Temporal and Spatial Scales of Autogenic Dynamics in Linked Fluvial-Marine Systems*

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Abstract

The role of nearshore processes in controlling the plan-view morphology of delta lobes is relatively well understood. Less clear is the potential in linked transport systems for shallow-marine processes to communicate 'upstream' and thus modulate autogenic processes in the attached fluvial environment. Using a combination of theory and observation, we investigated one form of this communication by considering how wave-driven longshore transport might set the tempo of distributary-channel avulsion and the length scale of individual delta lobes. We developed a semianalytical mathematical model that couples the rudimentary dynamics of an avulsing distributary channel to diffusive longshore transport in the associated surf zone. In our simple model, sand is sequestered in distributary channels and the shoreface; the unlimited mud supply fills space on the floodplain and seaward of the shoreface. Our analysis spanned a wide range of wave energy, sediment supply, and subsidence rate. In progradation-dominated model deltas, the effect of delta lengthening with time was a reduction in sand flux at the channel terminus, thereby causing a progressive shift to a more wave-dominated state. As a result, both the channel residence time and the length scale of individual lobes (extent of smearing) increased throughout progradation. For aggradation dominated deltas, where the bulk sedimentation rate balances the subsidence rate and the mean shoreline position is stationary, our analysis points to a rich interplay between fluvial and nearshore processes that controls the overall size (radius) of the equilibrium delta. As wave energy increases, longshore smearing of fluvial sand input increases, thereby reducing channel aggradation rate and hindering avulsion; consequently, individual lobes are larger and system sequesters less sand in channel belts on the delta plain, thereby providing proportionately more sand to maintain the equilibrium

shoreface at a larger overall delta radius. In addition to theory, we present data and preliminary interpretations from a suite of natural deltas; at first order, these data support our model predictions for the variation in avulsion frequency and lobe size with wave energy. It would seem that under appropriate conditions, the tail (longshore transport) can, in part, wag the dog (distributary channel).

Selected References

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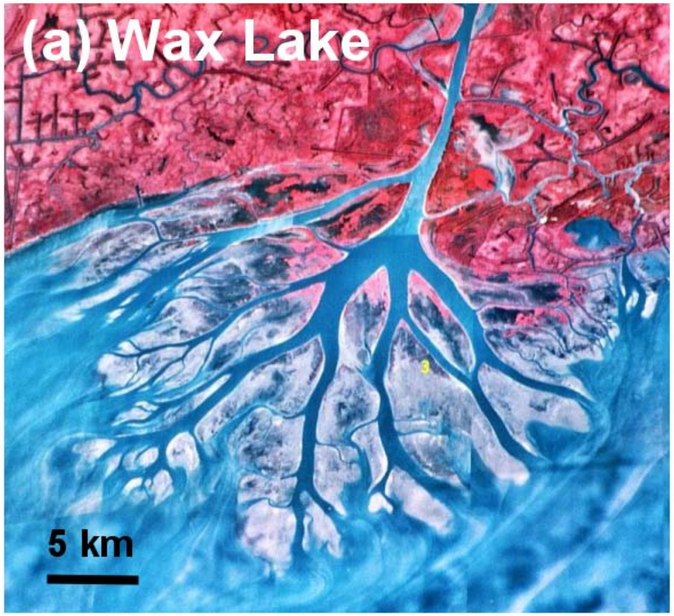
Motivation:



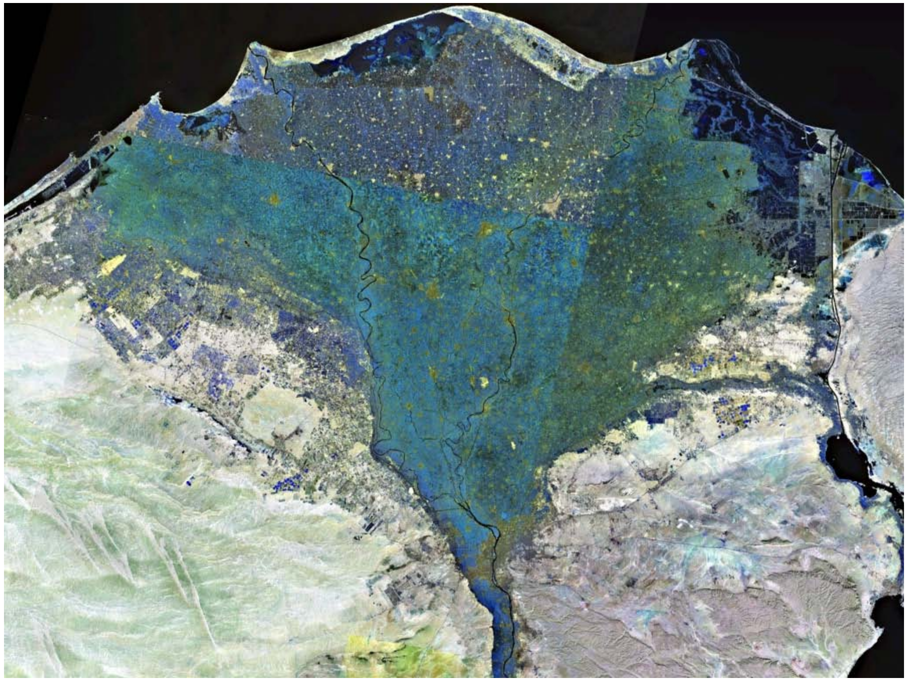
River-dominated deltas (multi-generational, bifurcating networks) are **rare**

