilar partitioning between delta top (channel and overbank deposits) and delta front deposits. A better insight into the ratio of bed load to suspended load is crucial to predicting morphologic and stratigraphic aspects of a delta.

CHAPTER 3: BREAKING DELTAS DOWN INTO ARCHITECTURAL ELEMENTS

This chapter is being prepared for publication as “Sediment fractionation across delta deposits”

A detailed description of the methodology and data used in this chapter is given in Appendix I

3.1 INTRODUCTION

Industry professionals and scientists who work with subsurface applications are faced with the challenge of predicting sediments in the subsurface in 3D from limited, discrete datasets. The key to accurate prediction is understanding the processes governing their deposition. While fluvial catchments deliver a range of sediment grain sizes to coastal delta environments, the preserved grain size composition at specific locations is notably different from overall supply by the fluvial system. This compositional alteration is not addressed in many source-to-sink studies, which are largely volume-based. We show that typically medium, fine and very fine sands occur in amplified proportions in deltaic mouth bar deposits compared to fluvial supply compositions, in some cases even overprinting the supply distribution. This could explain the bias towards sandy (medium to very fine sand) deltas, which dominate literature on ancient deltaic deposits. Therefore, interpretations of palaeo-conditions based on preserved deltaic deposits could lead to wrong assumptions about source and/or sink conditions. As we will show in this study, this bias is can be avoided by including the related, underlying prodelta deposits in the description of ancient systems. A combined description of sandy delta front and delta top, together with the finer-grained prodelta deposits provides a more complete image of the sediment supply at the time of deposition than considering the sandy deposits only.

Accurate subsurface predictions in geoscience require an understanding of the processes governing sedimentary systems as well as those affecting their preservation as substrate. Source-to-sink studies examine basin-scale partitioning and preservation of deposited sediment. These studies are still largely volume-based, but new work moves towards the deciphering of grain size distribution across the system (Helland-Hansen et al., 2016; Michael et al., 2014). Through modelling hydro-morphodynamic interactions, we show that understanding process-driven sorting along the sediment transport route is imperative when reconstructing sediment preservation in the subsurface.

Among the architectural elements constituting a delta, mouth bars are some of the most important elements preserved (Howell et al., 2008; Reading and Collinson, 1986). Mouth bars form in the highly complex transitional region influenced by both fluvial and marine forces. Hydrodynamically, a mouth bar develops when sediment-laden jets exit a channel mouth into a body of standing water. The jet spreads out and decelerates, whereby

sediment settles out of the water column. Wright (1977) was one of the first to describe mouth bar deposition in terms of inertial, frictional and buoyant forces, in addition to reworking forces (tides, waves). More recently, the detailed morphodynamic mechanisms of the formation of individual mouth bars have been investigated using numerical simulations in Delft3D (Canestrelli et al., 2014; Edmonds and Slingerland, 2007; Esposito et al., 2013; Mariotti et al., 2013). Some studies have also focused on the influence of various external parameters on these mouth bars, e.g. frontal waves in sheltered bays (Nardin et al., 2013), the presence of a tidal signal in a channel (Leonardi et al., 2013) and the basin slope (Jimenez-Robles et al., 2016).

But sediment grain-size distributions preserved in the mouth bar complexes are as much a function of their supplied sediment grain sizes as they are of the reworking and sorting processes. Therefore, we have studied delta-wide depositional behaviour to understand the extent to which sediment supply signals are retained in the mouth bar complexes. For the first time, we conduct a detailed analysis of mouth bar deposits in deltaic settings and their relationship to the fluvially supplied sediment to investigate if and how the sediment supply signal is translated into this delta sub-environment.

3.2 METHODOLOGY FOR CREATING 4D SYNTHETIC DELTA ANALOGUES

Using process-based models like Delft3D (Lesser et al., 2004) is a well-established method to investigate the effects of specific parameters on deltaic morphology (Caldwell and Edmonds, 2014; Edmonds and Slingerland, 2009; Geleynse et al., 2010; Storms et al., 2007), but applying these models to study detailed grain size distributions within deltas still provides a virtually unexplored research avenue. Using Delft3D to produce 4D synthetic deltas allows the study of preserved deposits as well as the delta's evolution over time.

We simulated four deltas in Delft3D (Figure 16) using four unique, bimodal, sediment supply compositions with varying proportions of very fine silt up to very coarse sand (Figure 17). In natural systems, bimodal grain size distributions in deltaic sediment supply are the results of the two dominating transport mechanisms, bed load and suspended load transport (Orton and Reading, 1993; Syvitski and Saito, 2007). However, the exact supply composition in any system strongly depends on area, relief, and climate regime of the source area (Bhattacharya et al., 2016; Milliman and Syvitski, 1992). In our models, the supplied sediment concentration is the same for all simulations. Discharge was chosen based on supply composition: the very-fine sand delta receives the smallest discharge (1200 $m3.s^{-1}$) while the coarse sand delta the largest (1800 $m3.s^{-1}$) since higher flow velocities are required to transport coarser grain sizes. This means that the rate at which sediment is supplied to each delta is slightly different. The discharge simulates a constant state of high fluvial input, and together with Delft3D's morphological scaling factor the simulations represent prograding deltas on a multi-century to millennial temporal scale. The simulations consist of a fluvial channel debouching into a sloped basin (0.1 degrees). The marine reworking for all models is equal and consists of a semi-diurnal tide with an

amplitude of 1m and waves (amplitude of 0.2m, period of 3m) arriving perpendicularly to the shoreline.

Using a combination of hydrodynamic, morphological and sedimentary data, an automated algorithm was created to classify deposits into architectural elements: channel accretion, channel fill, overbank, mouth bar, delta front background and prodelta. As with all classifications in modelling, experimental and field studies, this requires the definitions of cut-off values which divide naturally grading distributions into distinct classifications. The resultant classes may not be perfect, but are however consistent and therefore useful for comparisons. Mouth bars were defined as locations of rapidly depositing sediment in proximity to active channel mouths, below a geometrically defined delta top cut-off depth of the delta brink (van der Vegt et al., 2016) and above the wave base (4m in this case).

3.3 DESCRIPTION OF MOUTH BAR DEPOSITION WITHIN THE DELTA ANATOMY

Mouth bars constitute the bulk of the delta front, specifically, the sandy deposits in the upper delta front. It is difficult to decouple mouth bar deposits as such from background delta front sedimentation, as the sediment profile gradually changes from sandy mouth bar to muddy background sedimentation as we move away from the channel mouth. In fact when two channels prograde in close proximity from each other it can also be difficult to distinguish between their individual mouth bars.

The delta front is wedged between the delta top and prodelta. The bottom boundary of the delta front is determined by the volume of prodelta already deposited, as well as the acting wave regime. Finer-grained sediment supply compositions in shallow marine settings, lead to more developed pro-delta deposits, which may fill the accommodation from the basin floor up to the wave base. E.g. Figure 16 d shows the development of a thick prodelta filling the accommodation up to the wave base at 4m, whereas this is not the case in Figure 16 a. Such a filling of accommodation provides a more elevated platform for the delta front to prograde onto. The upper boundary of the delta front is determined by the delta top, which partially erodes into the delta front deposits. The extent of this upper constraint is determined mainly by the channel depth, noting that channels of different sizes exist together on the delta plain (Orton and Reading, 1993). It has been shown that channel bifurcations are typically asymmetrical, meaning that even channels of the same order are likely to differ in size (Kleinhans et al., 2008).

When more sediment is available than can be accommodated in delta front (delta front over-supply), sediment must bypass the delta front altogether and deposits in the prodelta. E.g. Figure 16 a has sandy pockets of sediment visible in the prodelta for almost the entire cross section, whereas in Figure 16 b the prodelta only becomes under-supplied towards the middle of the progradation so sandy pockets are only observed in the distal half of the cross-section. If, however, more delta front accommodation is available than sediment to fill it (delta front under-supply), the progradation of the delta can slow down allowing slower travelling of coarse grained bedload, otherwise stored in the distributary channels to bypass the delta top and deposit in the delta front. This bypass mechanism

can create pockets of coarse sediment within the mouth bar complexes. An example of such a coarse grained pocket in the mouth bar deposits can be observed in Figure 16 at 6.4km and at 7km.

3.4 COMPOSITIONAL ALTERATION FROM SUPPLY TO MOUTH BAR GRAIN SIZES

Once the mouth bar deposits have been isolated, their overall composition can be described by the relative contributions from individual grain size classes (Figure 17). Two factors control the overall grain size distribution in the mouth bar deposits. Firstly, grain size classes of sand, when supplied in large proportions, are also found in large proportions in the mouth bar deposits. Secondly, the grain size classes medium to very fine sand occur in greater percentages in the mouth bar deposits than in the respective supply composition. Coarser and finer grain size classes occur in reduced proportions in the mouth bar deposits.

This fractionation of sediment classes can be driven by both fluvial and marine reworking. Bedload from coarser grain size classes travel more slowly downstream along the channel network than finer, suspended, sediment. If there is a sufficient volume of finer sediment supplied, such that the progradation rate of the delta is faster than the time required for the coarsest sediment to reach the end of the channel network, then the coarse sediment is likely to remain within the channels. These coarse sands deposited in the channel beds causes the channels to shallow increasing delta top aggradation and the frequency of channel avulsion.

In the case of delta front under-supply (typically low supply of very fine to medium sand), coarse and very coarse sand can bypass the delta top to deposit in the mouth bars. This delta front undersupply slows delta front progradation, providing more time for fluvial processes to deliver coarse grained sediment to the mouth bars. This can be seen in Figure 17 a, where the mouth bar deposits include a large proportion of coarse sand, even though this fraction is not amplified compared to the supply composition.

Smaller, more cohesive grain size classes reach the channel mouths more readily in suspension. While fractions of these sediment classes are preserved in the mouth bars, these cohesive fines are readily eroded by marine reworking (waves, tides and along shore currents) and transported off- and along shore. For this reason, very little fine sediment is preserved in the mouth bars compared to the supply. By these mechanisms, mouth bar composition is altered by marine reworking processes.

This amplification means that the sediment composition preserved in the mouth bar is not linearly proportional to the sediment supply distribution. Instead there is a strong process-driven fractionation of sediment classes across the delta, whereby medium to very fine sand deposition is over represented in all mouth bar complexes.

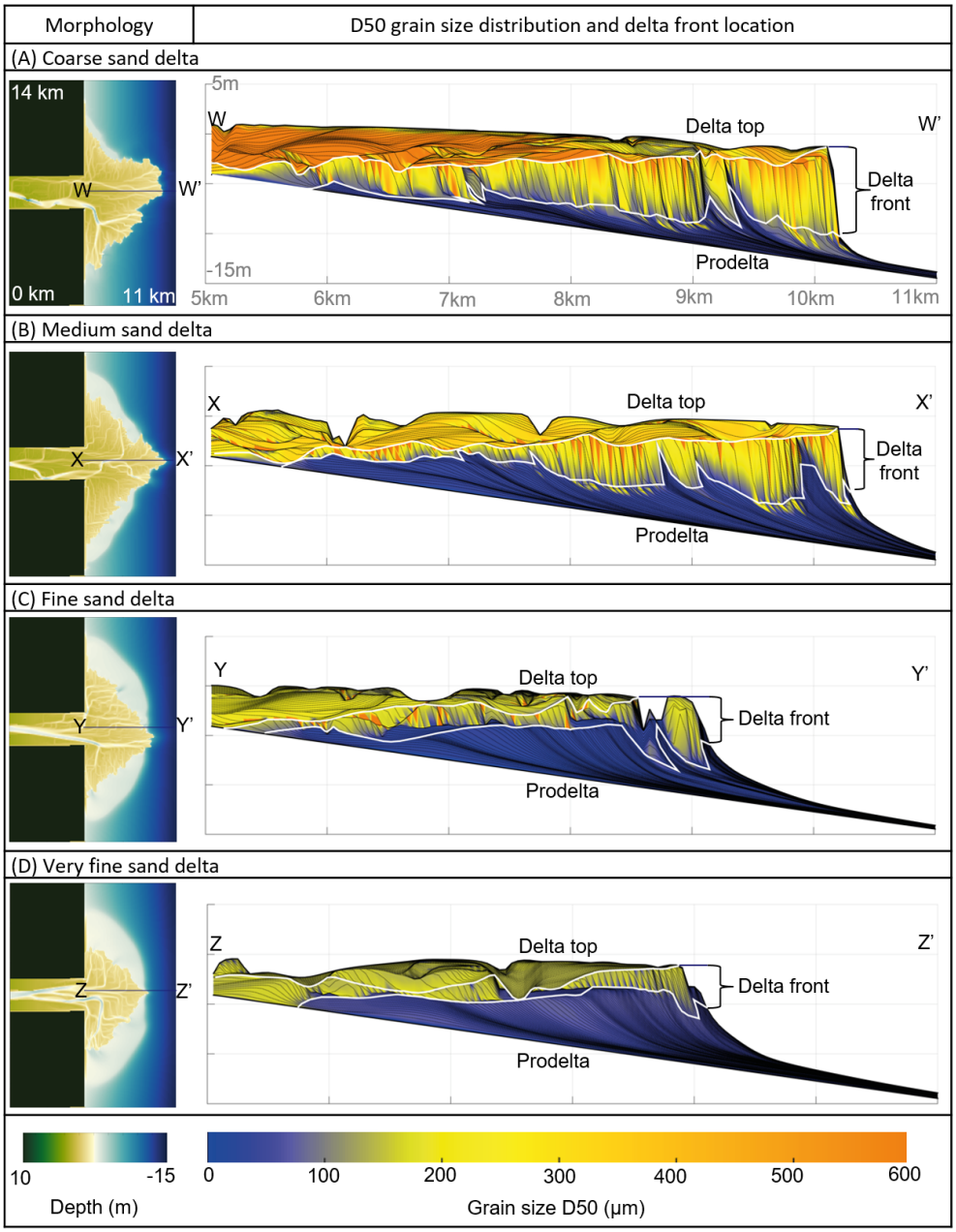


Figure 16: Final bathymetry of the 4 synthetic deltas with representative cross sections showing the location of the delta front in the delta anatomy. Mouth bars make up the bulk of the delta front, overlying a limited volume of lower delta front background sedimentation. The cross sections also include the sediment grain size D50 value at each location, highlighting the level of detailed data available in the 4D synthetic analogues.

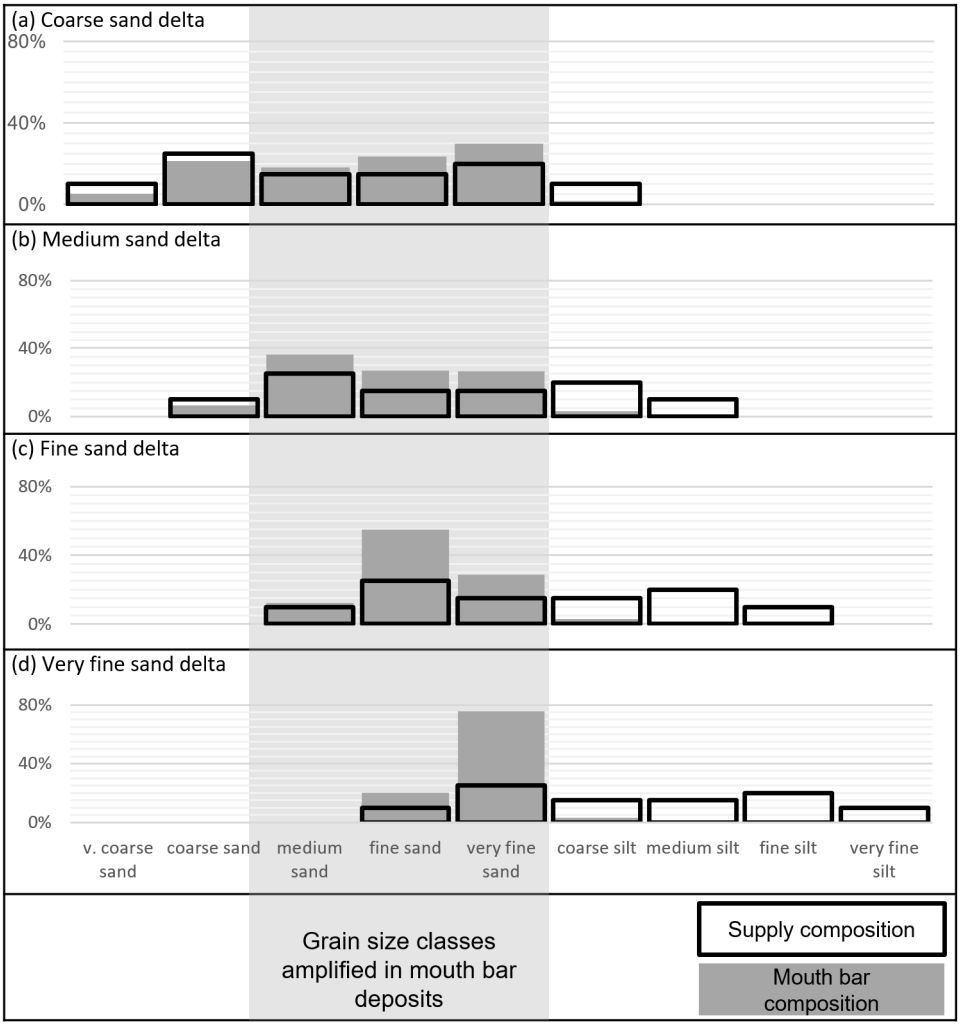


Figure 17: Overall sediment composition of the mouth bar deposits compared to the sediment composition supplied to the delta. Grain size classes medium to very fine sand occur in a larger proportion in the mouth bar deposits than in the sediment supply for all models. Grain size classes outside of this range are deposited in reduced proportions in the mouth bar deposits.

3.5 COMPARISON TO FIELD DATA

A discrepancy exists between descriptions of modern and ancient deltaic systems in the scientific literature: There is a strong bias towards fine sand deltas from the ancient rock records (Table 1). This bias could be due to preferential study of fine sand systems by geoscientists, since they serve as good analogues for oil and gas reservoirs. Alternatively, arid basins, where fine sand is abundant, could be preferentially preserved throughout the geological record (Nyberg and Howell, 2016). However, based on our findings, this bias

can also occur due to preferential preservation and description of deltaic mouth bar deposits.

Table 1: Ancient and modern deltas from the literature, classified by grain size (Ainsworth et al., 2016; Howell et al., 2008; Hubbard et al., 2010; Orton and Reading, 1993; Syvitski and Saito, 2007). Literature on ancient deltas show a bias for describing fine sand deltas

Grain size	Gravel/coarse-grained deltas	Very fine to medium sand deltas	Mud/Silt deltas
Modern deltas	Punta Gorda(NI), Waipaoa (NZ), Yallahs (JM), Alta (NO), Bella Coola (CA), Colville (US), Homanthko (CA), Klinaklini (CA), Noeick (CA).	Burdekin (AU), Shaolhaven (AU), Copper (US), Ebro (ES), Mackenzie (CA), Fraser (CA), Squamish (CA), Klang (MY), Mahakam (ID), Mekong (VN), Niger (NG), Po (IT), Tiber (IT), Rhone (FR), Sao Francisco (BR).	Amazon (BR), Ganges-Brahmaputra (IN), Huange/Yellow (CN),Irrawady (MM), Mississippi (USA), Ord (AU), Orinoco (VE), Yangtze (CN).
Ancient Deltas	Dorotea formation (Magallanes Basin, Chile)	Ferron Sandstone Mbr (Mancos Shale), Panther Tongue (Star Point Sandstone), Spring Canyon Mbr, Kenilworth Mbr, Sunnyside Mbr, Grassy Mbr (Blackhawk fm), John Henry Mbr (Straight Cliffs fm) (Mesaverde group, Utah, USA), Drumheller Mbr (Horseshoe Canyon fm, Canada), Rannoch fm, Ness fm (Brent group, North Sea)	?

