# The Role of Climate Variation in Sequence Stratigraphy: Lessons from Analogue Modelling*

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Search and Discovery Article #41170 (2013)**
Posted August 12, 2013

*Adapted from oral presentation given at AAPG 2013 Annual Convention and Exhibition, Pittsburgh, Pennsylvania, May 19-22, 2013

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## Abstract

Sequence-stratigraphic models for 5th to 6th order, glacio-eustatic sequences based only on relative sea-level variations result in simplified and potentially false interpretations. Glacio-eustatic sea-level variations form only one aspect of cyclic climate variation; other aspects of climate variation (e.g. variations in river run-off) can lead to variable sediment yield, thus adding complexity to sequence stratigraphic patterns normally attributed to sea level variation.

Based on analogue flume models, a significant impact of discharge is observed on the timing and character of sequence boundaries, as well as on changes in the relative importance (sediment volume expression) of systems tracts. Four deltas, generated under influence of an identical sea-level curve, but affected by different discharge cycles are generated in the Eurotank Laboratories: (1) constant discharge; (2) high frequency discharge variations; (3) high discharge leading high sea level by a quarter phase; (4) high discharge lagging high sea level by a quarter phase. High frequency discharge variations show little affect the overall delta architecture and might provide an explanation why 3rd order sequences in seismic generally do not show higher order climatic overprints. When high discharge leads high sea level, sediment delivery is high during sea-level rise, which results in the poor development of maximum flooding surfaces. Delta front erosion during sea-level fall occurs in multiple, small channels and does not result in a single connected, incised valley. In cases that high discharge lags high sea level, sediment delivery is high during falling sea level and results in rapid progradation during forced regression. Erosion from incised valleys is strong on the proximal delta top but dampened distally due to rapid progradation and valley backfill. During sea-level rise, low discharge result in sediment starvation and well-developed maximum flooding surfaces. Because sea level curves are identical in all models, the differences can be fully attributed to discharge variations.

Discharge variations thus provide an alternative explanation to the amplitude of sea-level fall for generating either Type 1 or 2 erosional unconformities. Based on the different responses of sediment yield to the delta apex, an influence of sea-level variations on the fluvial system is also inferred. A case study for scenario high discharge lagging sea level high stand (scenario 4) is presented.

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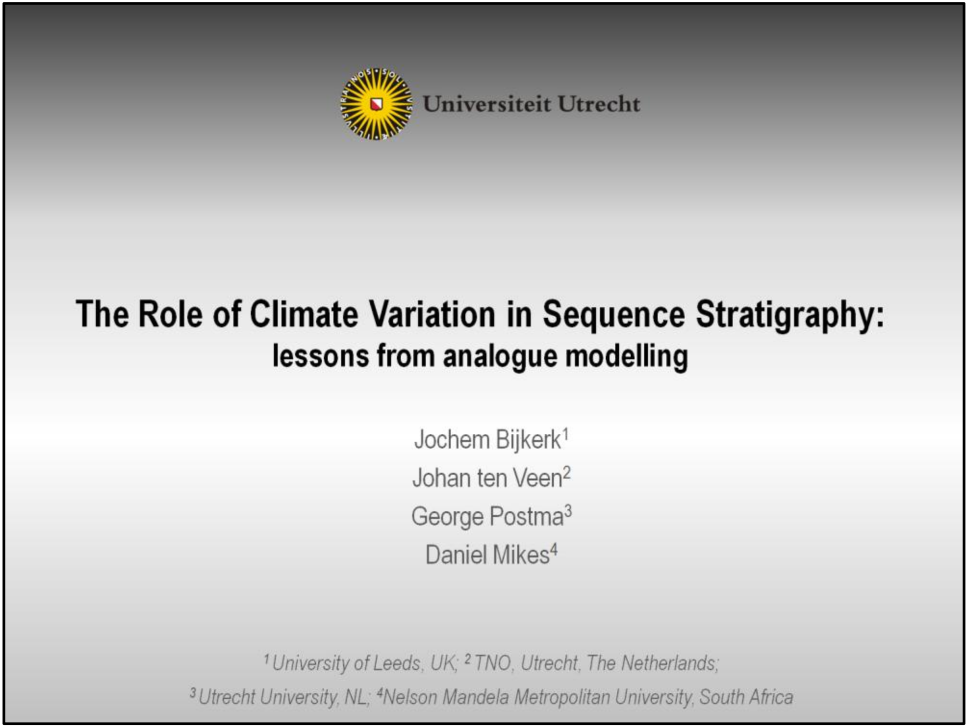

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# The Role of Climate Variation in Sequence Stratigraphy:
## lessons from analogue modelling

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Presenter's notes: Presentation is accepted as article for Basin Research. An early version is currently available (Aug. 2013).
http://onlinelibrary.wiley.com/doi/10.1111/bre.12034/abstract