…visually striking, very interesting, nice limiting cases, but…

Most deltas are **wave influenced**

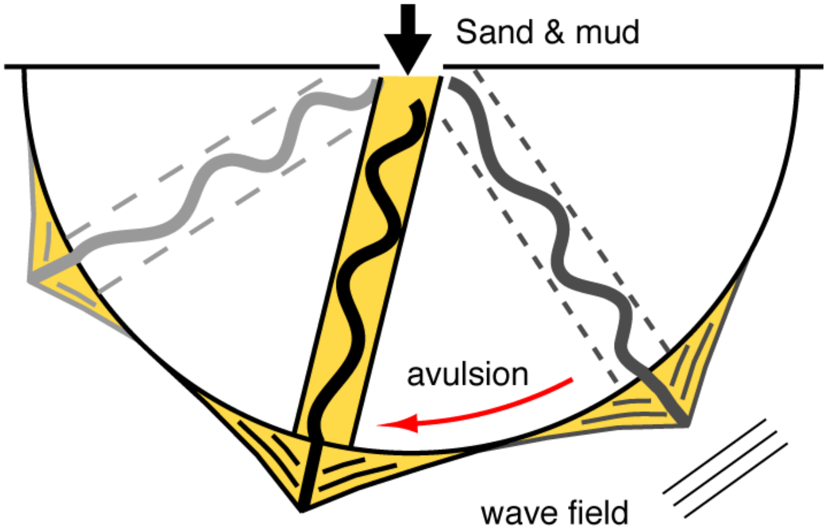
Particularly true of non-**highstand** times (ancient systems)

Role of waves in sculpting bulk delta morphology is well established



Question: To what extent do waves control autogenic dynamics in deltas?

Basic **model building block**: Nodal avulsion & ‘lobe’ construction



Model Approach:

Use **scaling relations** to predict space and time scales (lobe size, avulsion frequency) in terms of allogenic forcing

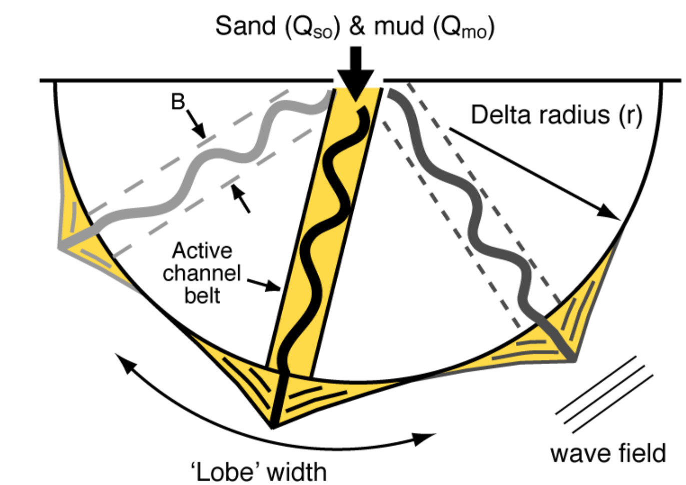
Maintain consistent level of complexity

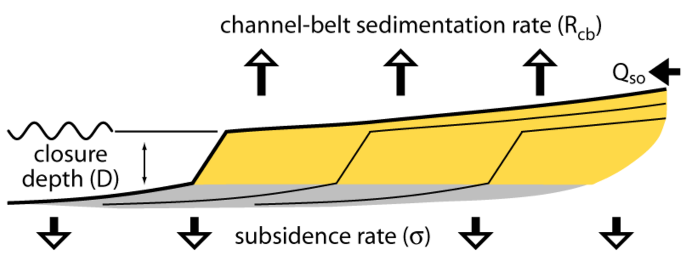
Note: Model is based (loosely) on the idea of ‘ensemble averaging’

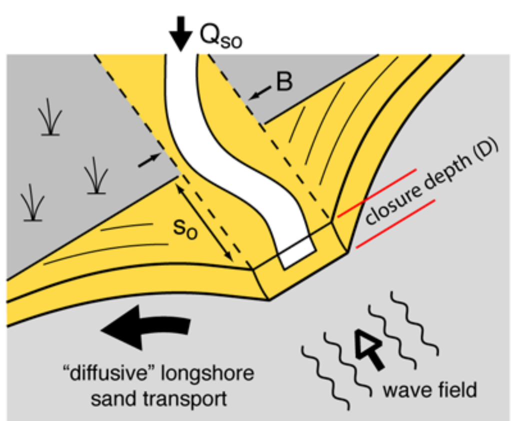
- Does not track evolution of a single delta
- Captures instead the behavior of an **average** delta

