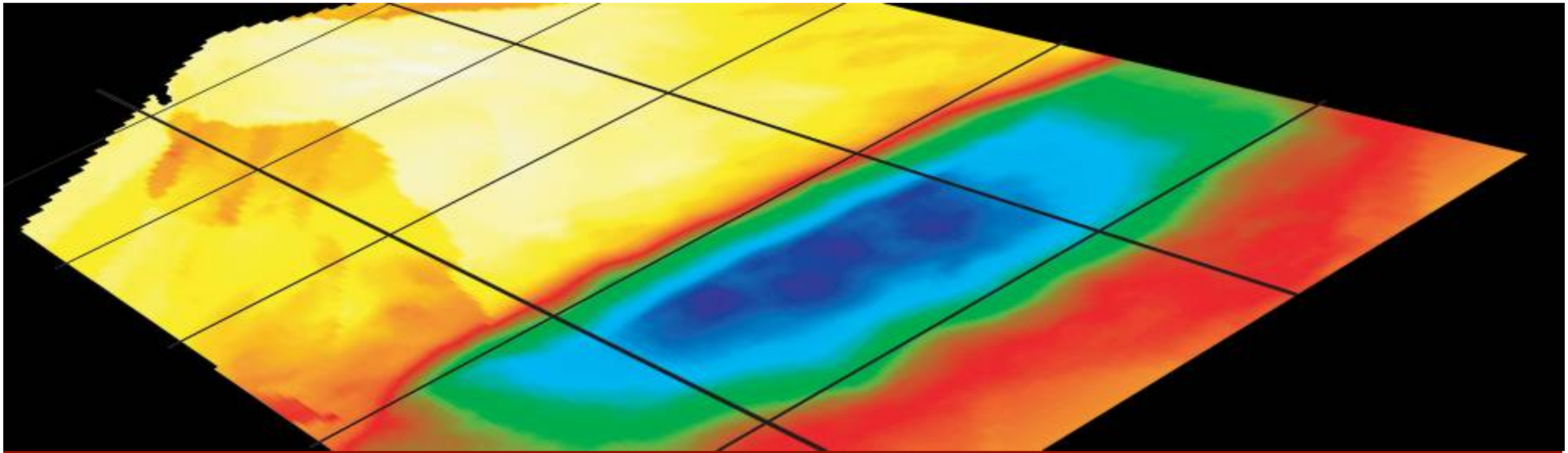


# Experimental results: source to sink

**Source to sink**

**AGU Chapman conference**


***Chris Paola***

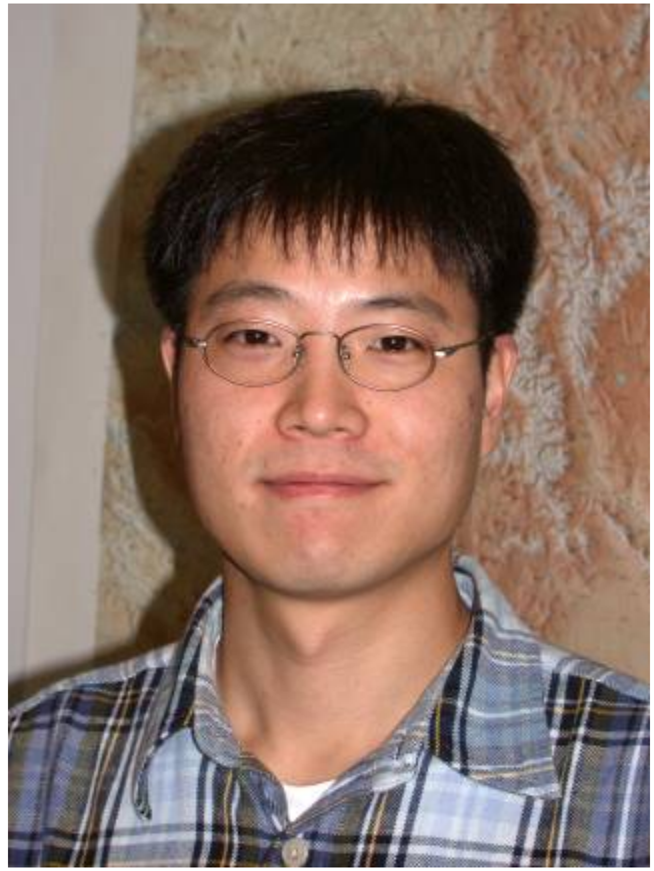
***Quantitative stratigraphy group***

***University of Minnesota***


**SAFL** Saint Anthony Falls Lab

**NCED** National Center for Earth-Surface Dynamics

# Particular thanks to…



John Martin, Exxon Mobil   Wonsuck Kim, UT Austin

# Key ideas

Source-to-sink thinking becomes *increasingly important with increasing time scale*

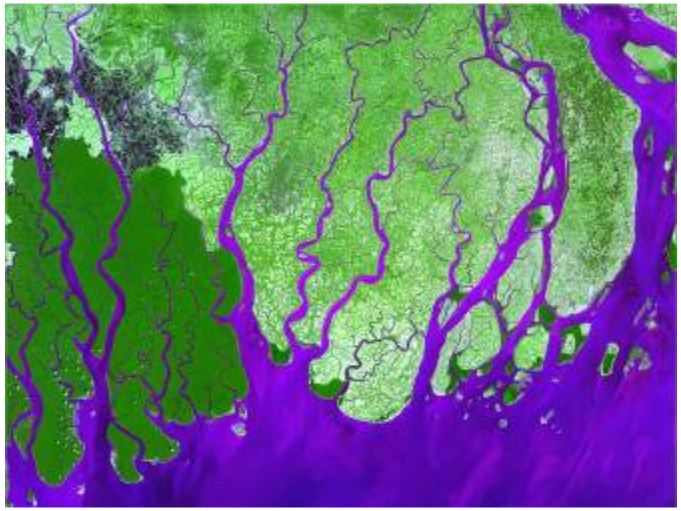
These ideas are readily seen in small-scale experiments because *time scale is directly related to system size*

On source to sink scales sedimentary environments are process domains linked via *moving boundaries*

On source to sink scales, *mass balance* is a first-order control on sedimentary facies

Signal transmission is strongly influenced by *sediment storage & release*

# Depositional steady state

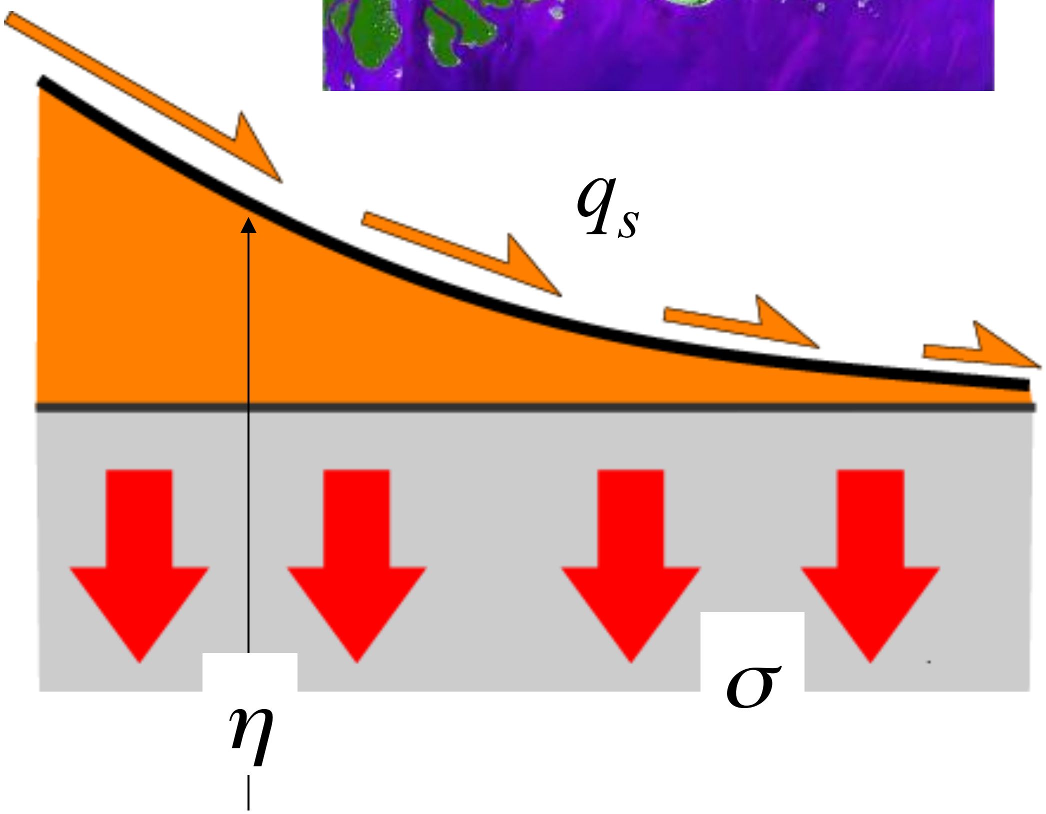


**Steady States**

**Grade: no mass loss or gain**

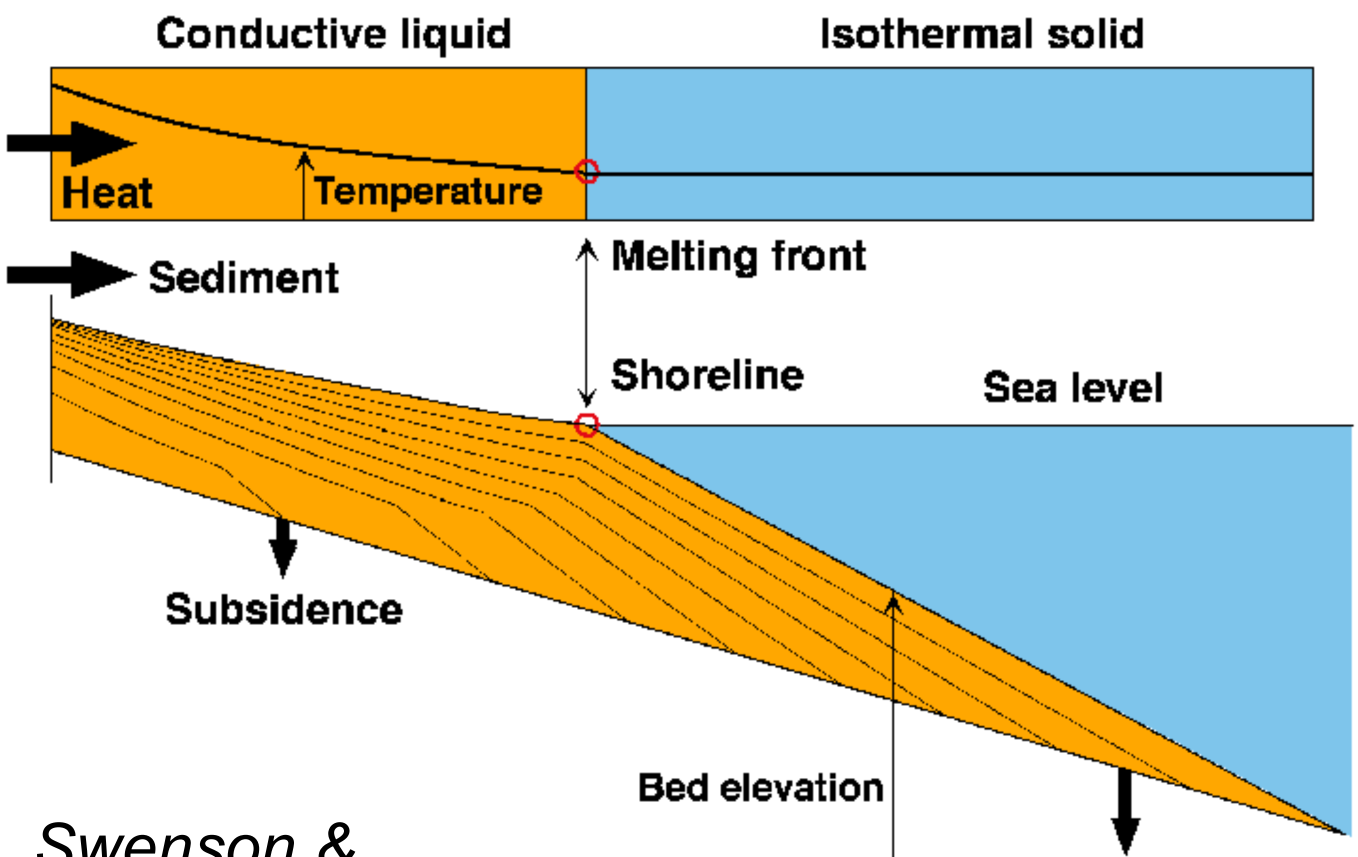
**Erosional: mass gain (erosion) balances uplift**

***Depositional: mass loss (deposition) balances subsidence***




$$\sigma = \frac{-\partial q_s}{\partial x}$$

# Moving boundaries: dynamic process domains linked by internal boundary conditions




*John B. Swenson & Vaughan Voller*

Poster M-28 by Matt Wolinsky has a complete S2S example

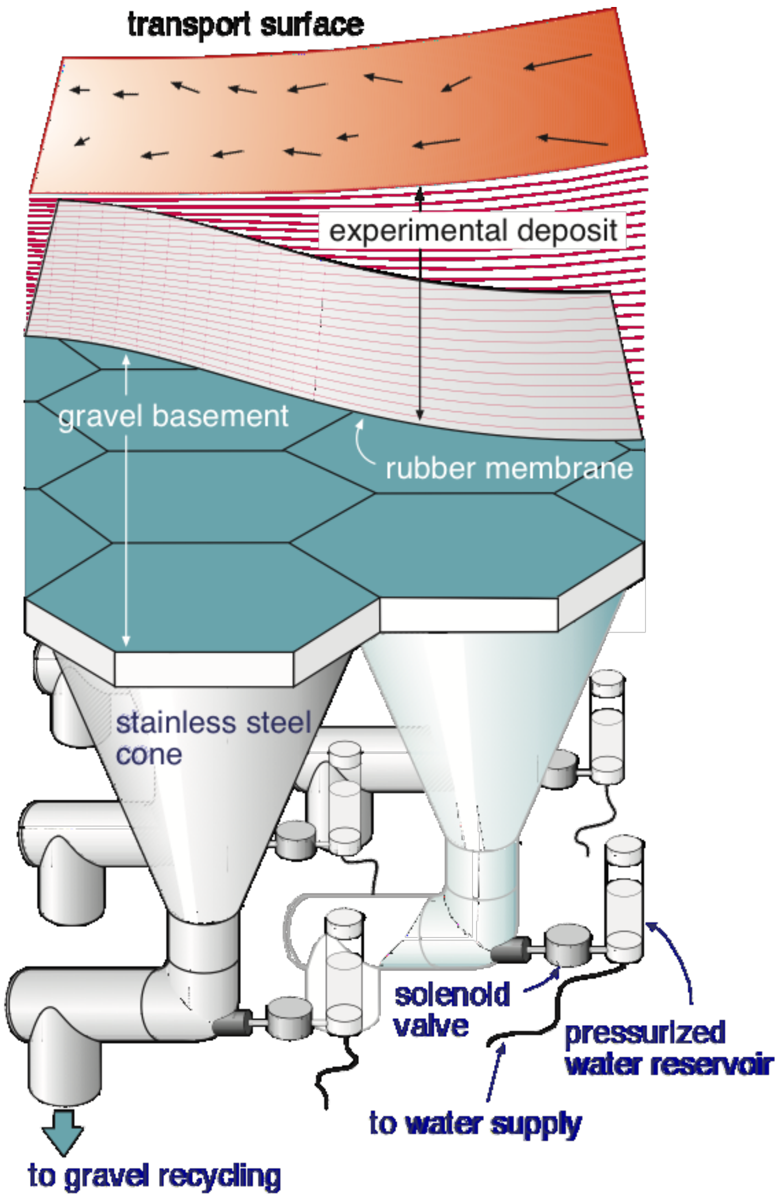
# DO NOT PANIC.

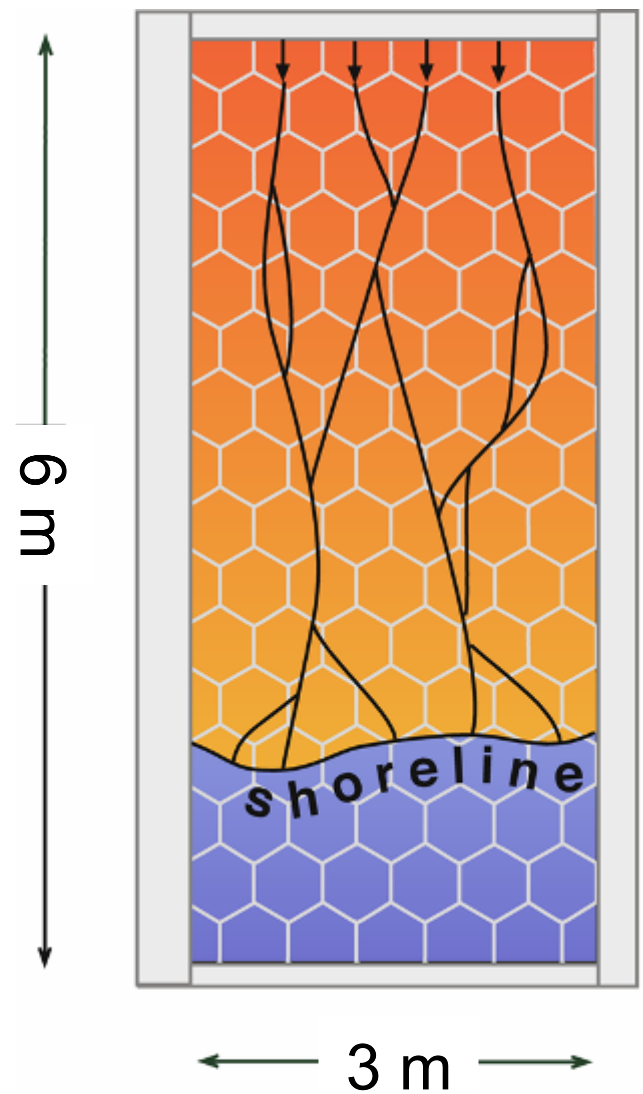
This talk contains images and data from ***laboratory-scale experiments***

These experiments ***are not miniature analogs*** of natural systems

*They are experiments, not models.* Their relevance to field scales comes from scale independence, not classical scaling

# Experimental Earthscape (XES) system



*Time is greatly compressed*

*Subsidence-surface interaction on accessible time scales*

*Sink In a box!*

# Quantifying mass balance: fractional sediment extraction

define a dimensionless distance $\chi$ in terms of mass loss down the depositional system:

*called $A_*$ in earlier papers*

*rate of deposition*

$$\chi(x) = \frac{\int_0^x r_{\Delta T}(x)\,dx}{q_{s0}}$$

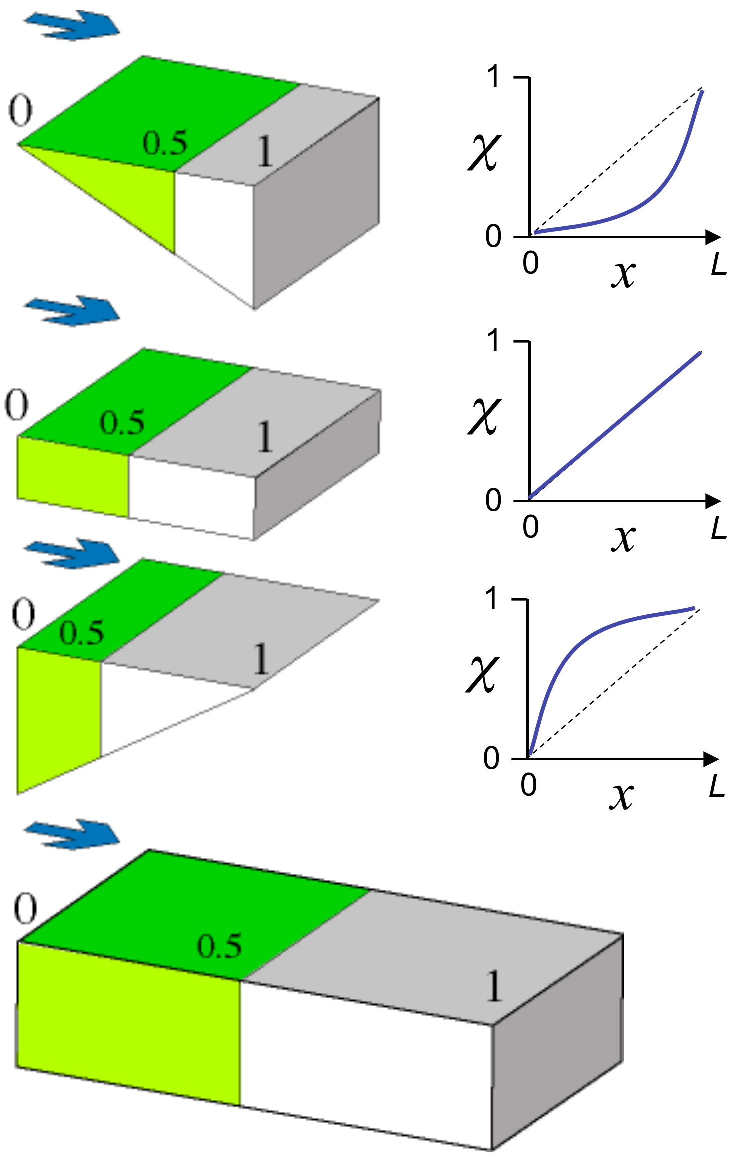
*sediment supply*

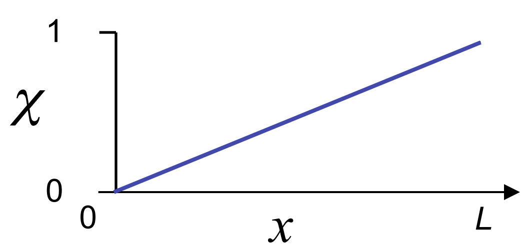
NB: the interval $\Delta T$ is chosen to be long enough to average out flow-controlled fluctuations

e.g. $\chi$ = 0.3 means the distance over which 30% of the sediment is extracted from the system.