# Introduction

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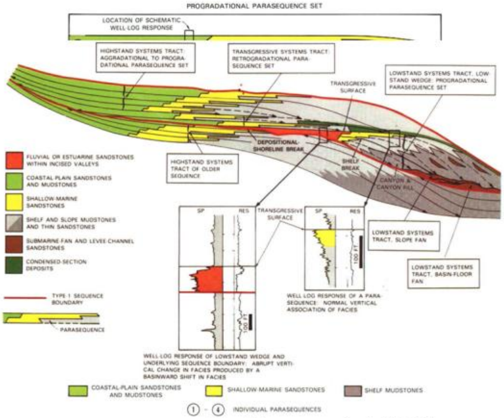
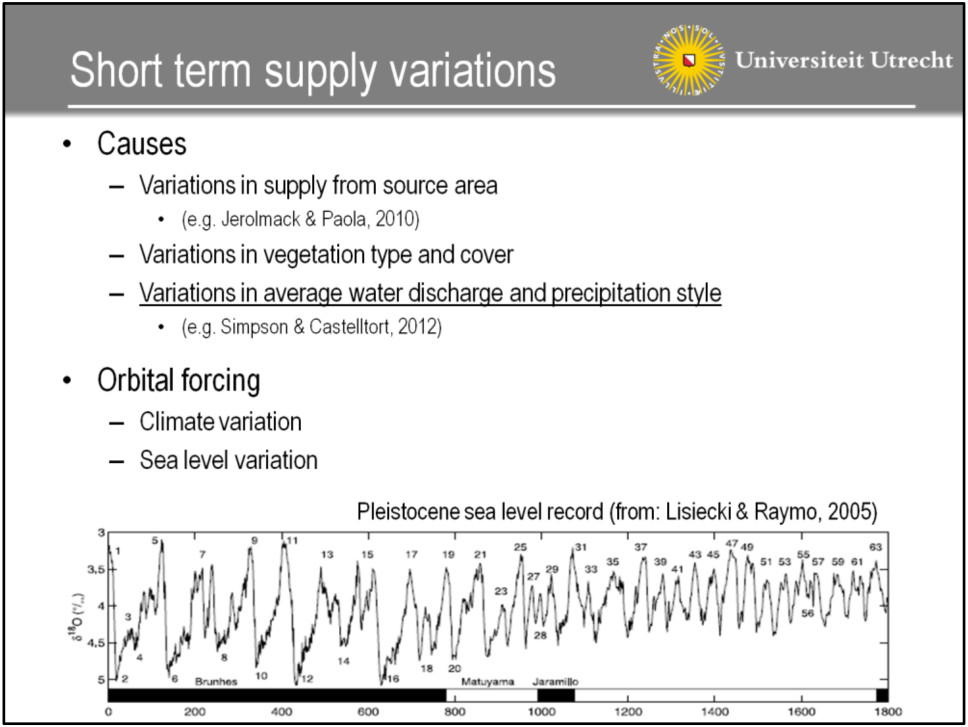
- Sequence stratigraphy
  - A/S ratio
  - A: Accommodation
    - Subsidence
    - Sea level
  - S: Supply
    - Kept constant
    - Short term variability



Van Wagoner *et al*. (1988)

Presenter’s notes: Sequence stratigraphy is largely determined by the ratio between accommodation and sediment supply. General models focus predominantly on accommodation (sea level and tectonics) rather than sediment supply. Most conceptual models keep sediment supply constant. This presentation explores the effect of short term variability on sequence stratigraphy.



# Short term supply variations

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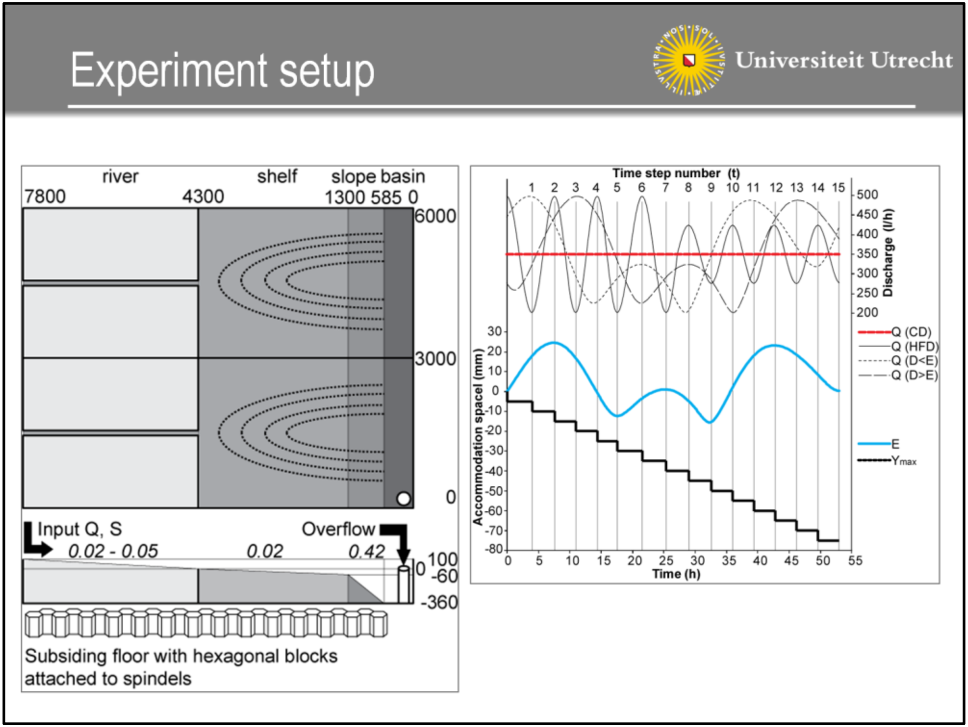
- Causes
  - Variations in supply from source area
    - (e.g. Jerolmack & Paola, 2010)
  - Variations in vegetation type and cover
  - Variations in average water discharge and precipitation style
    - (e.g. Simpson & Castelltort, 2012)
- Orbital forcing
  - Climate variation
  - Sea level variation

Pleistocene sea level record (from: Lisiecki & Raymo, 2005)

Presenter's notes: Short term variations in sediment supply might arise in several ways.