Model is ***very simple*** but allows rapid exploration of parameter space

Caution: Results should not be interpreted too literally







Model basics:

Single distributary channel / nodal avulsions

Sand limited ($Q_{so} << Q_{mo}$):

Sand → **channel** belts; **lobes**
Mud → floodplain; 'offshore'

Mud deposition rate ~ subsidence rate (σ)

Dynamic equilibrium: Bulk radius is steady

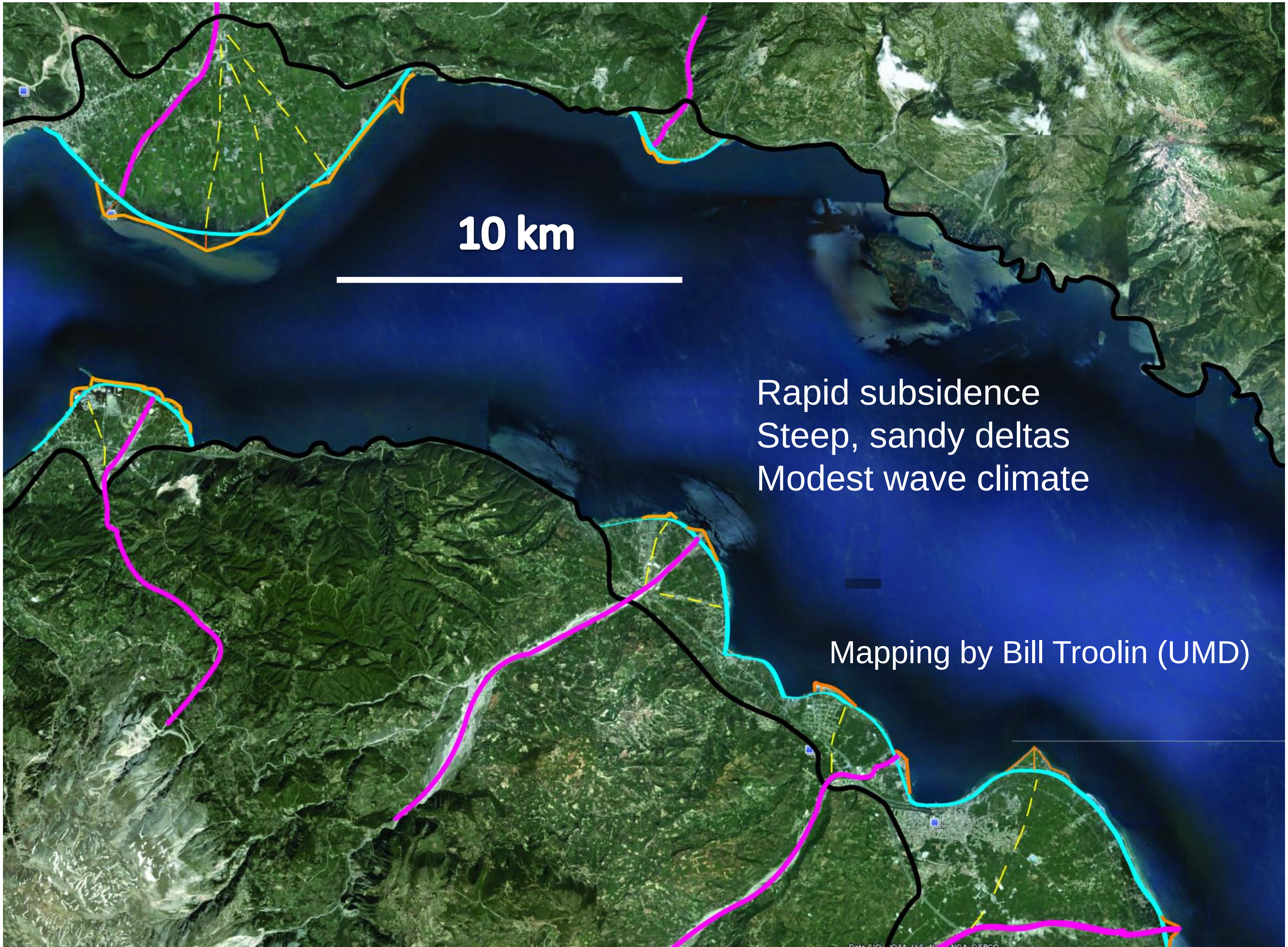
Wave climate:

Suppresses bifurcations
Longshore transport is diffusive (κ)
κ = *f*(wave height, intermittency)

<u>Four Unknowns:</u>

1. Channel residence time (τ)
2. Equilibrium delta radius (*r*)
3. Channel deposition rate (R_{cb})
4. Channel scars (N_s)