Modern deltas are classified by their fluvially supplied sediment composition or delta top grain sizes (Orton and Reading, 1993; Syvitski and Farrow, 1989; Syvitski and Saito, 2007). However, one of the most important identifying features of ancient deltaic deposits are the sandy clinoforms of their delta front mouth bar complexes (Forzoni et al., 2015). Mouth bar deposits also have the greater long-term preservation potential under base-level changes, compared to their overlying delta top deposits which will be eroded first. Our results show that medium to very fine sand grain sizes are preferentially deposited in these mouth bars.

Muddy clinoforms described in the literature typically refer to shelf formation distal to the delta itself, rather than delta front deposition(Cattaneo et al., 2007; Kuehl et al., 2005). Even modern deltas classified as muddy/silty, typically deposit sandy mouth bars e.g. the Mississippi (Esposito et al., 2013), Ganges-Brahmaputra (Goodbred et al., 2003), Huange (Li et al., 1998), Mahakam (Storms et al., 2005). Muddy mouth bar clinoforms are unlikely to form in deltaic systems prograding onto a shelf due to the presence of marine energy. Even small waves will stir up and remove silt-sized sediment from the mouth bars/delta front clinoforms. Tides can cause the formation of mud drapes, which can vary in

character based on the asymmetry of the tidal signal. But even under these conditions, the majority of the mouth bar will still consist of sand rather than mud (Reading and Collinson, 1986).

It is therefore important to ask oneself whether a sandy mouth bar complex identified in a field study necessarily deposited in a system where the sediment supply consisted mainly of the same sandy supply. If the corresponding prodelta deposits can be identified, this can provide clues, which can help to reconstruct the original sediment supply composition of the system. If the overlying delta top deposits are no longer preserved, then these were most likely eroded and redeposited in the younger deposits overlying the distal prodelta deposits.

Medium to coarse sand delta front deposits have been described in the Dorothea formation in the Magallanes basin in Chile (Hubbard et al., 2010). The sediment is interpreted to have been deposited on the edge of the continental shelf with significant wave and storm reworking. Based on our results, this type of environment forms the ideal conditions to preserve coarser sediment in the mouth bars. Firstly, a delta front prograding onto the shelf edge, where there is a marked increase in depth, will experience a marked increase in accommodation. This can cause coarser-grained sediment to bypass the channels and deposit in the delta front and even prodelta. At the same time, high energy storm waves are likely to remove finer sands from the mouth bars, leaving only the coarsest grain size fractions.

3.6 IMPLICATIONS AND CONCLUSION

These results highlight how sediment composition preserved in deltaic mouth bars differs from their fluvial supply as a result of sorting and fractionation during transport and reworking. This is important when mouth bar grain size measurements are used to infer sediment supply and sediment supply is used to infer morphological features at the time of deposition (e.g. shoreline rugosity which can be higher in systems with more cohesive material (Reading and Collinson, 1986)).

Our numerical experiments assume sustained input parameters – no changes in discharge, tidal signal or wave regime during the simulation. In natural systems however, sediment sorting along the sedimentary system is even more complex due to the non-linear responses to time-varying sediment supply, basin reworking processes and base-level fluctuations (Armitage et al., 2011; Jerolmack and Paola, 2010). It is known that short-lived sediment fluctuations may be dampened as they travel through the system, while sustained supply changes are still likely to reach the shallow marine and marine domains (Van Den Berg Van Saparoea and Postma, 2008). Our findings highlight an additional uncertainty, in that even under time-constant conditions the source grain size composition may be distorted in the preserved deposits at a specific study site.

Statistical study across an extensive database of synthetic and natural delta analogues containing both source and sink information would prove useful to better relate detailed grain size trends to palaeo-conditions and depositional geometries. While source-to-sink studies are imperative to understanding the development of sedimentary systems, detailed unravelling of downstream fining and sorting mechanisms should be a prerequisite for palaeo-environment reconstruction from preserved deposits.

CHAPTER 4: BUILDING DELTAS FROM SUB-ENVIRONMENTS

This chapter is in preperation as “Partitioned accommodation-to-supply balances due to process-based sorting”.

A detailed description of the methodology and data used in this chapter is given in Appendix I

4.1 INTRODUCTION

Modern deltaic systems are frequently used to better understand the distribution and properties of ancient deposits. However, it remains unclear to what extent the deposits in an active deltaic system are preserved in the geological record. On a sequence-stratigraphic scale, paralic deposition is strongly controlled by the balance between sediment supply volume and accommodation (Catuneanu et al., 2009; Muto et al., 2007; Neal and Abreu, 2009; Olariu et al., 2012). Sediment supply volume is sourced from terrestrial feeder systems as well as from sediment transported along the shoreline. Accommodation is determined by the relative sea level and initial basin bathymetry (e.g. depth, slope, lateral confinement etc.).

At the boundary between fluvial sediment supply and its receiving basin, deltas develop, as long as the energy exerted by the basinal reworking is not sufficient to redistribute all of the supplied sediment. The same processes may have a range of effects on deposition, depending on the properties of the sediment supply, its interaction with other reworking processes and even the changing bathymetry of the basin (Boyd et al., 1992; Orton and Reading, 1993). In addition, the fluvial supply properties and the reworking processes also vary in time and space across the delta, leading to vertical and lateral heterogeneities in the deposits (Howell et al., 2008).

The sedimentary records of deltaic environments can preserve significant lateral and vertical variations according to the localised balance between depositional and erosional processes. Deltaic deposits are often subdivided into 3 sub-environments based on geometry, depositional and reworking processes at play: delta top (or delta plain), delta front and prodelta (Reading and Collinson, 1986). These sub-environments can also be further subdivided into architectural elements (Table 2) (Howell et al., 2014). While these classifications are useful in understanding how the delta sediment is organised, the boundaries between the different classes are gradual. Any single sub-environment or architectural element will typically blend into the next, except in the case where they are bounded by one or more erosional surface, where the transition can be more abrupt. While this is a challenge for automated computation analysis in synthetic deltas, it is also a well-known challenge in e.g. assigning facies in field studies.

The balance between the presiding processes controlling deposition differs per sub-environment (Reading and Collinson, 1986). Basinward the fluvial influence weakens and the water depth increases. The delta top distributary channels are governed by fluvial processes, with gradually increasing marine influence towards the basin. At the delta front there is a balance between fluvial supply at the mouths of the channels and marine removal of fine sediment from these deposits which steepens the delta front slope. Prodelta deposition is controlled by the settling behaviour of fine sediment below wave base.

Sediment arriving at the delta apex from the fluvial domain has undergone process-related sorting while travelling along the downstream trajectory (Armitage et al., 2011; Michael et al., 2014). Sorting continues across the delta as sediment deposits in one of the three sub-environments, driven by the governing processes of fluvial, wave and tidal reworking. Sediment volume and grain size supplied to each sub-environment is determined by the sediment storage and bypass of the preceding (upstream) sub-environment. Ultimately each sub-environment has its own unique supply composition and accommodation, controlled not only by the sea level, but also by the evolution of their bounding sub-environments. However, since water depth, distance from sediment source, and angle to the basinal reworking processes all play a role in configuring the delta, the evolution of each sub-environment will differ spatially and over time.

Our aim is to show that the sediment distribution in deltaic environments is controlled by unique accommodation-to-supply ratios per sub-environment, rather than a single volumetric balance across the entire delta. We investigate process-sorting of the sediment supply quantitatively, by analysing results from four synthetic deltas with differing input sediment supply compositions. We consider the accommodation-to-supply balance for each sub-environment by looking at trends over time as well as spatial trends across the delta. The findings provide a framework to understand variability within deltaic deposits based on partitioned accommodation-to-supply balance. Not all deltaic deposits are equally likely to be preserved in the long term; overlying deposits (e.g. delta top) are more likely to be removed/eroded in subsequent sea level fall. The proposed framework of grain size composition portioned by sub-environment, can improve the correlation of sediment preserved in ancient delta deposits to observations made in modern deltaic systems.

Table 2: Definition used for automated classification of deltaic sediments by sub-environments and architectural elements

Sub-environment	Architectural element	Definition
Delta top	Channel accretion	• Lateral accretion: sediment stored as lateral bars as channels migrate. • Vertical accretion: Generally coarse sediment stored at the channel base in locations where bed load is over-supplied compared to the amount of bedload which can be transported further along the channel
	Channel fill	• Fining upwards sediment which fills channels as they become inactive
	Overbank/ background	• Overbank deposition and background sedimentation which depositing in locations between the active distributary channels
Delta front	Mouth bar	• Sandy sediment deposited where sediment-laden jet exits channel mouth, spreads upon reaching the basin and decelerate.
	Background	• Lobate deposits travelling further from the channel mouths than the mouth bar sands • Background sediment deposited as basinal processes (e.g. waves) rework the exiting deposits
Prodelta	Prodelta	• Fine sediment eroded and transported by basinal processes and deposited below the fair weather wave base. • Here deposits are only defined as prodelta once 15mm of deposition has occurred at that location.

4.2 MATERIALS AND METHODS

Computational process-based forward models such as Delft3D allow us to study the autogenic organisation of sediment within a delta in 3D (Geleynse et al., 2010; Hillen et al., 2009; Storms et al., 2007). Because these simulations record the evolution of the deposits over time, they can provide a better understanding of the preservation potential of the deposits. In this work we investigate the preservation of architectural elements (Table 2) as a function of the impact of autogenic processes experienced by deltas under constant forcing. We employ synthetic delta analogues created in Delft3D, which provide detailed

information of the sediment distribution within the resultant deltaic deposits. Delft3D has the potential to advance our understanding of the processes controlling deposition and sediment preservation in deltaic environments through high resolution forward modelling. The simulations allows us to better constrain the link between observations from modern active delta systems and ancient deposits in outcrop or subsurface data.

We created four models using the process-based modelling software Delft3D (Lesser et al., 2004). All models consist of a short fluvial channel debouching into a sloped basin. A small tide (amplitude 1m) and small waves (wave height 0.2m) were added to the marine domain to redistribute some of the sediment. Each model is supplied with a unique, constant distribution of grain size classes from very coarse sand to very fine silt. The sediment profiles vary from dominantly coarse sand to dominantly very fine sand. The bimodal sediment distributions consist of six sediment fractions with the overall concentration of all models equal to 0.06kg/m^3 of water. The sand fractions are assumed to be non-cohesive and transport is defined by the Engelund-Hansen formulation (Engelund and Hansen, 1967), which has been successfully applied to simulate deltas in Delft 3D in the past (Geleynse et al., 2010). The grain sizes from coarse silt and smaller are assumed to be mixed with clay and therefore are transported using a cohesive transport formulation, calculated by solving a depth-averaged (2DH) advection-diffusion (mass-balance) equation for the suspended sediment (Galappatti, 1983).

The fluvial inputs of the simulations are not the same, with larger fluvial input imposed on coarser-grained models. This ensures that the flow velocities in the delta are high enough to mobilise the coarser sediment fractions. For the finer-grained sediment supply deltas a smaller discharge is imposed to prevent the fine, easily mobilised sediment from flushing out of the system without any deposition. Although the simulations each receive the same sediment concentration, the weight of sediment supplied differs between models due to the different discharges. In addition the sediment volumes supplied to the different models are not directly proportional to the weight because deposited mud has a larger volume per weight than deposited sand. Finer-grained models, with more cohesive sediment fractions, therefore supply a larger volume of sediment under the same fluvial input. This complex relationship between sediment supply and deposited volume makes it difficult to define the ideal output interval at which to compare the resulting deltas. Since field comparisons are also not concerned with the stage of development of a delta, this effect is also neglected in our analyses. To facilitate comparisons we report the delta architectures as a function of the percentage of total accommodation filled over time, where accommodation is defined as the volume between the original basin floor and the water level.

The deposited sediment is separated into three deltaic sub-environments: delta top, delta front and pro delta. Each depositional sub-environment is further discretised into architectural elements and background sedimentation according to the criteria in Table 2.

The classification of deposition relies on the accurate assignment of an active channel network and the depth of the delta brink point, i.e. the depth at which the slope break between the delta top and delta front occurs. Channels are defined based on a pre-

defined cut-off velocity, where any cell with a higher velocity is considered to form part of the active channel network. The best cut-off velocity is assigned by detailed visual inspection of the entire model evolution, to closely match the channel depressions in the bathymetry without overestimation of channels at the distal locations. Connectivity between the identified channel cells in the active channel network is also considered. Distal overestimation can lead to misclassification of mouth bar deposits as channel accretion deposits. This is in part because the simulations mimic real world systems, where a gradual transition is encountered from channel to mouth bar at the channel mouth. Based on these criteria, the channel cut-off values range between 0.7m.s^{-1} for the very fine sand delta and 1.1 m.s^{-1} for the coarse sand delta. Cells with a very shallow water depth (0.5mm) are removed as these represent sheet flow rather than channelized flow at the 50mx50m element resolution used in these simulations. A description of the brink point calculation method used here has been previously described (van der Vegt et al., 2016).

Firstly, the delta top classification is assigned to the relevant elements, comprising channel accretion, channel fill and delta top background sedimentation (see Table 2). Any sediment deposited in an active channel network is considered to be channel accretion. This accretion can be either lateral or vertical. Deposition in a previously active channel will be classified as channel fill until the deposition reaches the delta brink, at which point a channel feature is considered to be filled. Any further sedimentation above the delta brink depth is defined as delta top background sedimentation.

Delta front deposits are defined as any sediment below the delta brink. In addition, the delta front deposits must occur to a maximum of 2m below wave base. Strictly speaking this should be fairweather wave base, but since the simulations included no storms we will refer simply to wave base. In our simulations wave base is defined at 4m, due to the size of the waves in the simulation. In natural systems, fairweather wave base is more commonly found at 5-15m depth. Within this depth range, cells which undergo significant volumes of deposition (more than 0.3m pre-output time interval) and occur in proximity (< 200m) of an active channel element are defined to be mouth bar deposits. The remainder of the delta front deposition, situated further than 200m from an active channel, is classified as delta front background sedimentation.

Active cells which have not been included in the delta front classification and which are below wave base constitute the prodelta. However, elements are not considered to form part of the delta until they have undergone at least 15mm of sedimentation and these elements are therefore assigned a classification of ‘”inactive”.

4.3 RESULTS

The volumetric evolution of the architectural elements and background sedimentation over time highlights differences in delta anatomy between the four deltas. The final preserved sediment composition for each sub-environment is a result of the sorting caused by autogenic processes during the delta progradation and is compared to the supply composition for each delta. Both the volumetric and sediment composition data is

provided across the whole delta, but also partitioned into six horizontal regions around the delta apex. This allows the study of lateral variability during deposition. The six regions are assigned as follows: a radially distal and proximal region with the delta apex as the origin, further sub-divided into three regions based on their angles from the coastline (Figure 18).

For each of the four deltas we show how the accommodation is filled by the architectural elements over time and how this varies across the six regions. In addition, we compare the grain size distribution of the preserved sediment by sub-environment and region of deposition.

4.3.1 COARSE SAND DELTA

The largest volume of prodelta is deposited in regions with deeper water (Figure 18). The deeper regions have more accommodation between the prodelta bounding surfaces, the bottom of the basin and wave base. By the end of the simulation the prodelta has not yet reached its maximum volume distally (Figure 18, regions 4, 5, 6) and the volume is still increasing.

The mouth bar volume in the proximal regions (Figure 18, regions 1, 2, 3) reaches a peak in deposition early in the simulation, then decreases gradually. At the same time the volume of delta top deposits (channel elements and background sedimentation) continue to increase. In region 1 the decrease in overall volume towards the end of the evolution coincides with an avulsion of the main feeder channel through this region. At the same time there is an increase in mouth bar and channel deposits in regions 4 and 5, which are being fed by the newly avulsed channel. By the end of the simulation the delta front deposits have not yet reached their peak in the distal settings and are still increasing.

The largest proportion of delta top sediment consists of coarse-grained sand (approximately 40%, Figure 19). The delta top contains slightly more coarse and very coarse sand proximally (Figure 19, regions 1, 2, 3) than distally (Figure 19, region 4, 5, 6). Coarse and very coarse sand proportions constitute slightly more of the delta top sediment in the basinward-oriented regions (Figure 19, region 3, 6) than coast-parallel regions (Figure 19, region 1, 4). From region proximal region 1 to region 3 it the coarse sand proportion increases from 40% to 42% and very coarse sand increases from 14% to 15%. For the distal regions 4 to 6 the coarse sand proportion increases from 36% to 39% and the very coarse sand proportion from 11% to 13%.

Delta front deposits contain larger proportions of medium, fine and very fine sand than in the supply composition. The coarser grain size classes, preferentially deposited in the delta top, are limited in their supply to the delta front. The finer cohesive grain size classes are readily removed by the wave energy and deposited in the prodelta. Coarser sediment (in particular more sand and less silt) is deposited proximally as opposed to distally. Coarser material is also deposited at a basinward angle as opposed to along the coastline.

The prodelta grain size distribution is dominated by cohesive coarse silt-sized sediment, which is the finest material in the input of this simulation. Different regions contains

different proportions of sand without exhibiting a clear trend. Region 1 contains a very small volume of prodelta (Figure 18) because of its limited accommodation below wave base. As such, the sediment signal in this region can easily be dominated by noise. If we disregard region 1, more sandy deposits are present in basinward-angled regions and distally compared to coast-parallel and proximal regions. The same trend was observed in the delta front deposits. Distal, basinward angled regions have the most accommodation available for prodelta deposition, between the floor of the basin and wave base. However the volume of fine sediment that is supplied does not change as the delta progrades to these regions. During the delta evolution the volume of fine material supplied will no longer be enough to fill this accommodation before the channels start to deliver sandier sediment. When this occurs sand is observed to bypass the delta top and delta front and gets deposited in the prodelta (Figure 19, region 6).