Changing rates in *sediment input* are unlikely. Jerolmack & Paola, 2010 have shown that short term variations are 'shredded' through transport and are unlikely to be recorded in the deltaic domain.

However, the transport system can behave differently over geological time. Vegetation type and cover have a strong effect on river behaviour and change due to changes in climate on Milankovitch timescales. Additionally, mean water discharge and precipitation style (e.g. monsoonal, flashiness) can change on such timescales. Therefore, Milankovitch timescale forcing both influences sea level variation as well as climate variation. Changes are thus expected on similar (100 kyr) timescales. These variations can be modelled in a flume and will be the focus in this



# Experiment setup

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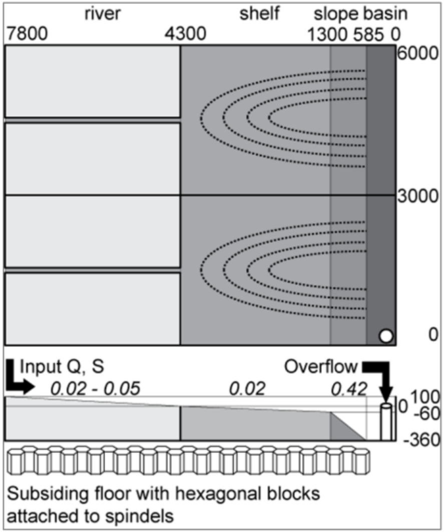
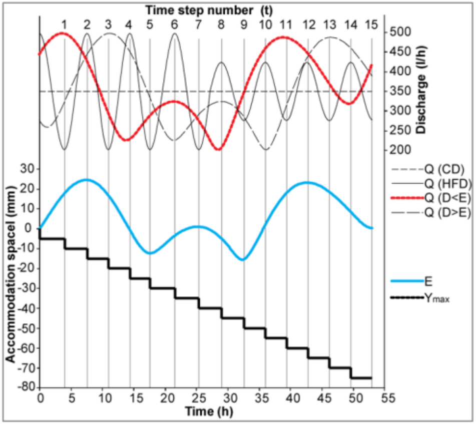
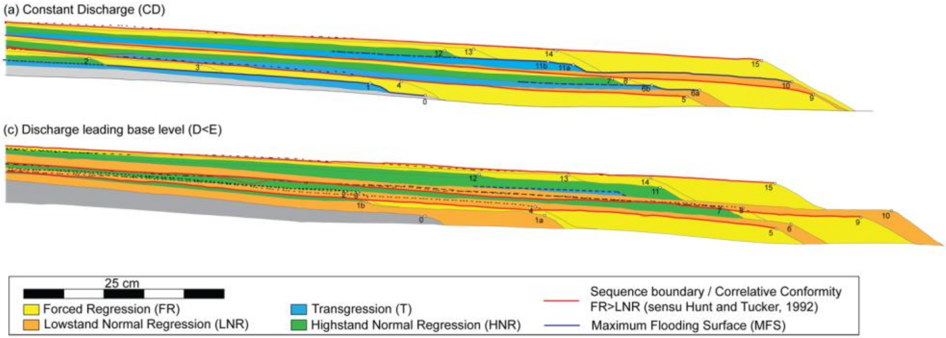
Presenter's notes: Experiment setup: Two flume models are run simultaneously, and four models are run in total. All models have equal sea level and tectonic parameters and equal sediment input (1.65l/h). The only difference between the 4 models is the water discharge curve.

# Experiment setup



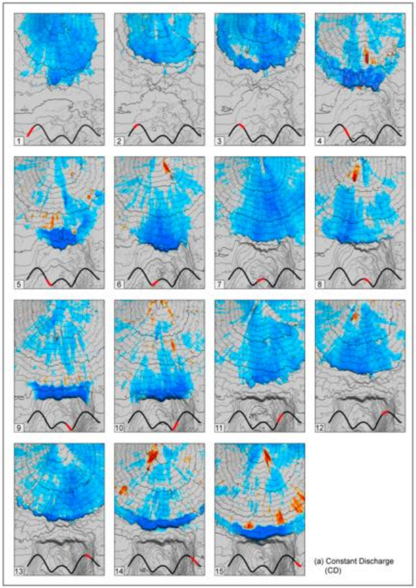


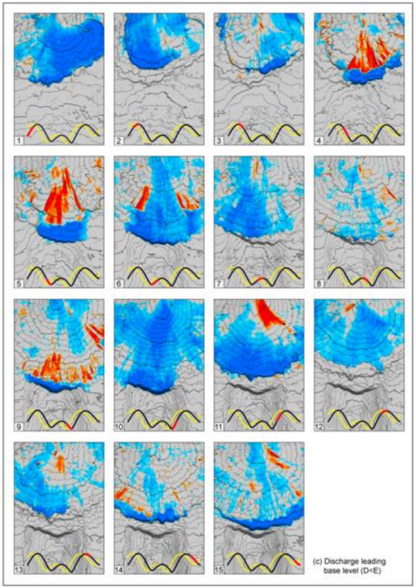
# Constant Discharge & Discharge leading Sea Level