“Type” locality: Gulf of Corinth

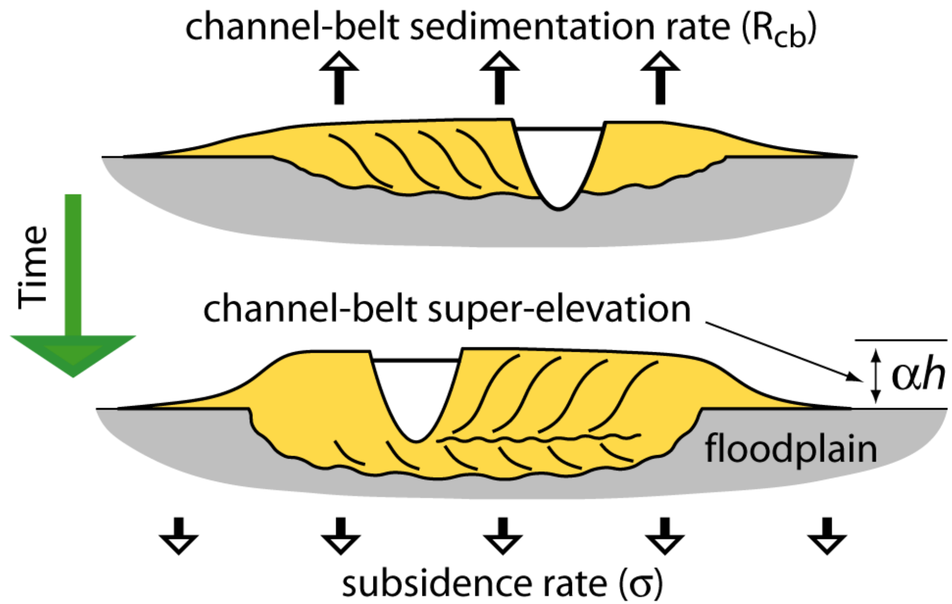


Avulsion (nodal) (E$^{\underline{qn}}$ 1 of 4):

Poorly understood process
(e.g., Slingerland & Smith, 2004)

Gravitational instability

We adopt "critical" super-elevation criterion



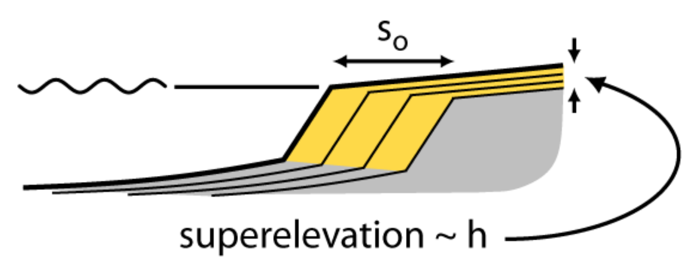
Residence time (τ)

$$\tau \sim \frac{\alpha h}{(R_{cb} - \sigma)}$$

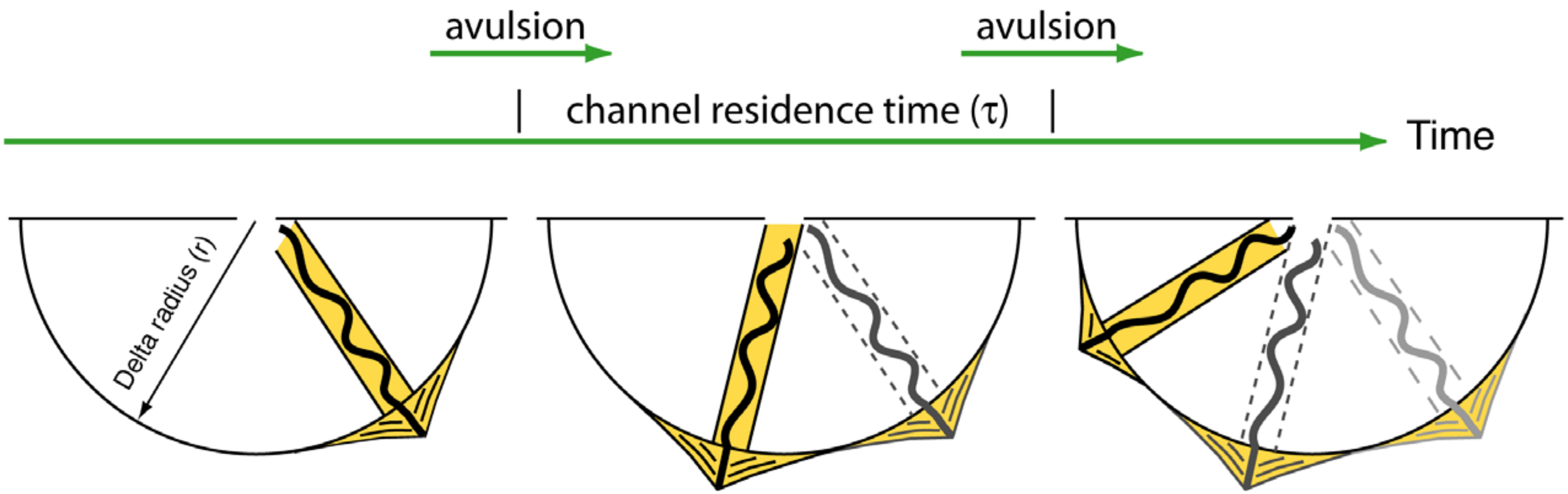
α ~ 0.4 - 1.2 (Mohrig et al., 2000; Tornqvist & Bridge, 2002; Mohrig & Jerolmack, 2007)