*Strong et al., 2005, IAS Fluvial Sedimentology 7*

# Quantifying mass balance: fractional sediment extraction




**Using mass extraction as a measure lets us compare basins of different shape and size on a consistent basis**

**Provides a quantitative way of expressing *proximal – distal***

**We can think of the point $\chi = 0.5$ as the "depositional midpoint" of the basin**

# Quantifying mass balance: bypass ratio

Bypass ratio $B$ is the ratio between deposition and bypass:

***local avg. unit sediment flux***

$$B(x) = \frac{q_s}{rL} = \left[ \frac{-L}{q_s} \frac{dq_s}{dx} \right]^{-1} = (1-\chi)\left[ \frac{d\chi}{dx} \right]^{-1}$$

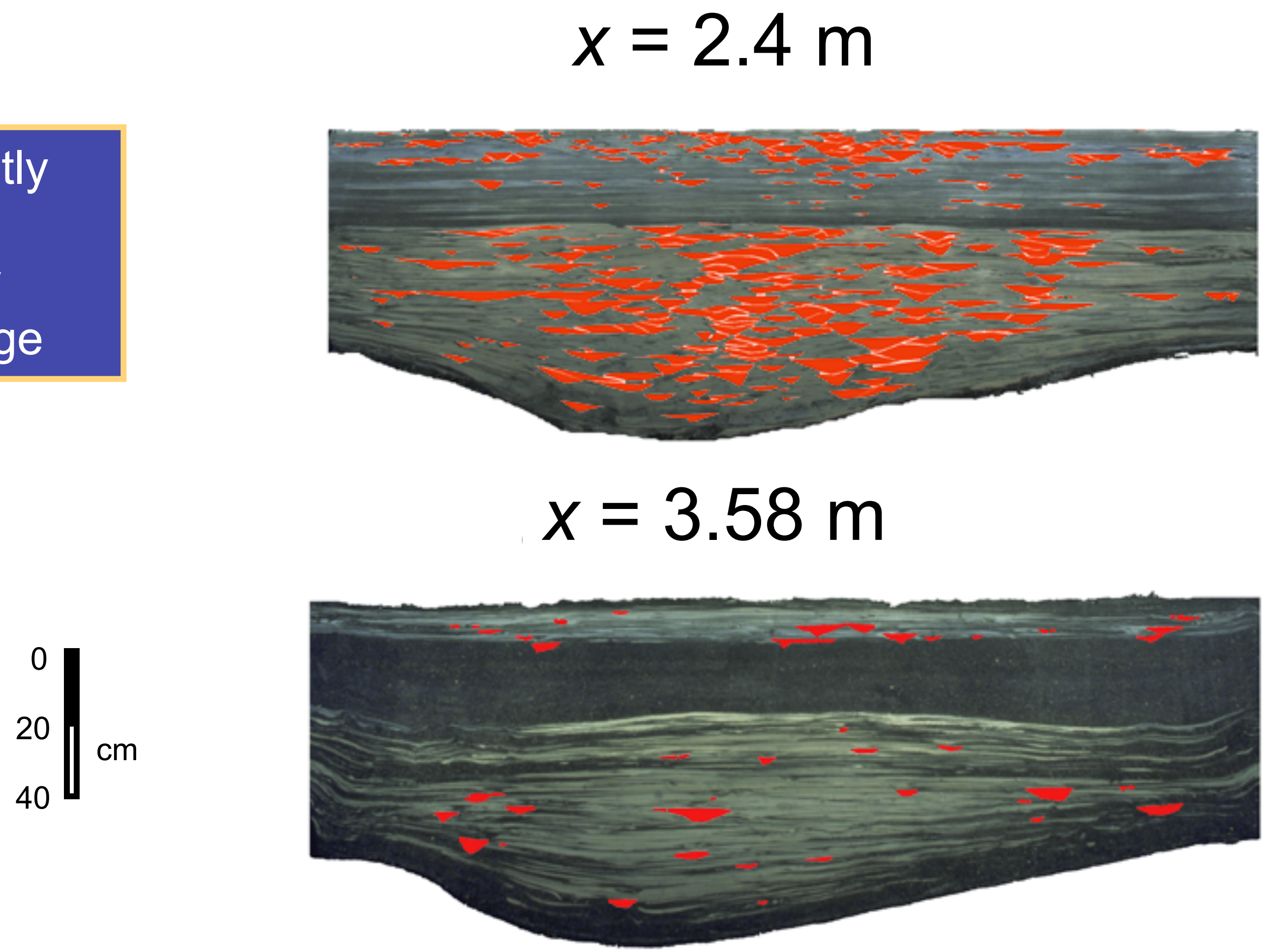
***rate of deposition***

***basin length***

*The two measures are directly related*

# Applying the chi transformation to stratigraphy

Note: consistently *lower* channel density for slow subsidence stage

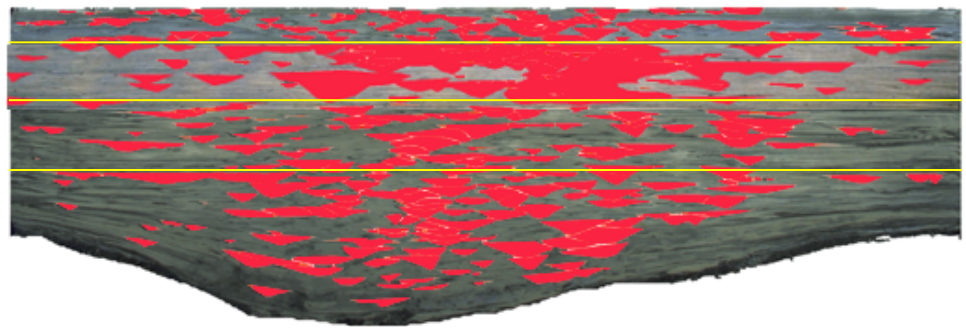



*Strong et al., 2005, IAS Fluvial Sedimentology 7*

# Applying the chi transformation to stratigraphy

At 40% mass extraction, the deposit is still channel dominated

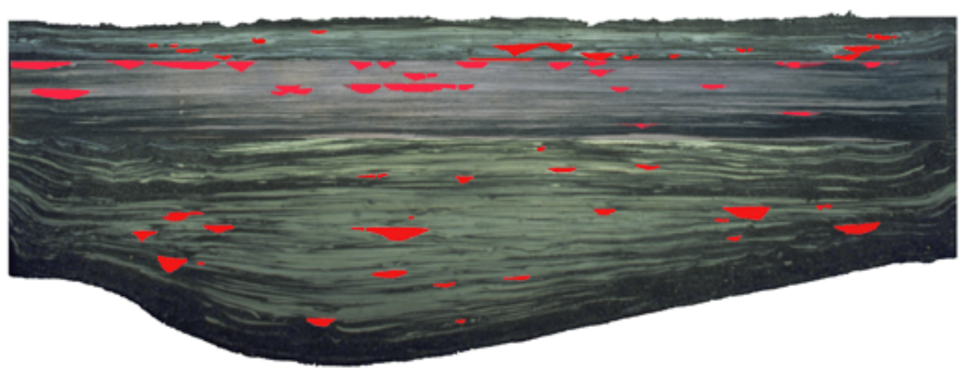
$\chi = 0.4$



X=2.4 m
X=1.64 m
X=2.44 m
X=2.4 m

But by 70% extraction, predominant depositional element is sheets (extensive, thin lobes)

$\chi = 0.7$



X=3.58 m
X=2.4 m
X=3.58 m
X=3.58 m

*Strong et al., 2005, IAS Fluvial Sedimentology 7*

# Why should mass balance affect stacking?

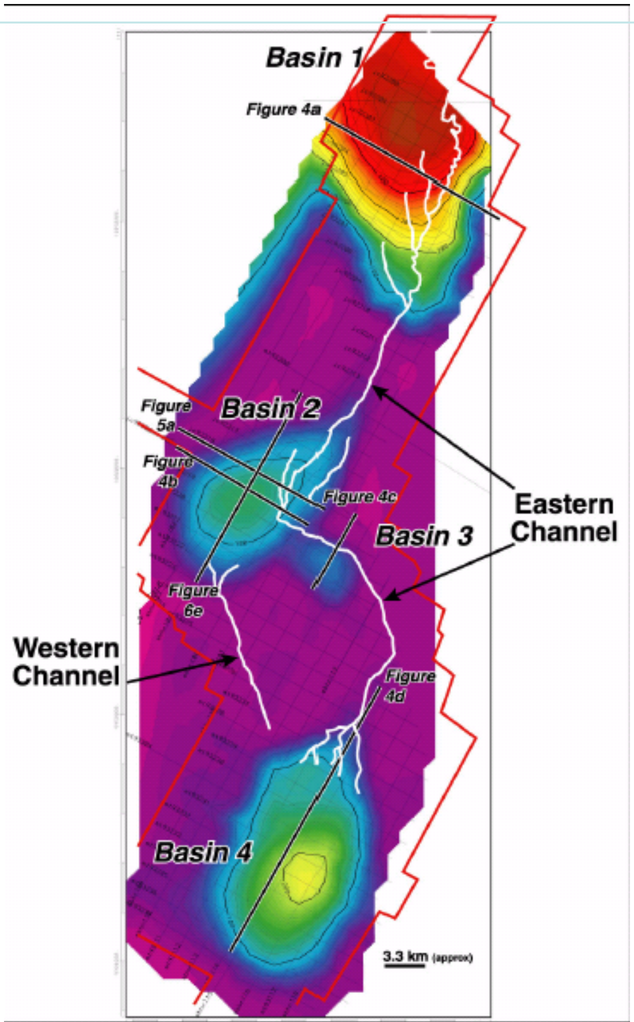
- channel fraction & stacking density depend on rate of channel mobility relative to rate of deposition
  - high mobility rel. to deposition → high channel density

- channel mobility $\propto$ bed-material flux

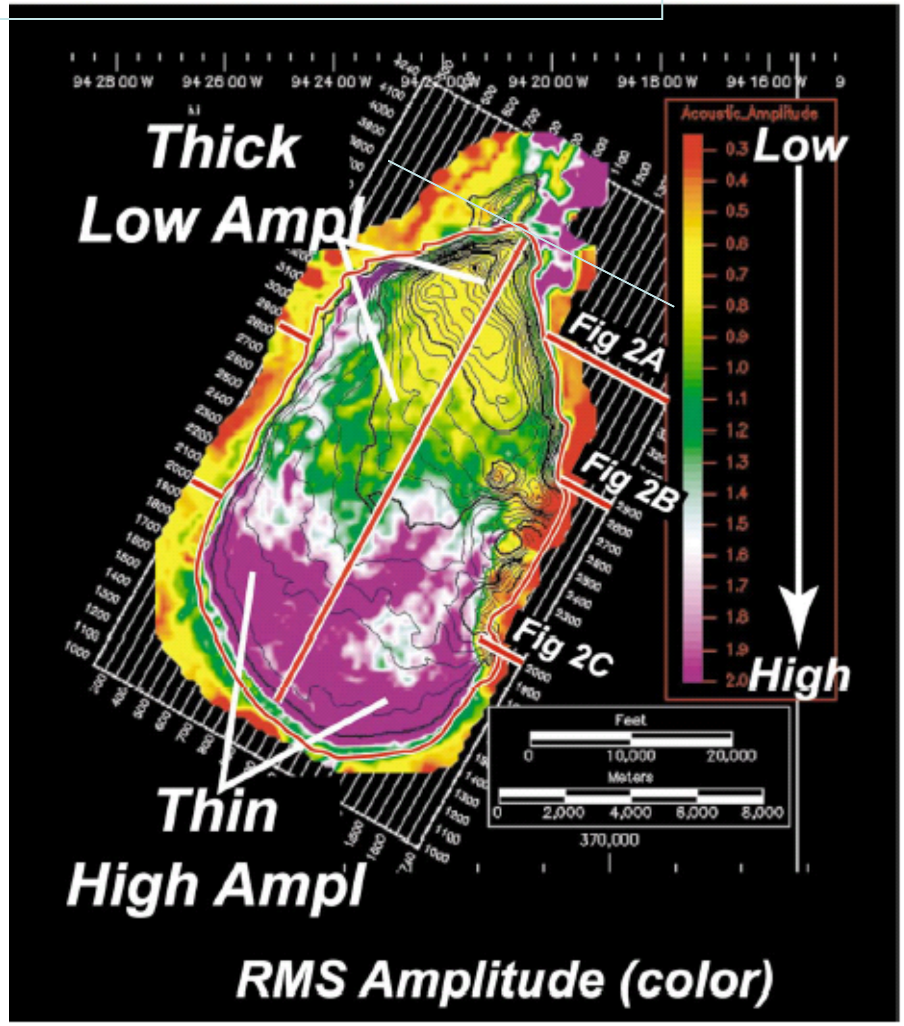
- thus high values of flux/deposition (bypass ratio) → more frequent + more active channels → increased channel density

# Application to turbidite mini-basins

## Brazos-Trinity System, offshore Gulf of Mexico



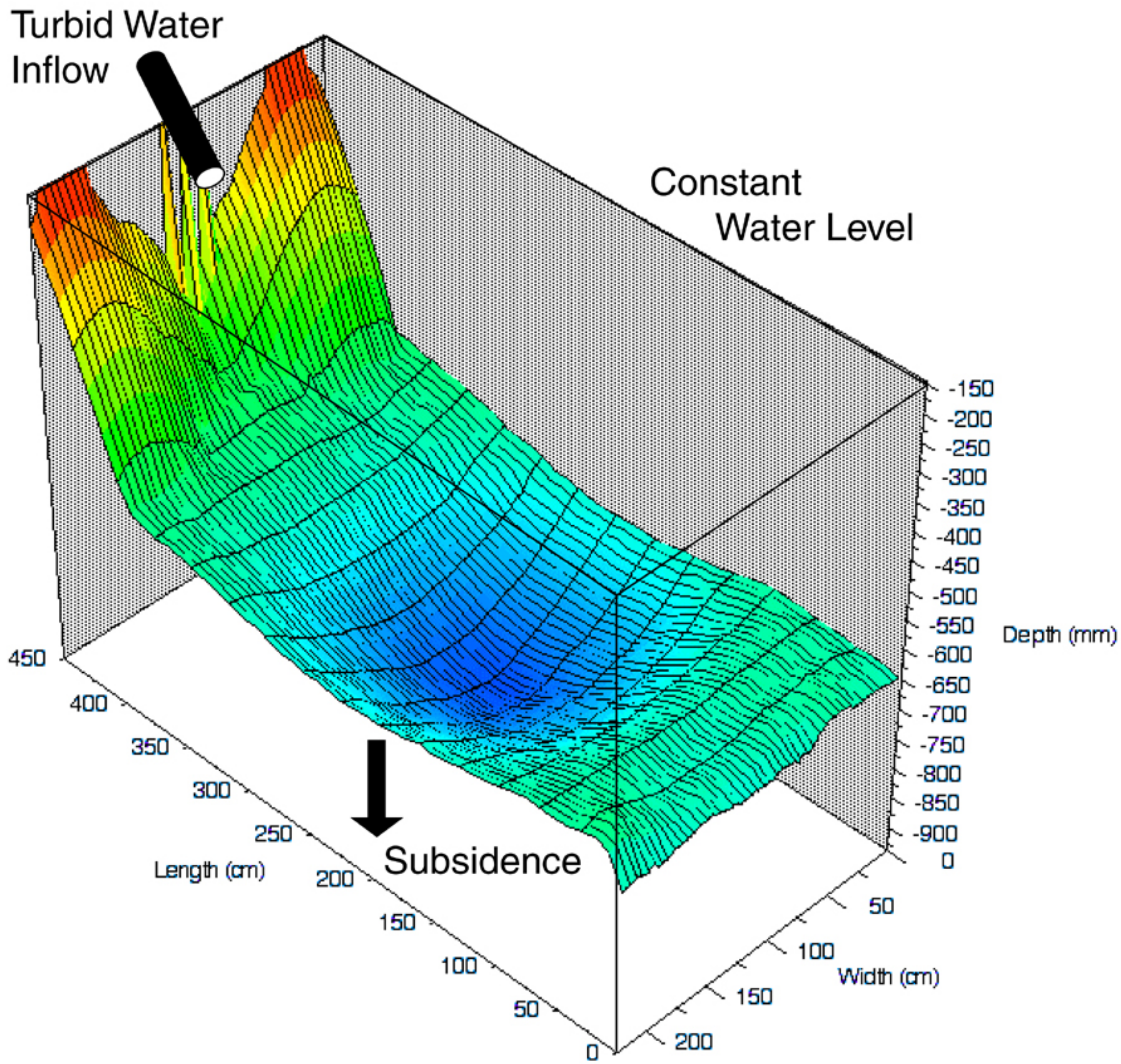

From Beaubouef and Friedmann 2000




Basin 4: From Beaubouef et al. 2003

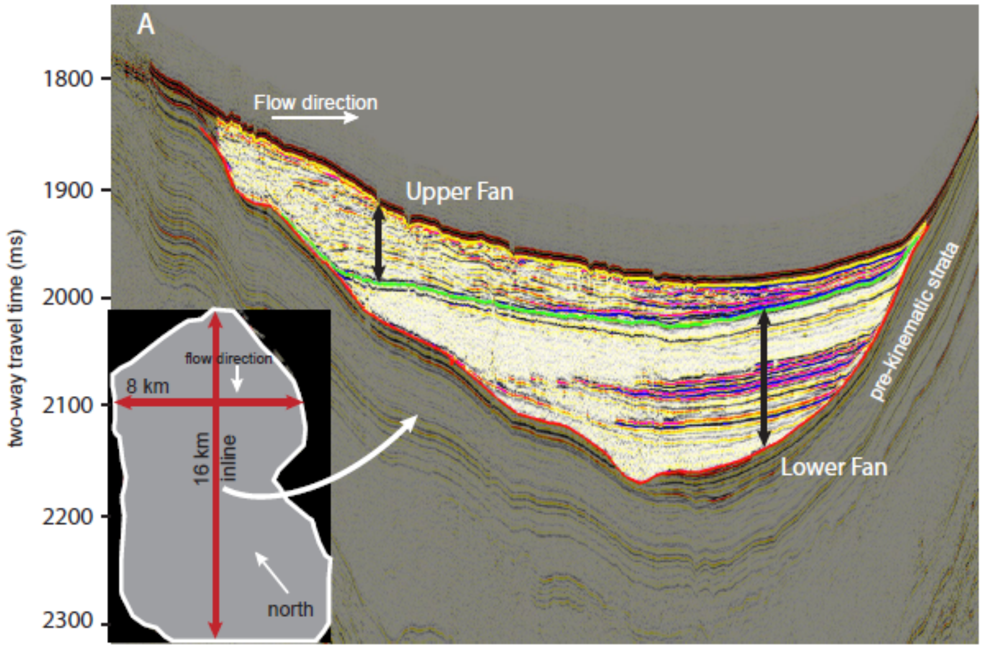
*Paola & Martin, in limbo*

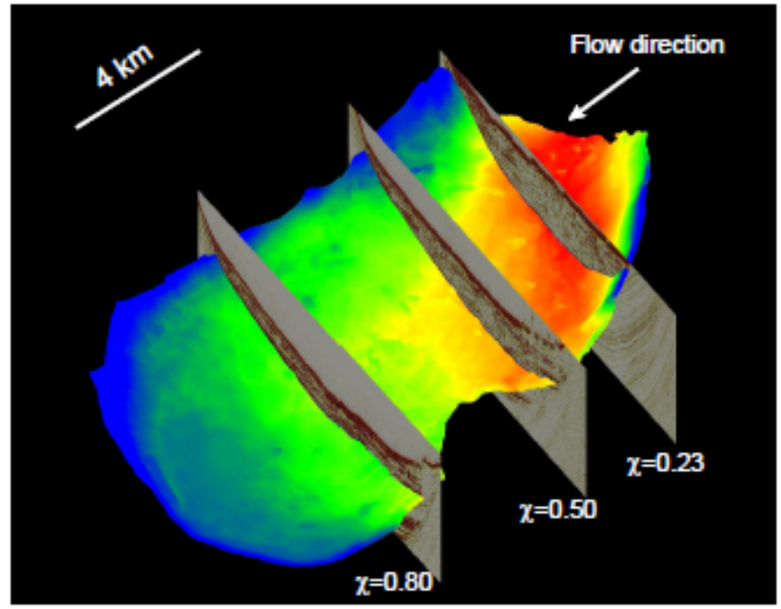
# XES 01 turbidity currents in a mini-basin