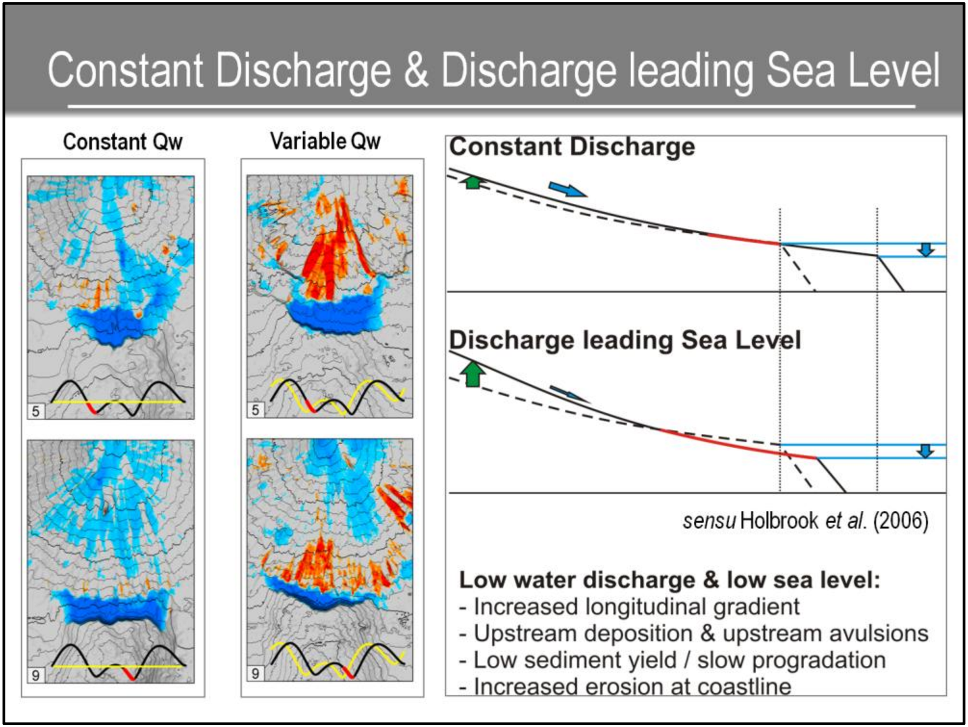
Presenter's notes: Differences in stratigraphic patterns between constant discharge and discharge leading sea level (see slide 7). Note the absence of transgressive deposits and the abundance of LNR and HNR deposits in the latter.

# Constant Discharge & Discharge leading Sea Level





Presenter's notes: Comparison of erosion deposition maps for the same models. Note the overall increase in erosion during sea level fall and the pattern of erosion in small gullies.



## Constant Discharge & Discharge leading Sea Level

Constant Qw

Variable Qw

**Constant Discharge**

**Discharge leading Sea Level**

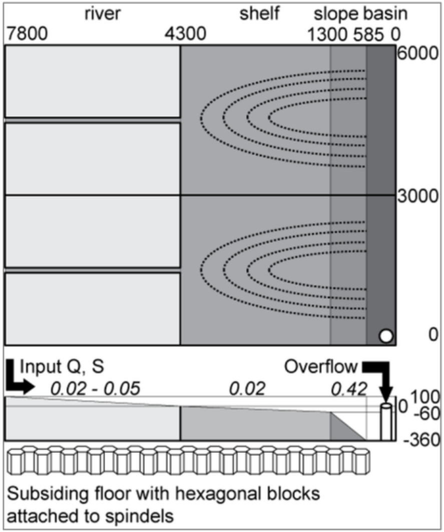
*sensu* Holbrook *et al.* (2006)

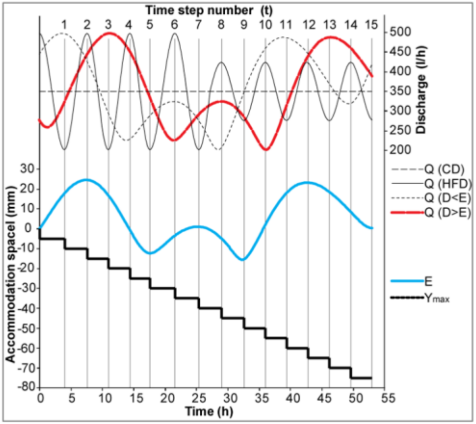
**Low water discharge & low sea level:**

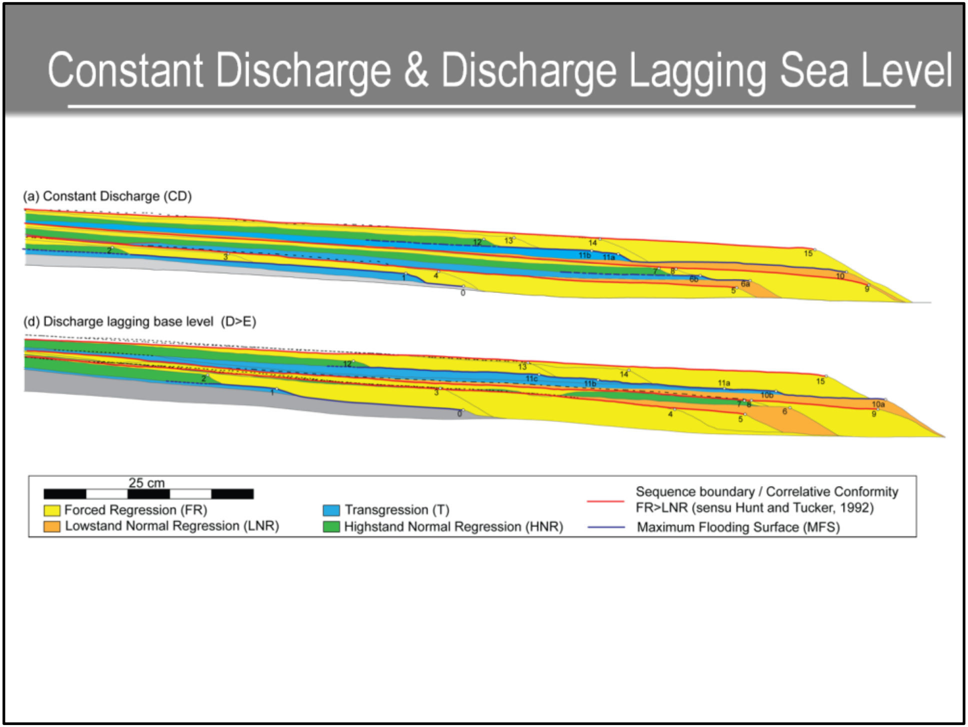
- Increased longitudinal gradient
- Upstream deposition & upstream avulsions
- Low sediment yield / slow progradation
- Increased erosion at coastline