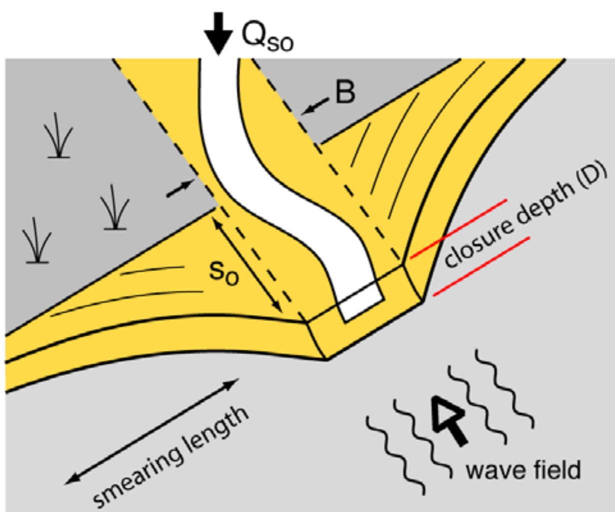
Aggradation begets progradation:

Progradation (s_o) scales with backwater length



Sand budget (E$^{\underline{qn}}$ 2 of 4):





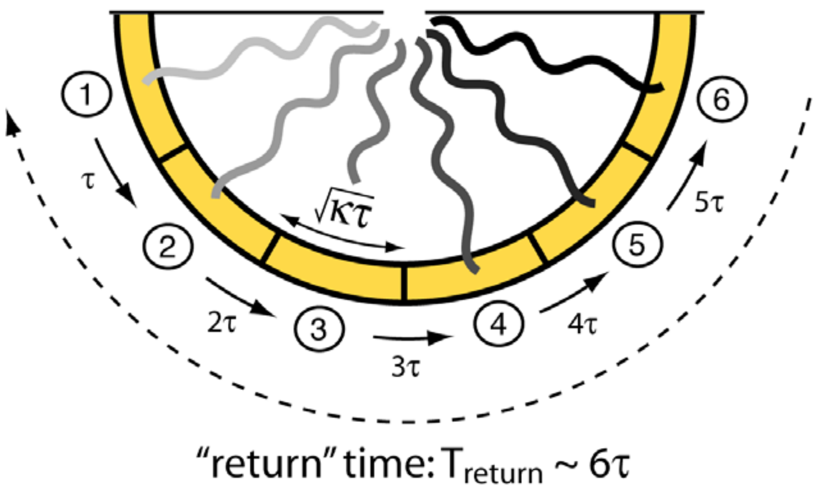
Smearing length ~ $\sqrt{\kappa\tau}$

$$Q_{so}\,\tau \sim Br\left(R_{cb}\,\tau\right) + Ds_o\sqrt{\kappa\tau}$$

1   2   3

1. Sand input during residence
2. Channel belt aggradation
3. Lobe progradation and smearing

Equilibrium (aggradation) (E$^{\underline{qn}}$ 3 of 4):

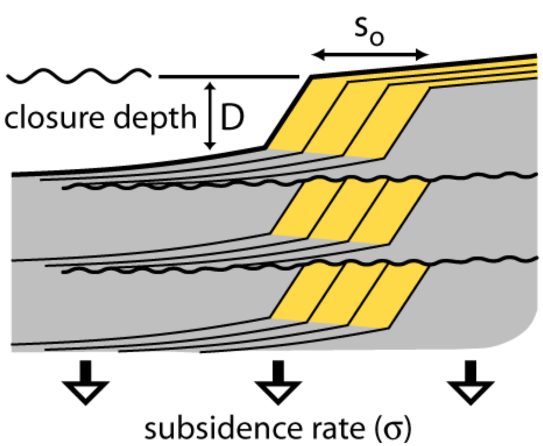


Simplest model for **return time**:

$$T_{return} \sim \left(\frac{\pi r}{\sqrt{\kappa \tau}} \right) \tau$$

'Drowning' time:

$$T_{drown} \sim \frac{D}{\sigma}$$



Aggradation requires: $T_{drown} \sim T_{return}$

$$\pi r \sqrt{\frac{\tau}{\kappa}} \sim \frac{D}{\sigma}$$

Channel-floodplain interaction: Relict channels ("scars")

Relict channels:

Measure of **avulsion frequency** (creation) and **floodplain deposition** (erasure)