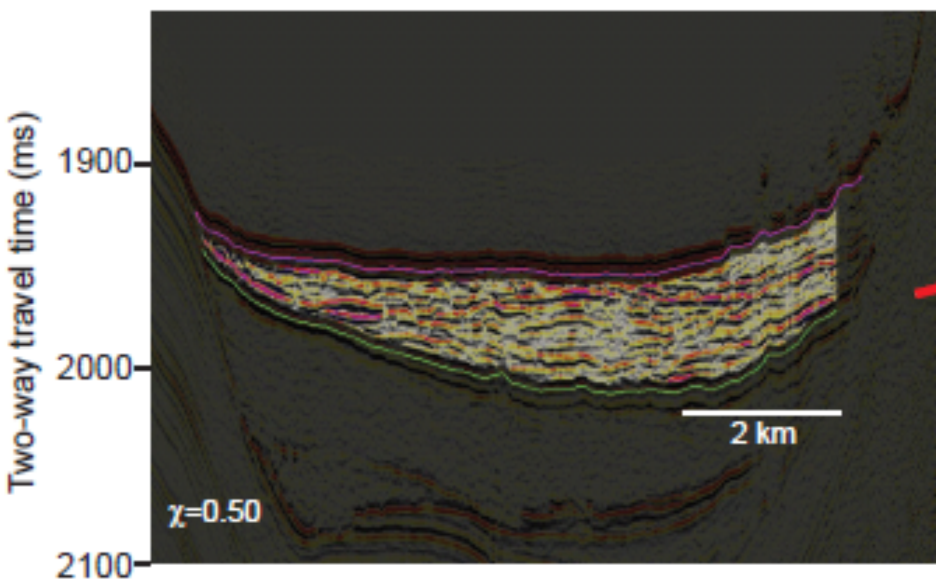


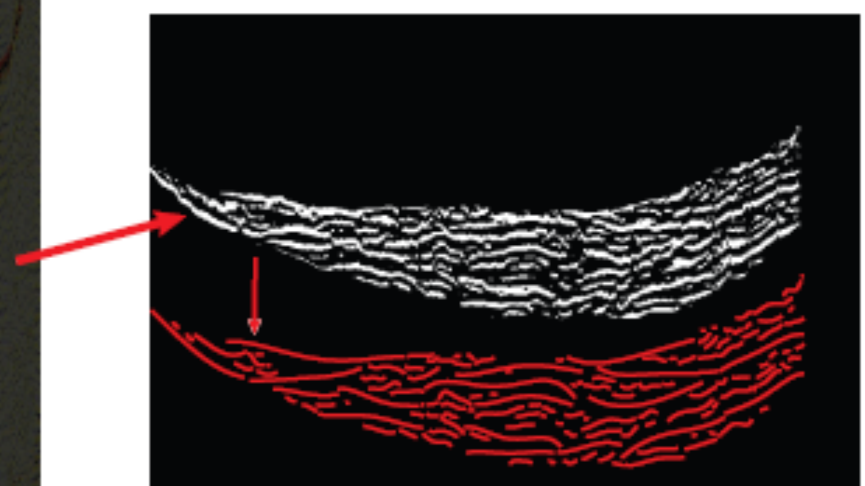

*Violet et al. 2005 JSR*

# East Breaks Minibasin

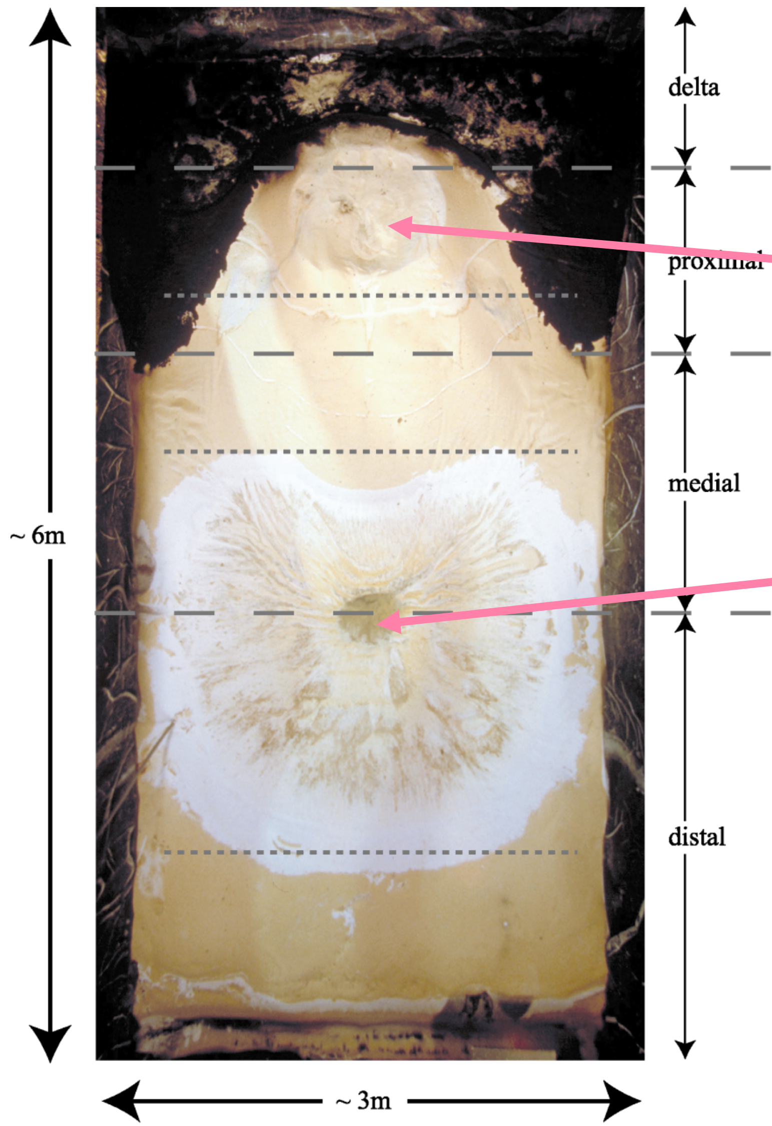


# XES 01 turbidity currents in a mini-basin



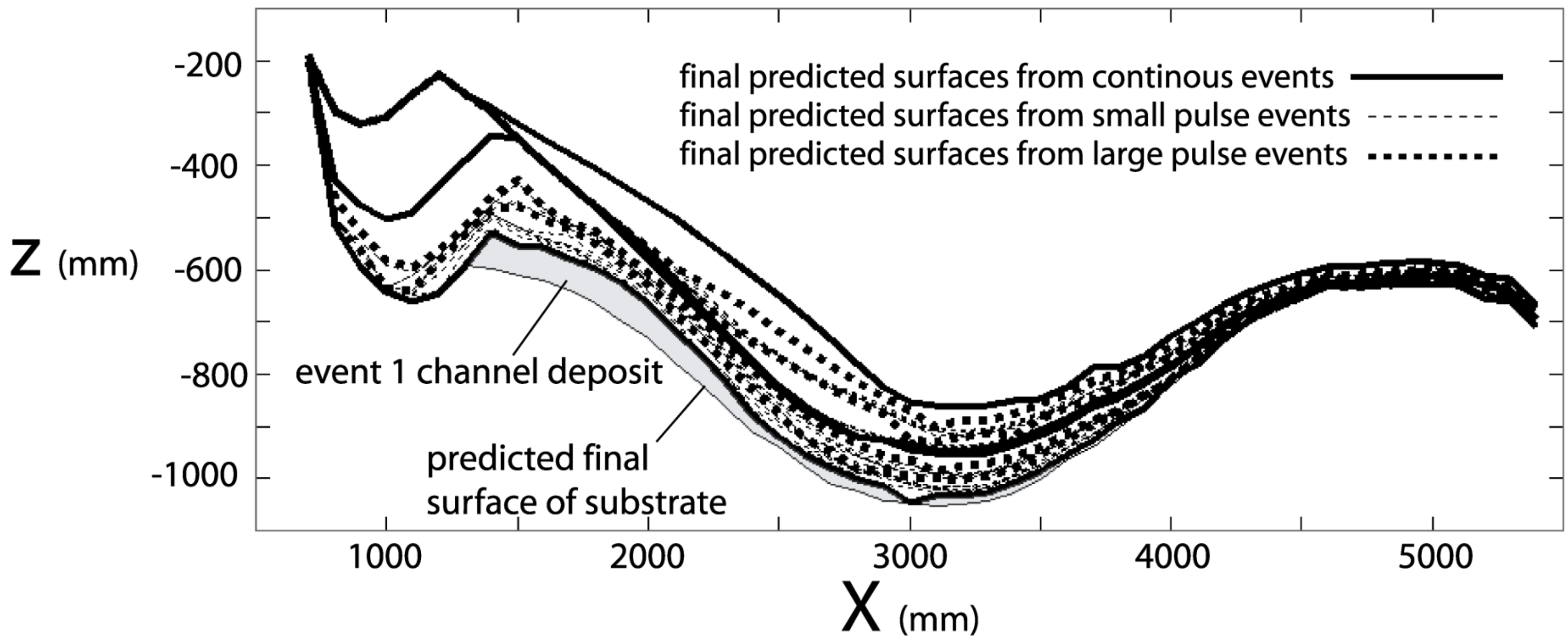

crater

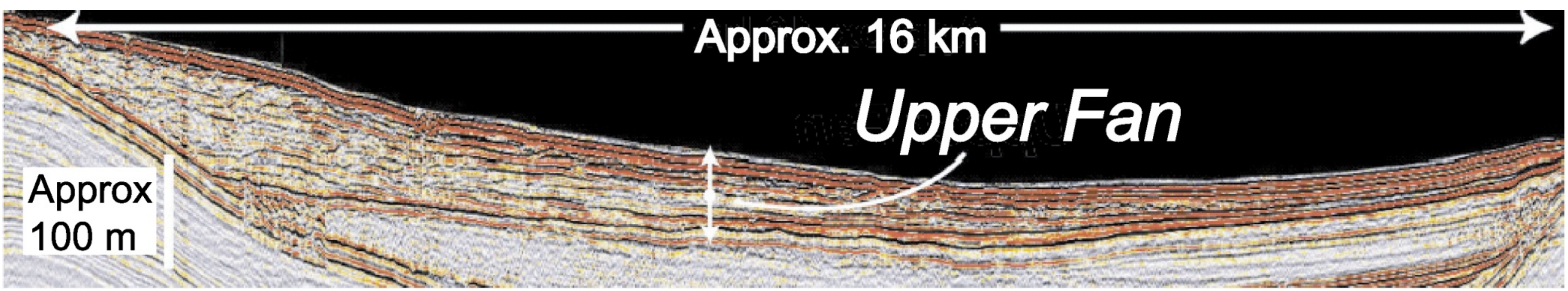
point of maximum subsidence

Violet et al. 2005

*Violet et al. 2005 JSR*

# XES01 vs. Brazos-Trinity System

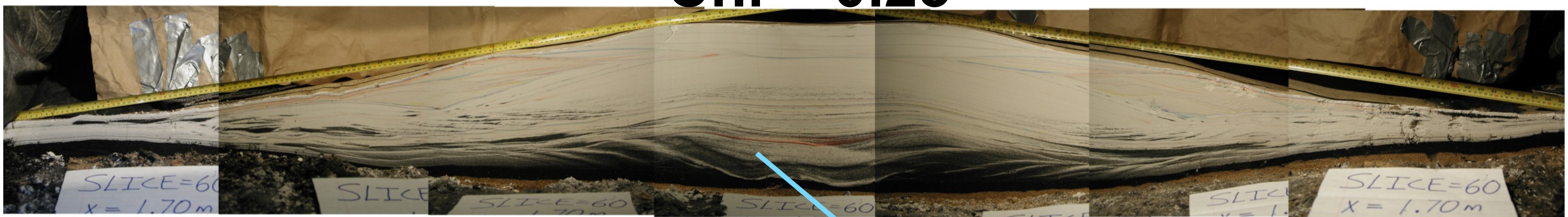



**From Beaubouef et al 2003**

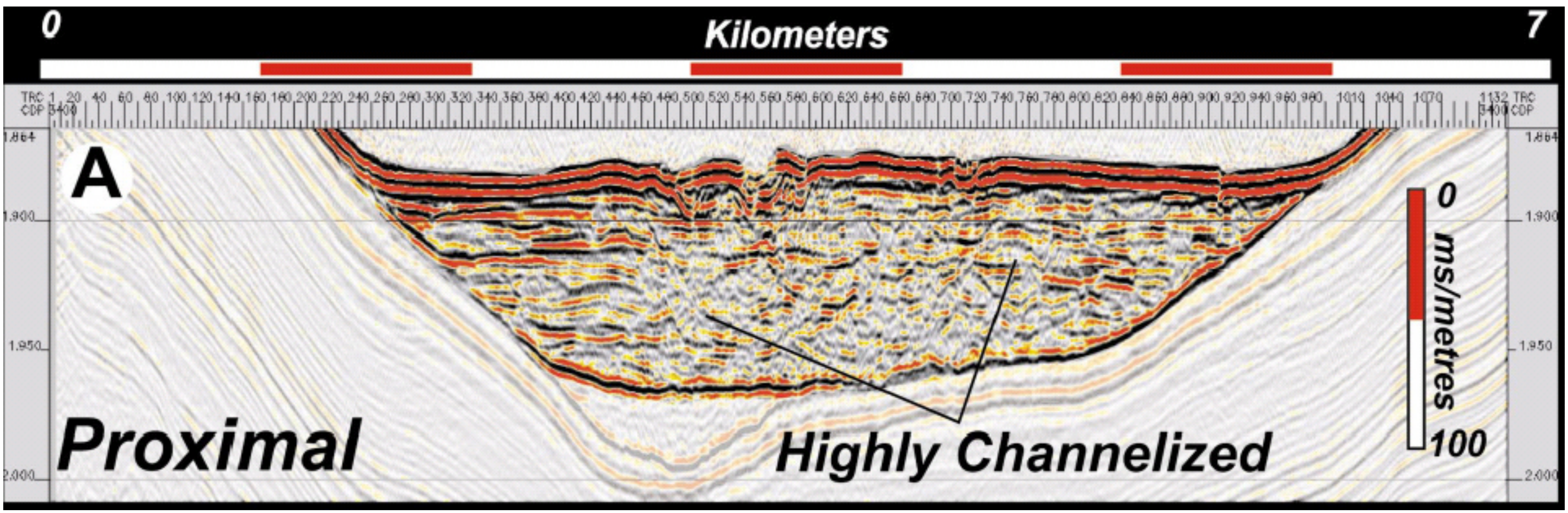
# XES01 vs. Brazos-Trinity System

Chi = 0.23




Channelized

1.70 m

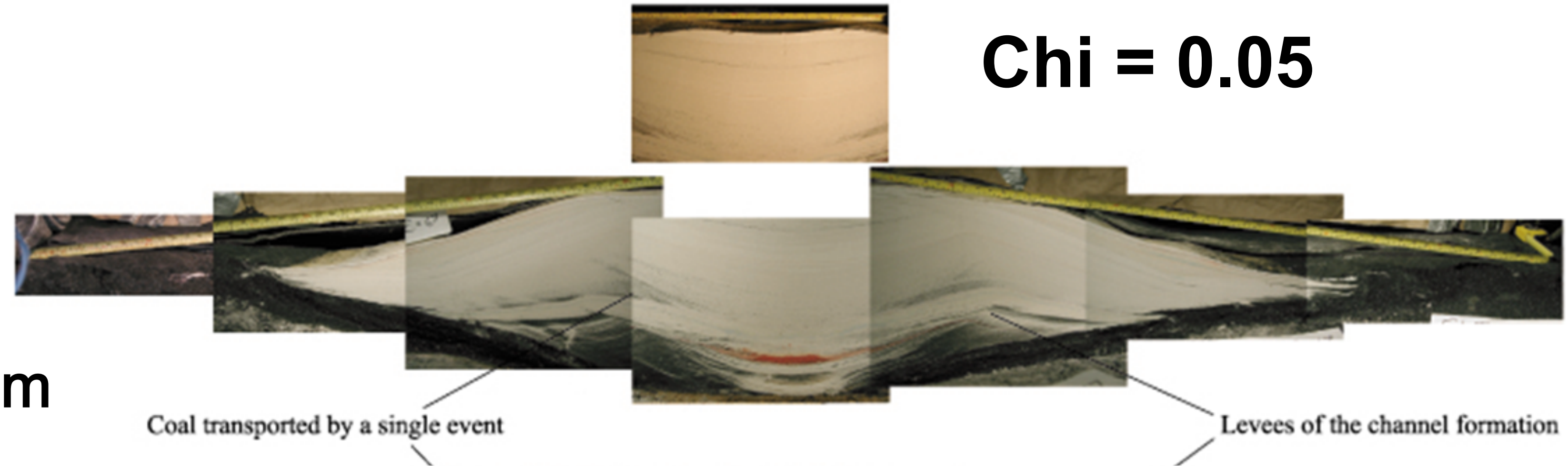



Beaubouef et al 2003

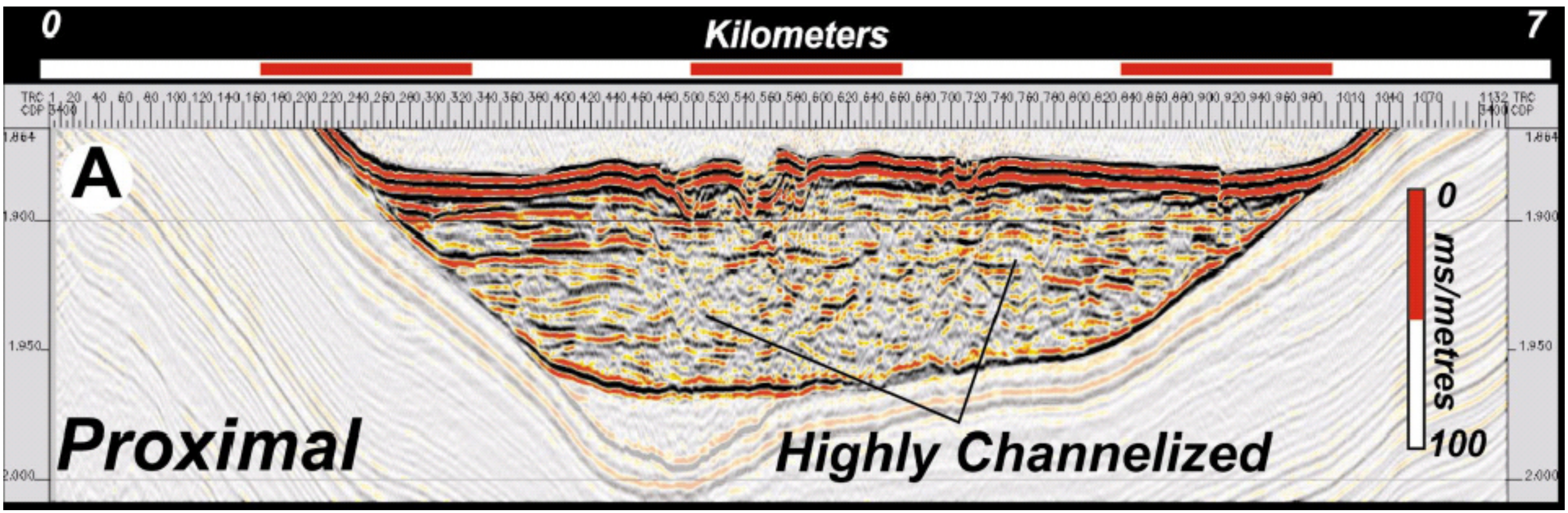
Chi = 0.1

# XES01 vs. Brazos-Trinity System

Chi = 0.05




1.3 m

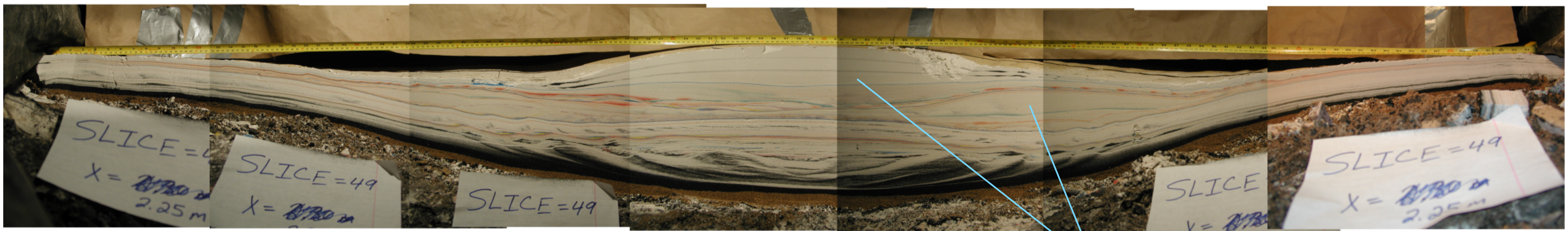



Beaubouef et al 2003

Chi = 0.1

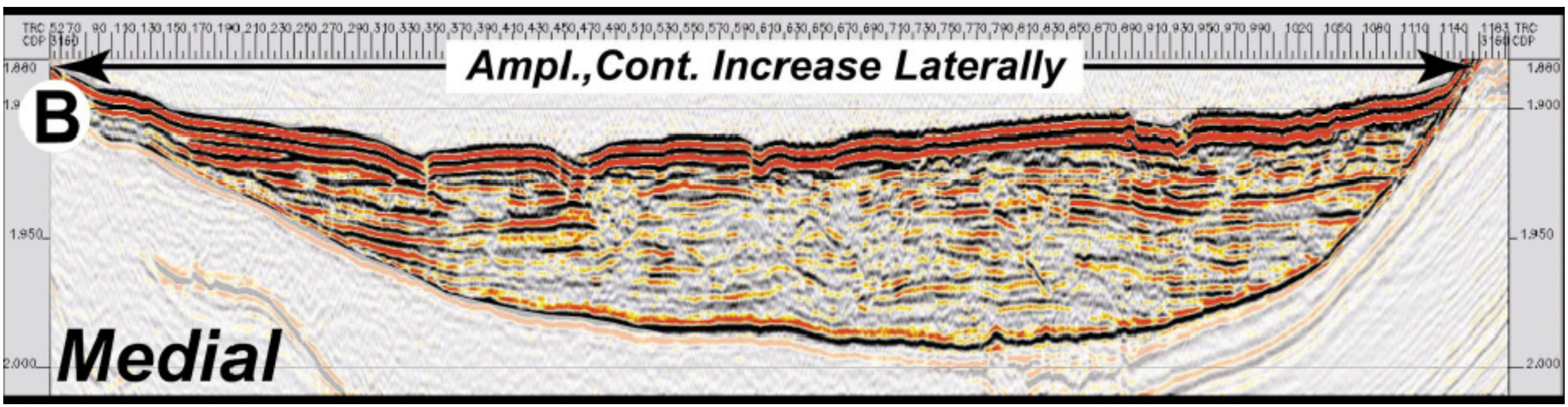
# XES01 vs. Brazos-Trinity System

Chi = 0.5




Lobe switching

2.25 m

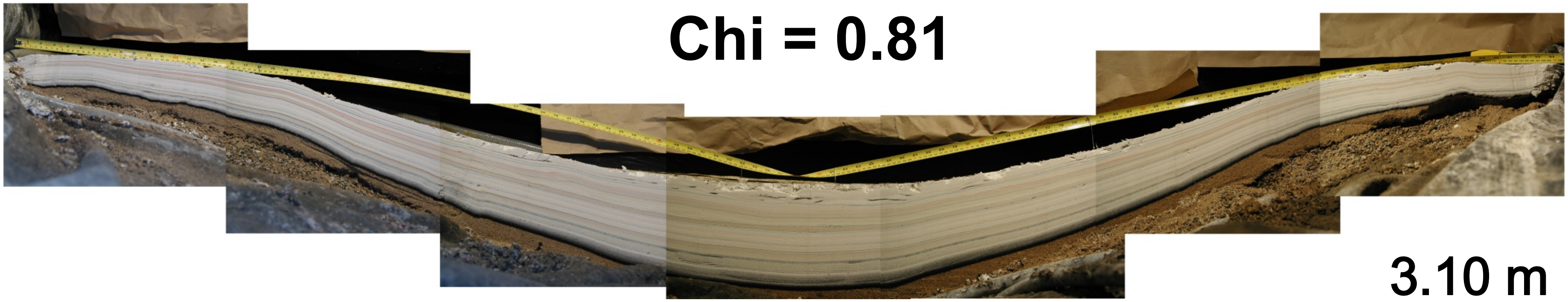



Chi = 0.61

Beaubouef et al 2003

# XES01 vs. Brazos-Trinity System

Chi = 0.81



3.10 m

Chi > 0.95