Presenter's notes: Explanation of the erosional style. Lower discharge leads to a steepening of the longitudinal profile. Simultaneously, lower discharge leads to reduced progradation, enhancing erosion of the at the seaward end of the profile. The pattern of erosion in small gullies is related to upstream deposition, resulting in frequent avulsion.

# Experiment setup







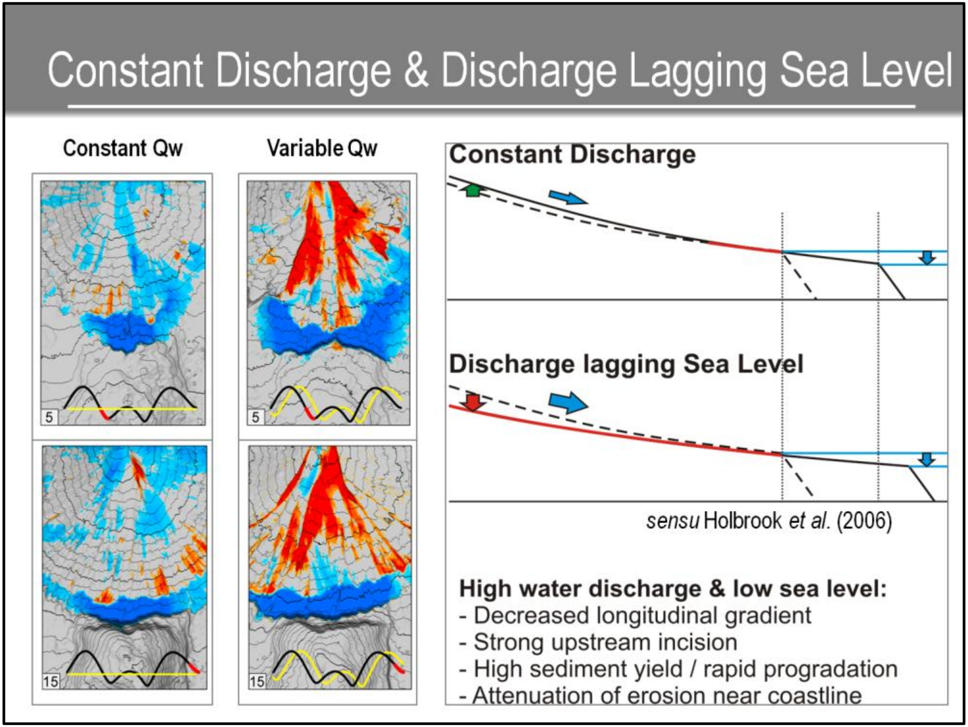
# Constant Discharge & Discharge Lagging Sea Level

(a) Constant Discharge (CD)

(d) Discharge lagging base level (D>E)

🟨 Forced Regression (FR)
🟧 Lowstand Normal Regression (LNR)
🟦 Transgression (T)
🟩 Highstand Normal Regression (HNR)
— Sequence boundary / Correlative Conformity FR>LNR (sensu Hunt and Tucker, 1992)
— Maximum Flooding Surface (MFS)

Presenter's notes: Differences in stratigraphic patterns between constant discharge and discharge lagging sea level (see slide 11). Note the increase is FR deposits and the more significant backstepping during transgression.



# Constant Discharge & Discharge Lagging Sea Level

**Constant Discharge**

**Discharge lagging Sea Level**

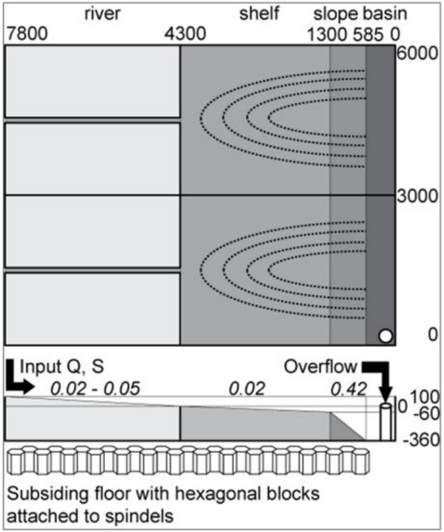
*sensu* Holbrook *et al.* (2006)