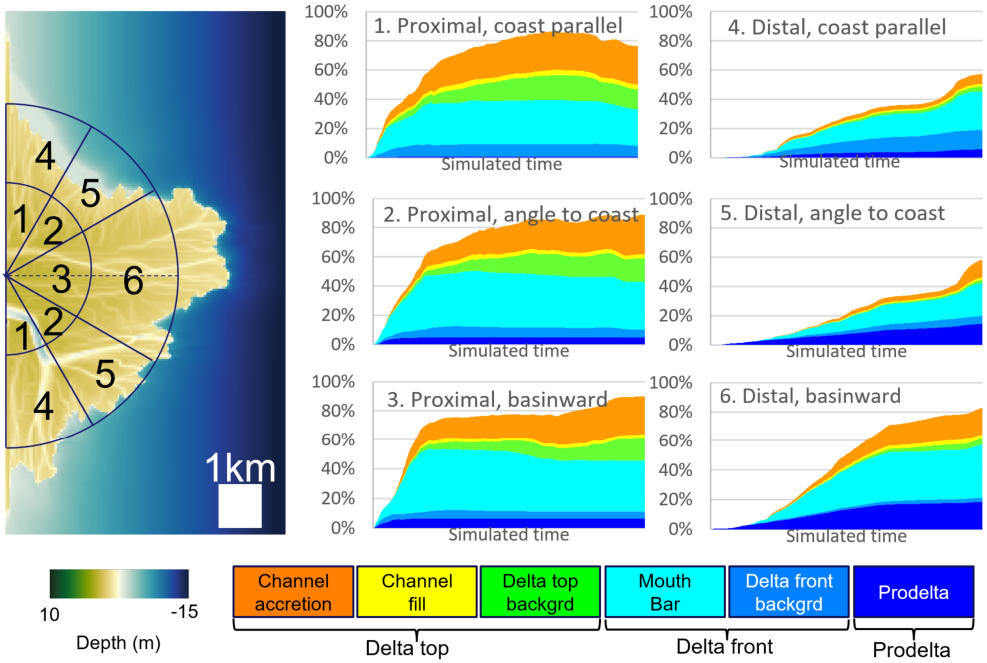


*Figure 18: Cumulative volume of preserved sediment filling the accommodation of the **coarse sand delta**. The accommodation within a semicircle of 4km radius centred at the delta apex has been subdivided by angle relative to the coastline and radius from the apex. Accommodation is calculated from the original basin geometry and water level. Sediment volume is separated by architectural elements.*

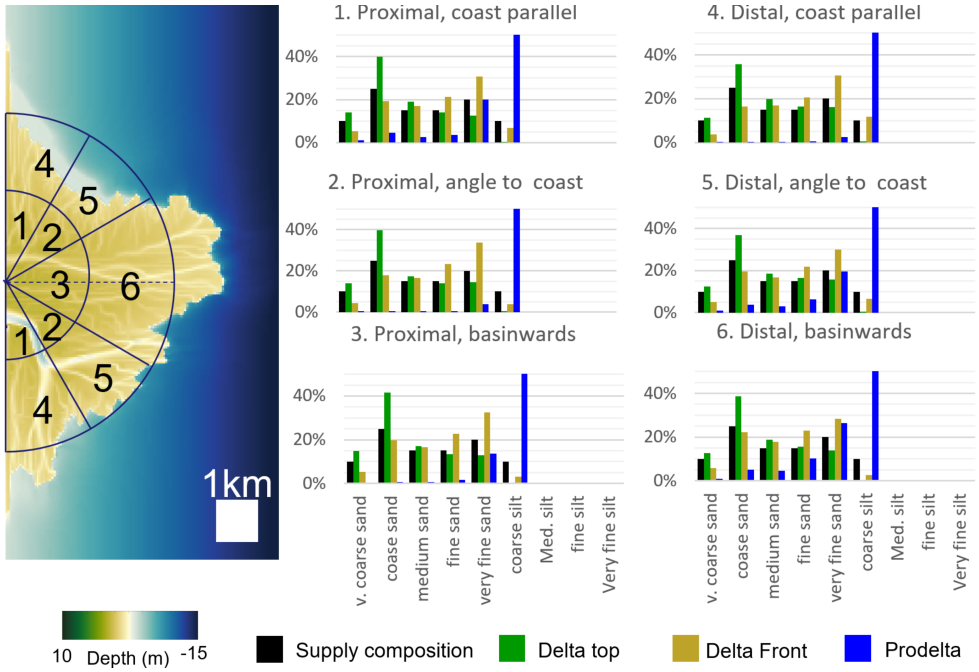


*Figure 19: The grain size distributions, for sediment in the supply and the preserved grain size distribution of the sediment deposited in the prodelta, delta front and delta top sub-environments calculated at the end of the **coarse sand delta** simulation. The deposited sediment within a semicircle of 4km radius centred at the delta apex has been subdivided into six regions by angle relative to the coastline and radius from the apex. Forces acting on the delta are symmetric, therefore equidistant regions in the delta are grouped together.*

4.3.2 MEDIUM SAND DELTA

As observed in the coarse-grained delta, the prodelta volume is larger in the distal regions (Figure 20). By the end of the simulation the prodelta deposits have not yet reached their peak in the distal regions and are still increasing.

Trends in mouth bar deposition in the proximal regions are similar to those observed in the coarse-grained delta, reaching a peak in deposition early on in the evolution, then decreasing slowly over time. This decrease is more gradual in the medium sand delta than in the coarse sand delta. Much less channel deposit is accumulated in the distal regions than in the coarse sand delta. The proximal regions reach an accommodation fill of 80% at a slower rate than in the coarse sand delta, while the distal regions accumulate deposits sooner than in the coarse sand delta. This means the supplied sediment is distributed over a larger area (Figure 18 compared to Figure 20).

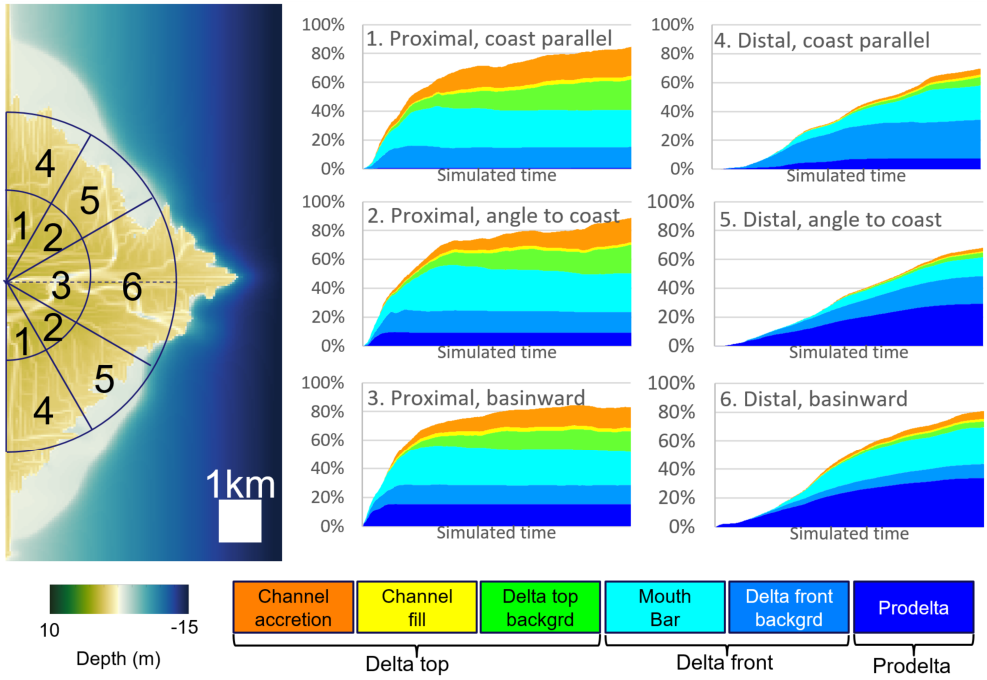


*Figure 20: Cumulative volume of preserved sediment filling the accommodation space of the **medium sand delta**. The accommodation within a semicircle of 4km radius centred at the delta apex has been subdivided by angle relative to the coastline and radius from the apex and is calculated from the original basin geometry and water level. Sediment volume is separated by architectural elements.*

The largest proportion of the delta top consists of medium-grained sand (approximately 45%, Figure 21). As with the coarse sand delta, the delta top contains slightly more medium and coarse sand proximally compared to distally. Medium and coarse sand proportions are also higher in basinward angled regions compared to coast-parallel regions. In proximal region 1 to region 3 the medium sand proportion increases from 47% to 48% while in the distal region 4 to region 6 the medium sand proportion increases from 43% to 47%.

Delta front deposits contain larger proportions of medium, fine and very fine sand than in the supply composition. Although the supply grain size distribution in the medium sand delta is different from the coarse sand delta, the same three grain size classes are amplified in the delta front. This is the case even though the medium sand fraction is now also preferentially deposited in the delta top limiting its supply to the delta front. However, overall the medium sand delta does contain a smaller volume of delta top deposits than the coarse sand delta.

The prodelta is dominated by cohesive coarse-grained silt-sized sediment, supplemented by varying proportions of medium silt-sized sediment in all regions. The prodelta does not contain a significant proportion of sand. An exception to this are the basinward angled regions 3 and 6, where the prodelta does contain a small (<5%) proportion of sand.

Distally, the volume of fine material supplied is not enough to fill the prodelta accommodation before the delta front and delta top progradation catches up with the prodelta progradation. Therefore some fine and very fine sand is seen to bypass the delta top and delta front and fills the remainder of the prodelta accommodation to allow the delta to prograde. This happens on a smaller scale than in the coarse sand delta, where the sediment supply to the medium sand delta provides a larger volume of fine cohesive material to fill the prodelta accommodation.

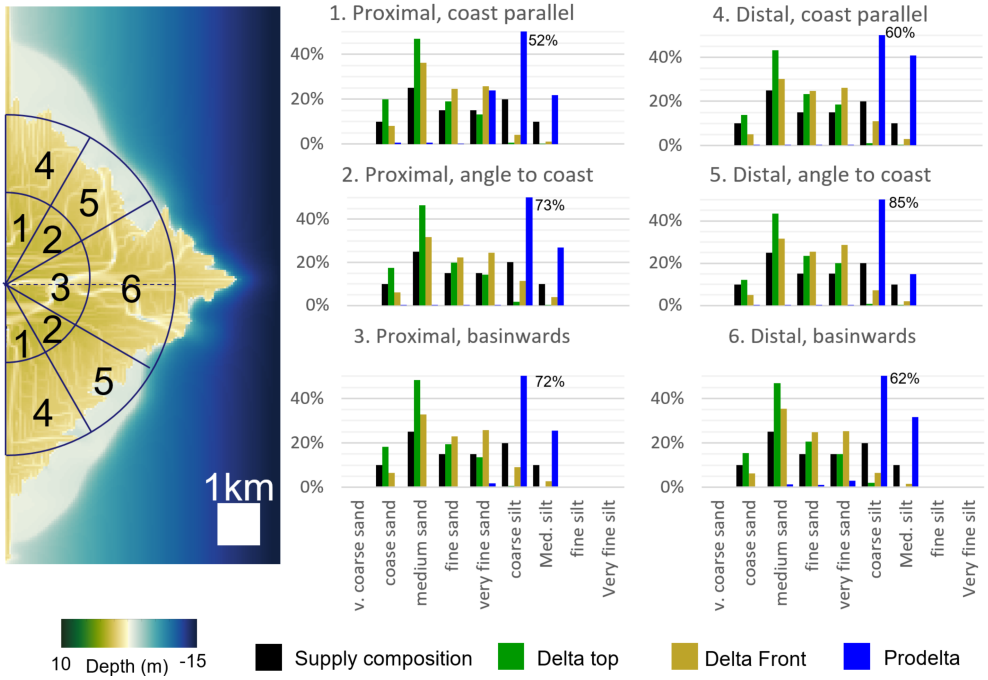


*Figure 21: The grain size distributions, for sediment in the supply and the preserved grain size distribution of the sediment deposited in the prodelta, delta front and delta top sub-environments calculated at the end of the **medium sand delta** simulation. The deposited sediment within a semicircle of 4km radius centred at the delta apex has been subdivided into six regions by angle relative to the coastline and radius from the apex. Forces acting on the delta are symmetric, therefore equidistant regions in the delta are grouped together.*

4.3.3 FINE SAND DELTA

Here the prodelta volume is larger in regions where more volume is available between wave base and the basin floor. By the end of the simulation, the prodelta volume has stabilised in all six regions and no longer increases (Figure 22).

In the proximal regions, the mouth bar component of the delta front reaches a peak in deposition early on in the evolution, then decreases slowly. In the fine sand delta very little volumetric decrease in the delta front is observed. This is accompanied by a much smaller volume of delta top which continues to increase, but at a slower rate than in the

coarse and medium-grained delta. By the end of the simulation neither the delta front nor the delta top deposits have reached their peak volume in the distal settings, where they are still increasing. In the fine-grained delta the sediment accumulation in the distal regions starts earlier, when the accommodation in the proximal regions is still significantly under-filled. This shows a more equally distributed deposition of sediment across a larger horizontal area (Figure 22). Distal regions show more prodelta and delta front background deposition than the medium-grained delta, even though the total proportion of the accommodation filled is comparable.

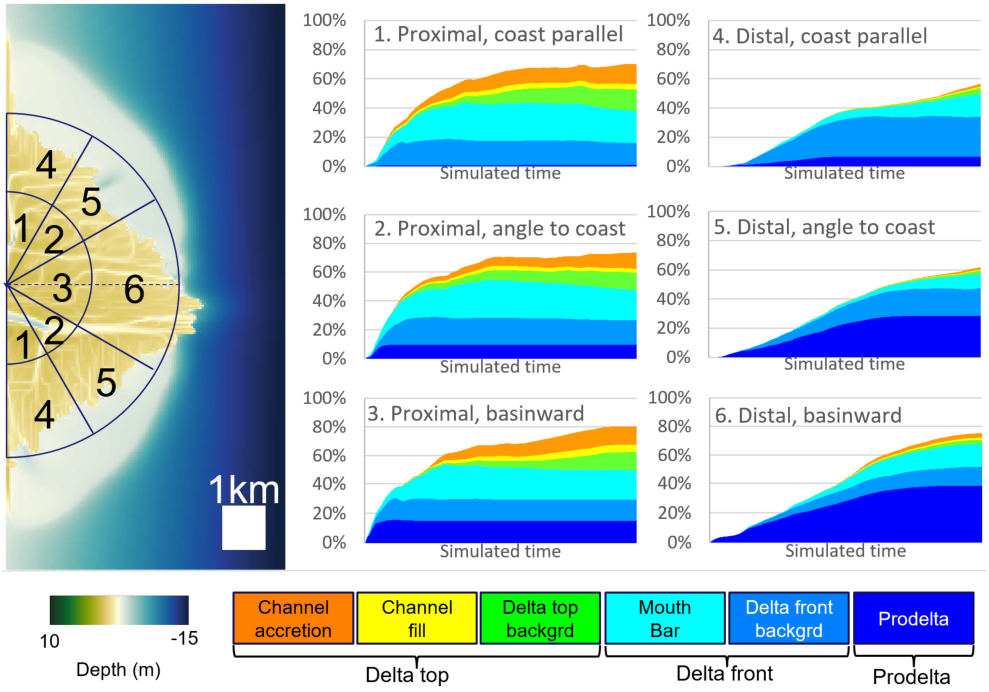


*Figure 22: Cumulative volume of preserved sediment filling the accommodation of the **fine sand delta**. The accommodation within a semicircle of 4km radius centred at the delta apex has been subdivided by angle relative to the coastline and radius from the apex and is calculated from the original basin geometry and water level. Sediment volume is separated by architectural elements.*

The proportion of delta top consisting of fine-grained sand is approximately 55% (Figure 23). As in the previously described deltas, the delta top contains larger proportions of coarser sands proximally than distally. The delta top is also coarser in a basinward direction compared to coast-parallel. From the proximal region 1 to region 3 the proportion of fine sand increases from 55% to 56% and the medium sand from 21% to 22%. From the distal region 4 to region 6 the fine sand proportion increases from 56% to 57% and the medium sand proportion 18% to 19%. The delta top has a smaller volume and is better sorted than in the coarser grained simulations, as less sandy sediment was supplied spread across a narrower grain size range.

The delta front deposits contain larger proportions of fine and very fine sand than in the supply composition, and a comparable proportion of medium sand. This preferential deposition of fine and very fine sand was also observed in the coarse-grained and medium-grained deltas, even though the supply grain size distribution in these coarser-grained deltas were different. The compositional amplification of medium sand is less pronounced in the fine sand delta. The available medium, fine and very fine-grained sands have to be shared between the delta top and delta front. Therefore, even though the delta as a whole received the same sediment concentration, the delta front and delta top could still be supply-limited if the available sediment is not of the sediment classes likely to be deposited in these sub-environments.

The prodelta deposits occupy a large volume and consist of a larger range of grain sizes. Clearer grain size trends emerge in the prodelta deposits than in the previously discussed models, where the prodelta may have been supply-limited. The prodelta is dominated by a combination of coarse- and medium-grained silt fractions. Proximal deposition contains more coarse-grained silt and less medium-grained silt. At more basinward-oriented angles the coarser-grained silt is also favoured over medium-grained silt. A difference to the previously discussed models is that no sand reaches the prodelta.

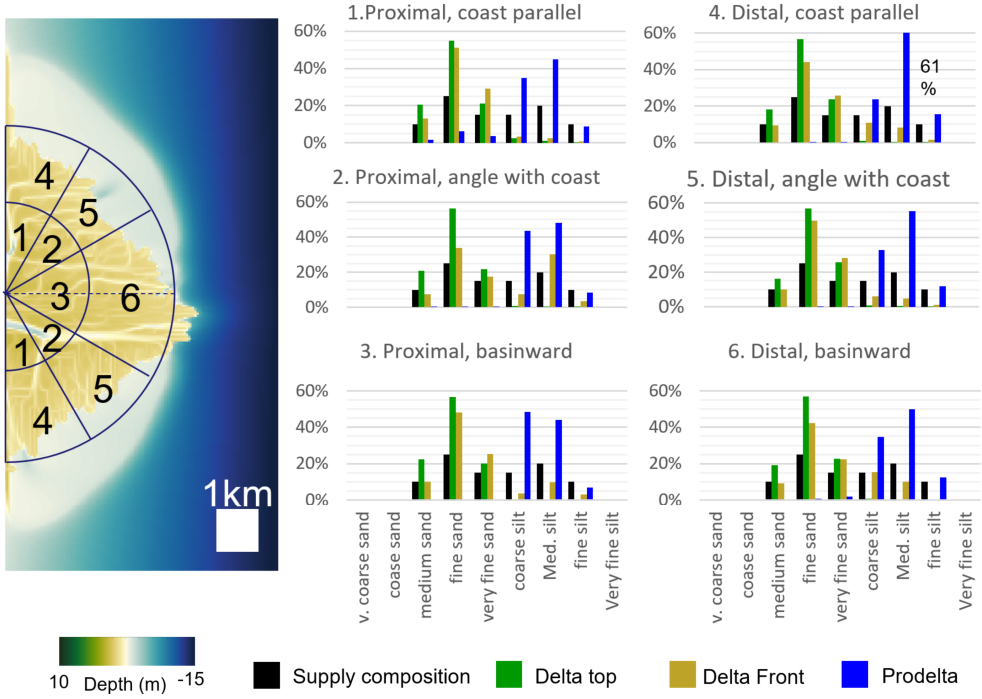


*Figure 23: The grain size distributions, for sediment in the supply and the preserved grain size distribution of the sediment deposited in the prodelta, delta front and delta top sub-environments calculated at the end of the **fine sand delta** simulation. The deposited sediment within a semicircle of 4km radius centred at the delta apex has been subdivided into six regions by angle relative to the coastline and radius from the apex. Forces acting on the delta are symmetric, therefore equidistant regions in the delta are grouped together.*

4.3.4 VERY FINE SAND DELTA

The prodelta volume in all regions of the very fine sand delta (Figure 24) is almost identical to the volumes of the fine sand delta. Since the very fine sand delta was supplied with a larger volume of cohesive fines this observation suggests that the prodelta development in both deltas is accommodation-limited rather than supply-limited. The delta front and delta top deposits both fill less of the accommodation than in previous models, leading to the overall accommodation also being less filled. This preference for progradation over aggradation indicates the delta front and prodelta may be vertically accommodation-limited rather than supply-limited.