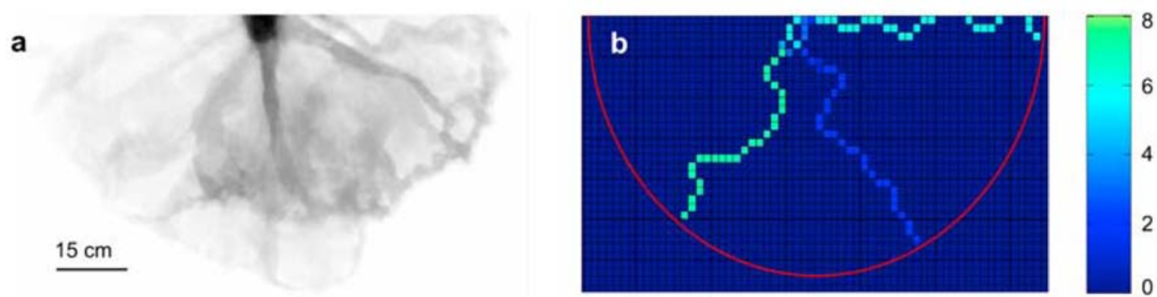
Relict channels = floodplain **topography**

Topography partitions ("steers") flow

Controls "depositional footprint" of channels

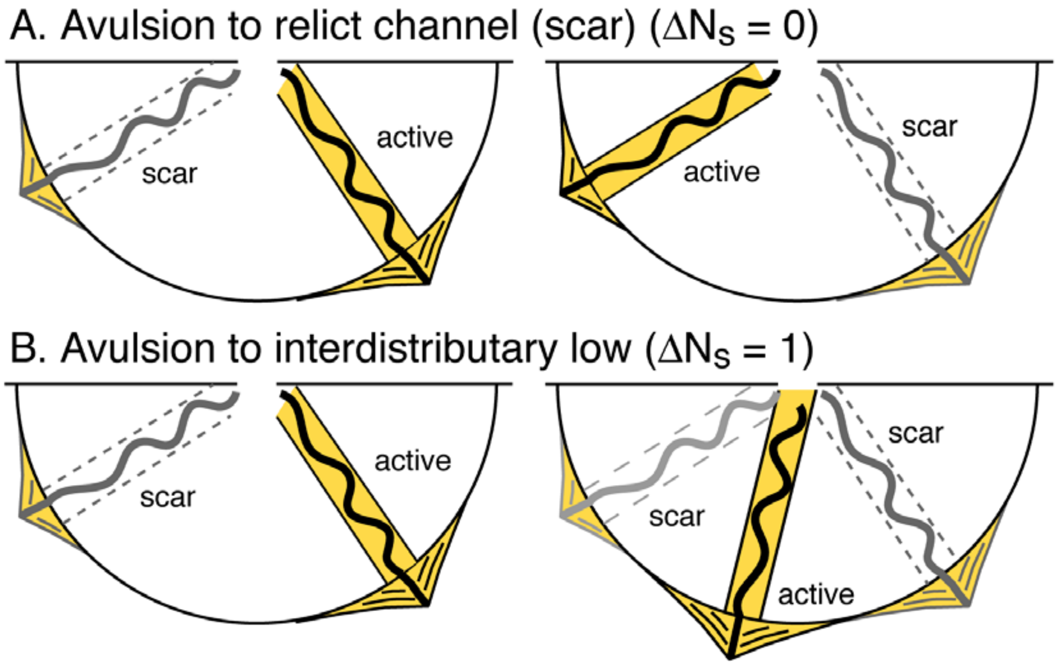
Provides mechanism for **hysteresis**

Current model has no 'feedback' between scar density and sedimentation



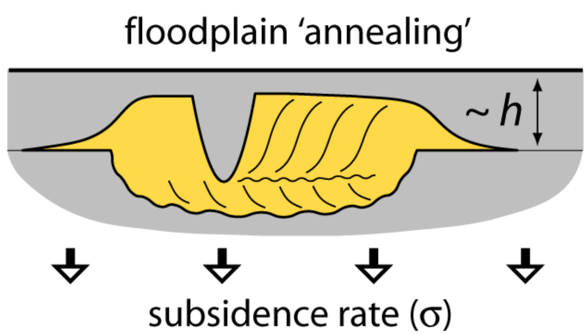
Experimental (a) and theoretical (b) investigation of channel reoccupation in fan deltas by Reitz et al. (2010)

"Scars" (E^qn 4 of 4):



Production → avulsion to inter-distributary low (τ, P_{low})

$$P_{low} \sim \frac{1}{(N_s + 1)}$$



Destruction → annealing via mud deposition (N_s, T_{anneal})

At **equilibrium**, scar production rate balances destruction rate:

$$\frac{dN_s}{dt} \sim 0 \Leftrightarrow \frac{1}{(N_s + 1)} \cdot \frac{1}{\tau} \sim \frac{N_s}{T_{anneal}}$$

$$N_s (N_s + 1) \sim \frac{T_{anneal}}{\tau}$$

Gathering up the bits… compact set of governing equations

$$R_{cb} \sim \frac{Q_{so}}{rB}\left(1-\frac{Ds_o}{Q_{so}}\sqrt{\frac{\kappa}{\tau}}\right)$$