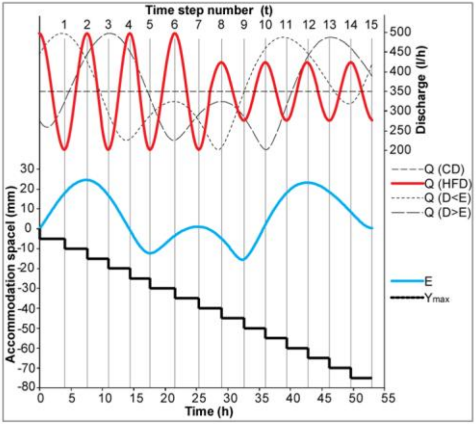
**High water discharge & low sea level:**

- Decreased longitudinal gradient
- Strong upstream incision
- High sediment yield / rapid progradation
- Attenuation of erosion near coastline

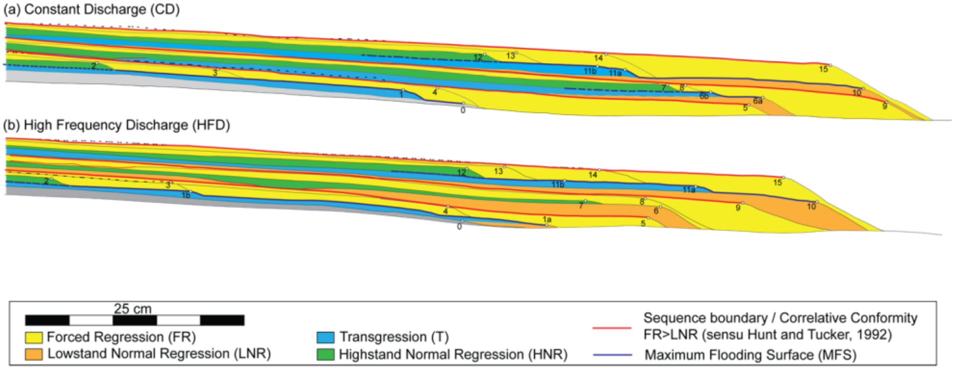
Presenter’s notes: Erosion deposition maps for constant discharge and discharge lagging sea level. Note that erosion is strongest on the proximal topset and dissipates downstream. The specific pattern is related to a lowering of the longitudinal profile due to increased discharge, resulting in proximal incision whereas the high progradation rates result in decreased erosion near the coastline.

# Experiment setup





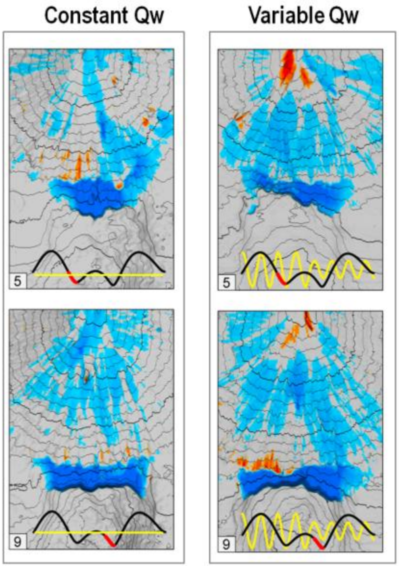
# Constant Discharge & High Frequency Discharge


(a) Constant Discharge (CD)

(b) High Frequency Discharge (HFD)

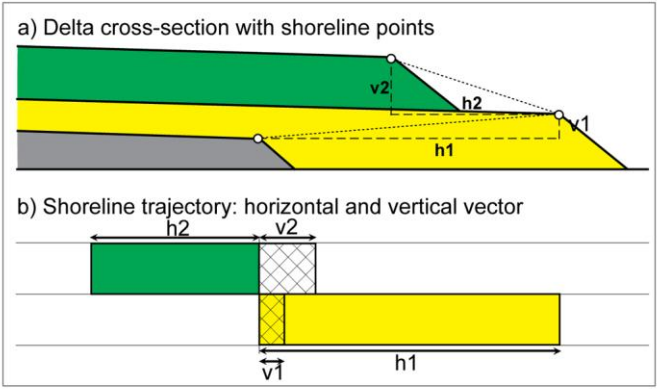
Presenter's notes: Comparison of stratigraphic patterns in constant discharge and high frequency discharge variation. (High frequency discharge variations can be compared to e.g. 20 kyr monsoonal fluctuations on a 100 kyr sea level cycle). Patterns are approximately similar (i.e. not a distinguishing effect).

# Constant Discharge & High Frequency Discharge



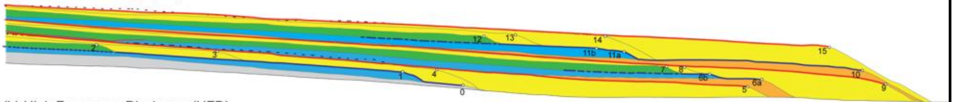
Presenter's notes: Erosion deposition maps for constant discharge and high frequency discharge variation show a strong similarity as well.