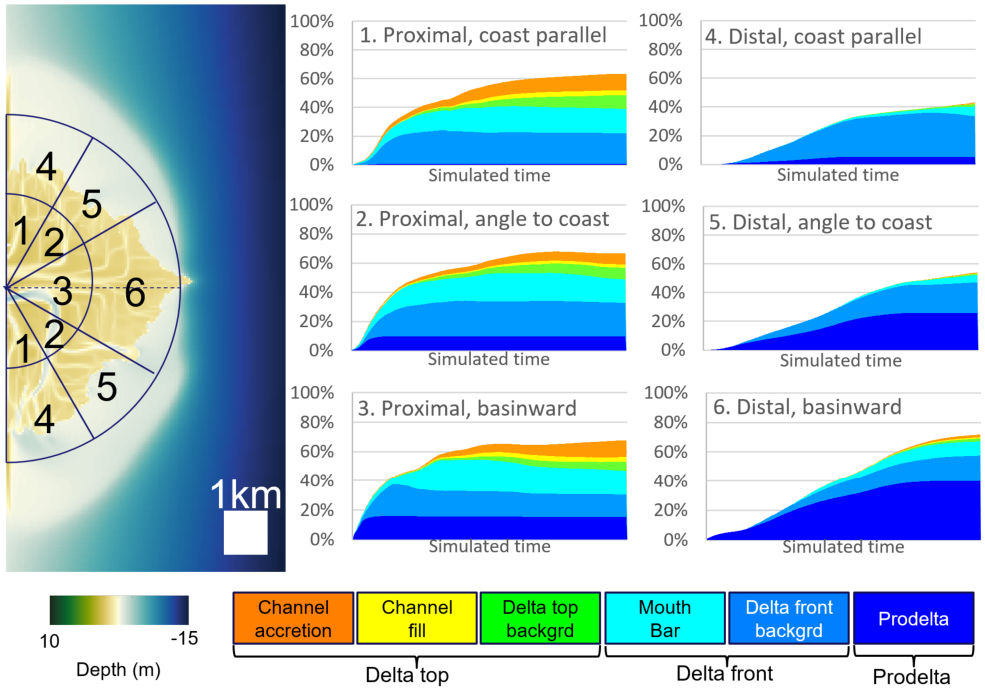


*Figure 24: Cumulative volume of preserved sediment filling the accommodation of the **very fine sand delta**. The accommodation within a semicircle of 4km radius centred at the delta apex has been subdivided by angle relative to the coastline and radius from the apex and is calculated from the original basin geometry and water level. Sediment volume is separated by architectural elements.*

The largest proportion of the delta top consists of very fine-grained sand (approximately 70%, Figure 25). There is no clear trend between the distribution of sand in the delta top of different regions. The delta top is supplied with a smaller amount of sandy sediment than the previously discussed deltas, and is also volumetrically much smaller and better sorted, with deposition occupying a narrower grain size range. Delta front deposits contain larger proportions of fine and very fine sand than in the supply composition, and medium sand was not supplied to the system. This is the case even though these fractions are also the main constituents of the delta top. Since the available volumes of fine and very fine-grained sands have to be shared between the delta top and delta front is it not

surprising that the volume which these sub-environments occupy is smaller than in previous models (Figure 24)

As in the fine sand delta, the prodelta fines proximally to distally, and coarsens with increasing angle relative to the shoreline.

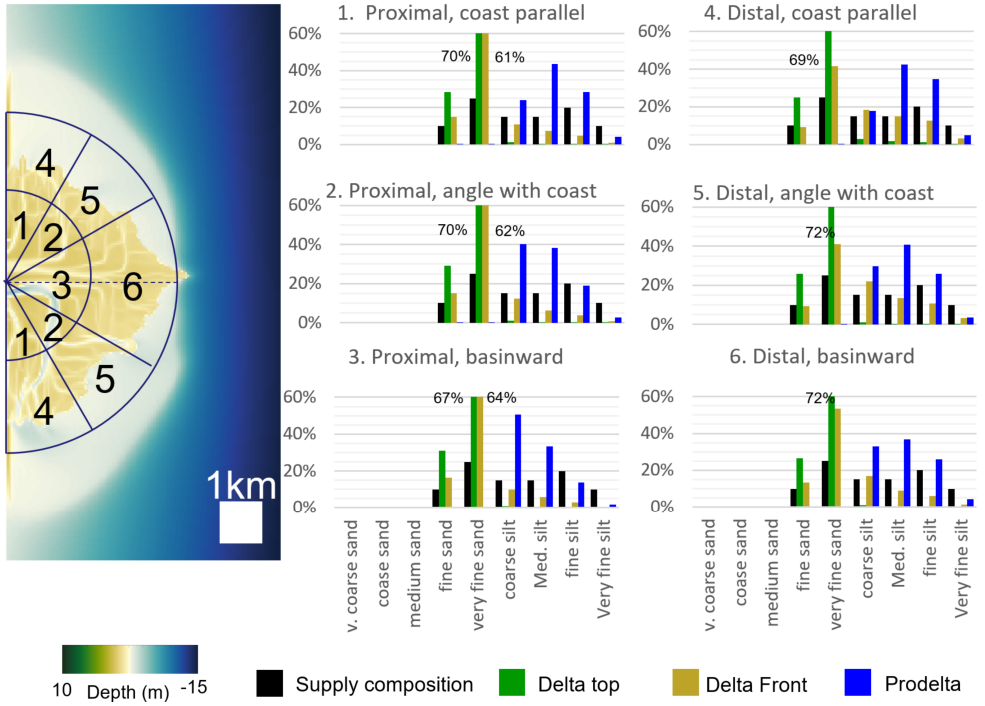


*Figure 25: The grain size distributions, for sediment in the supply and the preserved grain size distribution of the sediment deposited in the prodelta, delta front and delta top sub-environments calculated at the end of the **very fine sand delta** simulation. The deposited sediment within a semicircle of 4km radius centred at the delta apex has been subdivided into six regions by angle relative to the coastline and the radius from apex. Forces acting on the delta are symmetric, therefore equidistant regions in the delta are grouped together.*

4.4 DISCUSSION

We have shown how the supply- or accommodation limitations within a single prograding delta differ by sub-environment. It is entirely possible for one sub-environment to be supply-limited while another can be accommodation-limited at the same time. The processes controlling the deposition in each sub-environment lead to preferential deposition of a specific range of grain sizes, which can be either over- or under-supplied. Each sub-environment also has a unique accommodation, driven by the processes controlling deltaic deposition. Accommodation-to-supply ratios during deltaic deposition

should therefore not be viewed merely on a volumetric basis, but should account for the grain size distribution of the available sediment as well as the local processes controlling erosion, transport and deposition of the sediment.

Comparison of our findings with field data is challenging because of data scarcity. In these synthetic deltas we have varied only discharge and sediment supply grain size, whereas comparisons between active modern deltas will almost certainly differ on many more factors controlling sediment deposition. A number of comprehensive databases exist (Howell et al., 2014; Korus and Fielding, 2015; Syvitski and Saito, 2007; Vakarelov et al., 2010). However the level of detail available for (especially) sediment grain size distributions is not sufficient to allow direct comparisons with the synthetic deltas. We hope that in the future more detailed and extensive grain size data can be used to further validate findings from our synthetic analogues.

Coarser-grained deltas are more likely to have supply-limited prodelta development and accommodation-limited delta top sub-environments. The supplied coarse and very coarse sands require more energy to travel basinwards and are therefore more likely to aggrade on the delta top. These grain size classes, especially when transported as bedload, aggrade at the channel bases, causing channels to avulse more frequently leading to new channel formation. The new channels further increase the potential for coarse-grained channel deposition (Kuehl et al., 2016).

Medium, fine and very fine sands preferentially deposit in the delta front as coarser grains require high-energy channelized flow to be transported and may not be transported out of the backwater zone. Smaller grain sizes are removed by wave winnowing. Limited availability (under-supply) of the very fine to medium grain sizes will place a supply limitation on the delta front of these grain size classes causing delta front progradation to slow down. If however sufficient coarser grain sizes are still available, which continues to drive delta top progradation, the delta top will eventually “catch up” to the delta front progradation, causing the coarser-grained sands to bypass the delta top and deposit as part of the delta front. This sediment-bypass scenario will cause the development of a steeper delta front gradient as well as pockets of coarser material in the delta front.

When the prodelta does not receive sufficient mud to fill its vertical accommodation before the overriding delta front reaches the limit of prodelta progradation, the prodelta is considered to be vertically supply-limited, even if the delta as a whole may still aggrade and/or prograde due to a sufficient overall volume of sediment supply. Sediment-bypass then causes sandy sediment to move past the delta top and delta front and fill the remainder of the prodelta accommodation. When there is a large supply of mud in the system however, the prodelta can prograde much further basinward to build a large platform in front of the prograding – or potentially even retrograding – delta. This will also provide the lagging delta front and delta top with a very low-gradient basin slope over which to prograde. It is possible that the transgressive behaviour reported in the modern Mahakam delta could be an example of this mechanism (Salahuddin and Lambiase, 2013).

Finer-grained deltas are more likely to have supply-limited delta top deposition and accommodation-limited prodelta deposition. The finer sand is more readily transported to

the channel mouth to deposit in the delta front. In these cases, less of the delta top accommodation is filled while the delta front and prodelta deposits prograde further into the basin. Here, the distributary channel network serves mainly to convey the sands to the delta front, where it is deposited. Less aggradation occurs within the channels and their locations are likely to be more fixed. The supply-limited delta top in these finer-grained models progrades mainly as a means to deliver sediment to the delta front. The delta top progrades through progradation of a stable channel network rather than through a filling of the delta top accommodation. This could be why fine-grained deltas building into deeper basins are likely to form bird-foot type deltas (Olariu and Bhattacharya, 2006; Storms et al., 2007).

Furthermore, when considering grain size distributions within each sub-environment, we also observe lateral heterogeneity in grain size. Trends within this lateral grain size variability are discernible, but are most consistent in accommodation-limited deposition. In supply-limited deposition, sediment-bypass is likely to lead to the localised deposition of coarse grain sizes. These pockets of coarse-grained deposits, often observed close to the active channel network, do not correspond to the overall grain size trends observed.

In accommodation-limited sub-environments, grain size distribution trends show coarser grain sizes being deposited at larger angles from the coastline as well as a fining of sediment at greater distances from the delta apex. Proximal to distal fining is assumed to be related to sediment settling velocities whereas the slight coarsening of sediment away from the coastline is more surprising. Larger, more stable channels form in basinward directions. The deeper water and more direct tidal and wave effects could all serve to stabilise these channels (Anthony, 2015; Hoitink et al., 2017). Therefore coarser sediment, moving slower due to its larger bedload fraction, has more time to travel along these channels than would be the case in shallow water parallel to the coastline. It would be interesting to investigate how wave and tidal forces from different directions influence the grain size trends (Korus and Fielding, 2015).

The volumetric and grain size trends for each sub-environment is not only influenced by their own accommodation-to-supply balance, but also by the balances of its bounding sub-environments. Table 3 presents a conceptual model, which summarises the depositional effects caused by sub-environment accommodation-to-supply balance both internally and on their bounding sub-environments based on our experiments.

The results also show that a changing supply composition of an active deltaic system can have important consequences on its preserved deposits. This is true for modern, anthropogenic alterations in supply composition, but also important when studying ancient deposits. It relates to the question of how likely a sediment supply perturbation is to be preserved in the rock record (Bhattacharya et al., 2016; Jerolmack and Paola, 2010; Romans et al., 2016; Van Den Berg Van Saparoea and Postma, 2008). In addition to amplitude and duration of a supply perturbation, shredding of a supply perturbation can also depend on the grain size classes associated with the perturbation, as well as the supply-to-accommodation balances in the different sub-environments. For example, a perturbation leading to a temporary increase in fine sand is likely to increase deposition in

the delta front where it could easily stay preserved in the rock record. However if the delta top is supply-limited, this perturbation is more likely to increase the deposition at the delta-top, where it is less likely to be preserved over a longer timescale. In the case of longer term changes, the bypass-mechanism discussed here can also control the storage and release of sediment past the delta deposit and into deep water environments such as the continental shelf, from where it can drive turbidity currents under the appropriate conditions.

Table 3: Conceptual model of the effect of sub-environment accommodation and supply limitations on bounding sub-environments (where GS = grain size, DT = delta top, DF = Delta front, PD = prodelta).

		Observed depositional effect		
		Delta top	Delta front	Prodelta
Supply limited region	Delta top	• Unpredictable GS trends. • Thinner delta top	• Limits supply	• No direct effect
	Delta front	• More accommodation vertically = less channel erosion into DF • some sediment bypasses DT to deposit in DF	• Unpredictable grain size trends to DT supply limit • Thinner delta front	• Limits supply somewhat, although PD is mainly supplied through marine reworking, so has limited impact
	Prodelta	• No direct effect	• Some sediment bypasses DF to deposit in PD	• Unpredictable GS trends
Accommodation limited region	Delta top	• More avulsions and sediment reworking at DT • more predicable GS trends	• More erosion of DF by avulsion channels	• No direct effect
	Delta front	• No direct effect	• More reworking by delta top channels • More predictable GS patterns	• DF may prograde faster causing sediment bypass and coarser material in the PD – depends on rate of progradation of PD
	Prodelta	• No direct effect	• Smaller chance of sediment bypass to PD, so preferred GS retained by DF	• More predictable GS trends

4.5 CONCLUSION

We have shown how supply and accommodation volumes should not only be studied on a delta-wide scale. Due to process-sorting within the delta, a strong relationship exists between the grain size distribution in the supply and the accommodation available in each deltaic sub-environment. Therefore, in order to extract information on the sediment supply signal from the grain size distribution in a specific deltaic sub-environment, it is necessary to also know the accommodation and supply balance of its bounding sub-environments.

These findings also concern the sediment supply to deeper water systems, which are influenced by the efficiency of storage and sorting of sediment delivered to the shelf from complex river delta environments. Preserved deltaic deposits should be used to extract information on the selective, complex storage and release of sediments. This knowledge can then be taken into account in the reconstruction of climate signals from deltaic successions.

CHAPTER 5: THE DEVIL IS IN THE SCALE OF DETAIL REQUIRED TO DESCRIBE HETEROGENEOUS DEPOSITS

This chapter is based on an article in preparation entitled “The impact of fluvial discharge variation on heterogeneities in deltaic deposits”

5.1 INTRODUCTION

Sedimentary heterogeneities influence flow in hydrocarbon, geothermal and ground water reservoirs. But to what extent are heterogeneities in delta deposits related to changing fluvial discharge during their deposition? Understanding how depositional processes influence the preserved deposits requires experimental investigation, employing physical or computational approximations. Using the process-based forward-modelling software Delft3D (Lesser et al., 2004) to simulate delta progradation allows a detailed investigation of the factors at play during sediment deposition as well as the structure of the resultant deposits.

Deposition in a fluvio-deltaic environment is subject to a delicate balance between the fluvial input to a basin and the reworking potential of processes acting within that basin (e.g. waves and tide). The balance between sediment supply and reworking is key in understanding depositional patterns (Galloway, 1975; Orton and Reading, 1993; Postma, 1990). In natural systems this balance is not constant through time; processes can vary cyclically, intermittently or evolve slowly over long time scales (Ainsworth et al., 2016; Goodbred et al., 2003). Until now, 4D simulations (3D space over time) of fluvio-deltaic deposition has mainly considered constant conditions during deposition (Edmonds and Slingerland, 2009; Geleynse et al., 2011; Storms et al., 2007; van der Vegt et al., 2016). Temporal variability of the forcing processes are expected to more closely approximate natural systems, but it is not known to what extent these variations impact the character of the resultant deposits.

One recent computational study considered the morphological impact of discharge variations (Guo et al., 2015). They found that flow variation does not have a significant impact on the delta morphology compared to a constant, mean discharge scenario. Their study was primarily concerned with modern systems and as such did not investigate the impact of discharge variations on the preserved stratigraphy. While morphology provides a snapshot of the deltaic sediment dynamics, delta stratigraphy records the history of sediment delivery across the delta.

The deposits from the flood-driven Burdekin river delta have been reported to preserve mouth bars of sandy, fining-upward, beds overlying erosive surfaces (Fielding, 2005). This differs from the traditional description of prograding mouth bar deposits, which assume a

coarsening upwards trend. While mouth bar complexes may still be coarsening upwards, these internal heterogeneities can be important features in a reservoir. Thin layers of muddy deposits between sandy beds can act as flow baffles with a negative effect on flow, but are also known to decrease the risk of early water breakthrough in the case of hydrocarbon reservoirs (Jones et al., 1995; Kjønsvik et al., 1994; Weber, 1982).

Process-based model results can be used to inform geological reservoir models either directly, by conducting comparative flow simulations on the simulated sediment blocks, or as input for statistical techniques to create a whole range of conditioned geological models, e.g. multi-point statistics , object-based modelling or variogram-based indicators. However, process-based models themselves can also be computationally expensive, taking a few days to weeks to complete, depending on their complexity. Because of the computational restraints on fluid flow simulations, reservoir geologists are also required make choices on the scale of heterogeneity to include in their geological models. Computational detail of the process-based models should therefore match that required in the geological models which they aim to inform. Simulating heterogeneities which will not be included in the geological model is unproductive, while excluding heterogeneities which are important to the flow properties of the reservoir is also not desirable.

Geological models will have different spatial scales of interest, depending on the character of the specific reservoir (Jones et al., 1995; Kjønsvik et al., 1994; Ringrose et al., 2008). Here we investigate at which scale of interest, variations in fluvial discharge become an important factor in the quantification of sedimentological heterogeneity.

5.2 EXPERIMENTAL DESIGN

We simulated four prograding deltas with discharges which are constant (1600 $m^3.s^{-1}$), slowly increasing (600 $m^3.s^{-1}$ to 2000 $m^3.s^{-1}$), slowly decreasing (2000 $m^3.s^{-1}$ to 600 $m^3.s^{-1}$) and with wet-dry season cycles (22 cycles of [3 months increasing 600 $m^3.s^{-1}$ to 2000 $m^3.s^{-1}$; 3 months decreasing 2000 $m^3.s^{-1}$ to 600 $m^3.s^{-1}$; 6 months stable at 600 $m^3.s^{-1}$]).

In all other aspects the models were the same and correspond to those previously described in chapters 3 and 4. The models simulate a channel debouching into a sloped basin with a semidiurnal tide (amplitude 1m) and small waves (0.2m height, period 3m). Sea level was kept constant throughout the simulations. The sediment concentration was also kept constant throughout the simulations and has a bimodal composition ranging from coarse sand to medium silt, with the largest contribution coming from medium sand. The end of the simulations are defined as the time when 76% of their accommodation is filled within a half-circle (radius 2km) with the origin at the delta apex.

Table 4: Definition of the deltaic sediments by sub-environments and architectural elements

Sub-environment	Architectural element	Definition
Delta top	Channel accretion	• Lateral accretion: sediment stored as lateral bars as channels migrate. • Vertical accretion: Generally coarse sediment stored at the channel base in locations where bed load is over-supplied compared to the amount of bedload which can be transported further along the channel
	Channel fill	• Fining upwards sediment which fills channels as they become inactive
	Overbank/ background	• Overbank deposition and background sedimentation which depositing in locations between the active distributary channels
Delta front	Mouth bar	• Sandy sediment deposited where sediment-laden jet exits channel mouth, spreads upon reaching the basin and decelerate.
	Background	• Lobate deposits travelling further from the channel mouths than the mouth bar sands • Background sediment deposited as basinal processes (e.g. waves) rework the exiting deposits
Prodelta	Prodelta	• Fine sediment eroded and transported by basinal processes and deposited below the fair weather wave base. • Here deposits are only defined as prodelta once 15mm of deposition has occurred at that location.

The deposited sediment was subdivided into sub-environment and architectural elements as defined in Table 4. The final delta bathymetry and cross sections showing the simulated stratigraphy of the delta are shown in Figure 26. The subdivision into architectural elements, and calculations of grain size D50 followed the same methodology as described in Appendix I with one exception. The channel network definition has a temporal aspect to the velocity cut-off values. At each time interval the mean velocity of the elements at the fluvial input boundary is calculated. This velocity is then processed using four pre-defined constant values:

(1) Limit-cut-off-new (1 $m.s^{-1}$): The lowest value for cut-off-new can have in any time interval
(2) Limit-cut-off-old (0.75 $m.s^{-1}$): The lowest value for cut-off-old can have in any time interval
(3) Factor-new-channel (1.25): Used to determine the cut-off velocity for elements which are not currently part of the active channel network to be incorporated into the active channel network. The mean boundary velocity is multiplied by

factor-new-channel. If the result is larger than “Limit-cut-off-new”, it is used as the velocity cut-off for new channel elements. If it is however smaller, the limit-value is used.