Channel-belt sedimentation rate

$$\pi r\sqrt{\frac{\tau}{\kappa}} \sim \frac{D}{\sigma}$$

Equilibrium (aggradational shoreline)

$$\tau \sim \frac{\alpha h}{\left(R_{cb}-\sigma\right)}$$

Avulsion criterion

$$N_s\left(N_s+1\right) \sim \frac{T_{anneal}}{\tau}$$

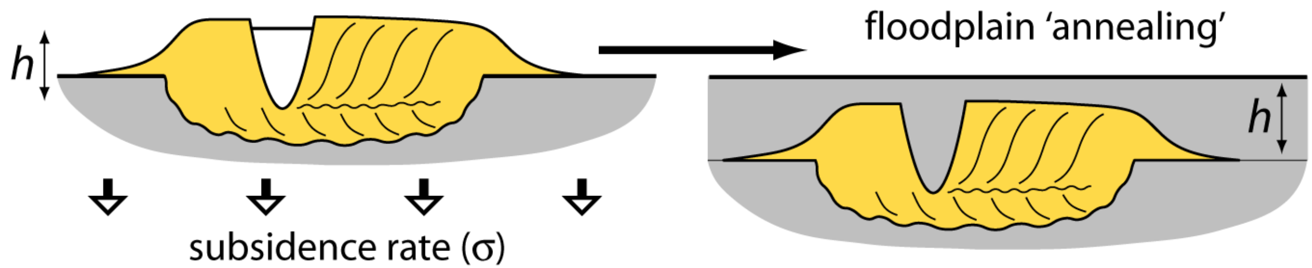
Scarring of delta surface (decoupled)

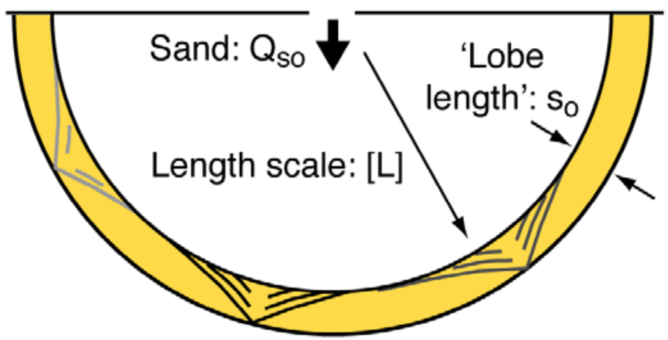
Unknowns: τ, R_{cb}, r, N_s

Natural scales ([T], [L], [ZT^{-1}]) for the problem:

$$[T] \leftrightarrow \frac{\alpha h}{\sigma}$$

"Annealing" time





Partition all sand to annulus of 'length' s_o
(No storage in channel belts)

$$[L] \leftrightarrow \frac{Q_{so}}{\pi s_o \sigma}$$

$$\left[\frac{Z}{T}\right] \leftrightarrow \sigma$$

Subsidence rate (σ) scales channel-belt deposition rate (R_{cb})

Non-dimensional (*) governing equations:

$$R_{cb*} \sim \frac{\pi}{\beta r_*}\left(1-\frac{\xi}{\beta}\frac{1}{\sqrt{\tau_*}}\right)$$

Channel-belt sedimentation rate

$$r_*\sqrt{\tau_*} \sim \frac{\xi}{\beta}$$

Equilibrium (aggradational shoreline)

$$\tau_* \sim \left(R_{cb*}-1\right)^{-1}$$

Avulsion criterion

$$N_s\left(N_s+1\right) \sim \tau_*^{-1}$$

Scarring of delta surface (decoupled)

Two controlling dimensionless numbers:

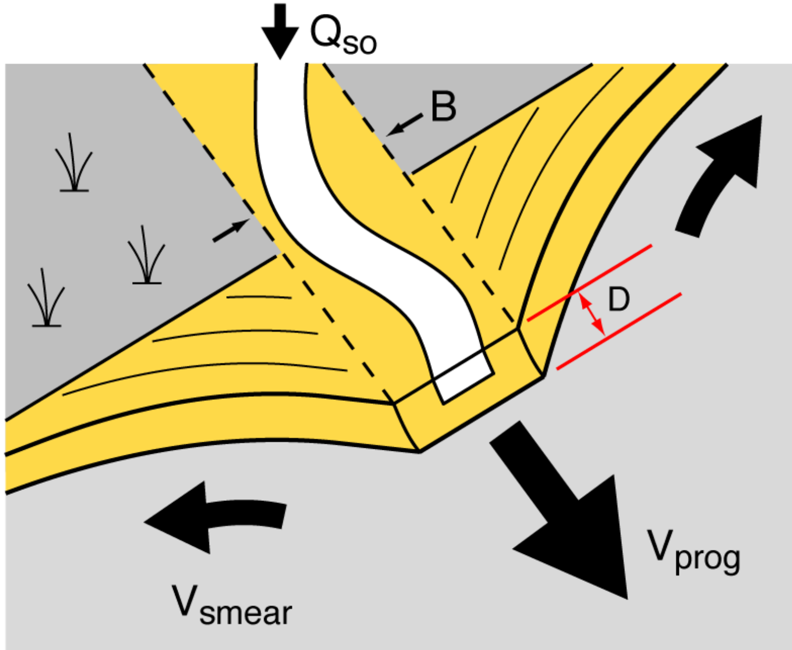
$$\beta = \frac{B}{s_o}$$

Normalized channel-belt width

$$\xi = \frac{DB}{Q_{so}}\sqrt{\frac{\kappa\sigma}{\alpha h}}$$

Relative measure of wave ‘energy’