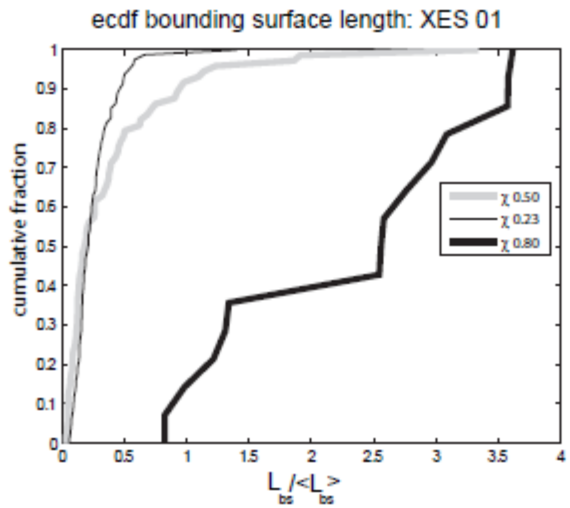
4.40 m

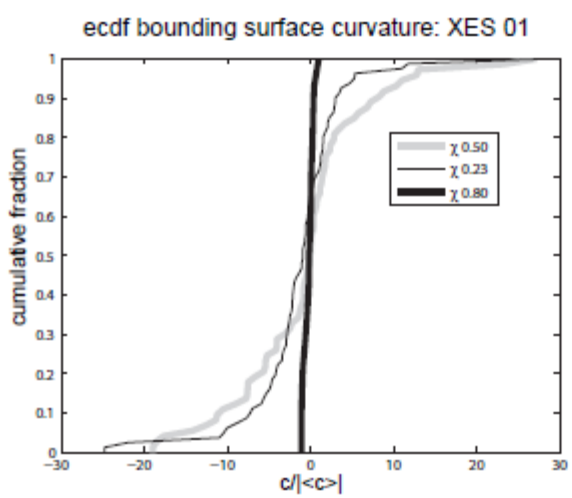

Beaubouef et al 2003

Chi = 0.86

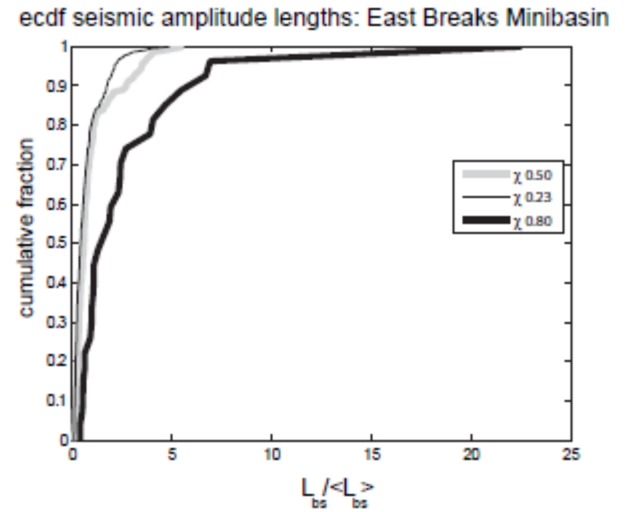
# Bed curvature statistics

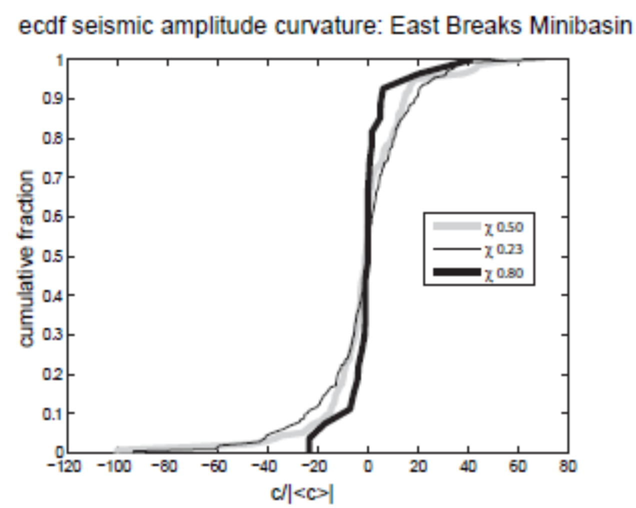
## XES 01



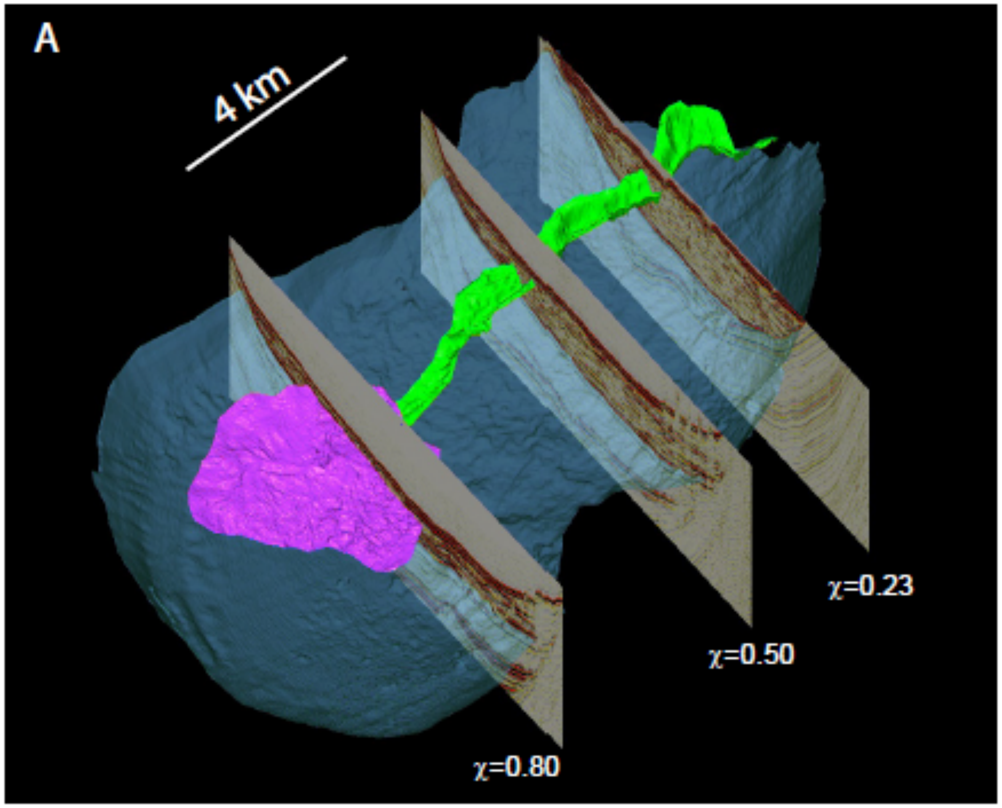



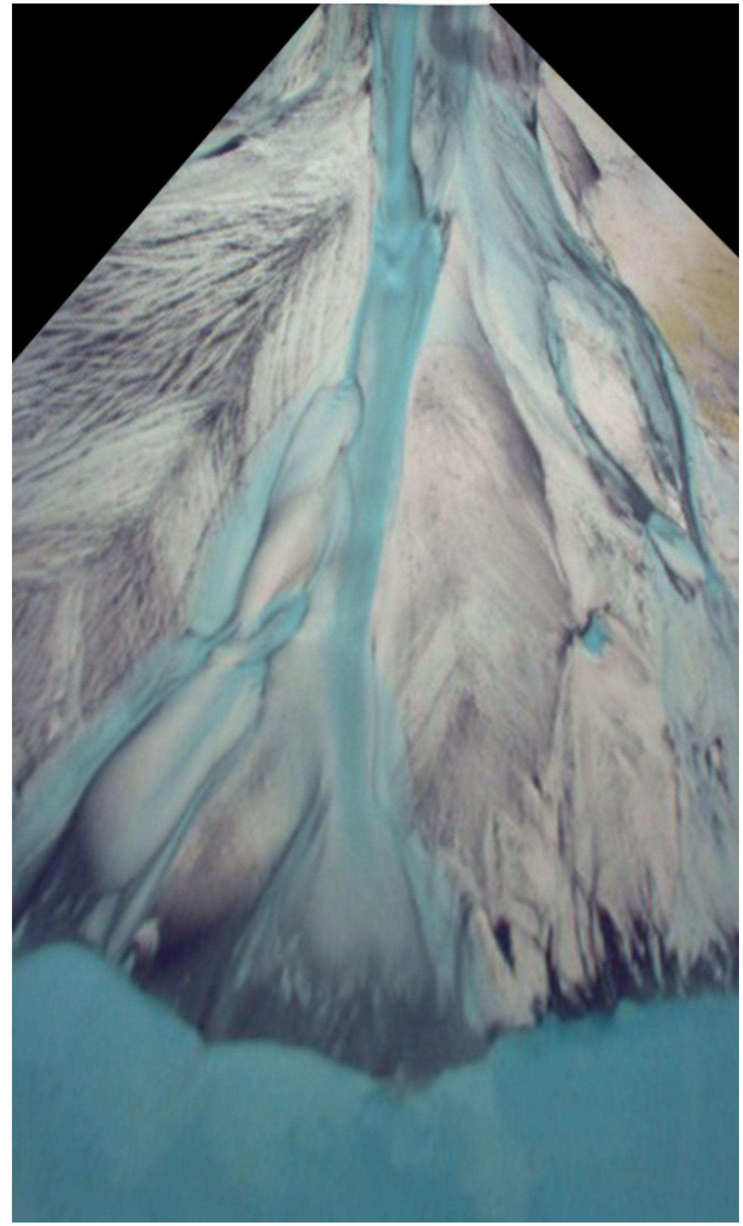

## East Breaks Minibasin



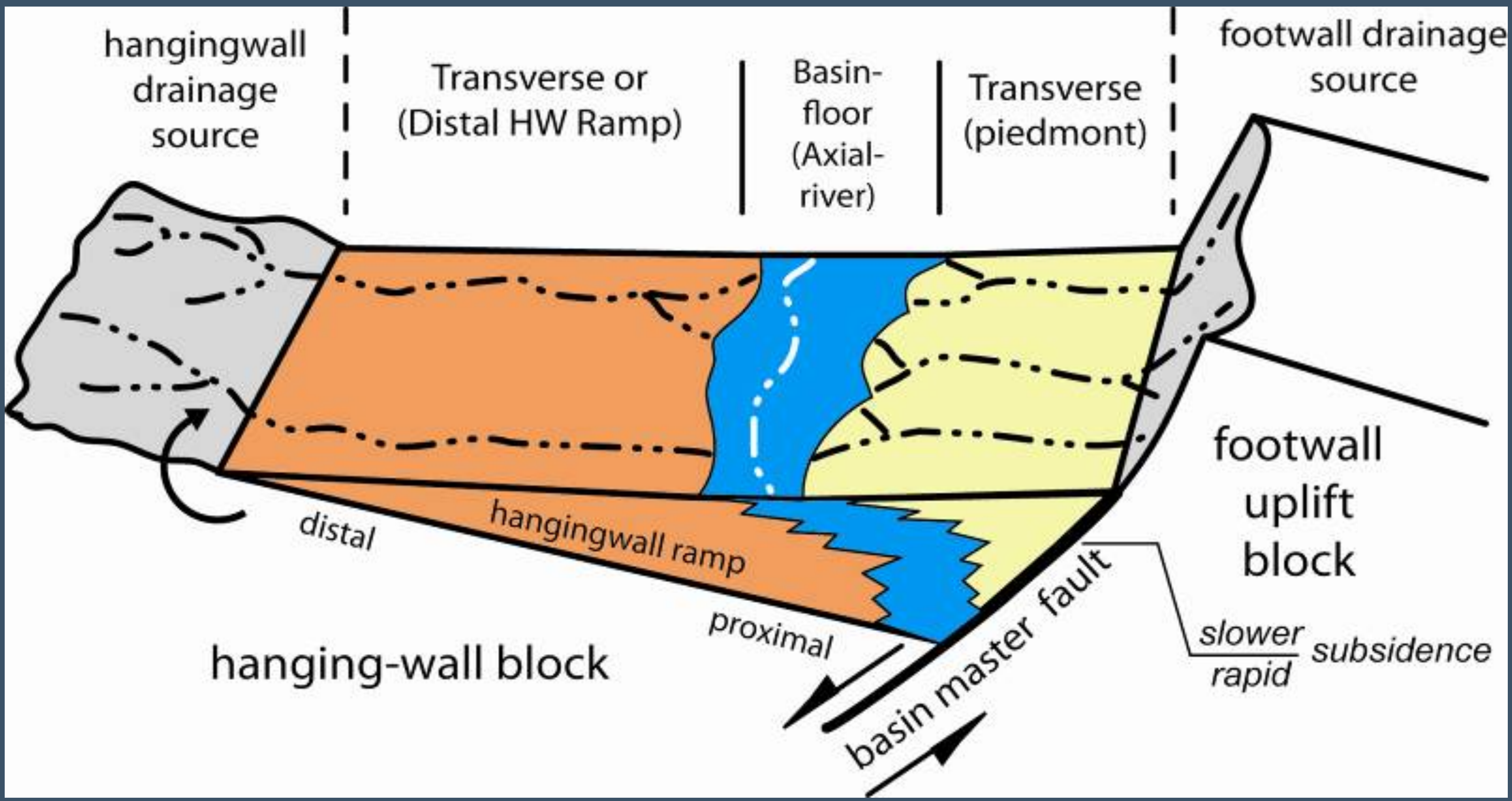
# Curvature: channels vs expansion deposits



*Similar changes with increasing mass extraction in unconfined turbidites and fluvial deposits*

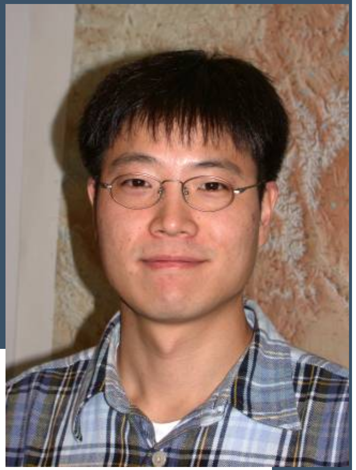
# Mass-balance effects: experimental half-graben basin

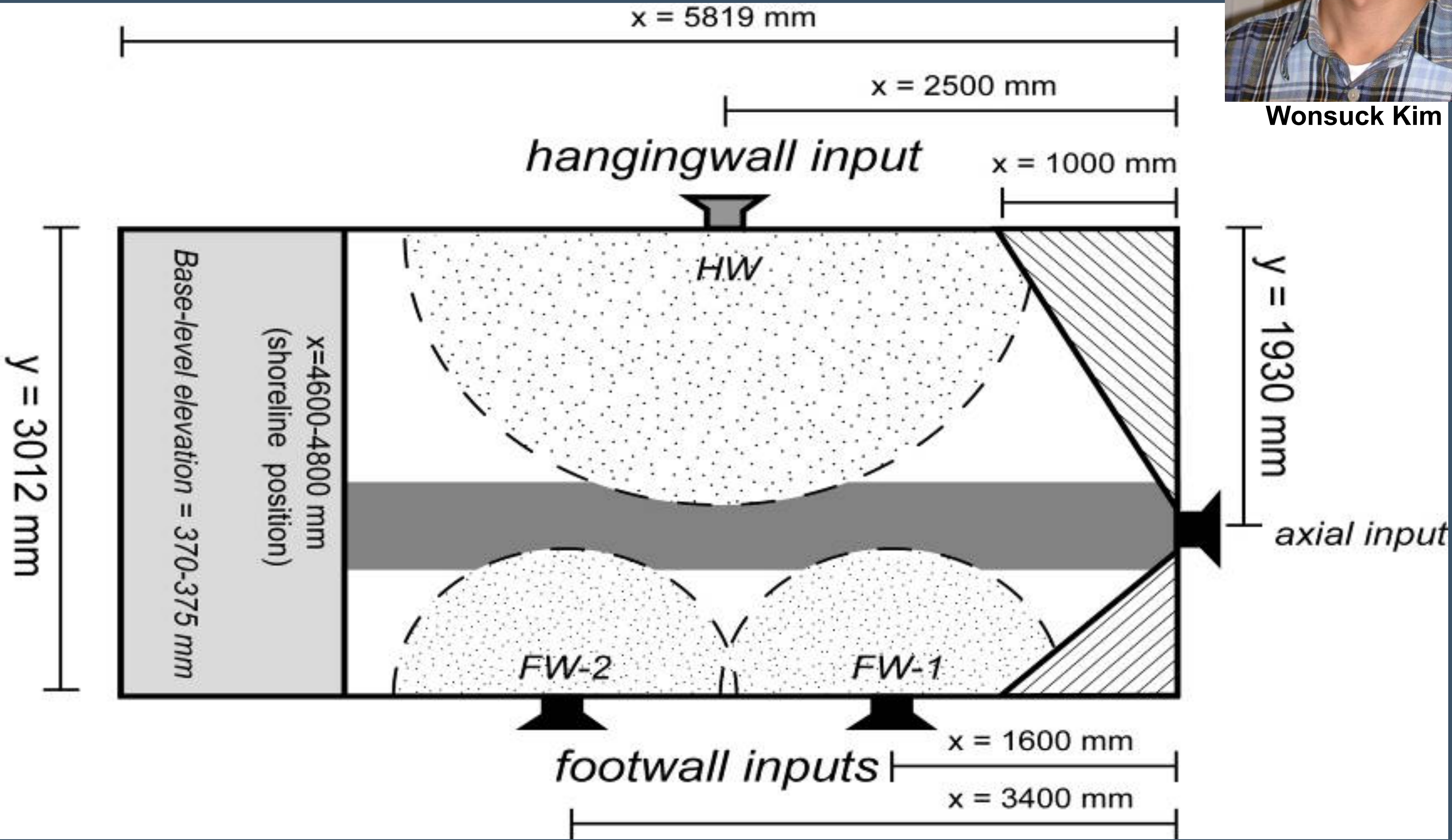



Modified from Leeder and Gawthorpe (1987) and Mack and Seager (1990)

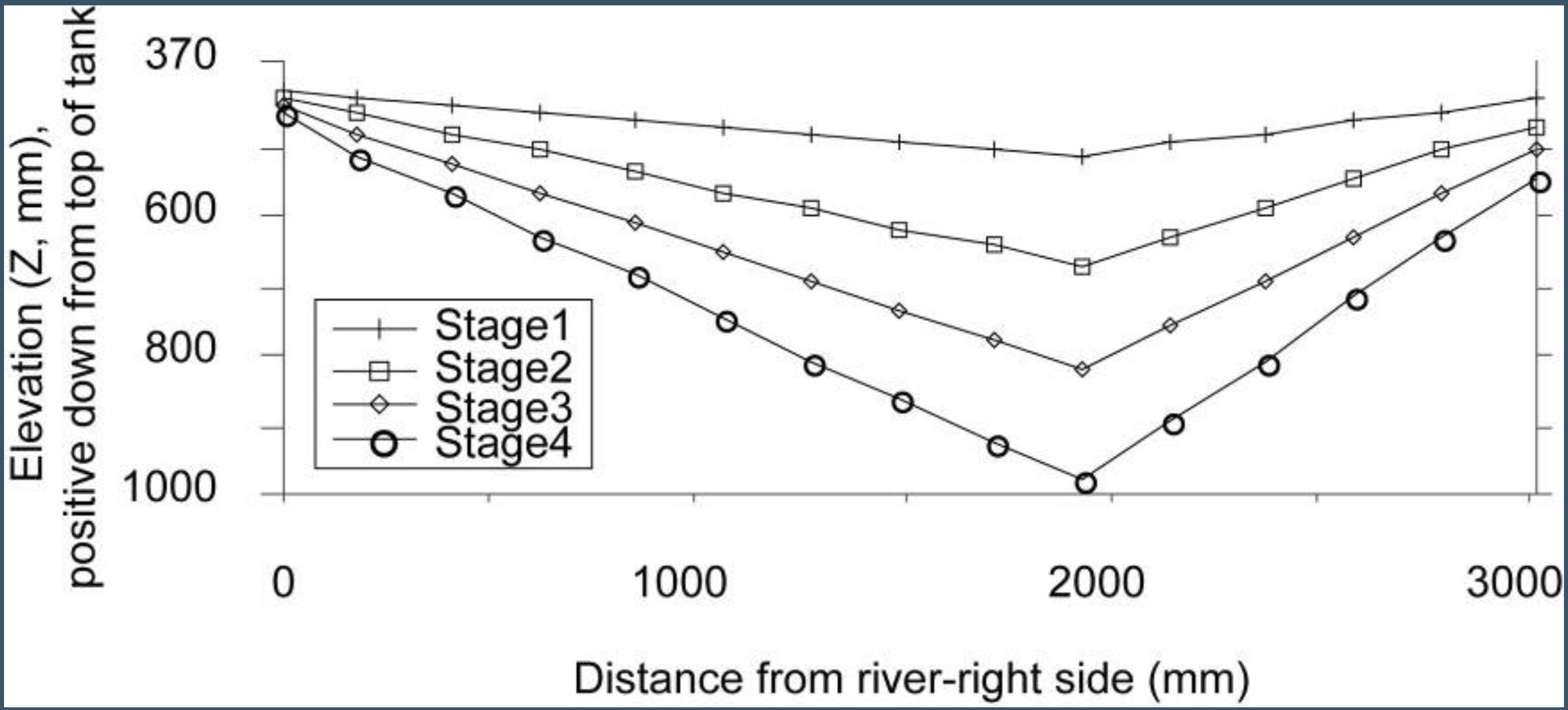
Sean Connell (UNM), Wonsuck Kim, Gary Smith (UNM), Chris Paola

# XES 06 plan view setup

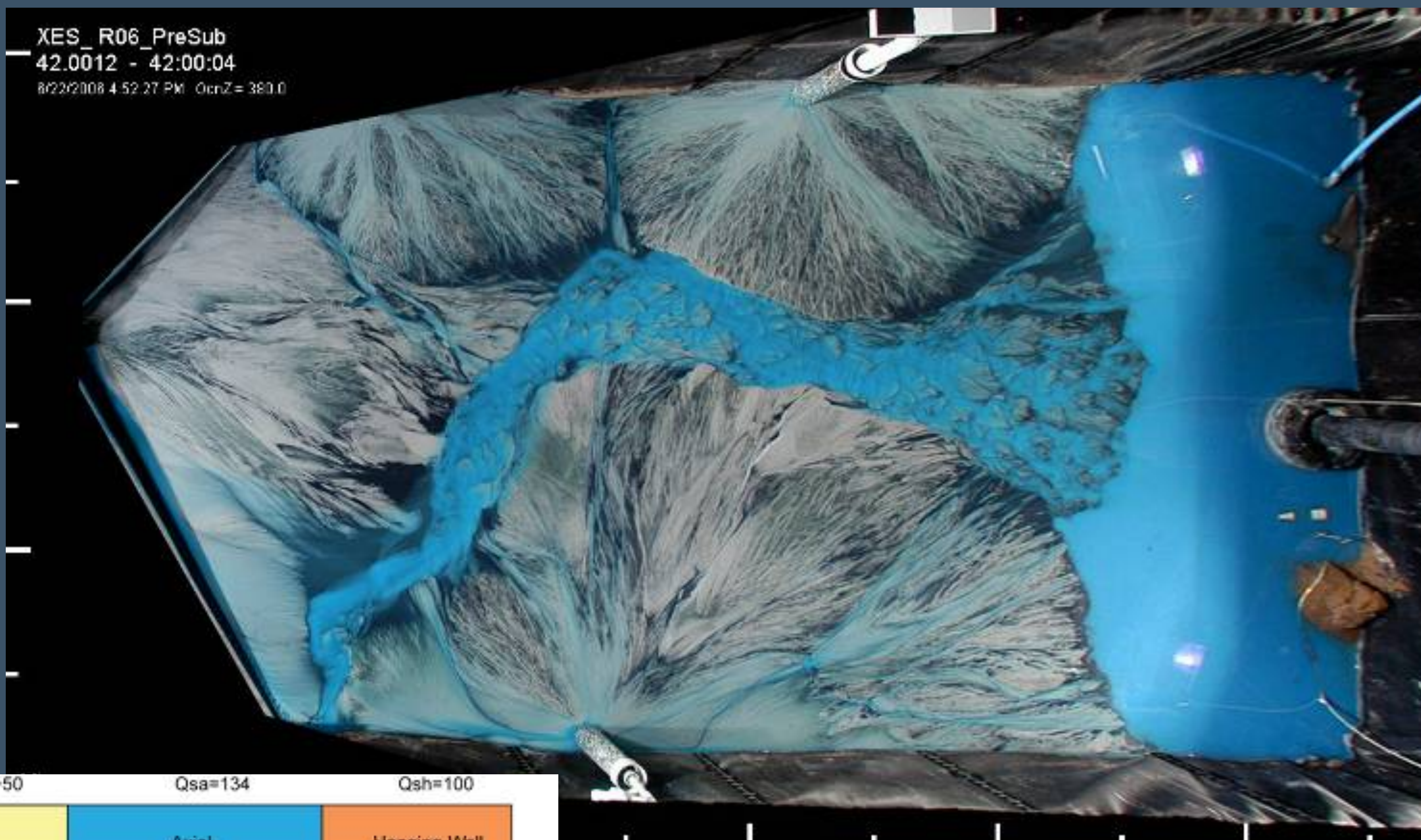


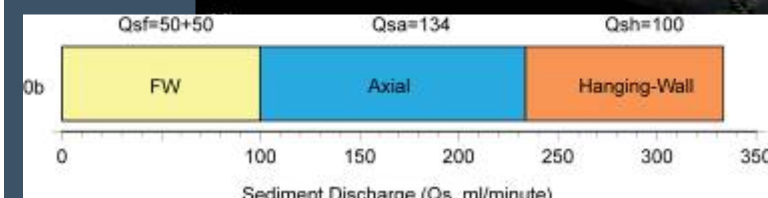


# XES06-1: Cross Section Profile

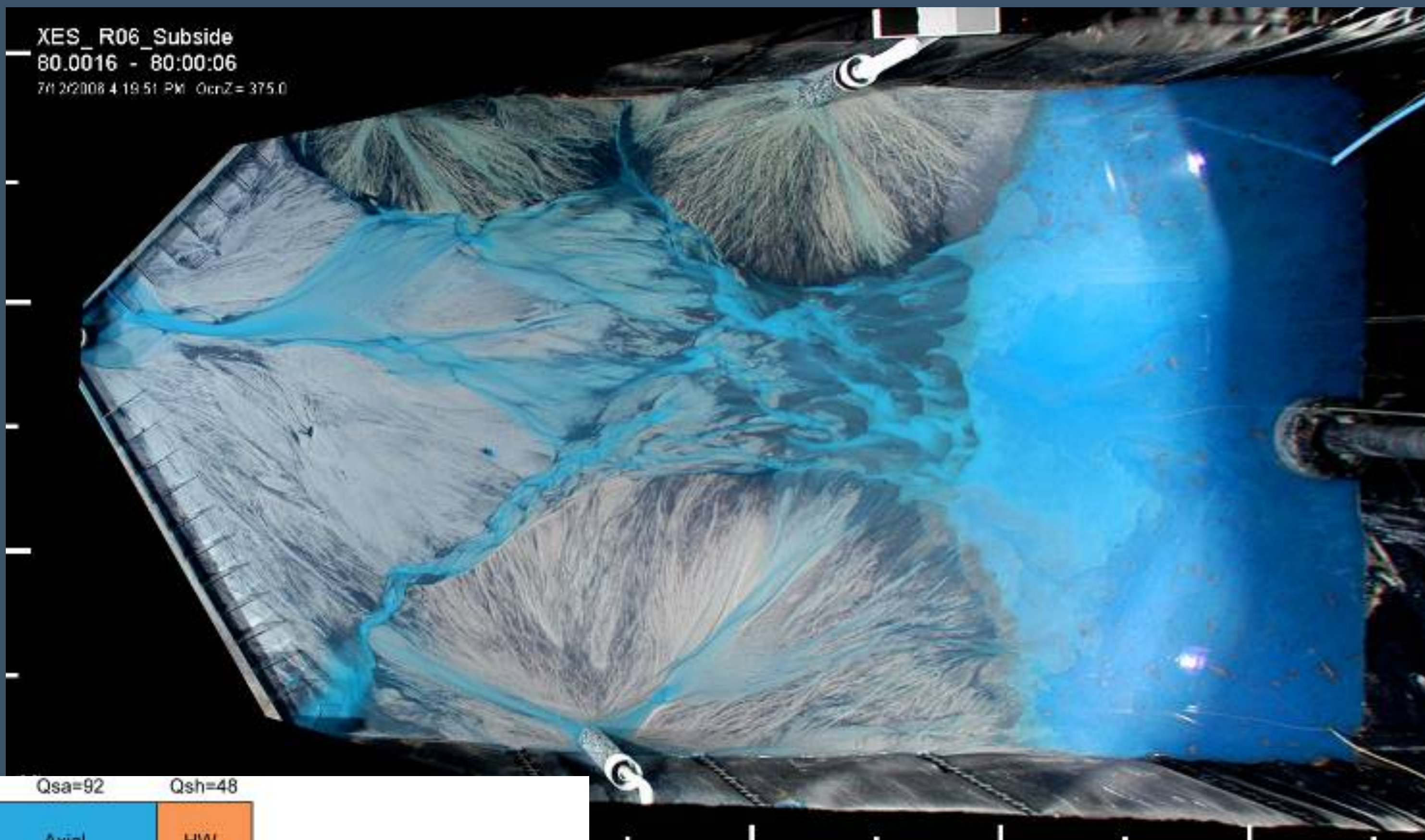


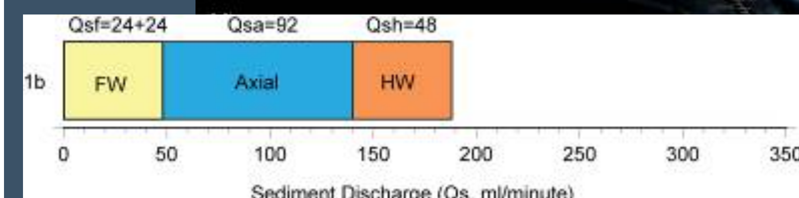
# Initial Conditions Stage 0b (0 hrs)