# Constant Discharge & High Frequency Discharge


a) Delta cross-section with shoreline points

b) Shoreline trajectory: horizontal and vertical vector

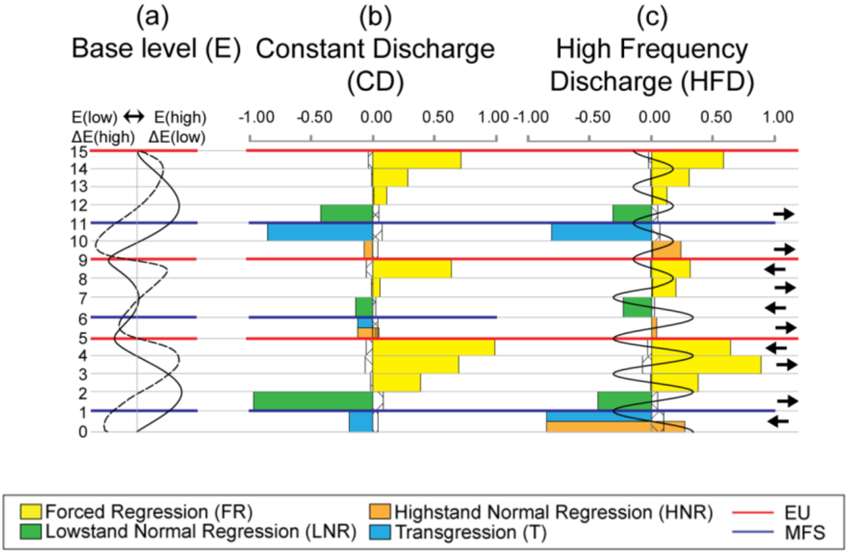
(a) Constant Discharge (CD)



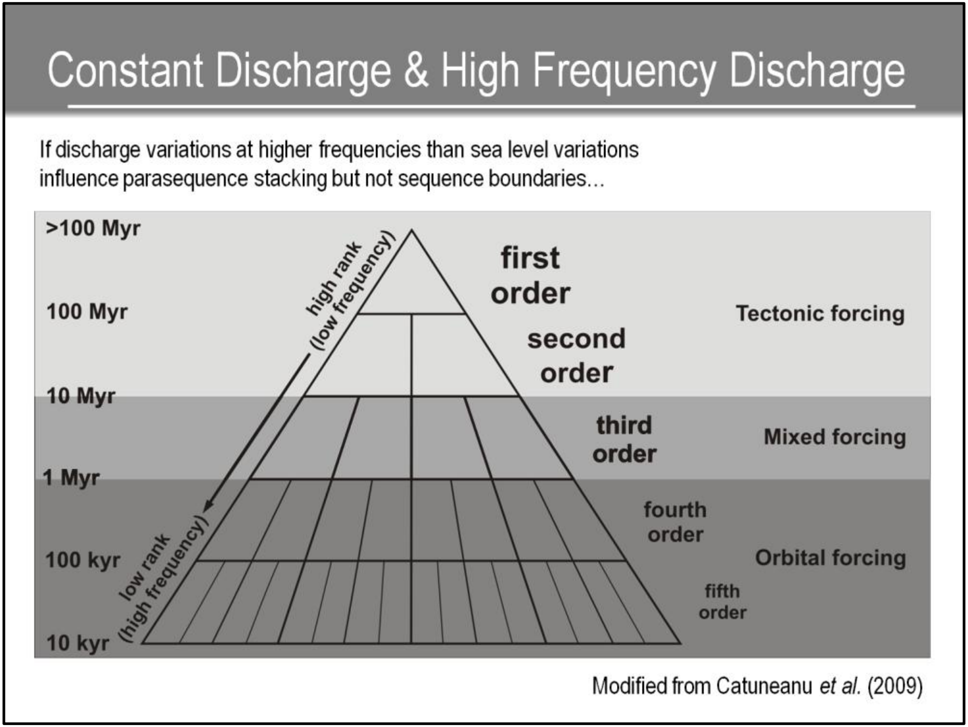
(b) High Frequency Discharge (HFD)

Presenter’s notes: Besides erosion deposition maps and architectural panels measurements are made of the horizontal and vertical migration of the roll-over points to quantify shoreline migration.

# Constant Discharge & High Frequency Discharge



Presenter's notes: Migration of the roll-over point does show a consistent difference between the constant discharge and high frequency discharge variation models. Note that during discharge rise, the coastline progrades further or retrogrades less than during discharge fall (i.e. coastline migration is affected by high frequency discharge variations even though we cannot observe the effect in a regular stratigraphic cross section).



# Constant Discharge & High Frequency Discharge

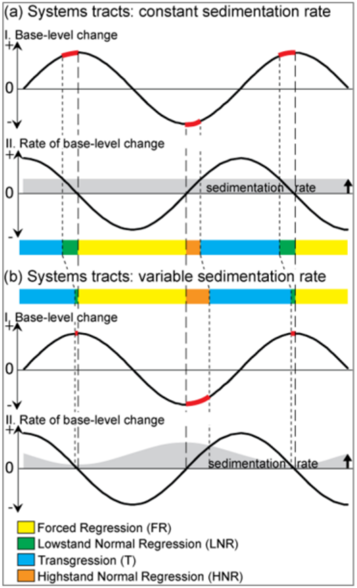
If discharge variations at higher frequencies than sea level variations influence parasequence stacking but not sequence boundaries…

Modified from Catuneanu *et al.* (2009)

Presenter's notes: Can we observe discharge variation in the stratigraphic record that are at higher order than the dominant sea level forcing? These experiments show that when discharge variations occur at the same frequency as sea level variations, they have a strong influence. However, when they occur at higher frequency these effects become more subtle.