(4) Factor-old channel (1): Used to determine the cut-off velocity for elements already part of the active channel network to remain part of the active channel network. The mean boundary velocity is multiplied by factor-old-channel. If the result is larger than “Limit-cut-off-old”, it is used as the velocity cut-off for new channel elements. If it is however smaller, the limit-value is used.

It is important to note that each simulation represents a single realisation for its discharge regime, not the potential range of natural variability. Adding different noise filters to the initial basin bathymetry, would enable the creation deltas which represent a range of natural variability in the deposits. While these realisations will differ in e.g. location of channel, or exact time interval when an avulsion occurs, the general behaviour of such a set of deltas are still expected to be the same, within an envelope of natural variability. When differences between results of different models are small enough to simply be coincidental, they fall within the range of variability which can be produced for a single set of boundary conditions (Li et al., 2017). Therefore, small difference in results for of the simulations in this study are described to lie “within the expected range of natural variability”.

5.3 RESULTS

We classified the sediment into architectural elements inside a 2km semi-circle centred at the delta apex for each delta. The proportions of the accommodation filled by the elements are plotted over time until the end of the simulations (Figure 27). Differences between the simulations include the small fluctuations in the initial stages of the wet-dry season simulation and the slow start of the accommodation filling in the increasing discharge model. The most striking observation is however not the differences, but the similarities between the architectures at the end of the simulations, once the accommodation reaches the 76% fill. The differences between the proportions of architectural elements of the different simulations are less than the natural variation we could expect for a single delta. We conclude that discharge variation alone, on medium to long timescales, leads to only minor differences in delta architecture.

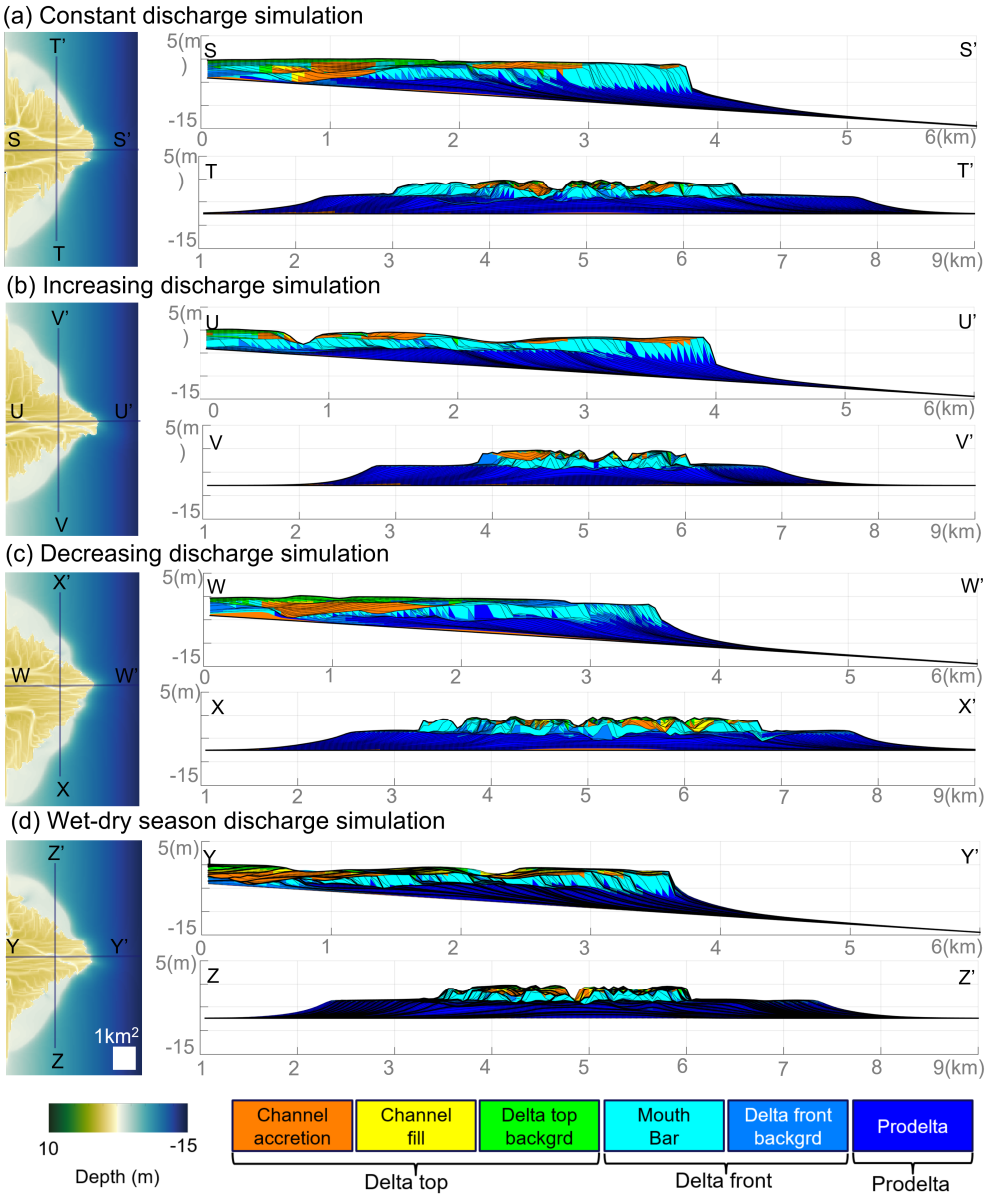


Figure 26: Final bathymetry of the four simulated deltas (left) and cross-sections showing the three dimensional delta architecture.

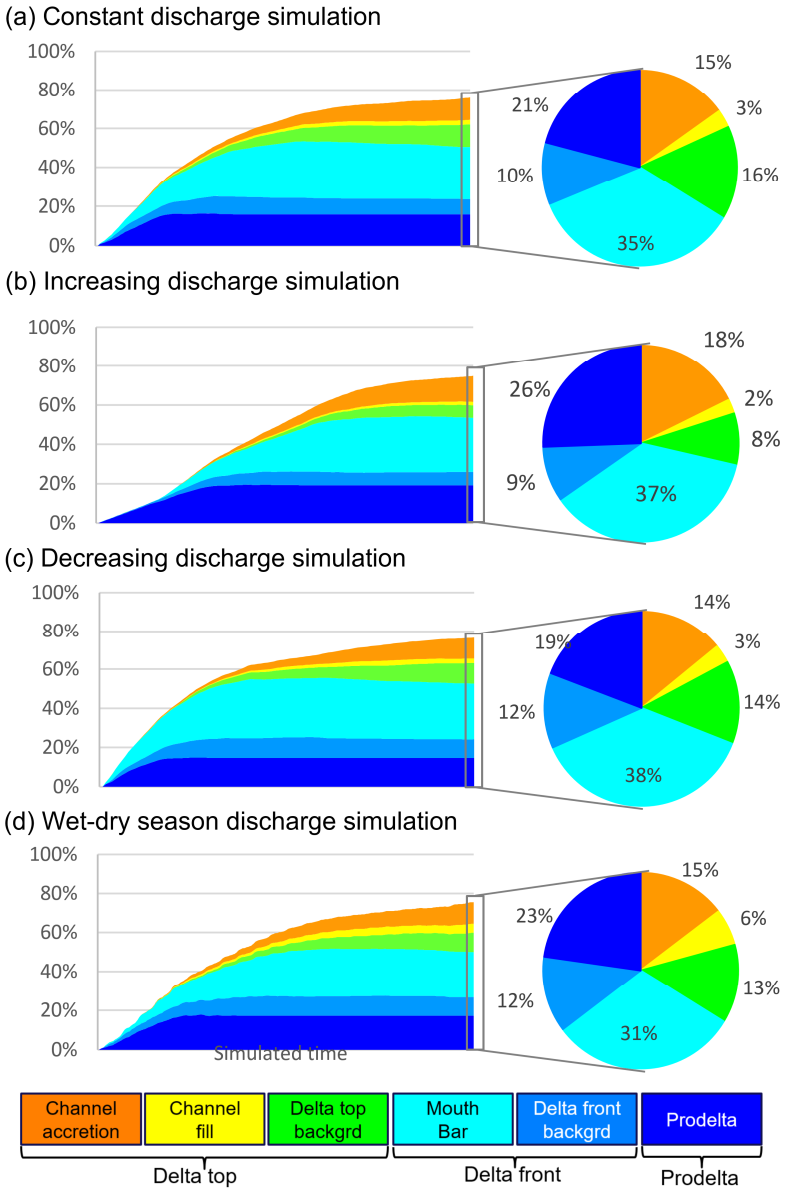


Figure 27: Delta architectural evolution over time. The area graph shows the filling of accommodation within a 2km semi-circle centred at the delta apex, and the pie chart shows the composition at the end of the simulation.

Grain size distribution within the delta volume is an important proxy for reservoir quality. Figure 28 shows the sediment composition deposited within the 2km half-circle centred at the delta apex. As in the case of delta architecture, the final compositions of all four simulated deltas are very similar and within the expected range of natural variation. Almost the same proportion of coarse sand is deposited as is supplied and some of this

grain size class is expected to be stored in the fluvial domain and does not reach the delta. Medium to very fine sand proportions are amplified in the delta while muddy coarse silt and medium silt sizes are found in reduced proportions. Coarse and medium silts are washed offshore more readily and therefore retained in the delta in reduced quantities. The similarity in sediment composition of the individual architectural elements and background sedimentation are also within the expected range of natural variation (Figure 29). We conclude that the overall sediment composition of a delta as well as the composition of its architectural elements is not significantly influenced by discharge variations. But this does not mean that the organisation of the sediment within these architectural elements will be the same for all four scenarios. We conclude that discharge variation alone, on medium to long timescales, lead to only to minor differences in delta sediment composition.

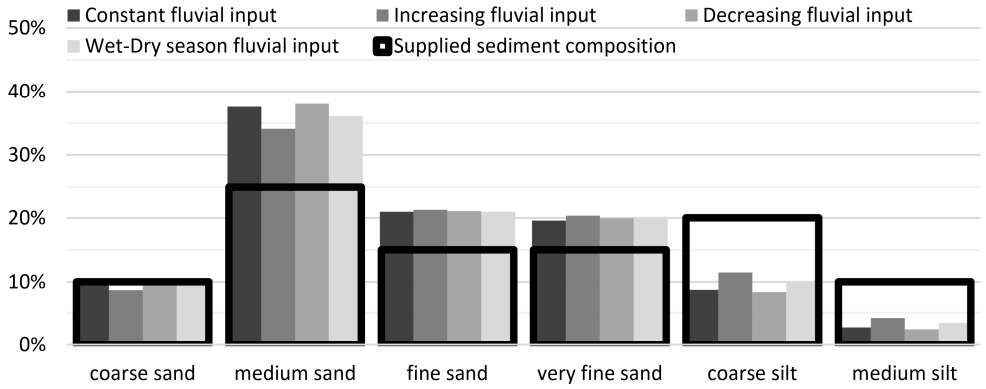


Figure 28: Sediment composition inside the 2km half circle centred at the delta apex at the end of all four simulations

Next we consider the internal structure of the deposits, on a smaller scale than the architectural elements. The normalised rate of deposition over the course of the simulation is an indication of preserved bed-thickness variation (Figure 30). Variations in the composition of the depositing sediment over time, give an indication of the variation in composition of final preserved beds. In simulations with constant, increasing and decreasing discharges, the compositions of the deposits over time, are almost identical throughout the simulations. The delta system compensates for the slow changes in fluvial supply to deposit sediment with the same characteristic composition. However, at the start of the increasing discharge simulation practically no sand is deposited in the basin. At very low discharges, sand takes longer to traverse the fluvial domain and reach the basin, therefore this lag in sandy deposition is simply an indication of a longer simulation 'spin-up' time. This same trend is not seen in the decreasing flow model, where sands are already available along the fluvial domain and in the basin by the time the discharge decreases.

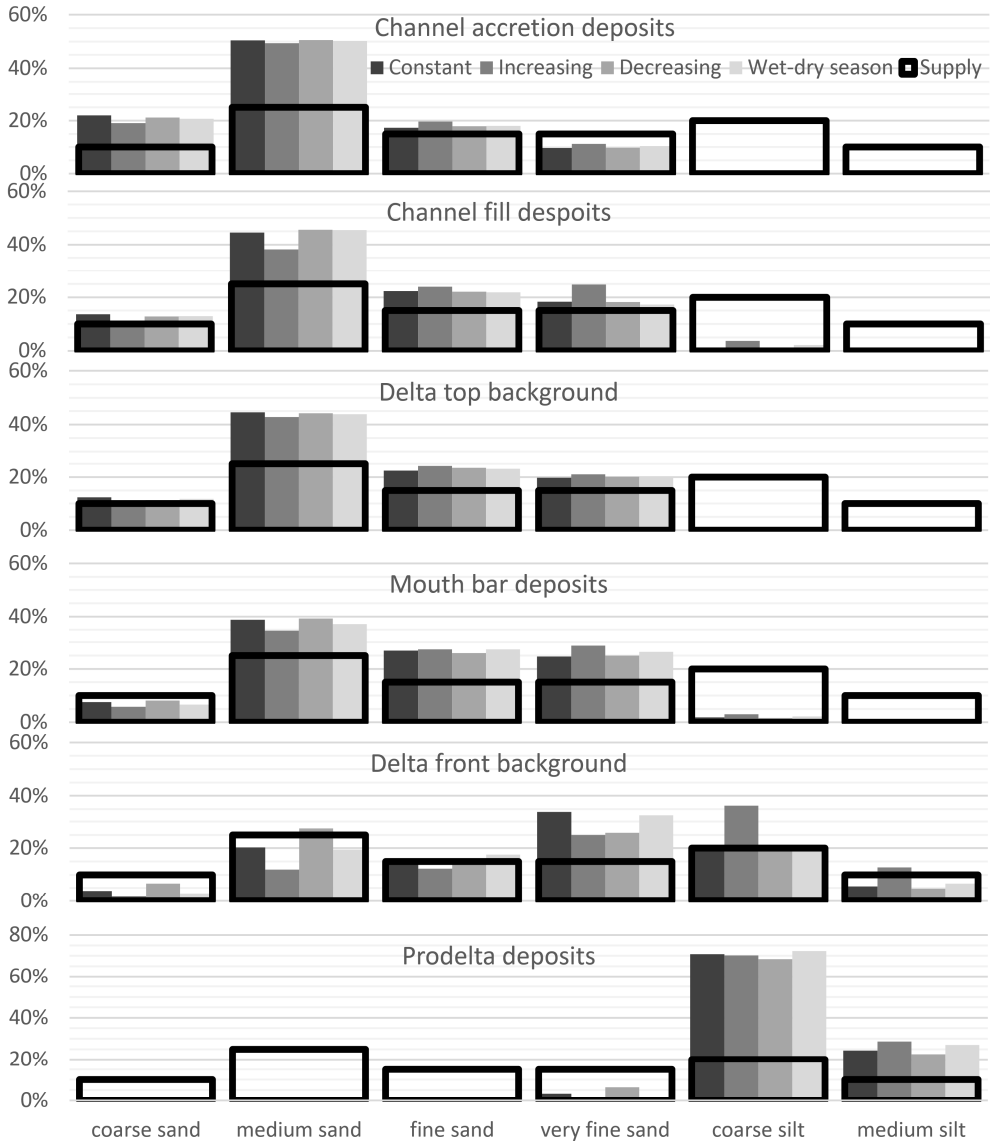


Figure 29: Sediment composition of architectural elements and background sedimentation of all four deltas are very similar

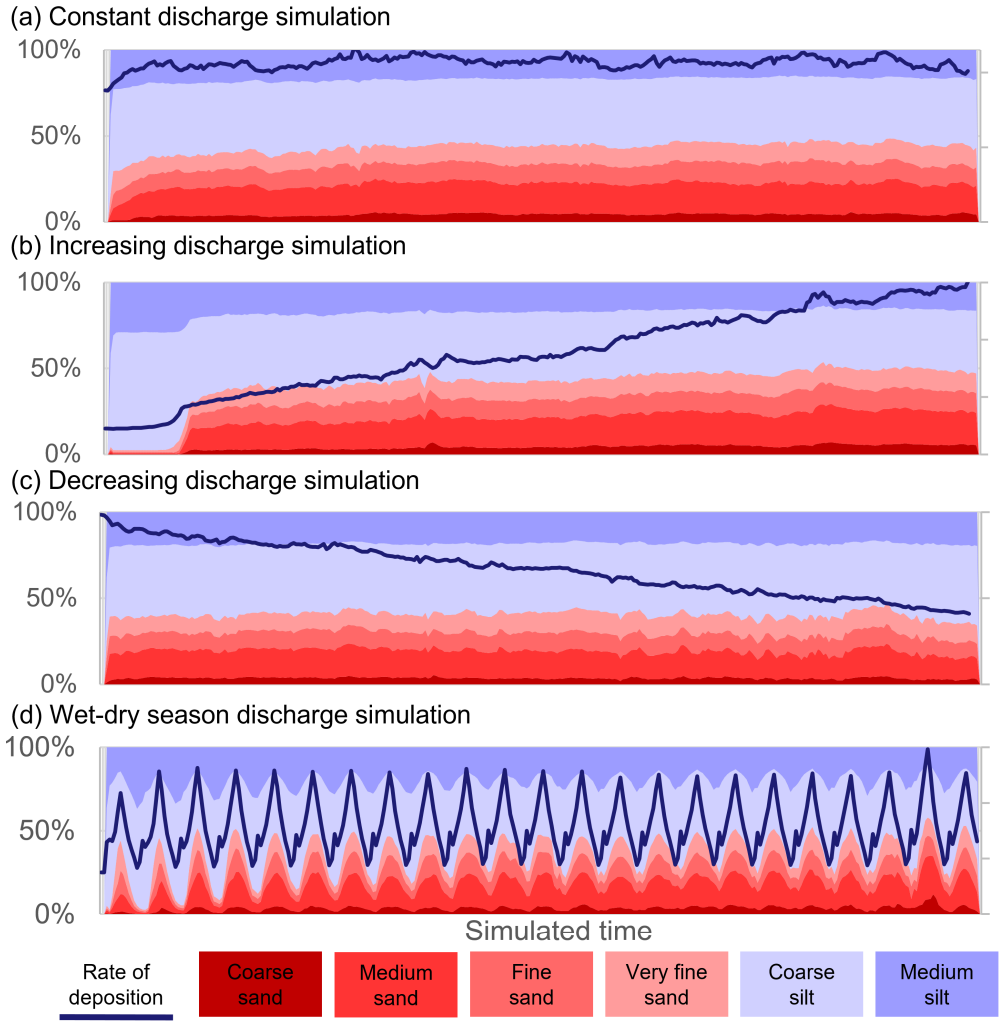


Figure 30: The blue line indicates the rate of deposition throughout the simulation, normalised by the maximum depositional rate within each simulation. It overlays an area plot of the grain size composition of the net deposited sediment over time. Together each graph shows how not only the rate but also the composition of deposition varies over time for each model.