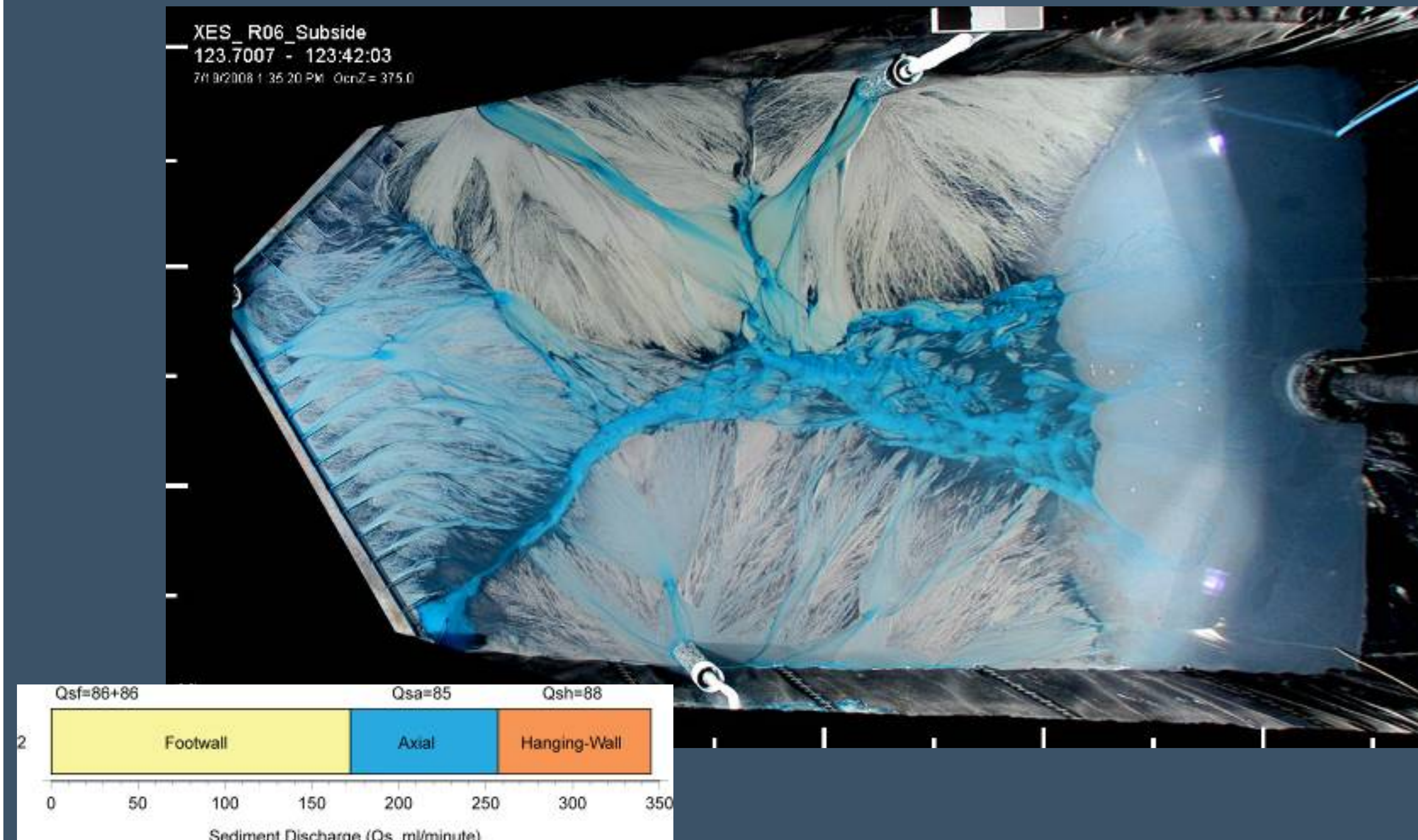



# Axial-Dominant Stage 1b (80 hours)

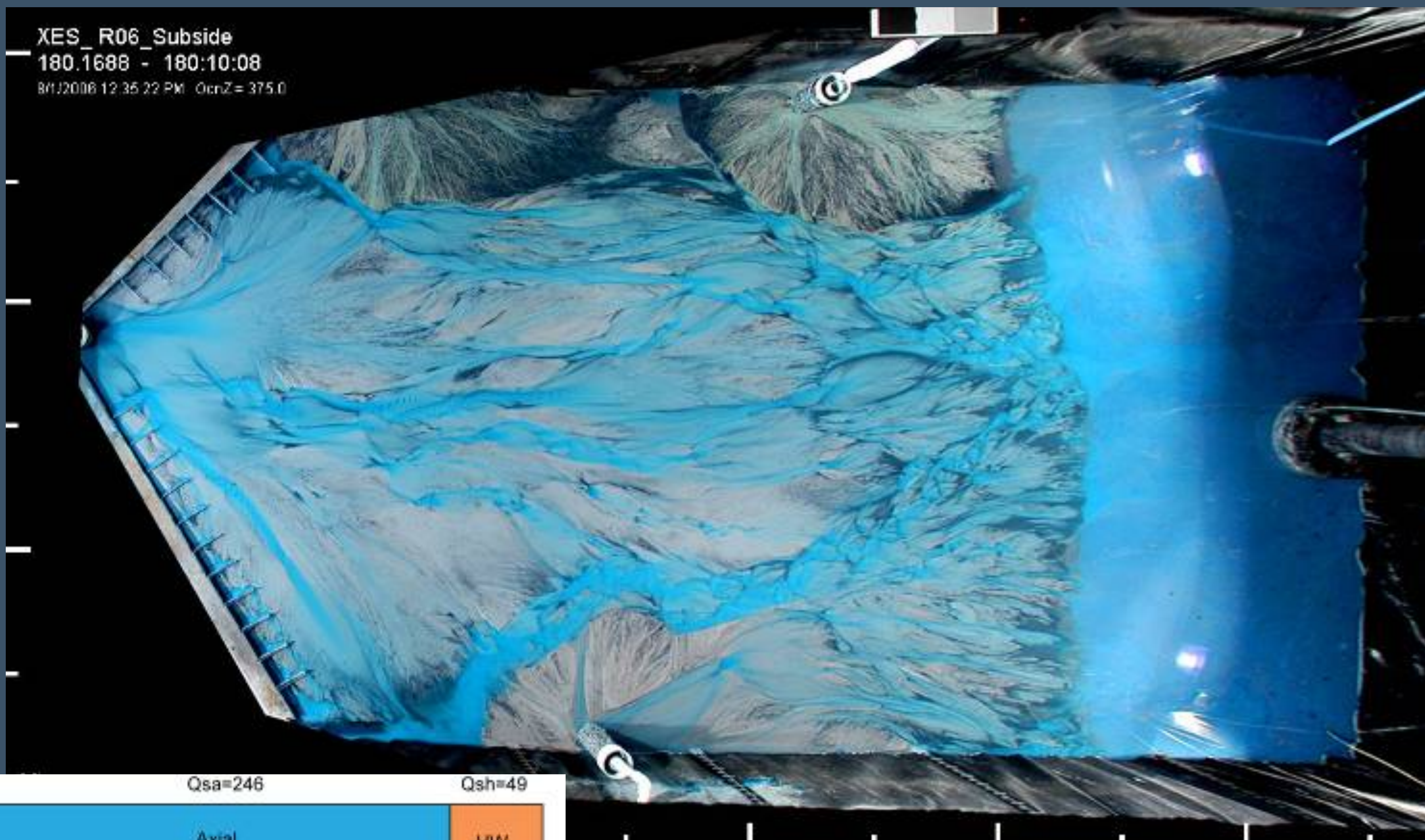


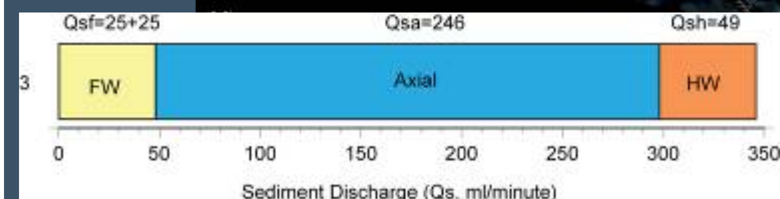



# Footwall-Dominant Stage 2 (123 hours)

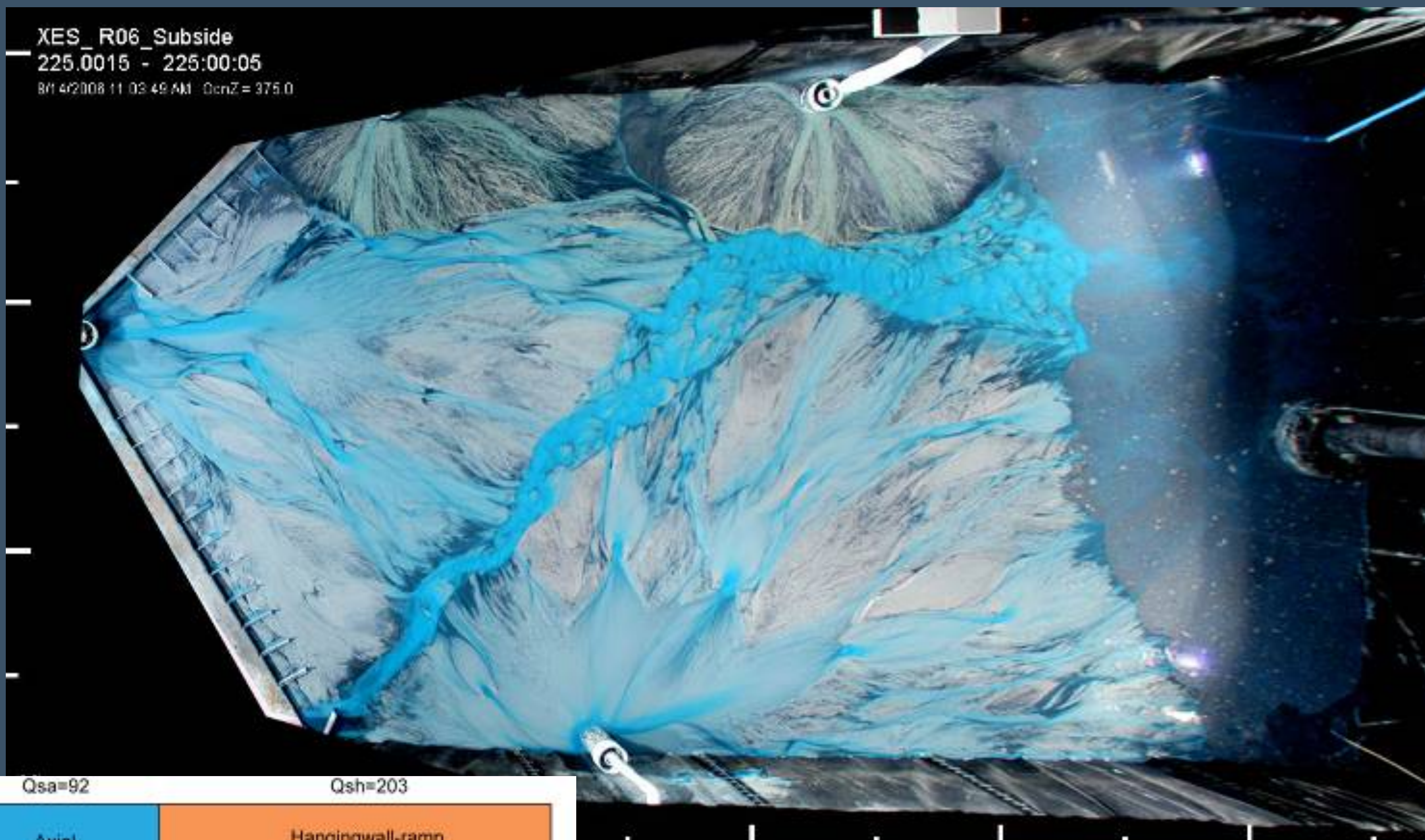


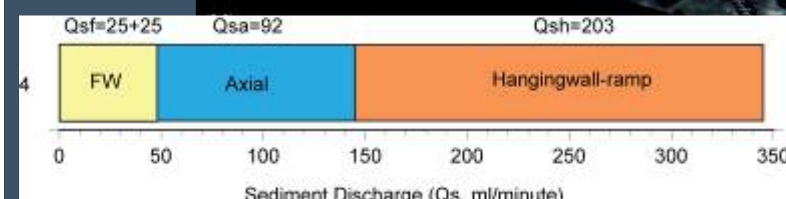
# Axial-Dominant Stage 3 (180 hours)



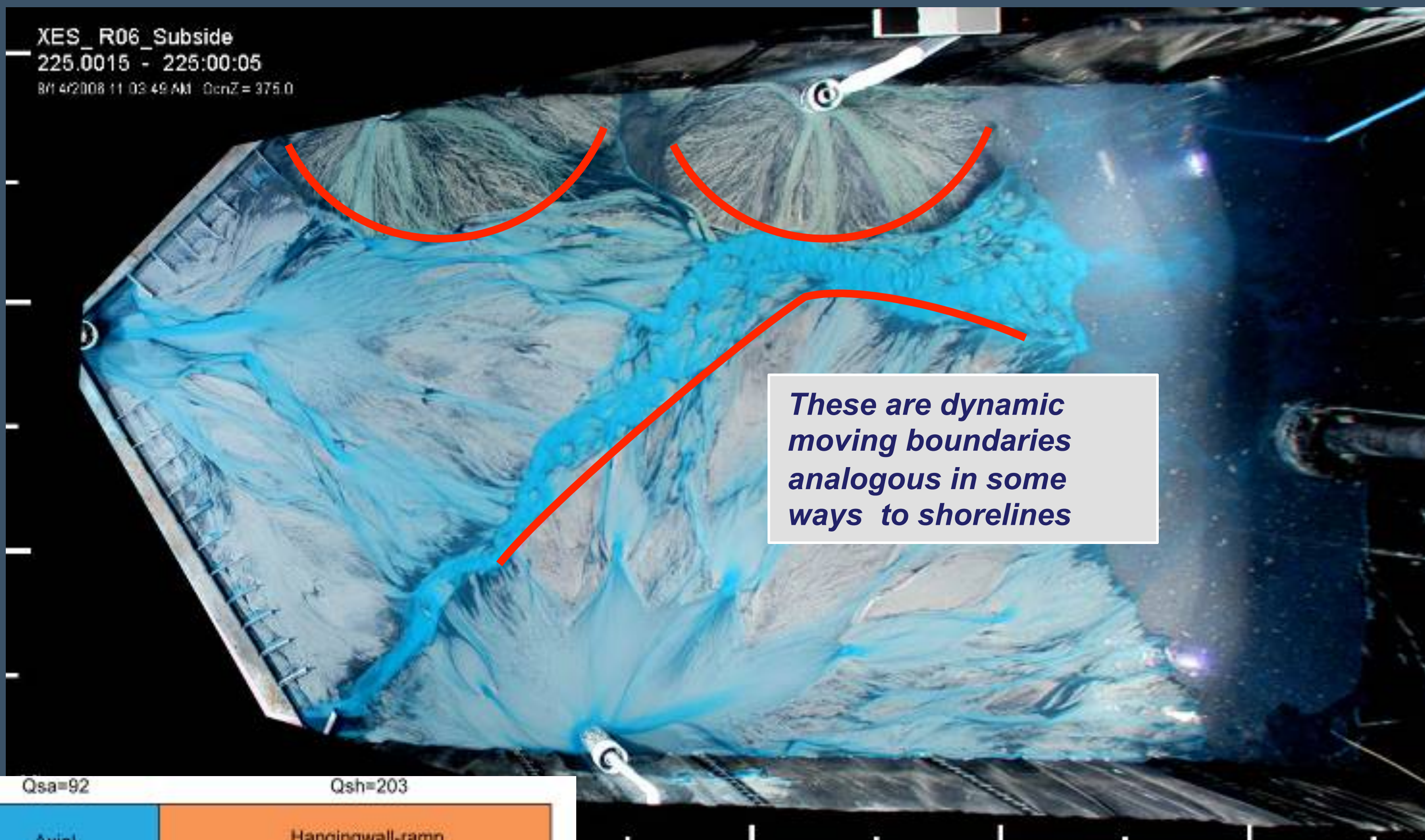



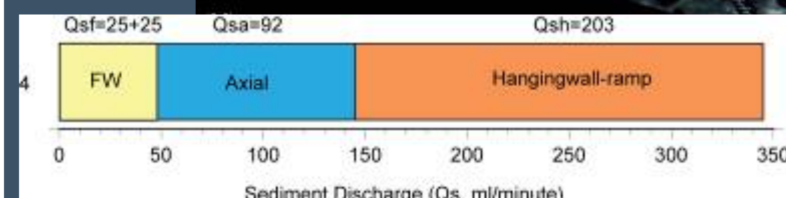
# Hanging-wall Stage 4 (225 hours)



# Hanging-wall Stage 4 (225 hours)




*Kim et al. 2011 Geology, in review*

# Eustatic sediment pumping: general idea

Sediment is transferred offshore during RSL falls

But it is preferentially retained in the fluvial system during RSL rise

So what is the *net effect* of eustatic cycling on sediment delivery to the deep ocean, and in particular, is there net ‘pumping’ effect associated with repeated eustatic cycling?

# XES 02 experiment

***Goal:***
***measure the stratigraphic effects of isolated & superposed eustatic cycles***

## run basics

### slow cycle

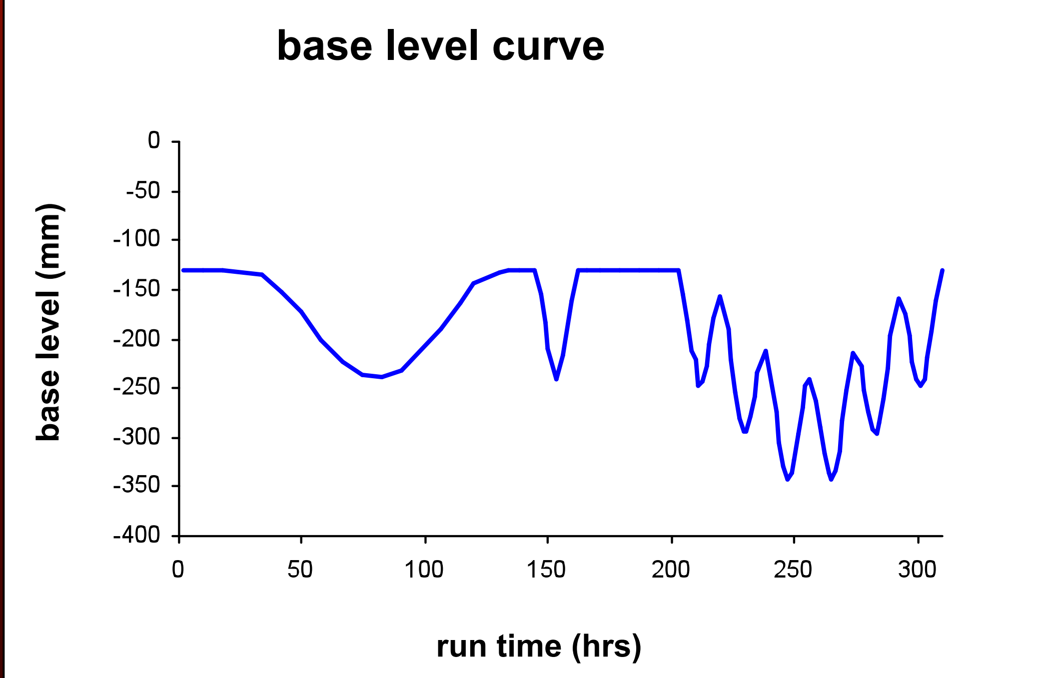
- symmetrical
- amplitude: 11cm
- duration: 108 hours