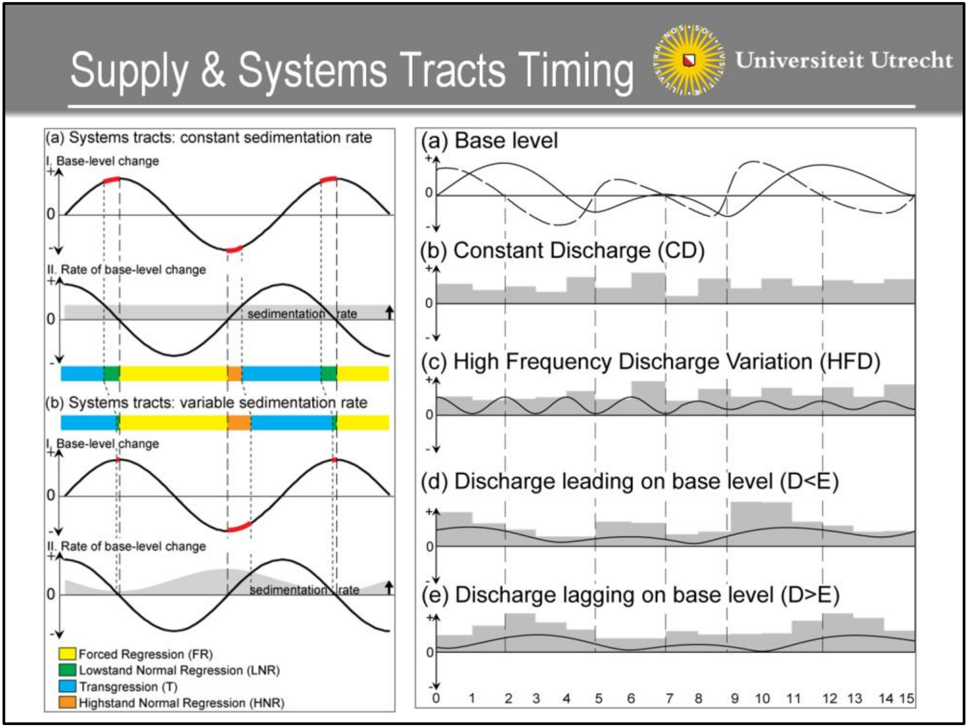
In nature, strong fluctuation in discharge occur on Milankovitch timescales at most (100 kyr) whereas most sea level cycles have longer periods, which suggests that in third and lower order sequences, climate signals might only be present as subtle influences. These influences might be present as slight differences in the parasequence stacking pattern (slide 19) while not affecting the erosion patterns on sequence boundaries (slide 15 &16).

# Supply & Systems Tracts Timing



Modified from: Catuneanu *et al.* (2009)

Presenter's notes: Discharge variations clearly influence the sediment supply to the delta (e.g. slide 8 & 12). Therefore, they can also affect the timing and duration of systems tracts.



# Supply & Systems Tracts Timing

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Presenter's notes: Sediment yield is calculated at the delta apex. The constant (and high frequency discharge) models seem affected by autocyclic variations in sediment yield, that are overprinted when an allocyclic (discharge) forcing is introduced such as when discharge leads or lags sea level variation.

# Supply & Systems Tracts Timing

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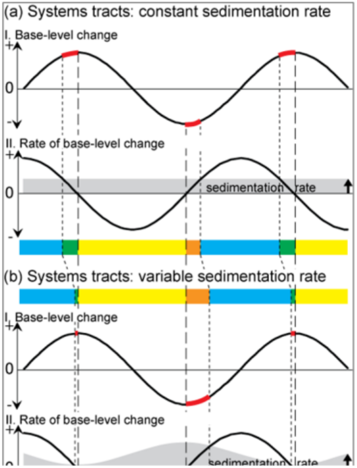
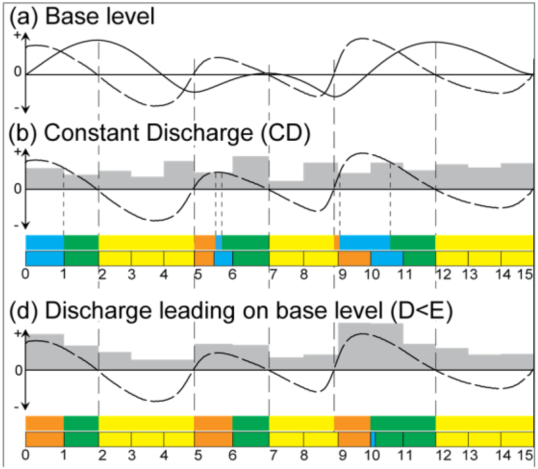
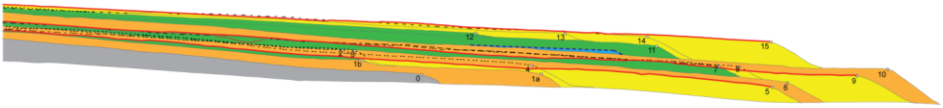




(c) Discharge leading base level (D<E)



Presenter's notes: Calculation of the Accommodation/Supply ratio (slide 4) for the constant discharge model and the model in which discharge leads on sea level. Because supply always outpaces sea level in the latter model, no transgressions are recorded in this model, indicating the importance of discharge variations and their timing.

# Summary

- Sequence stratigraphy: strong focus on accommodation (A/S ratio).
  - In high frequency sequences, supply variations can be expected

- Water discharge variations at higher frequencies than sea-level fluctuations:
  - Do not significantly affect sediment yield
  - Do not significantly alter patterns of Erosional unconformities
  - Result in changes in internal stacking of sequences
  - Potential explanation for lack of clear climate variability in long duration sequences

- Discharge variations at similar timescales as sea-level:
  - Affect sediment yield
  - Affect sequence boundaries by increasing erosion
    - High discharge during sea level fall: Large single incised valleys
    - Low discharge during sea level fall: Erosive braid plain & multiple small incisions
  - Can alter timing of systems tract boundaries

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