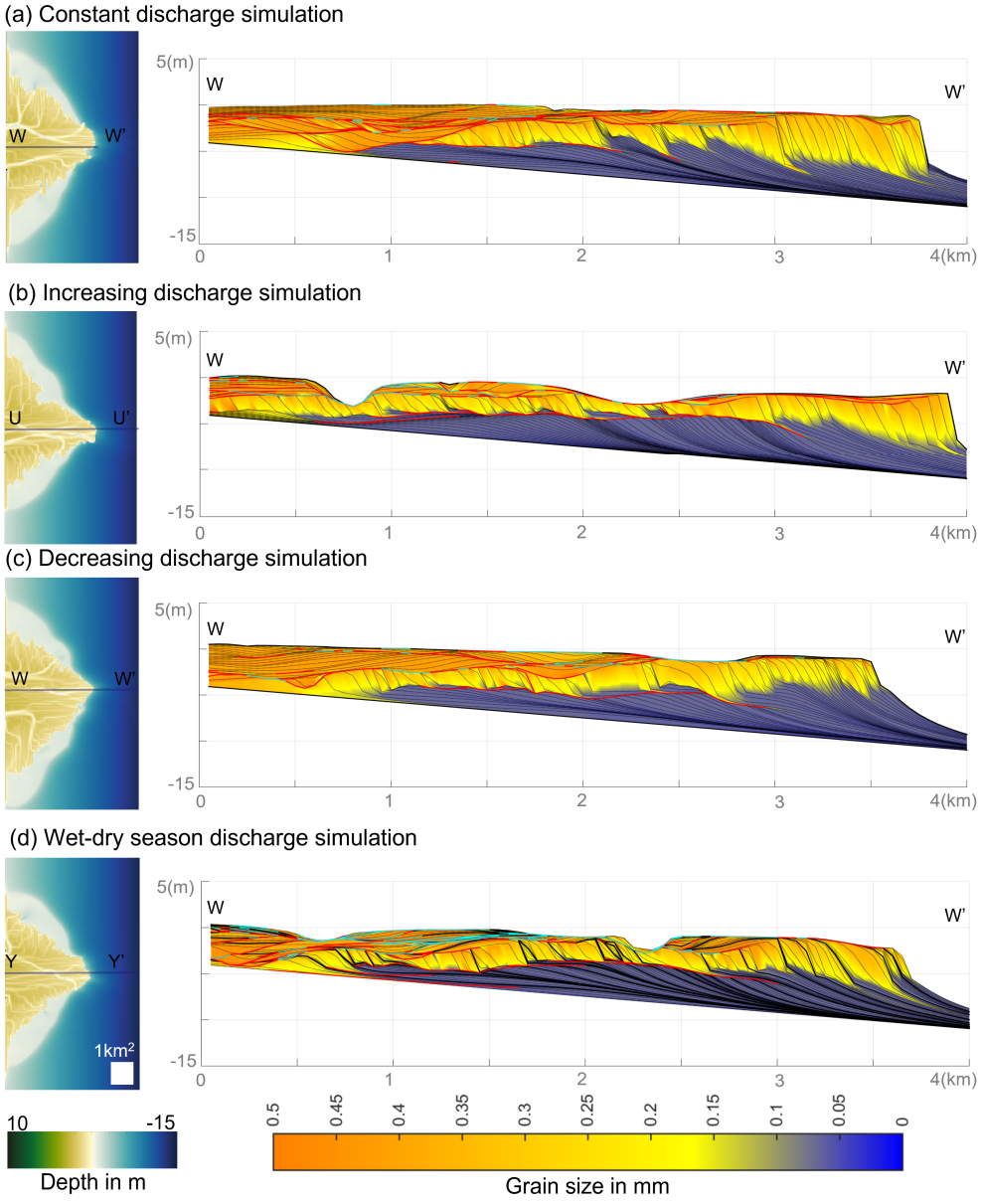


Figure 31: Cross-section perpendicular to the shoreline showing the grain size distributions in all four deltas. Light blue lines indicate the presence of flow baffles while red lines indicate erosional surfaces. The darker lines in (d) indicate the boundaries between wet/dry season cycles.

The results from the last simulation, where discharge simulates wet-dry seasonal cycles, is different from the other three simulation. The rate of deposition fluctuates cyclically, as does the composition of the deposits. The rate of deposition lags just behind change in discharge, with the lowest rates of deposition occurring during the dry season and the highest rate of deposition occurring just after the peak in discharge has been reached.

During times of low rates of deposition, the deposits have a muddy composition (with less than 20% sand deposited across the delta) while sediment deposited during high rates of deposition are sandier (up to 50% sand deposited across the delta). This behaviour causes sandy beds during the wet season to be interspersed with thin muddy beds deposited in the dry season.

5.4 DISCUSSION

We have found the morphology, architecture and sediment composition of the simulated deltas not to be affected by variations in discharge on the medium to long term. However, seasonal fluctuations in discharge did control the bedded structure of the deposits, creating sandy beds interspersed with thin muddy layers. These layers can act as flow baffles in reservoir rocks and are also visibly more abundant in cross sections of the deltas (Figure 31).

Our findings show little morphological impact of discharge variation. Similarity in delta morphology, irrespective of discharge fluctuations, was also found by Guo et. al. (2015). We also found seasonal changes in discharge to impact sedimentary heterogeneity preserved in the delta stratigraphy while slowly increasing and decreasing discharge had little effect. Therefore seasonal discharge variation during deposition can have an important impact on the reservoir connectivity of the deposited sediment (Jones et al., 1995; Kjønsvik et al., 1994; Weber, 1982).

In the future, this methodology could also be applied to quantify the rate of discharge variations required to deposit more heterogeneous sedimentary beds for different deltaic systems. We did not analyse models with discharge variation faster than seasonal variation, but it is certainly conceivable that at a very high rate of discharge variation, deposition may not have time to respond to the changes and the resultant sedimentary beds would be more homogeneous than for slower variations in discharge.

For the Yellow river system, mouth bar progradation has been shown to be directly related to changes in the fluvial supply (Fan et al., 2006). A decrease in sediment concentration at times of low discharge was found to cause retrograding mouth bars. The sediment supply concentration and composition was constant across our simulations, with only discharge changing over time. Complex terrestrial feeder systems supplying sediment concentration and composition which vary over time could add an additional, non-linear control on the sedimentary heterogeneity in the delta (Armitage et al., 2011).

At the delta front, flow velocity is known to influence bed friction and sediment spreading, leading to changes in mouth bar deposition between times of large and small discharge (Canestrelli et al., 2014; Edmonds and Slingerland, 2007). However, the simulations presented here do not capture all the heterogeneities at the delta front. The selected transport formula for sand classes does not accommodate the direct erosion of sand by waves. Flow barriers in delta front deposits are therefore expected to be underestimated in these simulations as mainly cohesive material is removed by the waves. The results support a further analysis of the effect which waves have on delta front deposition. This

should allow simulations to more fully capture sedimentary heterogeneity in this sub-environment.

At times of high discharges, large sediment loads can be delivered to the delta front causing hyperpycnal flows (Mulder et al., 2003; Mutti et al., 2000). The resulting sandy, lobate delta front facies will resemble that of turbidites. We did not consider hyperpycnal flows in this study. However, we did find that large channels, delivering sediment into deeper parts of the basin before the prodelta has fully development, causes sandy sediment to bypass the delta top and delta front and deposit directly into the prodelta. This leads to isolated sandy beds in the prodelta. These beds often overly an erosive surface where the discharge from the channels has caused some erosion into the underlying prodelta.

5.5 CONCLUSION

The 4D deposits from our simulations could be viewed as synthetic/numerical analogues. We use these simulations as computational experiments to study the effects of different physical conditions on sedimentary heterogeneities in the resultant deposits. In this work we investigated the effect of discharge variation on sedimentary heterogeneity. We found that seasonal variation in discharge causes increased laminations in the bedded structure of the deposits while slow increase and decrease in discharge had little effect.

These laminations can have an important effect on reservoir quality, therefore we conclude that further expansion of our understanding of these variations would be beneficial. We have shown the importance of quantifying the effect of variation in the rates of discharge. In addition, future computational work could include non-linear variations in sediment supply composition and concentration. The effect of wave reworking, especially important at times of low rates of deposition, could be the focus of further investigation in order to improve the quantification of the heterogeneities in the delta front.

CHAPTER 6: WE'RE ONLY GETTING STARTED

6.1 WHAT IS THE RELATIONSHIP BETWEEN FLUVIAL SEDIMENT SUPPLY AND THE 3D EVOLUTION OF THE PRESERVED DEPOSITS IN DELTAIC ENVIRONMENTS?

This dissertation addresses the question in four ways:

(1) It creates a set of quantitative analyses which can be applied to compare simulated deltas, active modern deltas, as well as ancient delta deposits. (Research question 1, chapter 2, 3, 4, 5)
(2) It explores the direct link between sediment transport on deltaic deposition. (Research question 2, chapter 2)
(3) It proposes a new way of looking at sediment fractionation and accommodation-to-supply ratios, partitioned into delta sub-environments. (Research question 3, chapter 3, 4)
(4) It highlights the importance of scale of heterogeneity when designing simulations and analyses. (Research question 4, chapter 5)

In addition, the methodology developed during this work opens up a wealth of opportunities for exploring the mechanisms of deltaic deposition. It also highlights some remaining questions, which need to be addressed in future research initiatives. It is my opinion that all the further work suggested in this chapter is achievable in Delft3D and will help to place these types of delta simulations into context within the sedimentary system.

6.1.1 DESIGNING QUANTITATIVE ANALYSES

Research question 1: Based on which metrics can we compare different deltas?

Designing a set of quantitative analyses requires a good understanding of the dynamics within the deltaic environment during delta progradation. For this purpose the importance of quantifying the channel network's dynamics cannot be overstated, as the channels form the conduits through which sediment is delivered to the delta. In addition, the depth of the channels determines the top of the preserved, underlying delta front deposits. While channel depth can be determined for modern active delta systems, large scale channel displacement typically occurs on a scale which is too slow to observe directly. In ancient deposits channel dynamics are not observable, for obvious reasons. Even channel depth can be elusive in the rock record. Channel deposits form part of the delta top, which has a lower long term preservation potential than underlying environments. Where a thick package of delta front sands are deposited, these sands are less susceptible to subsequent erosion than the overlying delta top. But even with the elusive nature of delta top channels in preserved rock records, it is still imperative to accurately classify the active channel networks as they determine the locations of the sandy mouth bar deposits of the

delta front. The mechanisms of mouth bar deposition can only fully be understood in relation to their supply channels.

During the course of the project we worked closely with Deltares to incorporate additions to Delft3D's output variables. Initially, it was only possible to extract instantaneous velocity at the end of each output interval, which had to serve as a proxy for the flow velocity during the entire preceding output time interval. However, in the subsequent versions of Delft3D, used from chapter three, the maximum, minimum and mean flow speed (excluding direction) were also recorded. These variables were extensively analysed to arrive at the final definition of an "active channel element".

Chapters two through to five have seen an evolution in the definition of architectural elements. Determining limits and cut-off values for the definition of these elements has proved a complex, iterative pursuit. It is unlikely that the latest definition that was implemented will be the final definition of this metric. The exact boundaries between different architectural elements remain difficult to define and the definitions continue to evolve with each new numerical experiment conducted. Improved knowledge after each study necessitates a refinement and generalisation to the definition of the architectural elements; not to adjust this definition for subsequent experiments would be to disregard the findings. However, this dissertation has presented a robust framework for defining architectural elements, which can serve as the base for future developments.

Strides were also made in the analysis of sediment grain size composition and its distribution throughout the delta. At each location in the delta, data is available on the fraction of each grain size class present. This enables the calculation of grain size D50 by defining a virtual sieve. It is also possible to define sorting, but due to the narrow range of grain size classes included in the models (coarse sand down to very fine silt), even the widest distribution of sediment will still fall into the "well sorted" range as commonly applied. However, while providing informative values for visual inspection, both grain size D50 and sorting calculation provides less information than the compositions provided in the Delft3D output. Far more can be learnt from analysing the grain size distributions by defined sediment classes, as was done in chapters three to five.

Another improvement made over the course of this work was to extract the sediment data per time interval. Previously, Delft3D was only able to output sediment deposition data on a fixed-size predefined, vertical grid. In the version used in chapters three to five, grain size data was available in "time layers" bounded by the output time intervals. This data format is imperative for producing accurate deltaic stratigraphy. While the new output format allows for the accurate representation of sedimentary heterogeneities (e.g. thin, often fine grained, layers of sediments) the risk is for the output interval to be too coarse to resolve the heterogeneity in thicker, sandy layers. Here the most important consideration is that selection of the output time interval needs to be sufficient to reproduce the scale of heterogeneity of interest.

Ongoing work will expand the analysis tools to include a prediction of bedforms, based on flow velocity, water depth and grain size composition. This will facilitate the development of automated facies definitions facilitating comparisons with outcrop data.

6.1.2 SEDIMENT TRANSPORT AND DELTAIC DEPOSITION

Research question 2: How does sediment transport influence preserved deposits?

In chapter two we explored how the mode of sediment transport can impact depositional patterns of deltas. Sediment transport controls the erosion, travel distance/direction and deposition of sediment. It is therefore also expected to be the most important factor controlling differentially preserved deposits in deltaic environments. All other processes are important only insofar they control the transport of sediment. Based on the findings from chapter 2, sediment transport definitions were adjusted in subsequent chapters. In simulations in chapter three to five, each sediment grain size class was assigned its own proportion of bed load vs. suspended load transport. The bedload consists mainly of the coarsest sand fractions, while the finer sands travel mainly in suspension. All cohesive sediment is transported in suspension.

A wealth of research exists in the field of sediment transport (e.g. Bagnold (1966), Parker (1990), van Rijn (1993)). However, in recent years there has been relatively little development in better constraining sediment transport on a delta-wide scale. New research instead focuses on flume-scale studies scale (Blom et al., 2008; Viparelli et al., 2017) and are not appropriate for application at the scale of our models. In addition, measurement of sediment transport at scales which are appropriate for our simulation (several meters), can be very challenging in active deltaic systems. This is especially true in extreme conditions (floods, storms), which coincides with times when large adjustments are made in sediment supply and deposition. In our simulations, the Engelund-Hansen formulation for sediment transport has been used, possibly to the limits at which it is applicable. In future studies, especially when investigating wave reworking of delta deposits, this formulation may not be the most appropriate. The work in this dissertation shows the importance of accurately parameterising sediment transport, and sediment transport is certainly a topic which warrants more detailed study in the future.

6.1.3 PARTITIONED SUB-ENVIRONMENT ACCOMMODATION-TO-SUPPLY

Research question 3: How does sediment supply composition translate into preserved composition across the delta?

Chapters three and four look at the fractionation of sediment grain size classes into architectural elements. Here we see the importance of simulating deltas supplied with a range of sediment grain sizes. Each grain size class interacts with the depositional processes in its own way leading to a fractionation across the preserved deposits. At different sub-environments within the delta, different processes play an important role of controlling sediment deposition and erosion. E.g. fluvial processes only contribute to reworking sediment down to the level of the maximum channel depth, while the wave reworking processes are only active down to the depth of wave base. The interaction of these processes with the different grain size classes determine whether each sediment class is likely to be preserved in the various sub-environments permanently or whether it will be eroded and moved further offshore during progradation.

The sediment supply composition determines what volume of the preferred grain size classes are available to fill each sub-environment's accommodation. If the prodelta, delta front and delta top prograde at the same rate, no sediment bypass would occur. However, if one sub-environment is under-supplied with its preferred grain-size classes, sediment-bypass can occur in the overlying sub-environment causing deposition of pockets of coarser grained sediment. Alternatively, an under-supplied sub-environment may also retain sediment normally destined for its underlying sub-environment, leading to areas with finer sediment. When a sub-environment is over-supplied with its preferred grain size classes, and therefore prograding faster than its underlying sub-environment, it will experience sediment bypass, causing pockets of coarser grained sediment to deposit in its underlying sub-environment.

These results highlight how the three factors controlling sediment deposition (Figure 3: hydrodynamics, sediment supply, basin geometry) influence the differential distribution of sediment throughout the delta. The basin geometry determines the overall accommodation, the sediment supply controls the volumes of each grain size class available to fill the accommodation and the hydrodynamic processes control how the sediment supply will be partitioned between the different sub-environments. The relative rate at which different sub-environments prograde will determine whether sediment composition is homogeneous within a particular sub-environment or whether heterogeneous deposits can be expected, with isolated pockets of coarse and fine sediment within a sub-environment. Of course an under- or over-supply of sediment to a specific sub-environment can also be caused on different timescales when the accommodation and supply conditions vary over time e.g. during floods or storms, between seasons or with changing climate.

6.1.4 CHOOSING A SCALE OF INTEREST

Research question 4: To what extent is heterogeneity in preserved deposits controlled by time-varying discharge?

Chapter five discusses the effect of time-varying discharge on the various metrics used to describe a delta. The time varying discharge had little impact on the architectural-scale metrics developed, e.g. architectural element volumes and on the grain size classes within these architectural elements.

A more detailed analysis of time varying deposition revealed that seasonal discharge variation was indeed recorded in the stratigraphy as alternating sandy and muddy beds at mm to m scale. Therefore, these simulations open a whole new direction of study into depositional heterogeneities at smaller scales. At these scales, tidal imprints on deposits may also become more important, however, simulation output intervals were only once per tidal cycle. This frequency is not sufficient to capture heterogeneities due to semi-diurnal tides. In future simulations, action should be undertaken to match the scale of heterogeneities to the processes represented in the simulation output.

The velocity-based channel definition is more challenging to apply to a system with constantly varying velocity profile. However, linking the velocity cut-off values to the fluvial supply boundary condition allows the channel network to match morphology and sediment transport to within acceptable error margins while limiting unconnected channel network sections. Future studies should refine and further generalise analysis definitions so that they hold across larger datasets of simulations. However, the methodology presented in chapter 5 paves the way for investigating different rates of discharge changes and better constrain the conditions leading to different scales of heterogeneity in deposits. Improving our understanding of the processes leading to heterogeneities can inform the likelihood of signal shredding (Jerolmack and Paola, 2010) of individual supply events upstream of the deltaic system. In addition, future studies can vary sediment supply independently from discharge to simulate even more of the non-linear behaviour observed in natural systems.

6.2 FUTURE OUTLOOK

There are still remaining questions for future investigations. Some questions relate to deltaic processes themselves and others relate to the implementation of the numerical experiments. Some of the more pressing questions are:

- **To what level of detail do wave effects need to be simulated to reproduce the most important heterogeneous sedimentary features?** One important shortcoming which can be seen in the delta front deposits in chapter 5 is the lack of bed alternations in the delta front. Interbedded structure can be observed in the delta top of the simulation with seasonal discharge variation, where channels active during the wet season can have an erosive effect on underlying muddy beds from the dry season. It was expected that some level of this variation also be recorded in the delta front, however this was not the case. Possibly, the wave module as applied in the simulations does not fully capture delta wide wave effects as it does not simulate direct wave stirring of sand classes. Therefore the wave module has a larger influence on cohesive sediment classes than it has on sand classes. We have also not included to the effect of wave asymmetry on different sub-environment deposition (Bhattacharya and Giosan, 2003; Korus and Fielding, 2015). The findings from Chapter 5 indicate we may still not be able to capture the appropriate extent of heterogeneities at the delta front required to facilitate such a study. These effects are of less importance for the very small wave energies applied in the current studies. However, when moving to larger wave environments and further to the simulations of storms, it will become increasingly important to properly constrain the wave simulation in our simulations.
- **What level of grain size refinement is required to represent the required depositional heterogeneity?** The most recent models are supplied with the following sediment classes: coarse sand, medium sand, fine sand, very fine sand, coarse silt, medium silt, fine silt and very fine silt. Clay is assumed to form part of the mixture of silt grain sizes, having undergone flocculation into particles equivalent to silt-sizes. The slit grain size classes are assumed to behave as

cohesive sediment. This level of refinement is much more detailed that previous studies (Caldwell and Edmonds, 2014; Geleynse et al., 2010; Storms et al., 2007). Considering the typical sediment grain size description of delta outcrops are often of a more refined scale, it could be appropriate to further subdivide some of the sand classes, when computation resources allows. In addition, we have only considered the very basic properties of silica-based sands. But in natural systems the sediment supply can have a range of chemical and physical properties. The definition of sediment properties provides an additional range of variables which should investigated, preferably as part of a comparison of simulation results to a modern/ancient deltaic system.