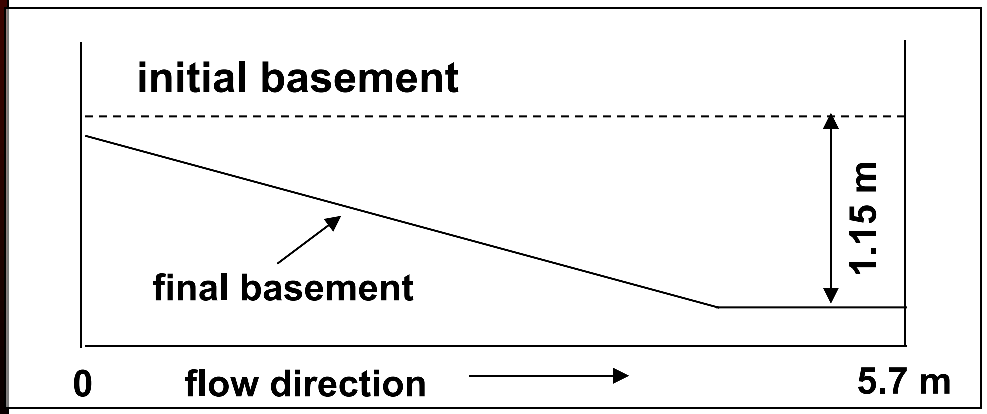
### rapid cycle

- symmetrical
- amplitude: 11cm
- duration: 18 hours

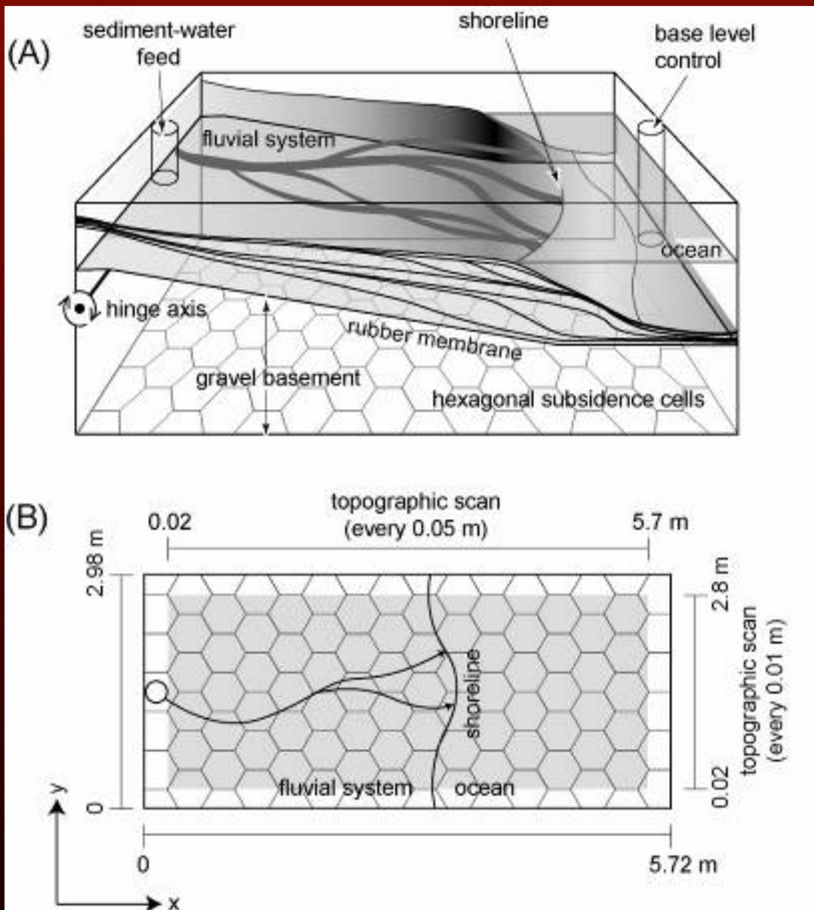
### superposed cycle

- 6 rapid cycles on one slow cycle



# XES 02



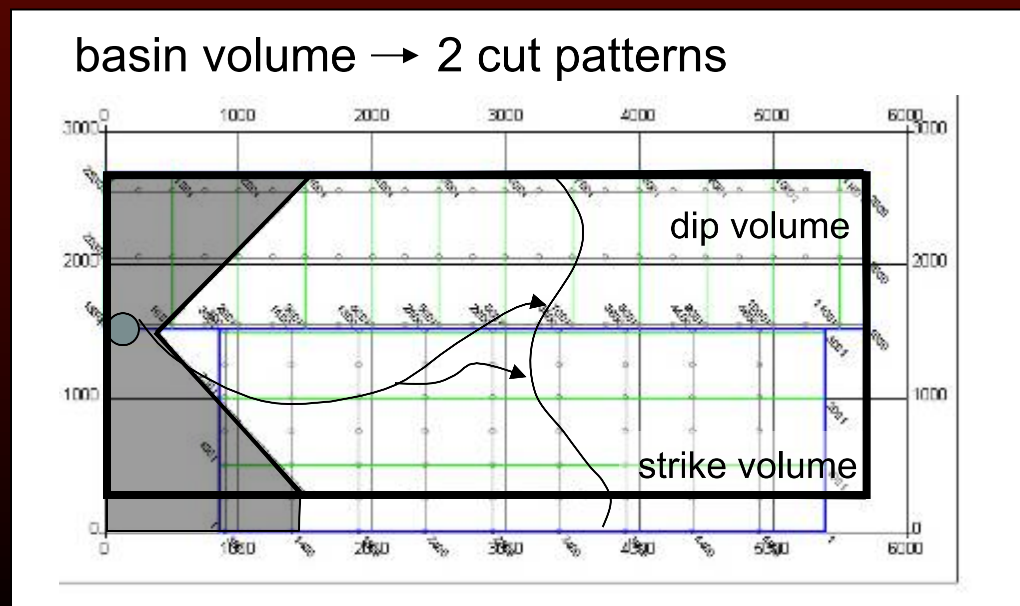

## data collection and preparation

90 usable scans of the entire experimental surface

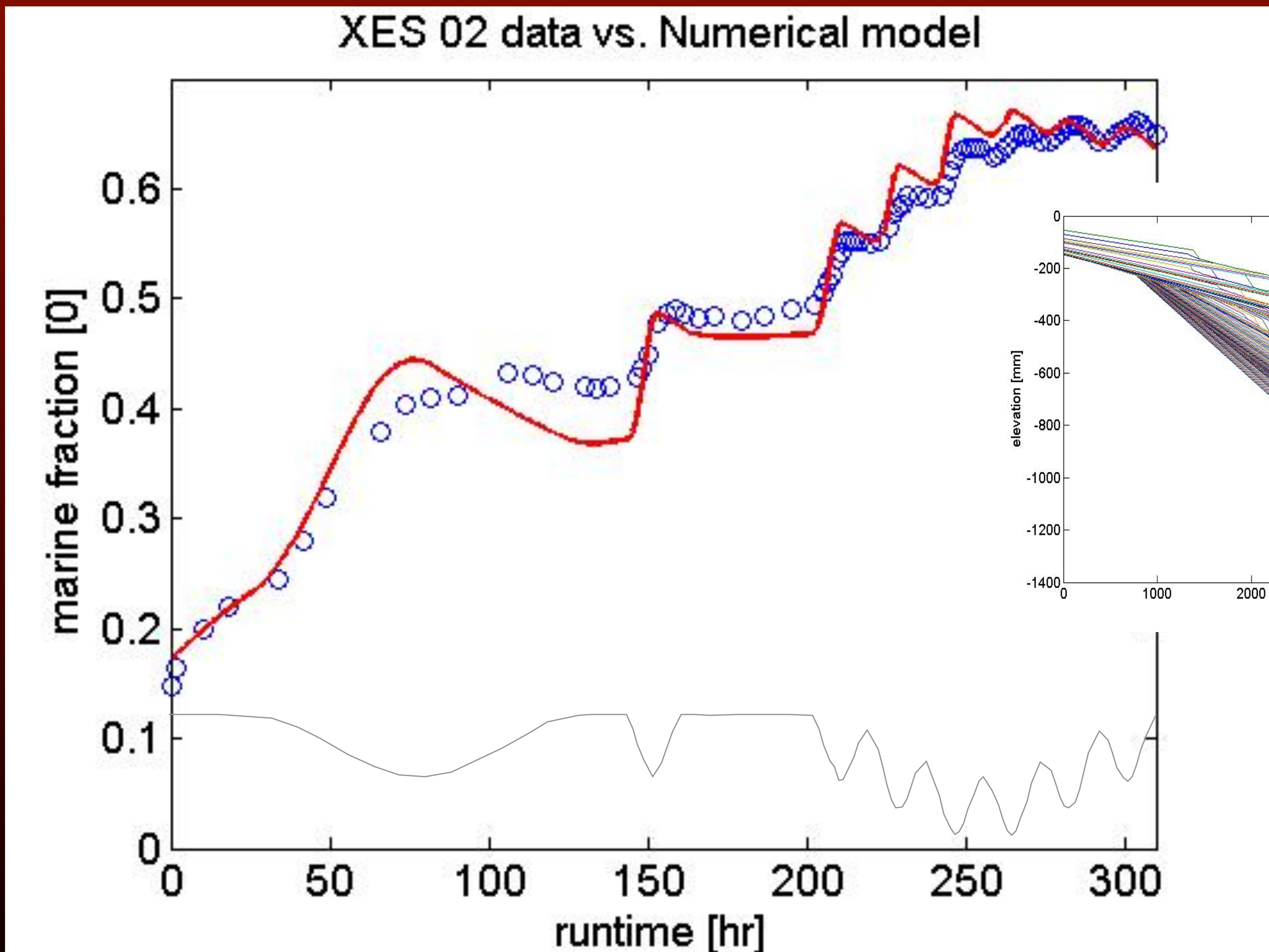
89 isopach maps

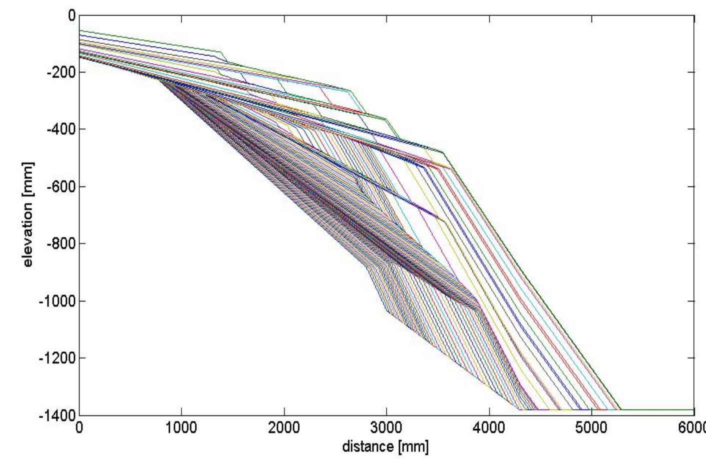
1 cm-resolution stratigraphic images

474 strike images
125 full dip sections



# Time-dependent cumulative marine fraction



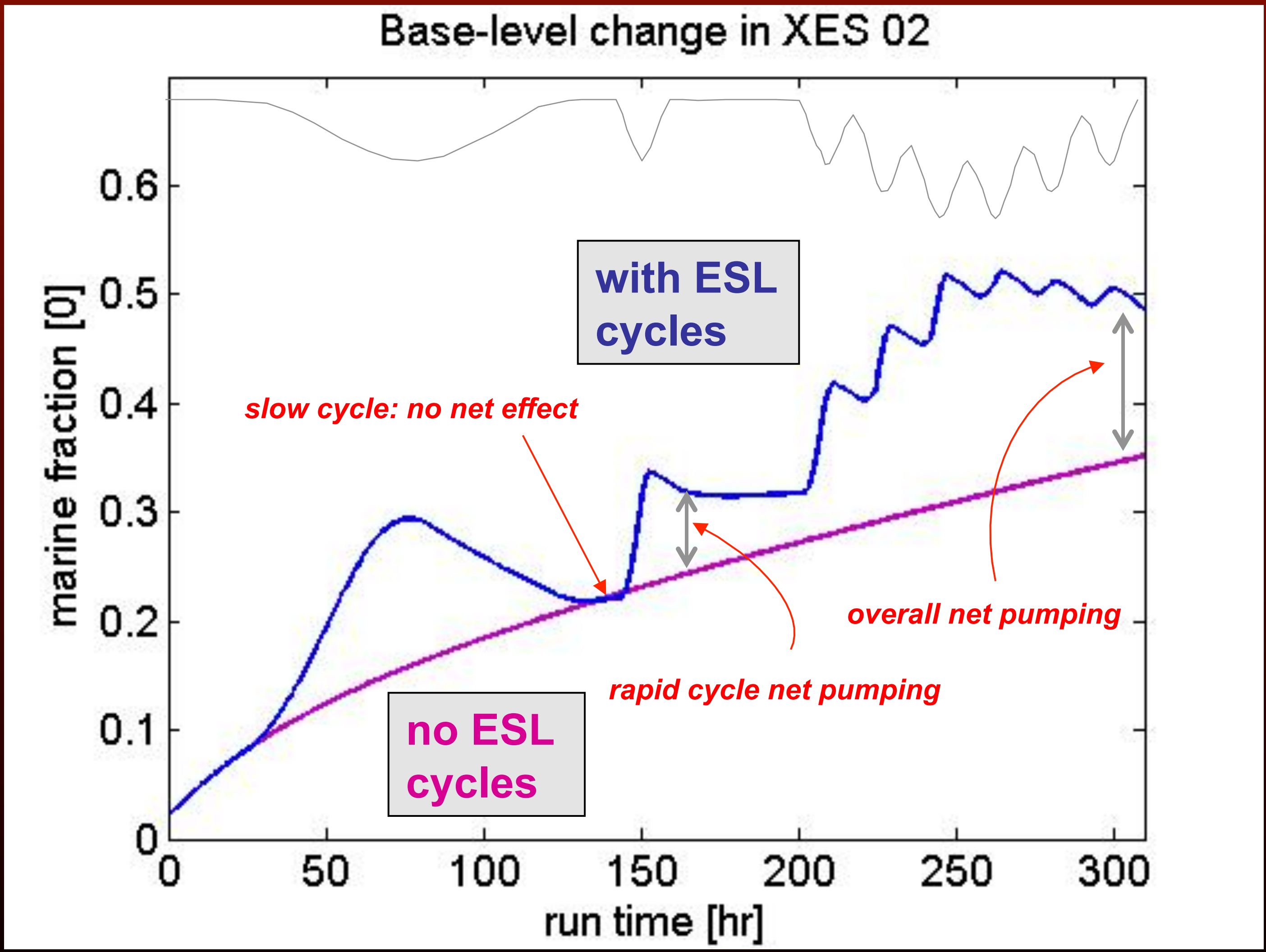




**The model:**

- **constant-geometry**
- **mass conserving**
- **2 moving boundaries**

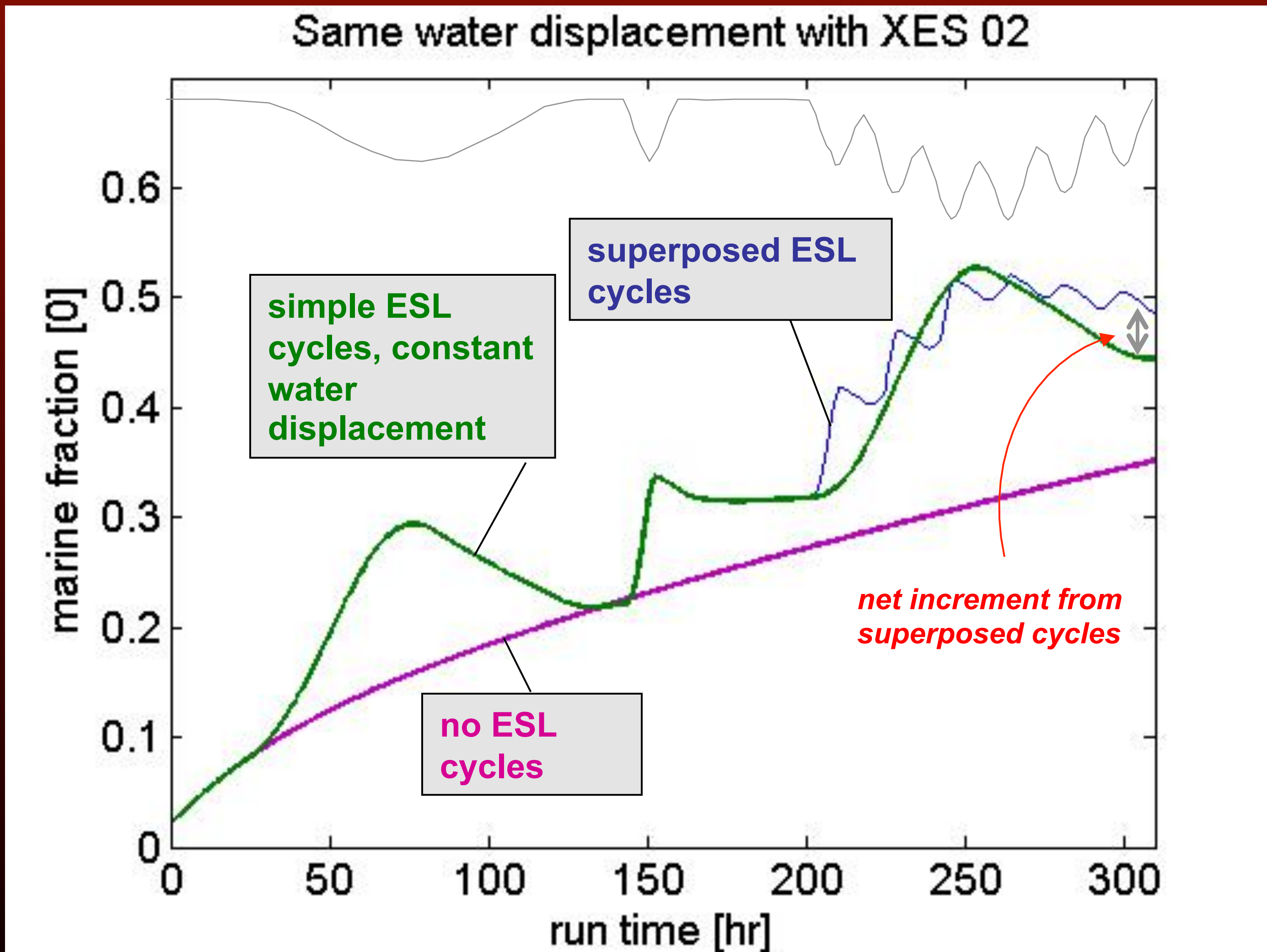
*Kim et al. 2009 SEPM Spec Pub 92*

# Time-dependent cumulative marine fraction



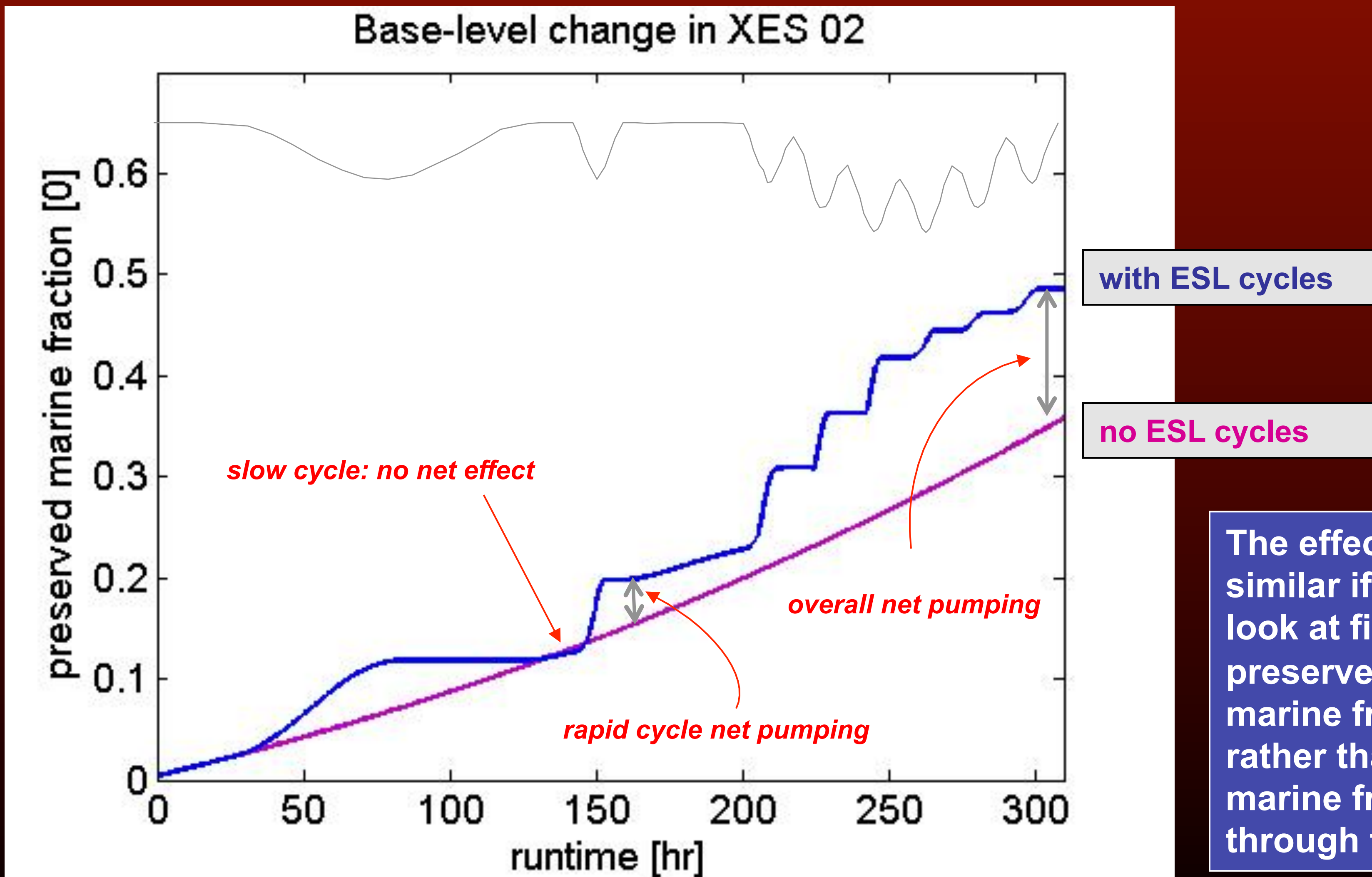

**To quantify the effect of eustatic pumping, we need a reference case: clinoform progradation with constant eustatic sea level (ESL)**

# Time-dependent cumulative marine fraction




Compare the case as run with superposed ESL cycles with the same scenario but with simple monofrequency ESL cycles, same water displacement

# Preserved cumulative marine fraction




**The effects are similar if you look at final preserved marine fraction rather than marine fraction through time**

# Summary of pumping effect

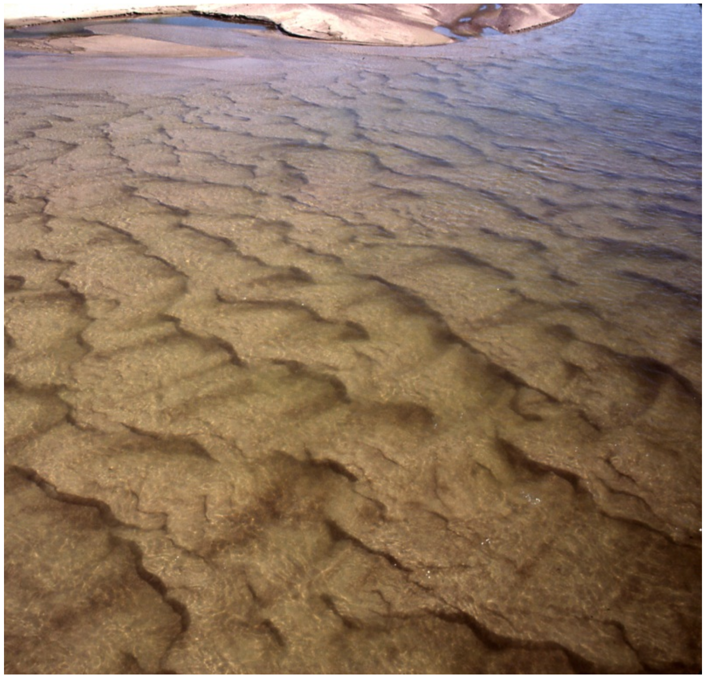
Little net pumping effect from ESL cycles that do not create net fluvial erosion – fluvial loss during fall is compensated exactly by fluvial gain during rise

Net effect including all slow and rapid cycles: increase final marine fraction from 0.35 to 0.49

Net effect of adding superposed high-frequency cycles: increase final marine fraction from 0.45 to 0.49

Net pumping effects become strong when sediment supply is phase-shifted relative to ESL (as originally proposed by Perlmutter et al.)

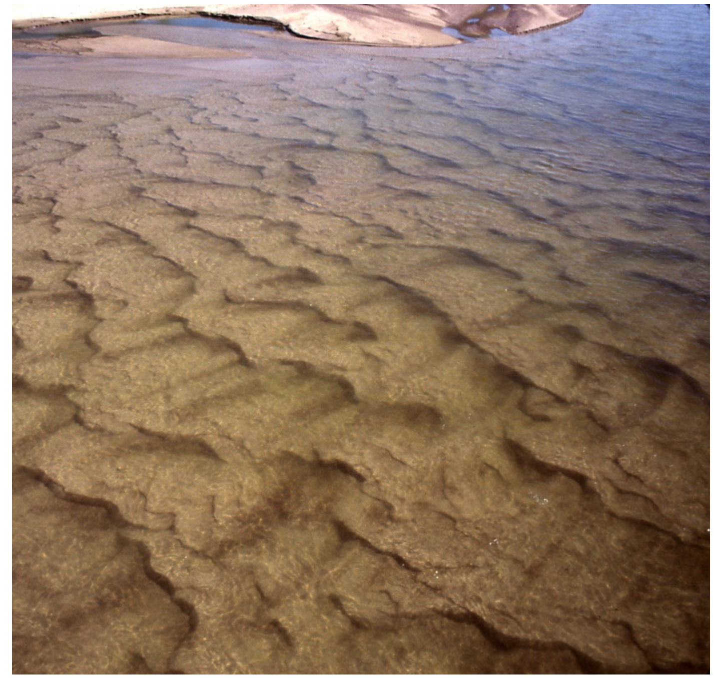
# Obliteration of supply signals by stick-slip sediment transport

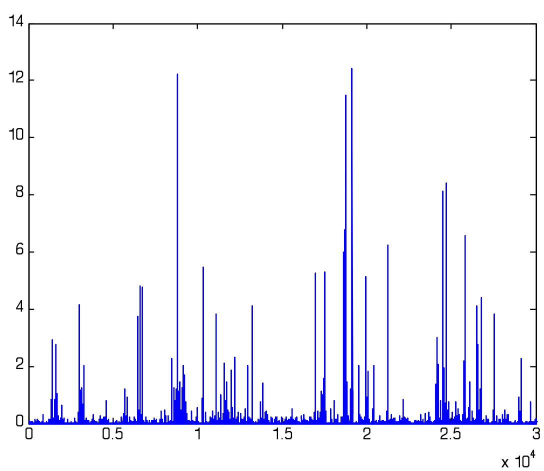
  

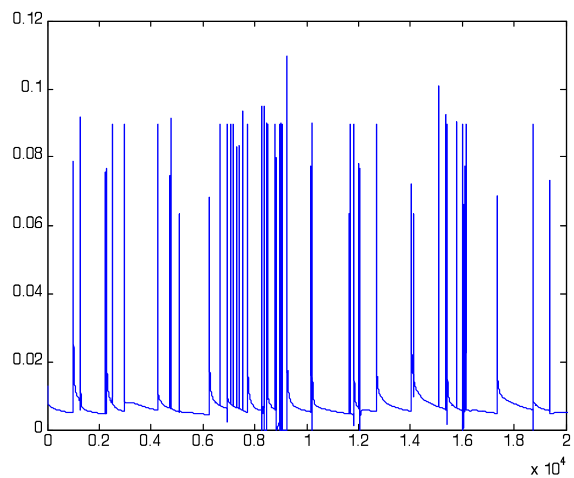
Key idea: threshold-dominated transport leads to sediment storage and release (stick-slip transport)

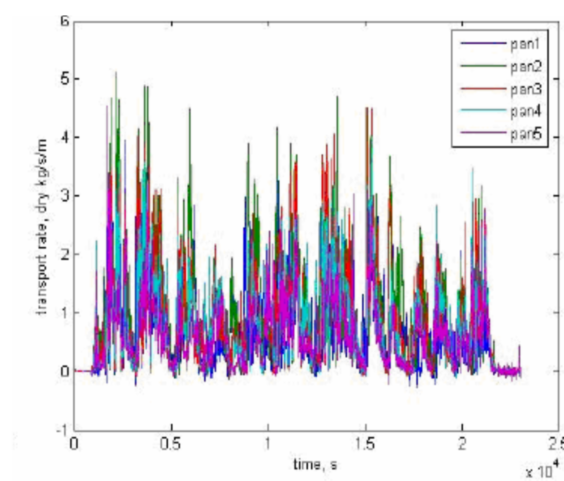
*Jerolmack & Paola 2010 GRL*

# Storage and release of sediment under steady conditions

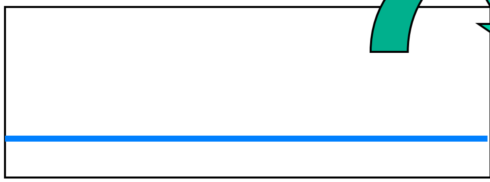




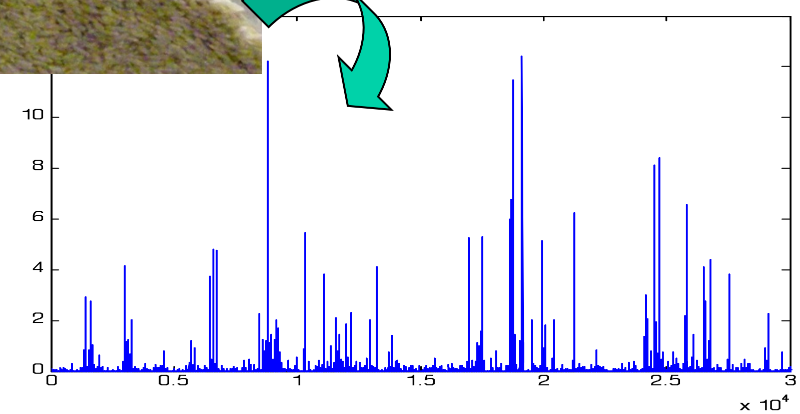
# Thresholds and randomness

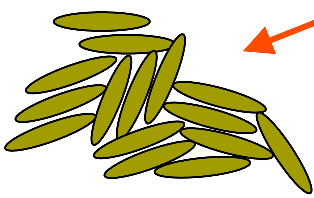


Steady input

Deposit of a rice pile is constructed from this output (avalanching and stick-slip)

Intermittent output

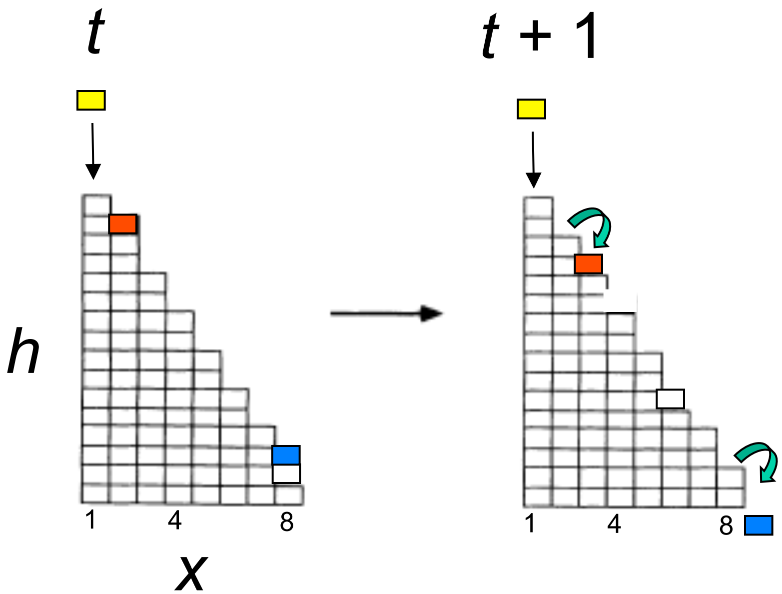


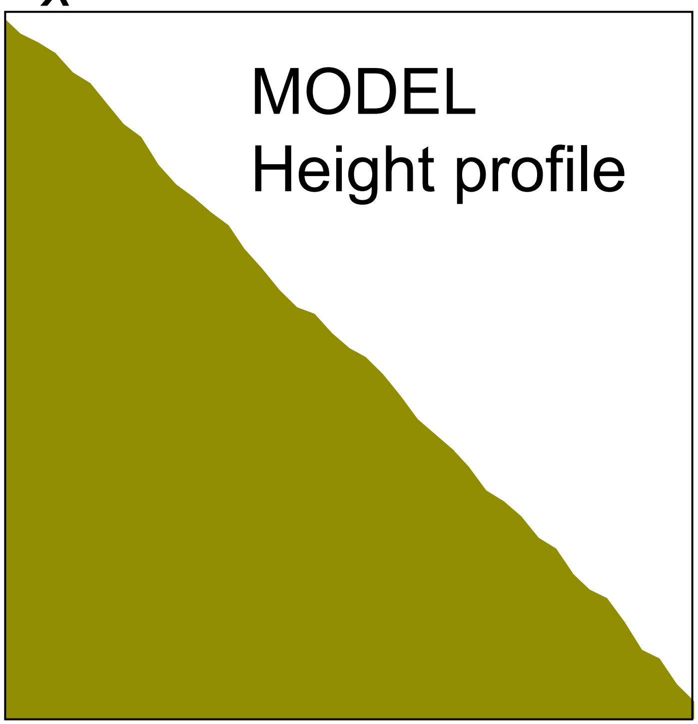
Steps of all sizes form in profile (storage)

Threshold exceedance causes failure (release)

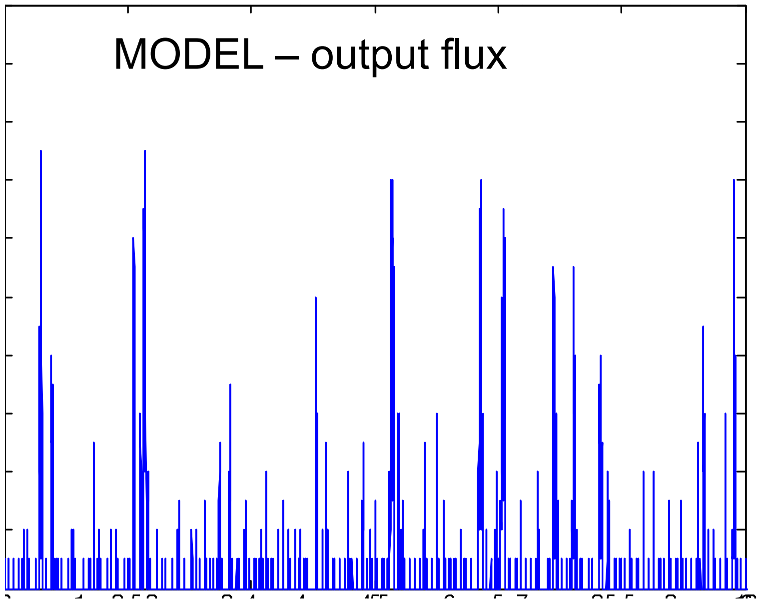
# Numerical Rice Pile [*Frette, 1993*]

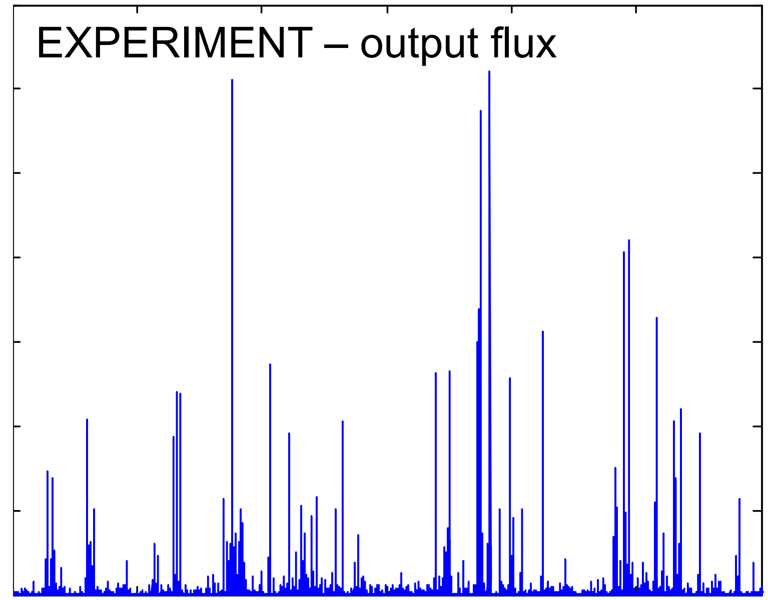


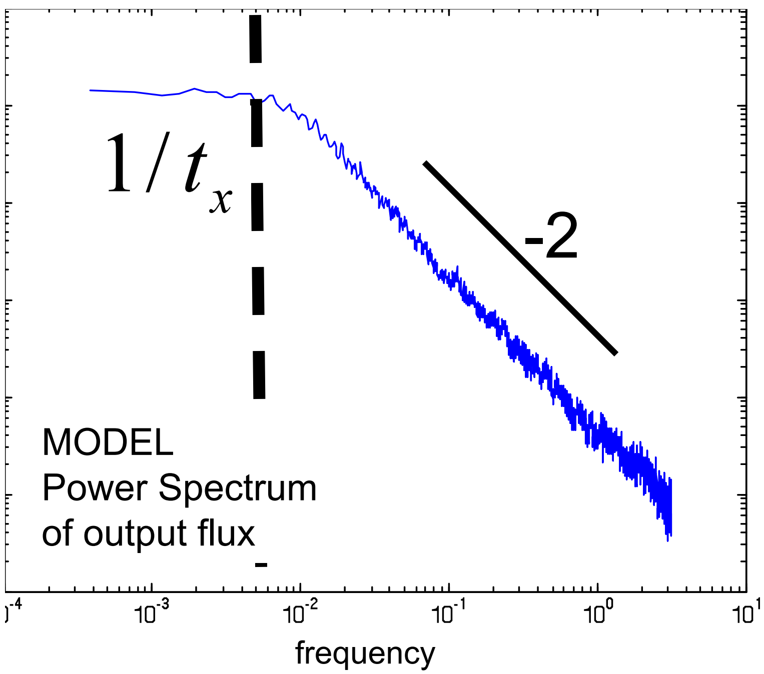

A simple, threshold-based toppling transport model




# Numerical rice pile - results

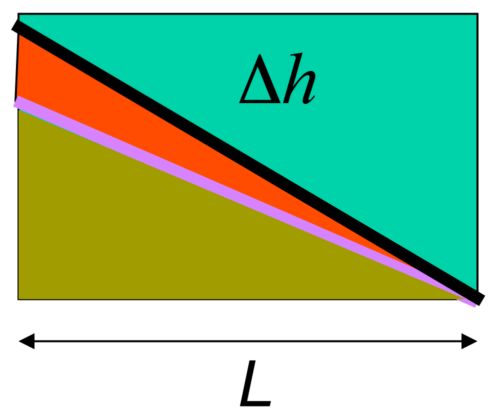


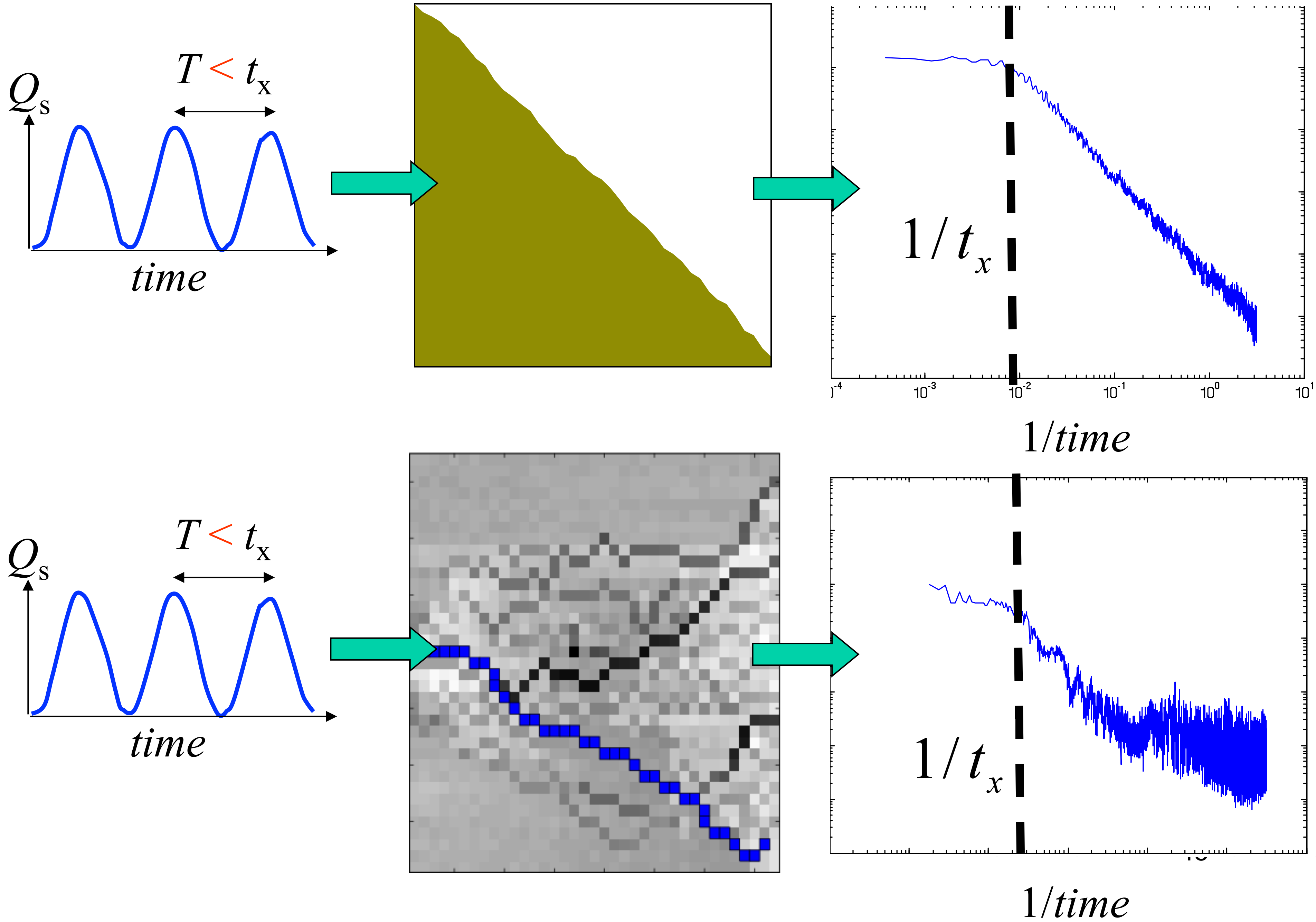

Fluctuations over a wide range of scales

Variability saturates at $t = t_x$

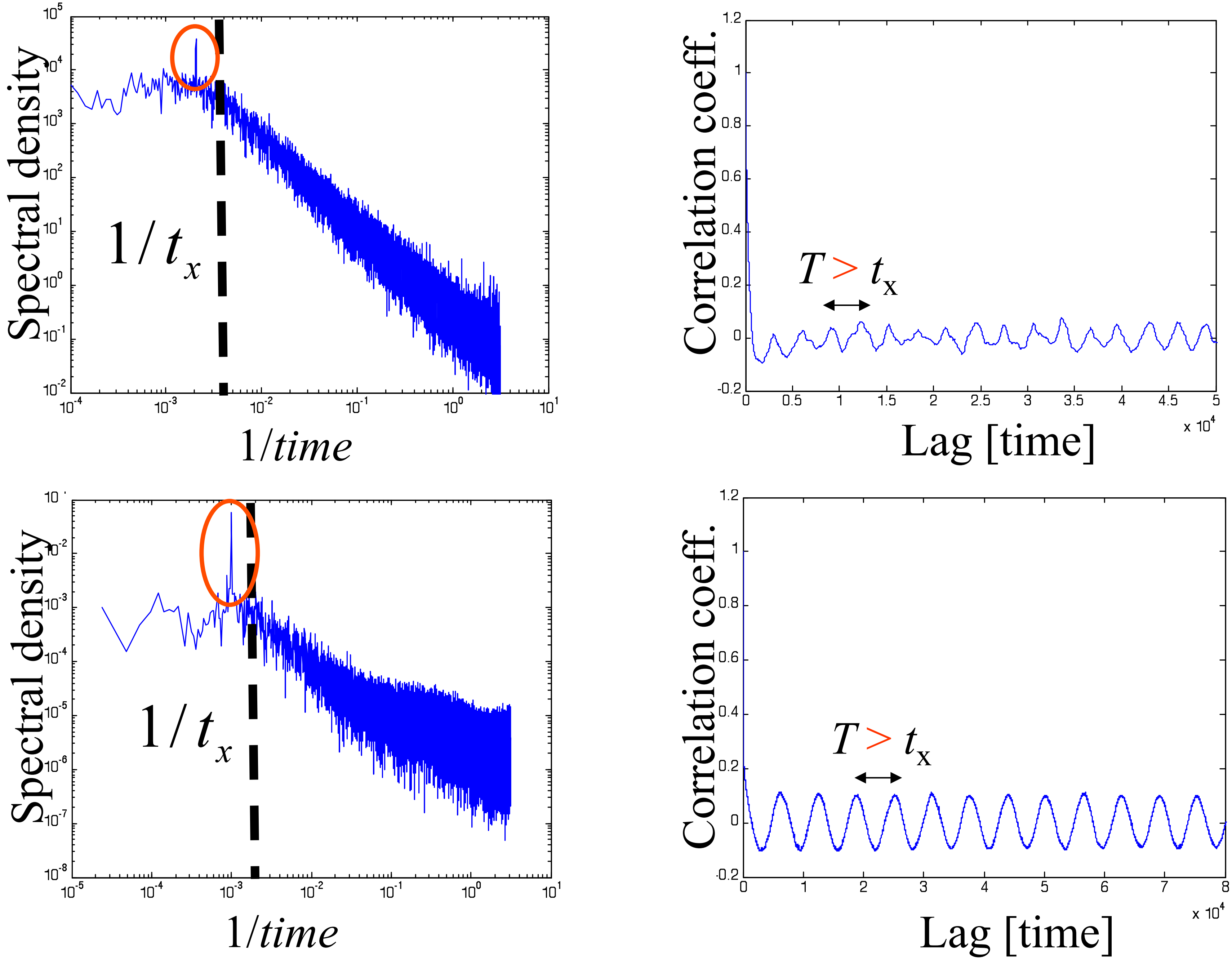



$$t_x \sim \frac{L(\Delta h)}{q_{\sin}}$$

# Stick-slip transport obliterates high *f* sediment cycles, but…



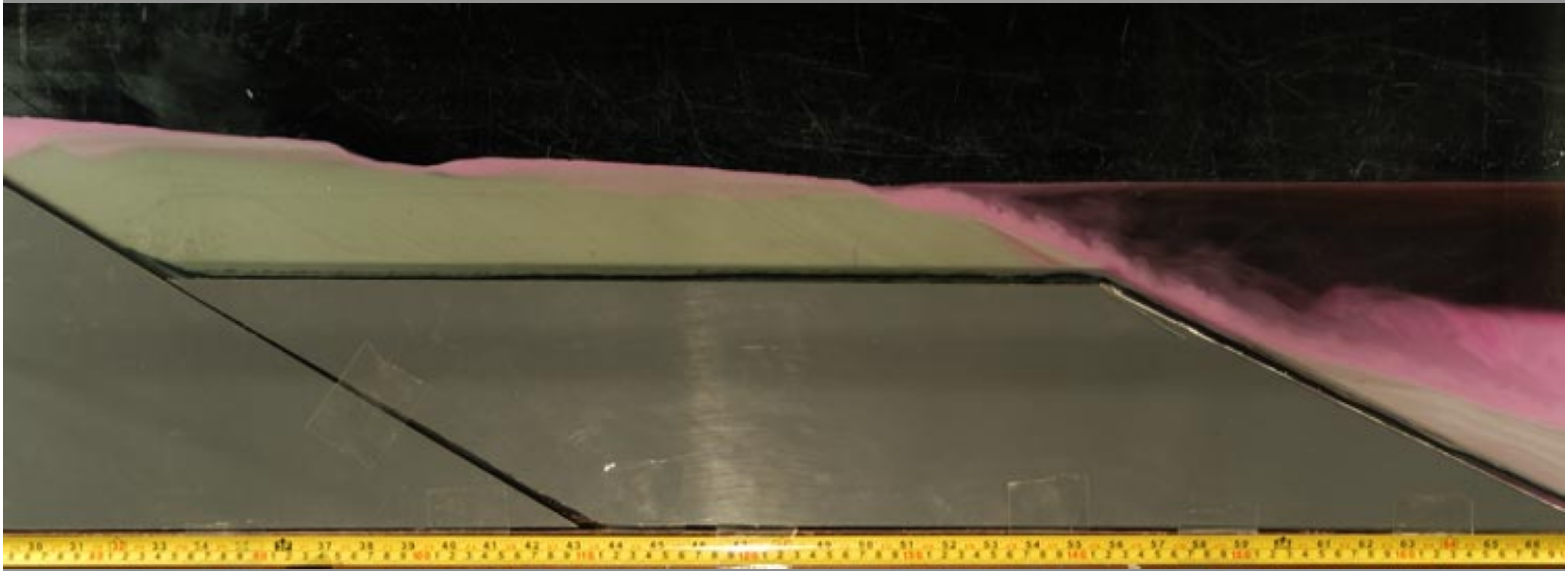
# Cycles with period larger than largest avalanche are preserved



# Summary: S2S ideas

- Mass balance as  first-order control on deposit architecture across the sink
- Mass balance and moving boundaries explain domains fed by multiple inputs
- Weak net offshore pumping from base level cycles under steady sediment supply
- Signal shredding by stick-slip transport

# How is fluvial sediment mass balance influenced by offshore conditions?



John B. Swenson[1], Jeré A. Mohr[1], Chris Paola[2,3], & Lincoln F. Pratson[4]

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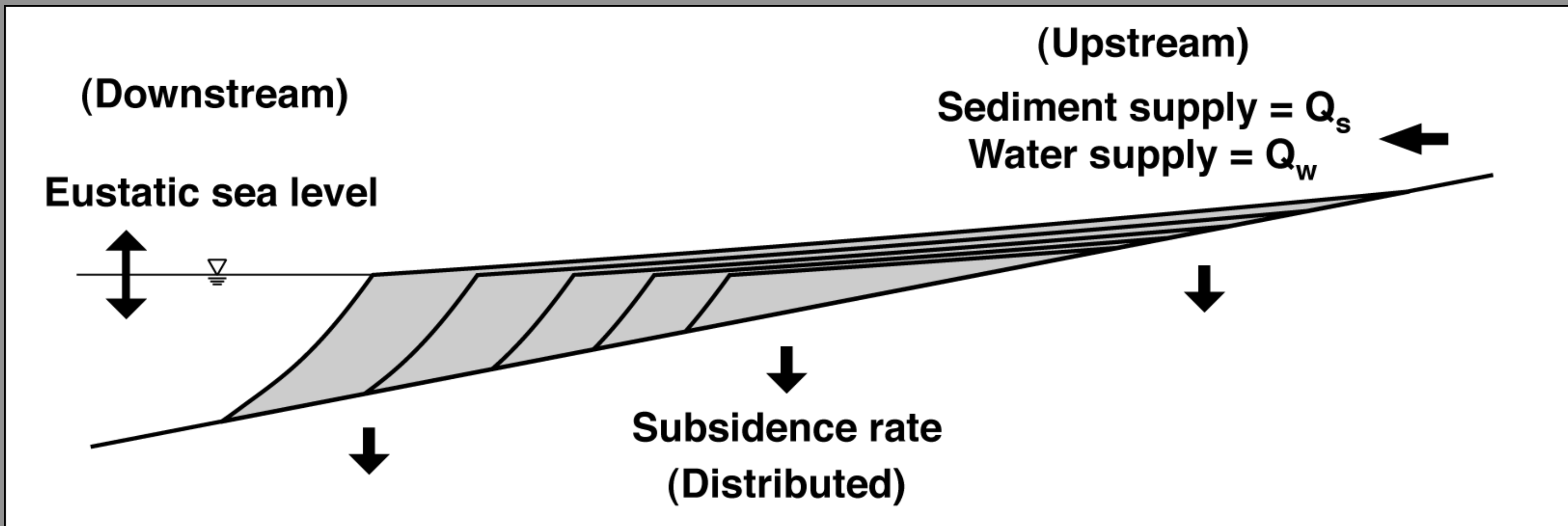
(4) Division of Earth & Ocean Sciences, Duke University, Durham, NC, USA

**Ask a fluvial geomorphologist what controls erosion and deposition in the fluvial system, and you hear things like:**

- Water discharge
- Sediment supply
- The ratio of the above
- Slope
- Grain size

*The answer involves local fluvial variables*

# Let's look at the problem another way…

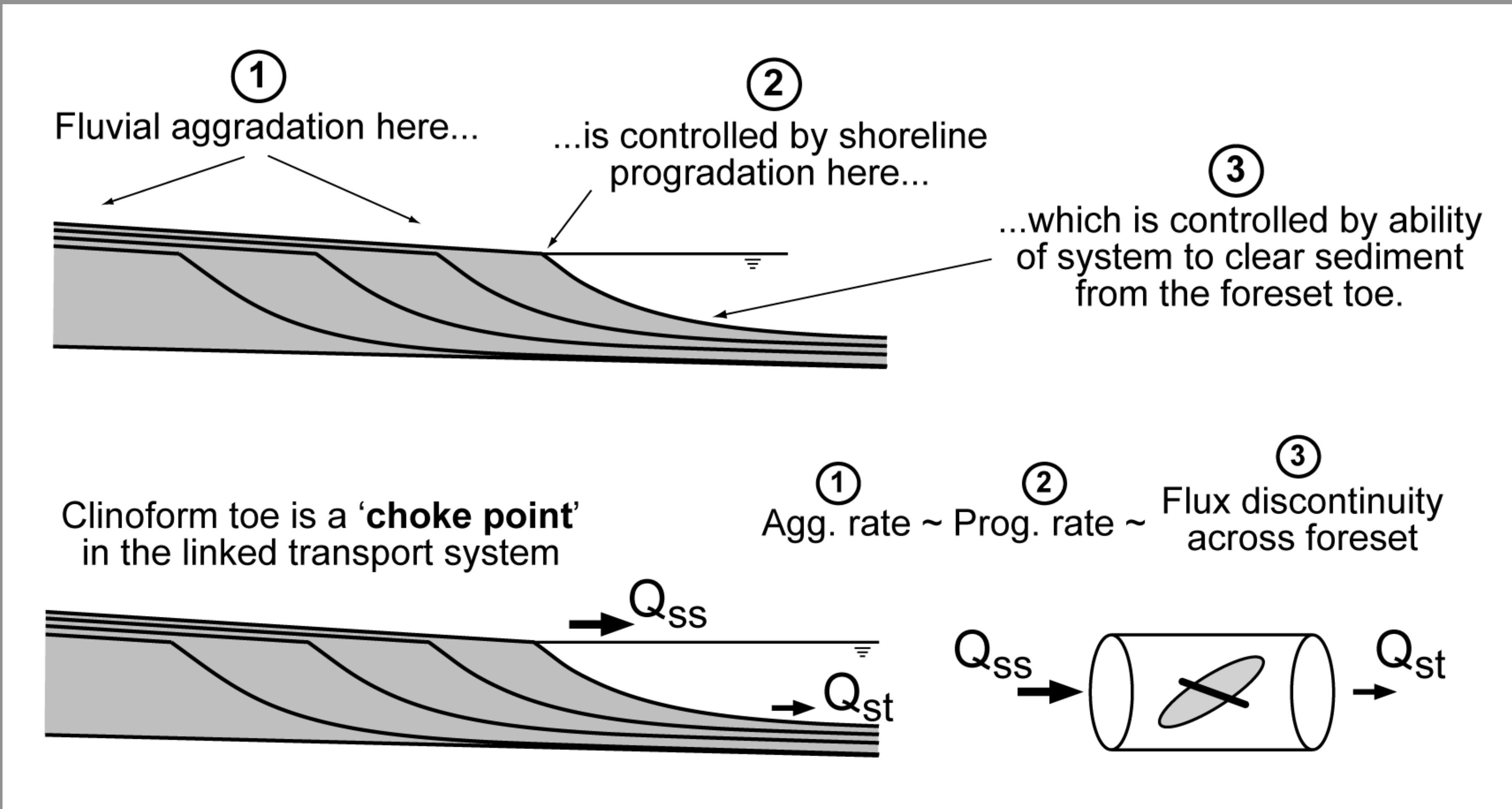



**Fluvial system is one part of linked depositional system**

**What role do non-eustatic, downstream processes play in controlling large-scale fluvial sedimentation?**

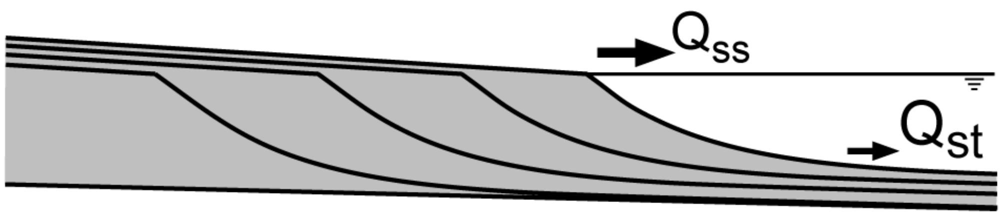
# Choke Points – A Conceptual Model

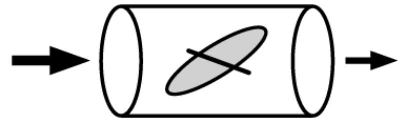
*Motivation: Fluviodeltaic clinoforms migrate as approximately self-similar waveforms.*



# Choke Points - Limiting Cases

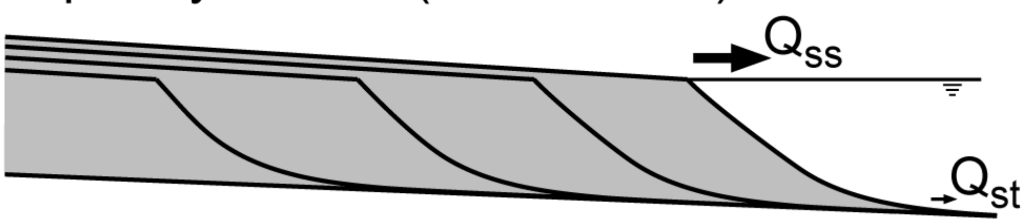
**A** General case: Partially choked

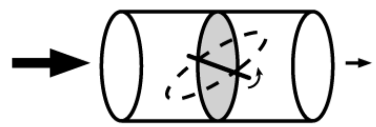


Prog. Rate ~ $Q_{ss}$-$Q_{st}$

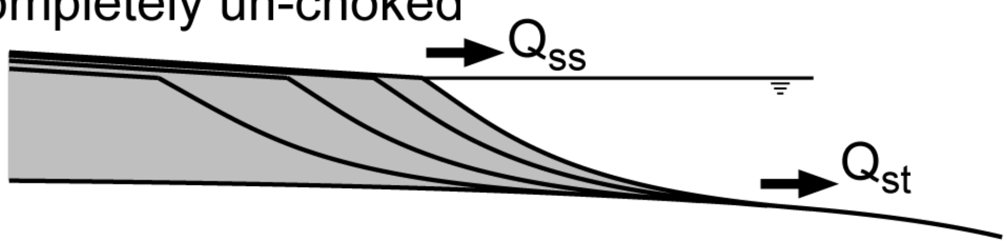
**B** Completely choked (Gilbert delta)