- **What appropriate time and spatial scale is required to capture different levels of heterogeneity?** Simulating time-dependent variations in the different forcing conditions, necessitates the explicit specification of which processes control heterogeneities on the scale of interest. This will allow more appropriate simulation of deltaic sediments across a range of scales. But we are yet to determine which variation are important at which scales.
- **What are the effects of flocculation and salinity?** Delft3D is already capable of simulating these process. Including these mechanisms could lead to more cohesive muds depositing at the delta front, thereby more accurately representing the delta front heterogeneity. The parameters for these processes vary significantly between natural deltas, and they could play an important role in some deltas (Gugliotta et al., 2017). In addition, salinity can cause density differences which influence the distance that sediment-laden plumes are transported prior to deposition. As a first approximation, these processes could be added to the delta simulations in their simplest form to investigate the effect on existing metrics.
- **Would it be more appropriate to conduct simulation of the hydrodynamics in 3D rather than 2DH?** Density differences within the vertical water column, which may result from the inclusion of salinity in the models, may warrant simulating hydrodynamics in the water column in 3D rather than 2DH. As the delta front and prodelta prograde into deeper water, is the depth averaged approximation still appropriate at these depths? It would be informative to do a comparative study to determine at which water depth the 2D simulation are no longer sufficient and 3D simulations should instead be undertaken. Additionally, wave influences on hydrodynamics can also be resolved into 3D to more closely approximate their effect on sediment deposits.
- **What are the effects of subsidence, compaction and consolidation on depositional patterns?** Sediment begins to change once it has been deposited. Cohesive sediment may lose some of their absorbed water and become hard upon drying, making them harder to subsequently erode. Large bodies of subaqueous sediment may also compact and subside post-deposition, creating additional accommodation during the evolution of the delta. Both the change in geometry as well as the change in sediment properties during the course of delta progradation should be investigated is the time and spatial scale of the simulations are to be extended.

- **How can we simulate peat growth and the stabilising effect of vegetation on the delta plain?** Peat growth is another process which impacts the behaviour of delta dynamics. This has not been included in the current study as there is not currently a mechanism which allows for the change in sediment properties over time, post-deposition. However, once such a mechanism is included in the code (e.g. to simulate compaction/consolidation) this could also be adapted to simulate peat growth or simplistic changes in vegetation on the delta plain.

In addition to answering these questions, a number of other topics warrant investigation for the further development of the methodology.

6.2.1 AUTOMATED DEFINTION OF FACIES

In this work we have developed automated definition of the following:

- Active channels: Defined based on flow velocities
- Sub-environments: Defined based on active channel locations and geometric averaging across the delta
- Architectural elements: Defined based on active channels, sub-environments as well as rate of deposition.

From this list it is clear that the accurate, automated definition of active channel elements is key to the accuracy of subsequent interpretive classifications. The architectural elements can already be compared to interpretive facies descriptions. However with the detailed grain size, flow velocity, water depth and shear stress information available from the simulation, output should allow the prediction of bedforms. Together with grain size, bedforms would facilitate the prediction of descriptive facies. This would enable the investigation of the extent to which descriptive facies correspond to the interpretive facies in deltaic systems.

6.2.2 INFORMING STATISTICAL STUDIES

Delft3D-simulated synthetic deltas can be applied to build improved reservoir models. The synthetic analogues could e.g. serve as 3D training images for multi-point statistical techniques (e.g. Aarnes et. al. (2017), Mullins et. al.(2017)). This research avenue is currently being pursued through various collaborations with researchers working on multi-point statistical techniques

Delft3D simulations are deterministic whereby a model with the same boundary conditions should deliver the same resultant delta each time the simulation in performed. However, in natural deltas, small variation in starting conditions can have large impacts on the final organisation of sediments. It has however been shown that small perturbations in initial bathymetry, while leading to variations in morphology, lead to overall dynamic behaviour which stay within an envelope of variation, also called the envelope of uncertainty (Li et al., 2017). By imposing small variation in boundary conditions it becomes possible to produce a range of models covering this envelope. Such an ensemble

could then also be used to further improve statistical methodologies for building reservoir models.

6.2.3 QUANTITATIVE VALIDATION AGAINST FIELD DATA

The development of new analysis frameworks now enables the quantitative verification of Delft3D-generated deltas against comparable outcrop measurements or modern deltaic systems. In addition, the interactions between forcing parameters explored in this dissertation enable future studies to select the most appropriate forcing parameters to reproduce aspects of real world deltas. Applying this to an outcrop and modern deltaic system should be the logical next step towards improved calibration of the analysis methodology.

6.2.4 SCALING UP: LATERALLY, VERICALLY AND IN TIME

In order to contextualise the role of deltaic deposits in source-to-sink systems, it is important to link the sediment interaction within the delta both to the upstream terrestrial supply and the downstream deep water deposits. The use of Delft3D is well established in the terrestrial, fluvial domain (Schuurman et al., 2013). However, to enable the downstream deep-marine systems, 3D mass flow events would have to be simulated in Delft3D. The first steps have been made in achieving this in 2DV (2 dimensional vertical slice) (Ooms, 2017). A feasible short term contribution to studies of the deep water domain is the prediction the sediment supply from the delta system to the deeper areas of the basin, e.g. the continental slope.

To facilitate investigation of deltaic deposition on geological timescales, it is necessary to simulate the progradation of deltas across the continental shelf until they research the shelf edge. This could take place under different sea level scenarios as systems with large sediment supplies would allow deltas to prograde to the shelf edge even during a sea level rise. Current simulations only consider delta progradation under constant sea level, far from the shelf edge. However, sediment supply to the continental slope is more likely to take place from shelf edge deltas. These deltas prograde into significantly deeper water and may also be more susceptible to basinal forces such as waves and off-shore currents. The available data on such systems are limited. Firstly, we are living in an era of relatively high sea level, meaning there are few currently active shelf edge deltas. Secondly, sedimentation at the shelf edge during a sea level low stand is likely to undergo significant reworking during the subsequent sea level rise. Sediment from shelf edge deltas is the most readily available source of sediment for shelf slope deposits and they should be investigated in more detail.

6.4 CONCLUSION

Delft3D, together with the set of quantitative analyses develop in this project, is a well suited tool to broaden our understanding of the processes at play during active deltaic progradation. An improved understanding of deposition during active delta progradation furthers our knowledge on sediment heterogeneity in the subsurface. Further numerical

experiment should start with the determination of the scale of heterogeneity to be studied and the model design should be adjusted to this scale. This means choosing the appropriate simulated time, calculation time step, output time step, element size horizontally and vertically and, very importantly, the appropriate processes to include in the simulation. In addition, analyses should be generalised and refined by conducting the studies suggested in this chapter. But one of the most important steps in furthering this research is a comparative study between a simulated delta and a modern or ancient field example.

It is my aim for the work presented in this thesis to facilitate the evolution of this methodology beyond the simulation of single, prograding deltas, far from the shelf edge. In the near future, this methodology should find its place within the context of source-to-sink systems and facilitate collaboration between researchers from many sub-disciplines in earth sciences.

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APPENDIX I: CREATING NUMERICAL ANALOGUES OF DELTA DEPOSITS FOR GEOLOGICAL STUDY

The data relating to this appendix can be accessed at:
http://dx.doi.org/10.4121/uuid:8499763f-99e0-4df2-9f53-ff1c30572aae

I.1 INTRODUCTION

Generating synthetic deposits from numerically simulated physical processes constitutes a valuable and growing data source in sedimentological studies (Edmonds and Slingerland, 2009; Esposito et al., 2013; Geleynse et al., 2010; Li et al., 2017; Storms et al., 2007). Using well-established software together with boundary conditions which mimic deposition in natural systems produces synthetic sediment bodies which can be studied to supplement traditional sedimentological studies. Not only can the simulated deposits be studied in 3D, but the evolution of the deposits can also be studied, as well as the hydrodynamic conditions at the time of deposition. However, the large volume of simulated data needs to be post-processed to make it comparable to geological descriptions of deposits in field studies.

The strength of employing a computational methodology is that individual processes can be examined within the context of a complex depositional system. The methodology can be used to deconstruct hypotheses about the formation of complex deposits in the field. With and increased understanding of the system, these deconstructed findings can then be pieced together with field data to deliver robust geological models.

Here we describe and make available one such a dataset containing simulated and post-processes deltaic deposits. To create our dataset we employed Delft3D, an open source modelling tool, which simulates hydrodynamic processes and sediment transport processes across a range of depositional environments (Lesser et al., 2004). It has been a useful tool in studying the evolution of river delta deposition for more than a decade(Edmonds and Slingerland, 2007; Geleynse et al., 2010; Li et al., 2017; Storms et al., 2007). However the majority of the studies to date have focussed on morphological evolution rather than on the analysis of preserved sediment bodies in 3D. This paper discusses the core post-processing methodologies, while we are continuously striving to further improve these analyses. In making available both the Delft3D input and output files, as well as the post-processing methodologies and post-processed data, we hope to encourage collaboration and discussion within the modelling and sedimentological communities, bringing these disciplines closer together.

I.2 SIMULATION DEFINITION

We simulated the progradation of 4 river deltas in a fresh water basin, which differ only by fluvial supple (grain size composition and discharge). We describe the physical basis for our choices in boundary conditions, as well as the input and output file structure. Delft3D provides its users with the opportunity to customise their simulations by controlling hundreds of variables. It is not possible, nor necessary, to adjust all of these variables for each simulation. Therefore, where appropriate, the default values were used. We only discuss boundary conditions and variables which were altered. More details can be found in the accompanying Delft3D input files (http://dx.doi.org/10.4121/uuid:8499763f-99e0-4df2-9f53-ff1c30572aae) or in the Delft3D User Manual available online (Deltares, 2014).

Simulations were conducted in Delft3D (FLOW2D3D Version 6.02.08.6738). The horizontal dimensions of the calculation elements used are 50mx50m.

I.2.1 ACCOMMODATION

Accommodation constitutes the sub-aqueous volume available to the supplied sediment for deposition. This volume is determined by the shape of the receiving basin (i.e. the bed level) together with its water level. No long term sea level variation is assigned to our simulations, therefore the accommodation is only a function of the bed level. The initial bathymetry consists of a river, in a laterally confined, sloping, floodplain, debouching into a sloped basin. The river has a width of 500m and slopes from a depth of 3m proximally to a depth of 4m at the basin. This river is located centrally in a 2km wide floodplain. The floodplain slopes from an elevation of 1m above the water level proximally to a water depth of 1m when it reaches the basin. Proximally the basin has a depth of 4m at the coastline and gently slopes to 21m distally at an angle of 0.1 degrees (Figure 32).

The dataset simulates muddy to sandy deltas, prograding onto a gently sloping continental shelf, typically found in foreland basins or passive margins (Helland-Hansen et al., 2012). Fan deltas and grain sizes larger than very coarse sand are not included in the dataset. Many previous simulations have used simulated delta progradation prograding onto shallow to flat basins, allowing the morphology to develop quickly (Canestrelli et al., 2014; Mariotti et al., 2013). However care should be taken when selecting the basin slope for simulations as the slope will influence the dynamics of the sediment laden plume and thereby the way in which the stratigraphy develops (Jimenez-Robles et al., 2016; Storms et al., 2007).

Open Neumann conditions were assigned to the lateral basin boundaries, allowing sediment which reaches these boundaries to leave the system.

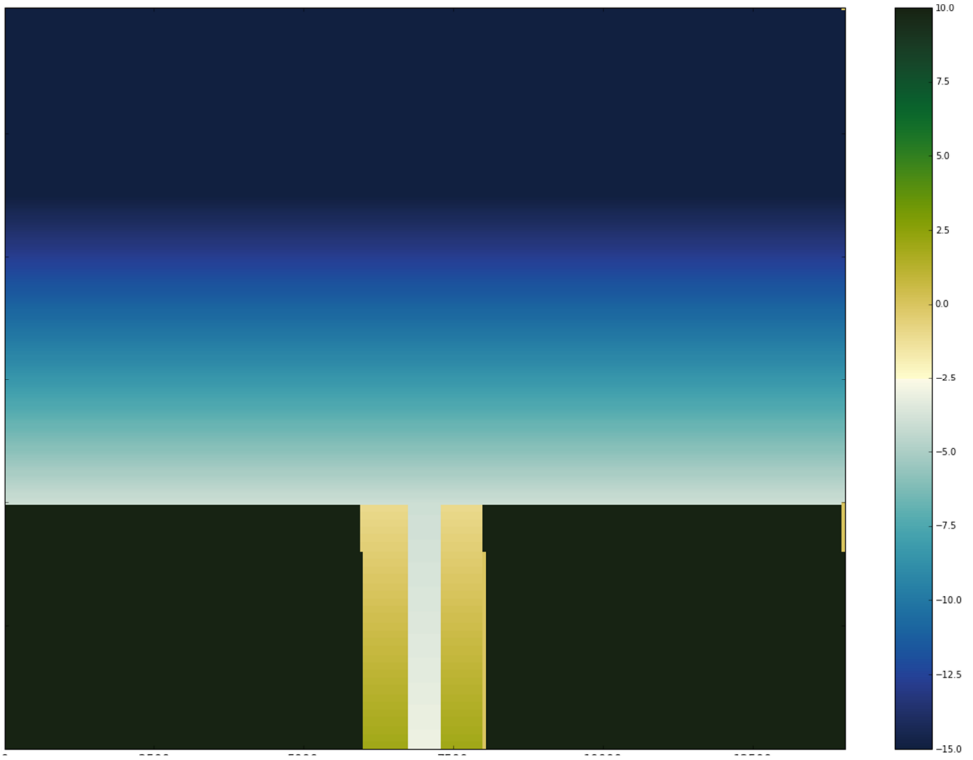

Figure 32: Initial bathymetry at the start of the simulation.

I.2.2 HYDRODYNAMIC CONDITIONS

The dataset was designed to study the effect of a variation in sediment grain size composition on depositional patterns. To this end, the hydrodynamic conditions are assigned for the efficient delivery of sediment from the fluvial domain to the basin. Limited post-deposition reworking of sediment by wave and tidal forces was added, to preserve the impact of the fluvial supply signal while still stimulating a level of natural motion within the system.

The fluvial supply to the basin was assigned as discharge with a sediment concentration at the channel boundary. The fluvial supply of each simulation is constant over time. It is difficult to select the most appropriate discharge for the simulations, as the river discharge in natural systems varies on a range of time scales form hourly to millennial and even longer. In a study of 51 modern river systems, the median fluvial discharge was recorded to be 1890 $m^3.s^{-1}$ (Syvitski et al., 2005). However, values in their dataset vary between 198,676 $m^3.s^{-1}$ in the Amazon river (Brazil) to 41 $m^3.s^{-1}$ in the Waipaoa (New Zealand). In the simulations the coarse sand system received a larger discharge in order to move the larger grains to the basin within the simulation time. However, a large discharge in the very fine sand delta flushes the finer grain size classes out of the system without any

deposition. For this reason, the fluvial boundary was assigned such that the models with coarser grain sizes had larger discharges (see Table 5).

Table 5: Fluvial discharge for simulations in this dataset

Simulation	**Discharge ($m^3.s^{-1}$)**
Coarse sand delta	1800
Medium sand delta	1600
Fine sand delta	1400
Very fine sand delta	1250

A semi-diurnal tide with an amplitude of 1m was assigned the by harmonic variation of the water level boundary condition at the distal basin boundary. Small waves were added, with 0.2m amplitude and period of $3m.s^{-1}$, approaching perpendicular to the initial coastline.

I.2.3 SEDIMENT SUPPLY

In order for supplied sediment to be displaced within the system, a sediment transport equation needs to assigned. In Delft3D, cohesive sediment (mud) uses a pre-defined formulation (Galappatti, 1983). Non-cohesive sand transport can be defined by a range of formulations (Deltares, 2014). Past simulations of delta deposits have used both the default van Rijn formula (Caldwell and Edmonds, 2014; Canestrelli et al., 2014; Esposito et al., 2013) or the Engelund-Hansen formulation (Geleynse et al., 2010; Li et al., 2017; Storms et al., 2007; van der Vegt et al., 2016). In our deltaic settings, the van Rijn formula tends to produce channel shapes with sharp 90 degree angles more frequently that is commonly observed in natural systems. In addition, simulations using the Engelund-Hansen formula calculate much faster than those using the more sophisticated van Rijn formulation.

To obtain gradual variations in grain size profiles within the deposits, multiple sediment fractions has to be defined in the supply, including at least one cohesive mud fraction and one non-cohesive sand fraction. When there is a large difference between grain size fractions, the settling velocities of the sediment are so different that there is very little overlap in their preferred regions of deposition. This was avoided by assigning multiple sediment classes with small subsequent changes in sediment properties.

We have chosen to assign sediment grain size fractions based on the Wentworth scale, frequently used in geological studies. The limiting factor in the number of sediment fractions remains the calculation time, which increases significantly with increasing number of sediment fractions, especially non-cohesive sand fractions. Each simulations in our dataset is supplied with a concentration comprising of 6 separate sediment grain size classes (Figure 33).

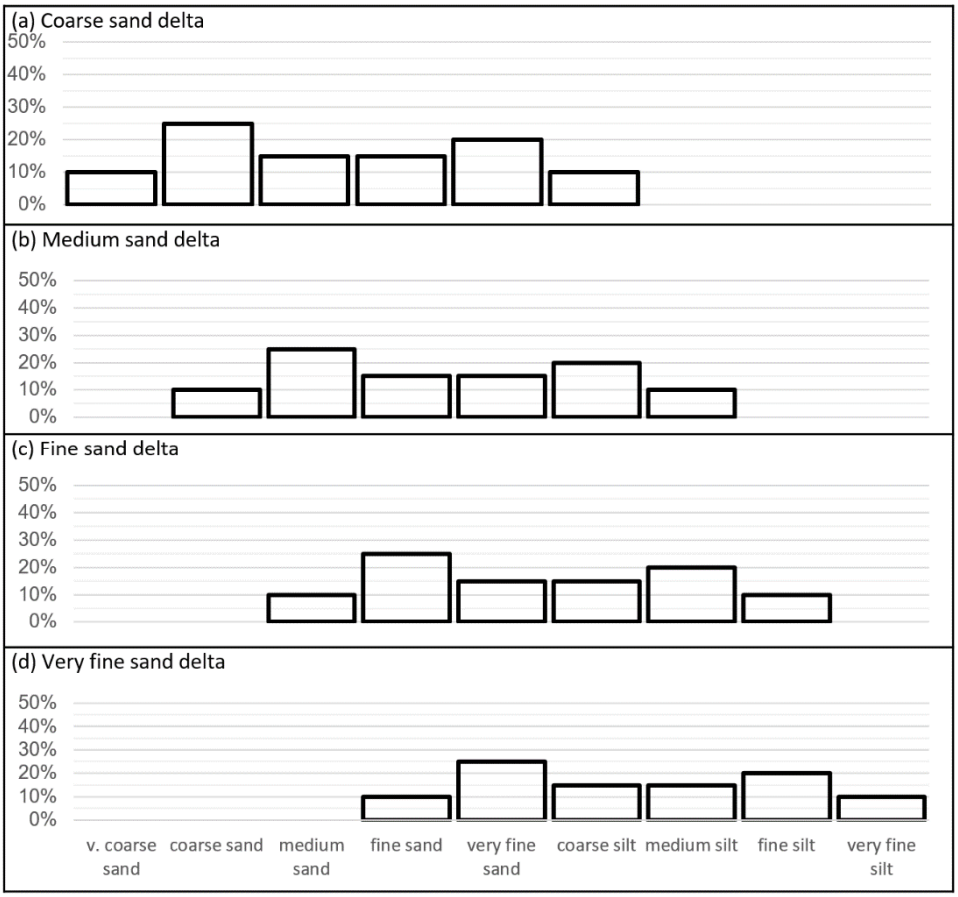

Figure 33: Percentage of each grain size class comprising the sediment supply to the 4 deltas in the dataset

I.2.4 TIME

There are three times associated with each simulations: calculation time, hydrodynamic time and represented time (Li et al., 2017).

I.2.4.1 CALCULATION TIME

The calculation time represents the time is takes from when the user switches on the simulation to when the simulation has finished executing. This time strongly depends on the hardware used to conduct a simulation, whether calculations were performed in parallel or not and on the complexity of the computations. In the case of the current dataset simulations were all conducted on the same server and were not conducted in parallel. While parallel computation is possible in Delft3D we were advised that in the

version we were using work was still underway on parallel computing for the wave module integration. Our simulations varied in running time from 18 days for the very fine sand delta to 28 days for the coarse sand delta. One of the most computationally costly aspects of the simulations is the non-cohesive sediment transport (sand classes). Therefore models with more cohesive sediment (silt sized) classes are executed faster than sand-rich systems.

I.2.4.2 HYDRODYNAMIC TIME

The hydrodynamic (flow) module simulates a user-defined amount of time, where an initial and final date is prescribed. Wave, tidal and fluvial boundary conditions are prescribed to conform to this timeframe. In the case of our simulations this was 320 days.

I.2.4.3 REPRESENTED TIME

Two methods are used in order to scale-up the depositional time represented by the final deposits. Firstly a morphological scaling factor of 30 was applied (Ranasinghe et al., 2011). This means that 1 hydrodynamic year represents 30 years of deposition and erosion. In addition, the fluvial input is kept at a constant, high level representing bankfull discharge. This is when the most sediment is expected to be delivered to the basin. However, in natural systems fluvial supply typically varies over the course of a day, year decade or longer. Considering the volume of deltaic deposition the represented time is expected to be in the order of century to millennial scale (Li et al., 2017). When simulations are used to investigate the behaviour of a specific, modern or ancient delta, this time frame can, and should, be more closely investigated and calibrated.

I.2.5 SIMULATION INPUT FILES

The simulation input consists of an ensemble of text files describing various aspects of the simulation. For the “coarse sand” simulation these files are:

- The grid and initial bathymetry (a.enc, a.grd, a.dep).
- Description of the sediment properties and transport (coarse-sand.sed, md-tran.tr1, md-tran.tr2, md-tran.tr3, md-tran.tr4, md-tran.tr5).
- The hydrodynamic and sediment concentration boundary conditions (a.bcc, a.bch, a.bct, a.bnd).
- Location of observation points at which the history file is recorded (a.obs).
- The interaction between the sediment transported in the hydrodynamic layer and the underlying stratigraphy. (.mor, morlyr.ini).
- Files describing the wave simulations in the SWAN module (wave.enc, wave.grd, wave.dep, wave.mdw).

- The main Delft3D-Flow simulation file which refers to all the other simulations input files (coarse-sand.mdf).

For the other simulations in this dataset, all files entitled “coarse-sand.*” are named to correspond with the name of the simulation.

I.2.6 SIMULATION OUTPUT FILE

The main output file from each simulation trim-*.nc, a NETCDF4 file containing all stored output parameters at intervals defined by the user in the .mdf file prior to simulation. This well-established file format allows any the storage of a diverse range of output parameters, including their descriptions and can be queried in most widely used programming languages (e.g. matlab, Python etc.).

I.3 DATA POST-PROCESSING

The direct output is useful for Delft3D experts to gain a detailed understanding of the exact dynamics in the simulated system. However we aim to use the simulation output within a geological context, and therefore a level of data post-processing was conducted on the data to make the translation from simulation output to descriptions frequently used by geologists. To this end, our post-processing identifies the active channel network, describes delta architecture and analyses grain size distributions within the delta deposits.

I.3.1 CHANNEL IDENTIFICATION

Syvitski (2005) described the distributary channel network as the most important factor controlling the three dimensional shape of a delta. The distributary channel network acts as the conduit through which sediment is delivered to the entire delta area. When channel networks in modern systems are identified from satellite images or channel networks in experimental studies are identified using LIDAR scans, the focus typically lies on channels as geomorphic features. However, the presence of a geomorphic channel feature does not automatically imply that the channel is an important sediment delivery conduit at that time. A large geomorphic channel feature may represent an abandoned channel which is in the process of being infilled after a major avulsion. In geological studies of ancient systems the definition becomes even more complex, as limited subsurface or outcrop data means that channel features are often not identified and when they are their dimensions can be poorly constrained. Gibling (2006) provides an extensive review of channel dimensions including width-to-depth ratios. Geologists often view channels as elements forming part of channel belts of valley infill rather than individual channel features. Channels are often not well preserved in the geological record as individual elements at geological timescales, as younger channels may incise into older, underlying channels.

A geomorphic definition of channel features can identify large bed gradients across the system which are then associated with the channel network. However in a delta environment large gradients are also found at the proximal delta front, especially in the

presence of waves. Therefore a solely geomorphic definition makes it is difficult to separate the channel network from the delta front.

In this dataset we build on the approach of previous modelling studies linking the presence of an active channel to the water depth and flow velocity of an individual cell (Tejedor et al., 2016; van der Vegt et al., 2016). The Engelund-Hansen transport formula, used in building this dataset, relates sediment transport rate to flow velocity. Therefore we did not include transport rate as a separate condition for active channel definition.

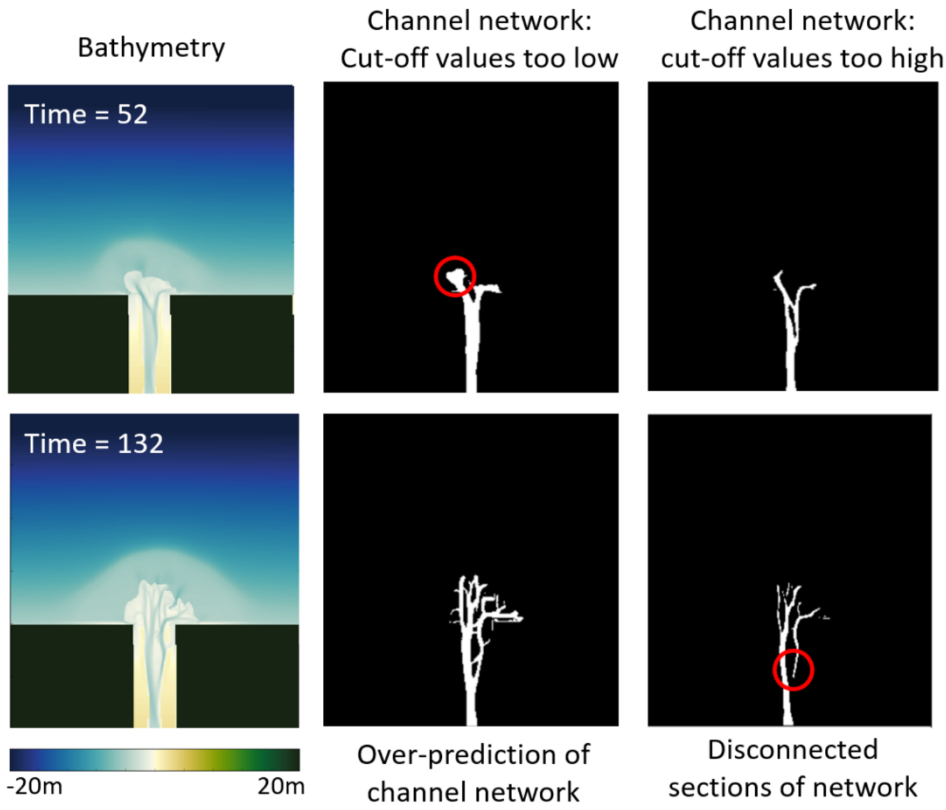

Figure 34: Channel network cut-off values need to be selected to minimise both over-prediction of the network as well as limiting the formation of isolated channel network fragments

This channel identification method requires a cut-off velocity to distinguish between channel and non-channel elements. However, flow velocities within a channel network are not uniform. As channels bifurcate, meander, avulse and become abandoned over time, a range of widths and velocities are present simultaneously. In addition, flow velocities in the channels can also be influenced by marine reworking forces as well as discharge variations which can amplify of retard flow. These complex interactions cause the response to forcing parameters to differ temporally and spatially (Syvitski et al., 2005). This variation complicates the selection of an appropriate cut-off velocity. If the value is too low, part of the decelerating sediment plume is also included in channel network,

while it should instead form part of mouth bar or in some cases even distal delta front deposition. If the cut-off value is too large, some of the lower velocity, wider sections of the channel network will not be included, causing parts of the channel network to be disconnected from the delta apex (Figure 34).

The identification procedure used in this dataset employed custom cut-off velocities for each delta by visually inspecting to what degree the identified channel network matches with the evolution of the delta morphology.

Two cut-off values were selected for each simulation:

(1) New channel element: A cut off value was selected above which a previously non-channel element will be included in the channel network

(2) Existing channel element: A second, slightly lower value was selected above which an existing active channel network element remains part of the channel network.

Simulation output occurs at distinct, pre-defined intervals, which do not necessarily have to coincide with incidences of channel migration. Therefore the instantaneous velocity at the output interval is not a good indicator for the presence of an active channel, especially channels at the smaller, short lived end of the spectrum. We inspected the results for instantaneous velocity, but also for maximum, minimum and mean velocity (calculated over each output interval). The maximum flow velocity measured within each output interval was selected for the calculation. The values are provided in Table 6.

Table 6: Velocity cut-off values for active channel network identification

Model	**Cut-off velocity new channel ($m.s^{-1}$)**	**Cut-off velocity old channel ($m.s^{-1}$)**
Coarse sand delta	1.19	0.95
Medium sand delta	1.14	0.9
Fine sand delta	0.98	0.8
Very fine sand delta	0.72	0.62

More complex mathematical or statistical algorithms may provide better address the channel identification procedure. However, the aim of this work was to analyse architectural elements and active channel network is only part of the procedure. We therefore also recommend that a future, more detailed study is conducted focussed specifically on the identification of active channel network elements.

I.3.2 SUB-ENVIRONMENTS AND ARCHITECTURAL ELEMENTS

Deposition in coastal to continental slope settings consist of multiple scales of clinoforms architectures (Patruno et al., 2015). The simulations in this dataset reproduce three deltaic sub-environments: delta top, delta front, and prodelta. Figure 35 shows how the simulated delta environments fit into these scales. We further subdivided these environments into architectural elements (the sandy bodies which form the building blocks of the delta deposition) and the remaining background sedimentation (Miall, 1988). The most important sandy deposits in deltaic environments are channel accretion deposits and the distributary mouth bars. An overview of the subdivision of deltaic deposits into sub-environments and architectural elements is provided in Table 7.

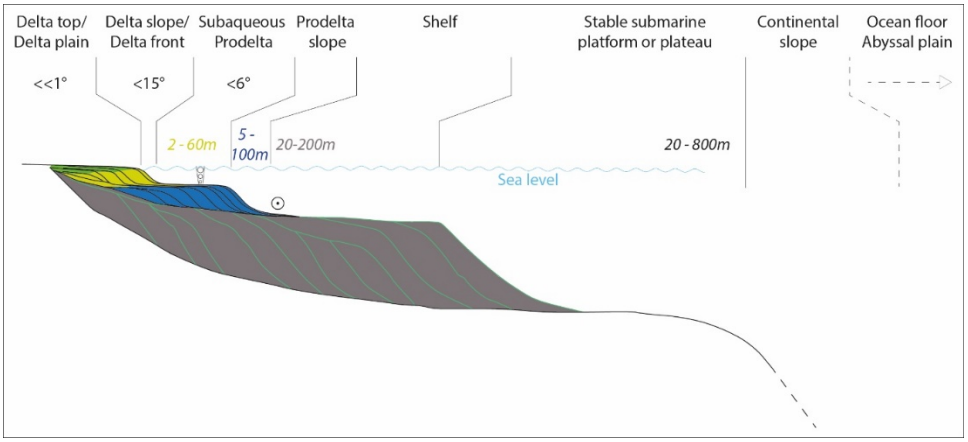

Figure 35: Compound clinoforms from shallow marine to deep sea environment. Our dataset classifies deposits based on the delta top, delta front and prodelta sub-environments. Figure adapted from Patruno et. al. (2015).

To determine the approximate shape of the delta clinoforms, a representative cross section is constructed. First the bathymetry for each time interval is mapped to polar coordinates centred at the delta apex. Then the active channel elements are removed for calculation purposes. Radial cross sections starting from the delta apex are averaged to provide a representative delta clinoform shape. These topographic lines are used to obtain the representative delta brink for each time interval, the value which represents the break between delta top and delta front.

A number of cut-off values are defined. Firstly the pro delta is defined to start below a water depth of 5m. Secondly the delta front deposits can only deposit down to 10m water depth. Also, cells which have not received at least 15mm deposition in one output time interval are defined as inactive/low deposition.

The sub-environment definition starts with the definition of the delta top. Deposition within the active channel network is defined delta top. Once a channel is no longer active, deposition at its location is still defined as delta top until the brink point depth is reached. Any deposition above the brink point depth is defined as delta top deposition. In addition,

any cell that is 0.5m below the brink point, was defined as delta top in the previous time interval and contains at least 1% sand is also defined as delta top.

Sediment above the delta front limit that contains at least 1% sand is defined as delta front. Of the remaining cells, which are not defined as "inactive", anything above the prodelta cut-off depth is defined as delta front; everything below the prodelta cut-off depth is defined as prodelta.

Table 7: An overview of the sediment subdivision into delta sub-environments and architectural elements

Sub-environment	**Architectural element**	**Definition**
Delta top	Channel accretion	• Lateral accretion: sediment stored as lateral bars as channels migrate. • Vertical accretion: Generally coarse sediment stored at the channel base in locations where bed load is over-supplied compared to the amount of bedload which can be transported further along the channel
	Channel fill	• Fining upwards sediment which fills channels as they become inactive
	Overbank/ background	• Overbank deposition and background sedimentation which depositing in locations between the active distributary channels
Delta front	Mouth bar	• Sandy sediment deposited where sediment-laden jet exits channel mouth, spreads upon reaching the basin and decelerate.
	Background	• Lobate deposits travelling further from the channel mouths than the mouth bar sands • Background sediment deposited as basinal processes (e.g. waves) rework the exiting deposits
Prodelta	Prodelta	• Fine sediment eroded and transported by basinal processes and deposited below the fair weather wave base. • Here deposits are only defined as prodelta once 15mm of deposition has occurred at that location.

The delta top deposits were divided into channel accretion, channel fill and background overbank deposition. Channel accretion deposits include both the lateral accretion deposited as the channels migrate to the side, as well as vertical accretion at the channel base. The channel fill deposits are defined as deposits within previously active channels until it reaches the delta brink. Overbank deposition is the remainder of the delta top

deposition. In literature, levee deposits are often assigned separately at the delta top (Reading and Collinson, 1986), but this is not yet feasible in the current simulations. Within this dataset we are not able to discretely separate levee deposition compared to other overbank deposition, especially in settings with many active channels and frequent avulsion. In the case of smaller channel bodies, the levee deposits may also be narrower than the 50mx50m element size. In the simulations described in this dataset, the morphology does not show clearly identifiable levee deposits, however previous simulations with shallow basins showed clear levee morphology (Storms et al., 2007). Further development of the simulation space and post-processing is required to clearly isolate levee deposits from the delta top overbank deposition.

The delta front is divided into mouth bars and background sedimentation. Mouth bar deposition is dependent on the proximity of a distributary mouth delivering a sediment laden plume to the delta front. For this purpose mouth bar deposits were defined as delta front deposition within four cells (200m) from the active channel network. In addition a critical rate of deposition for mouth bars is defined to be 30cm of sediment deposition per hydrodynamic day. The remainder of the delta front deposition is defined to be background sedimentation. The prodelta deposition is not subdivided.

The accuracy with which channel and mouth bar sands are isolated is highly depended on the accuracy with which the active channel network was identified. This shows the importance of further improvement of the channel identification scripts. So while this definition is not perfect, it is consistent between simulations. This enables comparison between results from different simulations in a dataset. The definitions of architectural environments may have to be adjusted for datasets of different simulations, but definitions presented here serve an a starting point for further development of these post-processing tools.

I.3.3 SEDIMENT GRAIN-SIZE DISTRIBUTIONS

Each simulation has distinct, predefined grain size classes assigned. These grain size classes are not only used to define the sediment input at the fluvial boundary, but also form the framework for recording sediment deposition at each element across the simulated domain. At each output time interval we record the sediment flux of each grain size class at each element. This allows the construction of a detailed stratigraphy with the deposited sediment composition. For each element and time interval statistical calculations were performed on the deposited/eroded/preserved sediment. These calculations can also be grouped for all sediment deposited in a specific architectural element or sub-environment classification, allowing us to calculate their characteristic sediment properties e.g. per sub-environment or architectural element.

To calculate the D50 value at each location for each time interval, the grain size weight deposited provided by Delft3D is transformed into volume fraction data using the user pre-defined density for each sediment class. The grain size values are converted into the logarithmic phi scale ranging from -1 (coarse) to 8 (fine). A sieving curve is constructed to create a cumulative probability function and the phi value at 50% probability is

determined by linear interpolations between the data points. The mm-scale D50 value is then calculated from this phi value.

I.3.4 POST-PROCESSED DATA FILE DESCRIPTION

Two post-processing files are provided: sediment.nc and archel.nc. Like the Delft3D output file, both of the two post-processed files are in NETCDF4 format.

sediment.nc contains three variables:

(1) diameter: D50 calculated as described above
(2) sorting: calculated according to Folk (1966)
(3) fraction: sum of the volume fractions of sand classes at any one location.

archel.nl contains two variables:

(1) sub-environment: classifies the 3D stratigraphy by sub-environment as described above
(2) archel: classifies the 3D stratigraphy by architectural element as described above.

The files provided for this dataset include movie clips of cross section sweeps showing the architectural elements and sediment D50 both parallel and perpendicular to the shoreline.

I.4 DATA APPLICATION AND RE-USE

The simulations have been carefully constructed, based on a detailed literature study, to mimic delta progradation onto shelfs with low slopes. For the first time, we have separated simulated deposits into architectural elements in an automated way. We welcome the sedimentological and modelling community to discuss this classification scheme and suggest future improvements.

The data, as it stands, can already be used to study depositional implications of different sediment supply compositions. This can be done either based on our classifications or by reclassifying the Delft3D output from the simulations according to a different scheme, if required. Access to our data allows the scientific community can benefit from the experience gained over hundreds of test simulations we conducted before settling on this final dataset of stable, representative simulations. The dataset and description of post-processing analyses aims to advance the research field by limiting the repetition of lengthy simulation work.

In addition, the simulations presented here can serve as templates for detailed studies into other aspects of delta deposition and as a starting point for simulations designed to test hypotheses on the depositional processes controlling deposition of existing deltas. The authors welcome opportunities for collaboration on these topics.

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PUBLICATIONS

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