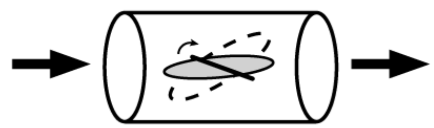


Prog. Rate ~ Max

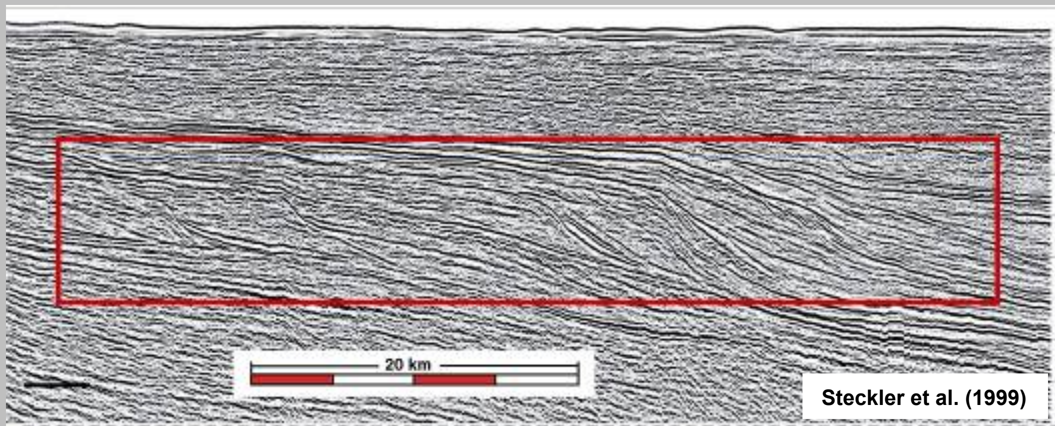
**C** Completely un-choked



Prog. Rate ~ 0

# Mechanisms for Affecting Flux at the Foreset Toe ($Q_{st}$):




## Pre-existing basin geometry

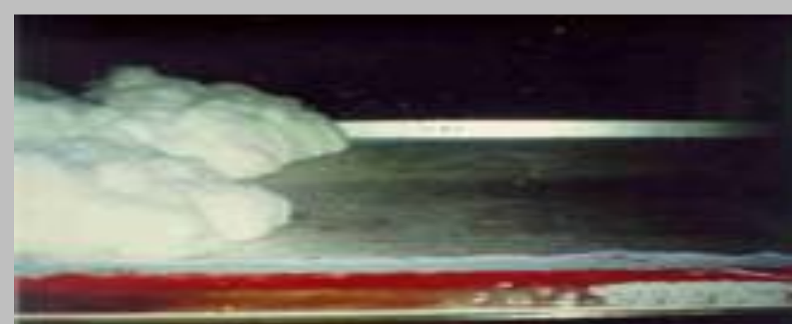
Clinoform toe "feels" underlying topography

## Alongshore transport

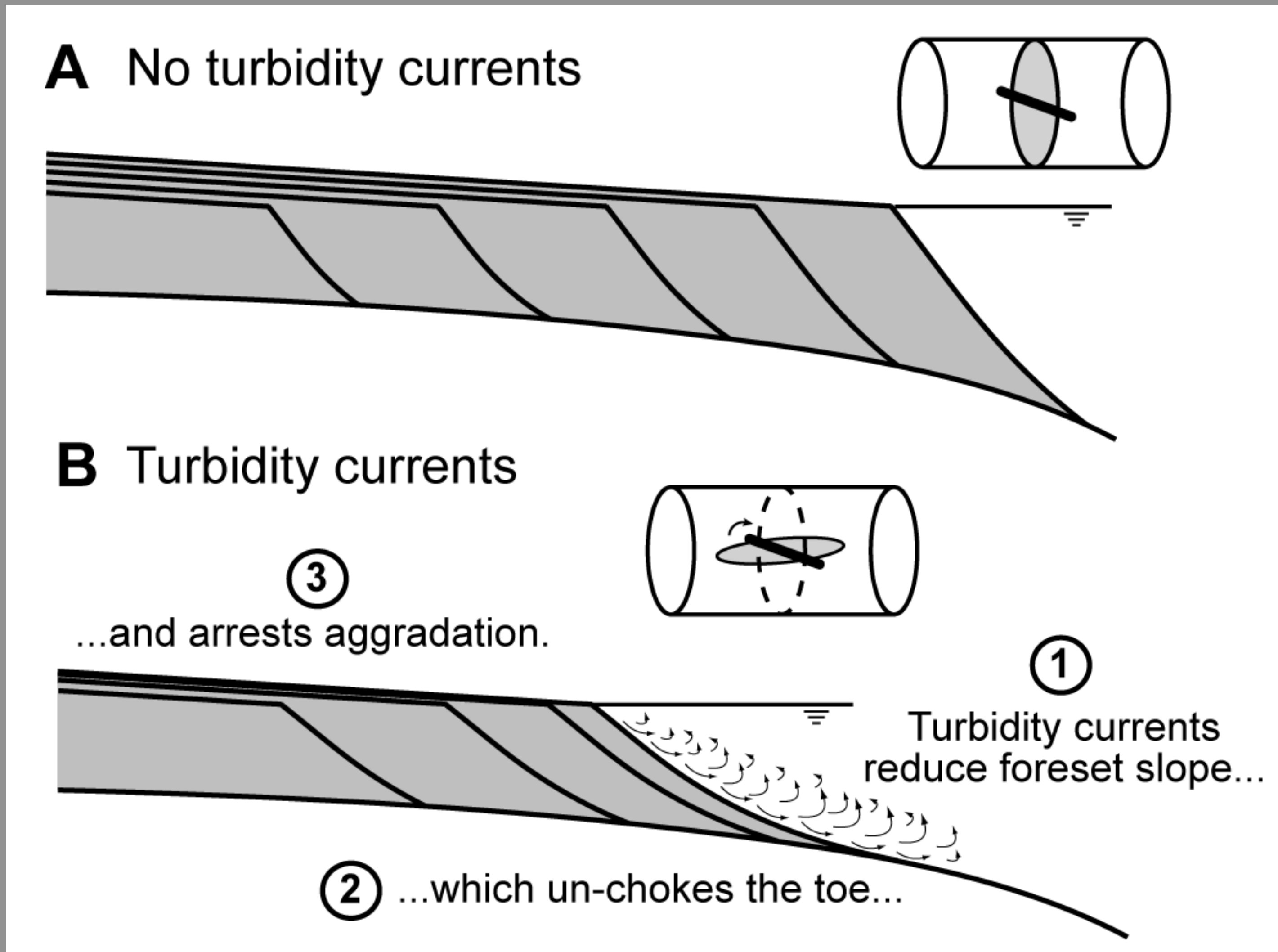
High wave energy can 'smear' fluvial sediment flux laterally, effectively un-choking toe

## Turbidity currents

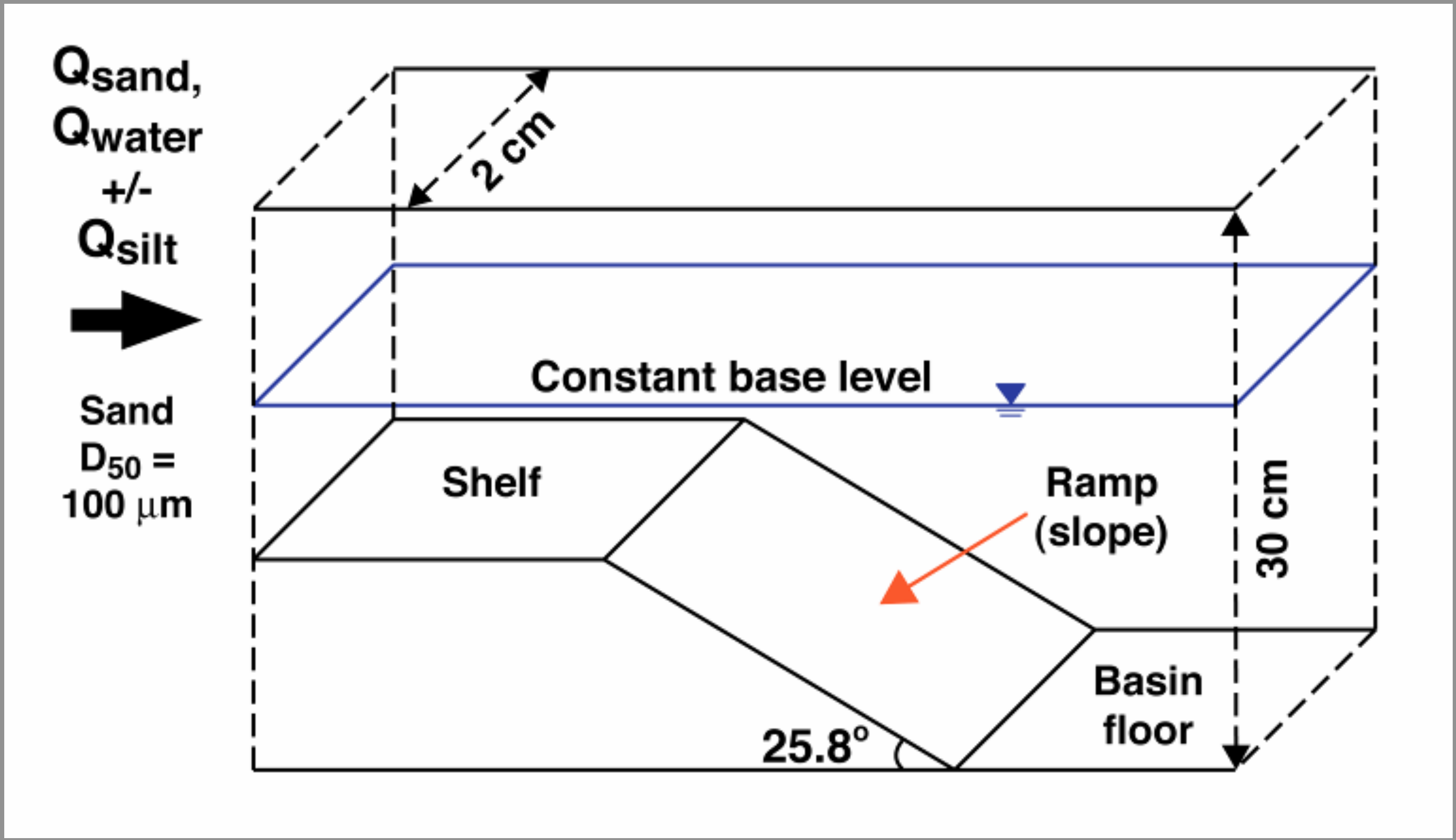
Sustained turbidity currents can reduce foreset slope (Kostic *et al*., 2002) and affect how foreset toe interacts with underlying topography



# Un-choking the clinoform system with a combination of underlying topography and sustained turbidity currents:



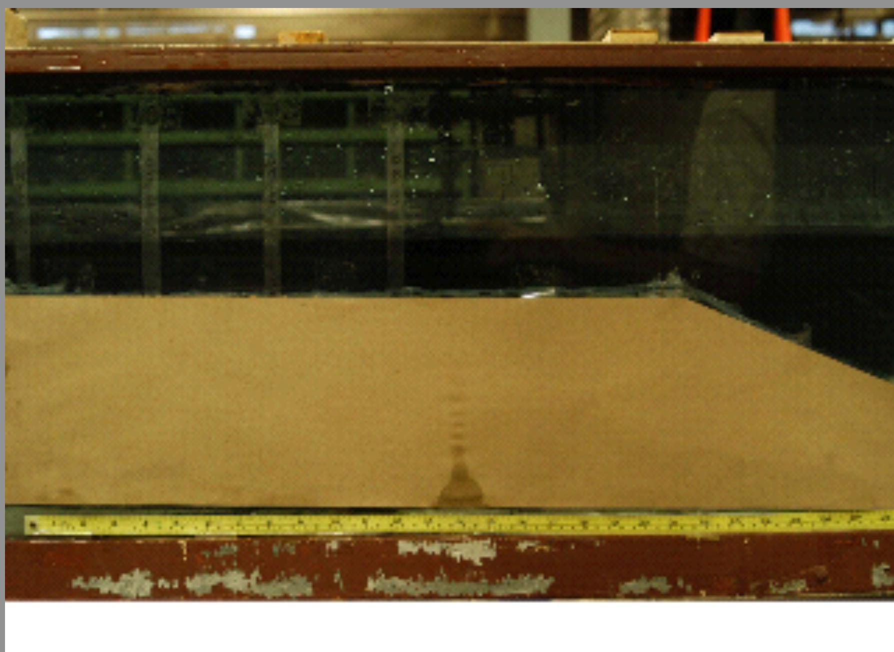
# Supporting flume experiments (J. Mohr):



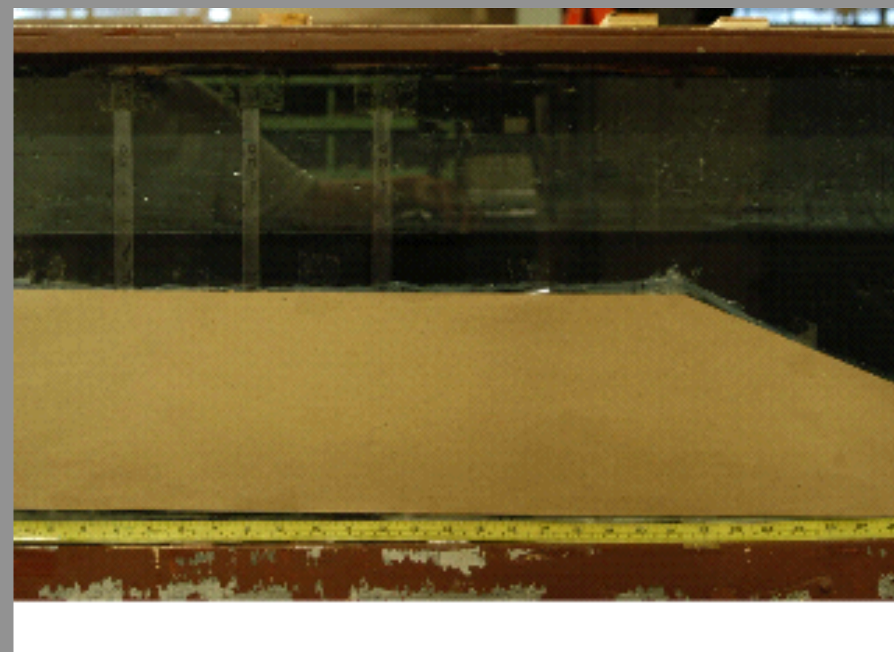

**Ramp angle ~ 26º ( ~ 20% < angle of repose)**

**Silt (40 µm) fed once clinoform toe reaches ramp**

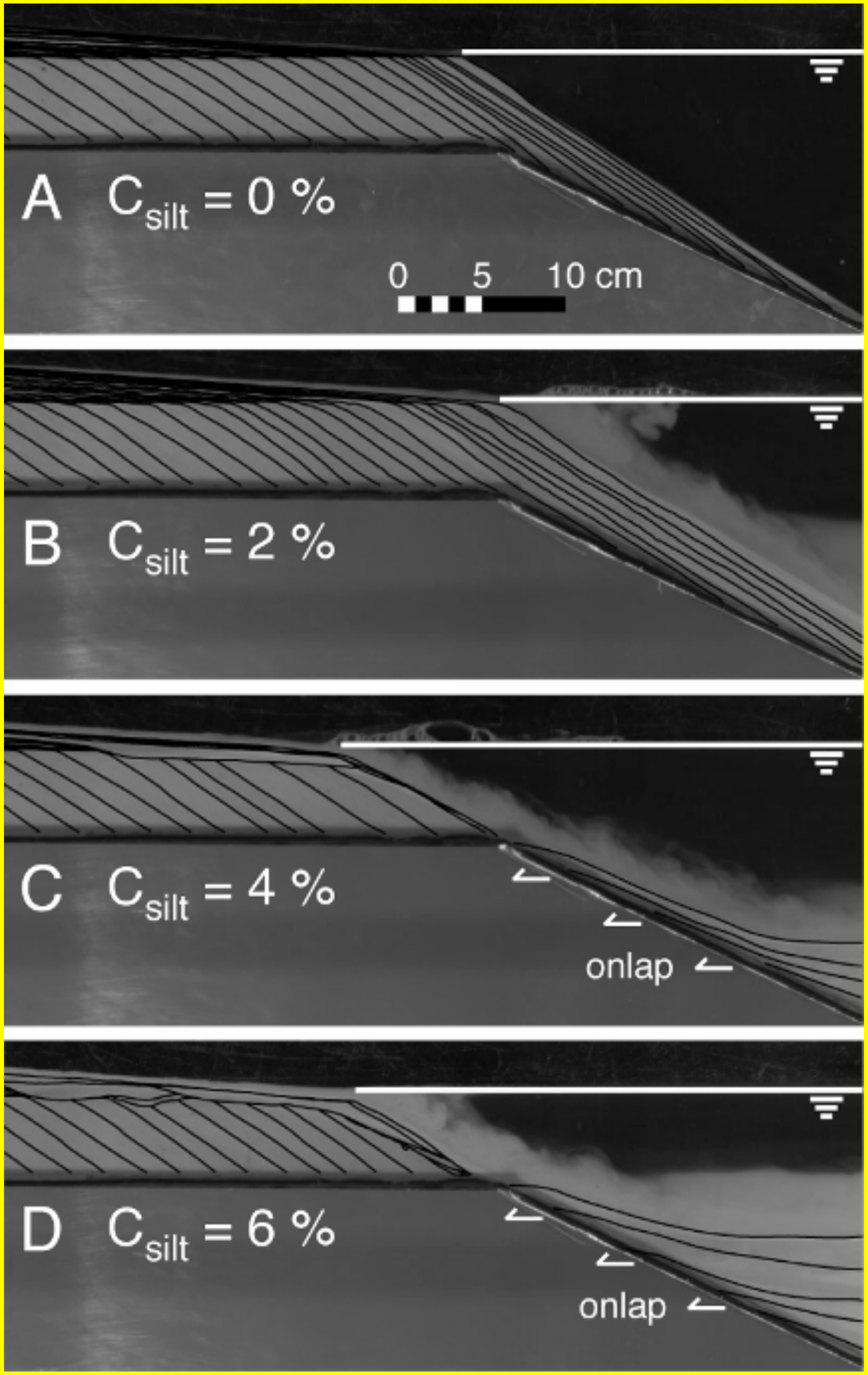
# Experimental Results – Sustained Turbidity Currents



No turbidity currents

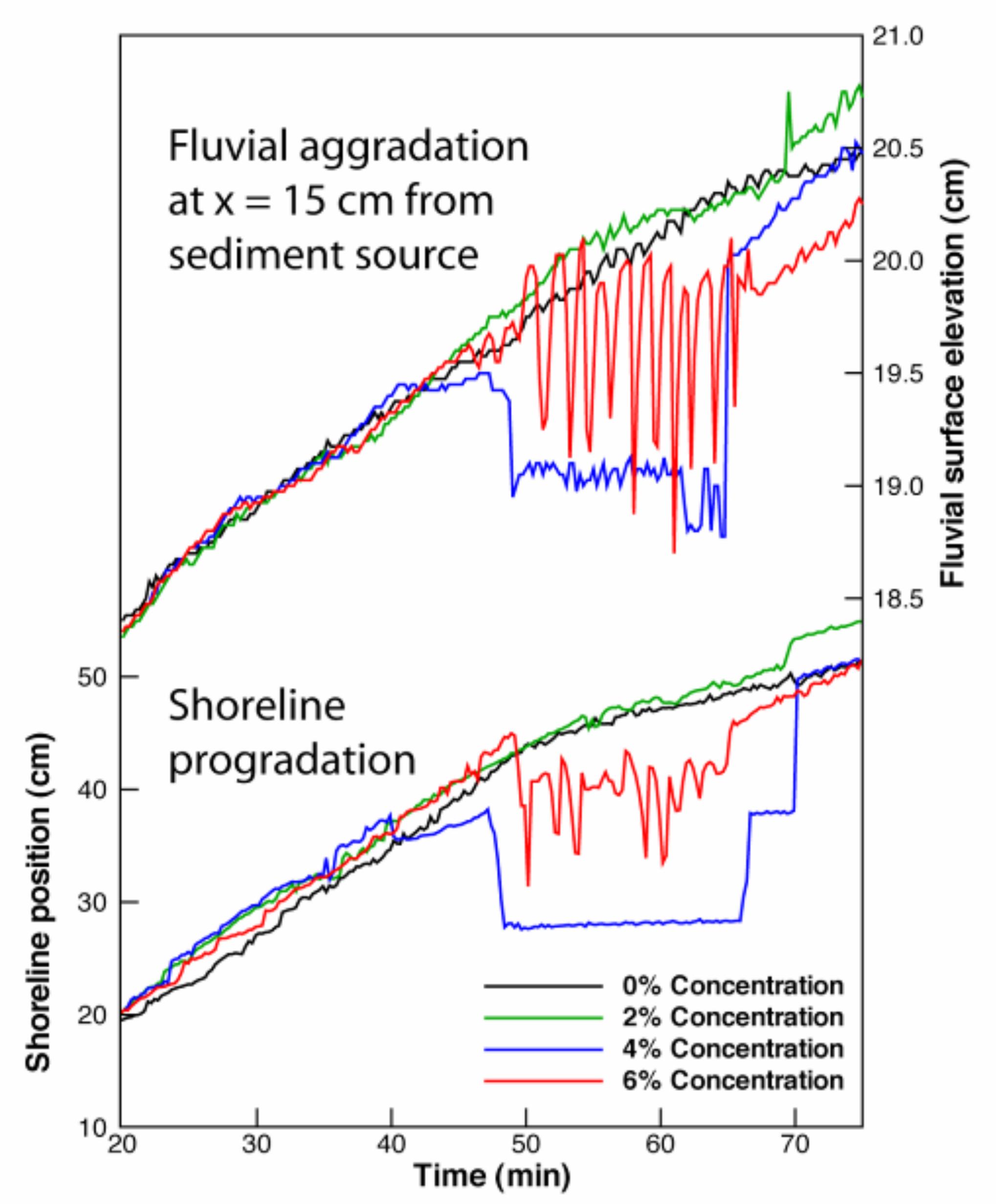


Turbidity currents




# Results: Sensitivity to concentration of suspended silt ($C_{silt}$)

# Results: Fluvial aggradation and shoreline progradation




**Fluvial aggradation:**

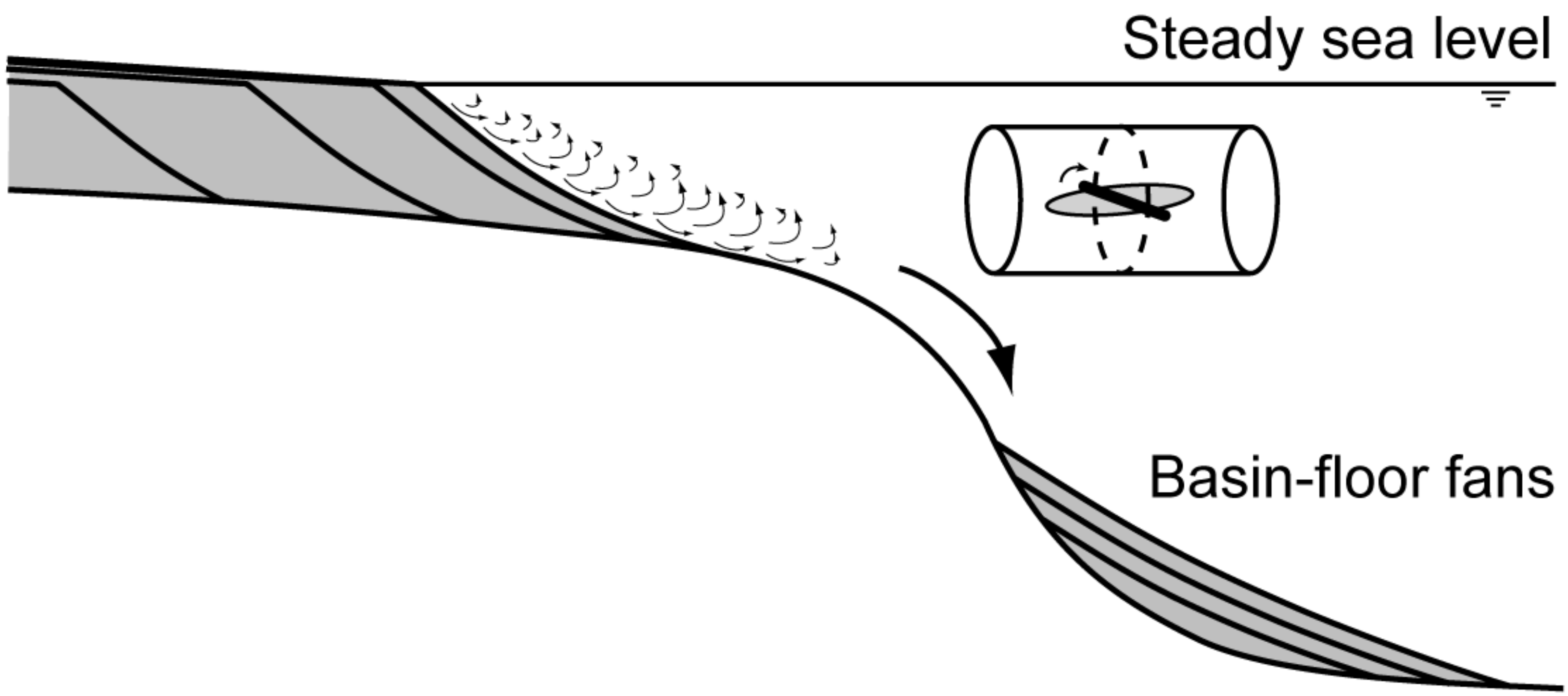
For $C_{silt}$ > 2%, reduction of foreset angle stalls system, resulting in fluvial bypass and incision

**Shoreline response:**

For $C_{silt}$ > 2%, reduced foreset angle un-chokes clinoform toe, thereby arresting progradation

# Stratigraphic implications:

Un-choking the clinoform toe provides a mechanism for sand bypass to deeper-marine environments w/o a change in sea level



## Conclusions:

- **Clinoform toe is a critical point (a 'choke point') in the linked depositional system**
- **Flux *discontinuity* across foreset controls shoreline progradation and large-scale *fluvial sedimentation***
- **Turbidity currents in combination with basement geometry can 'un-choke' the clinoform system**
- **Un-choking is a mechanism for *sediment transfer to deep-marine environments***