Simple interpretation of relative 'wave energy' (ξ)



Channel-belt progradation rate:

$$V_{prog} \sim \frac{Q_{so}}{DB}$$

Longshore 'smearing' rate:

$$V_{smear} \sim \sqrt{\frac{\kappa}{[T]}} = \sqrt{\frac{\kappa\sigma}{\alpha h}}$$

ξ is ratio of rates:

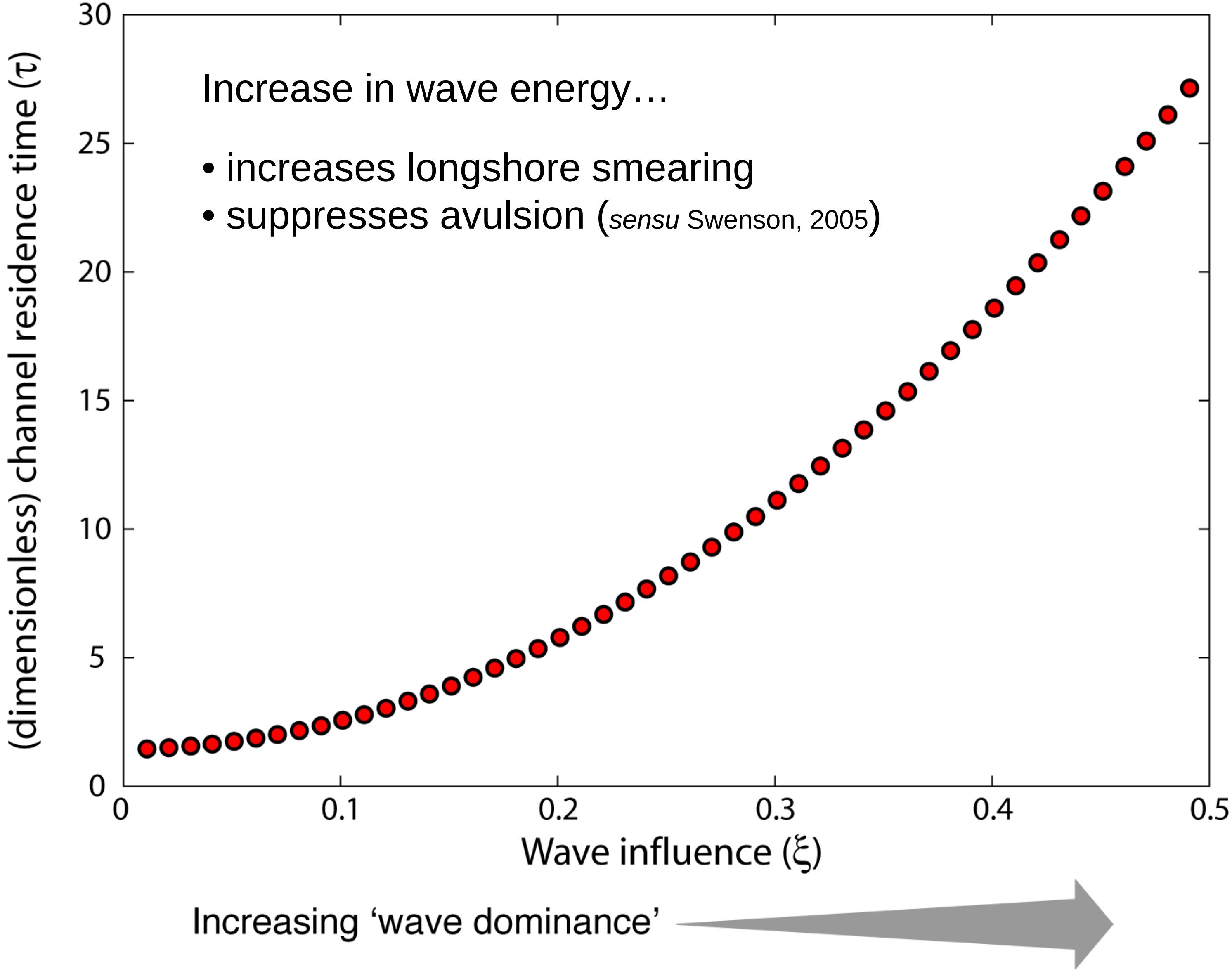
$$\xi = \frac{DB}{Q_{so}}\sqrt{\frac{\kappa\sigma}{\alpha h}} \sim \frac{V_{smear}}{V_{prog}}$$

Complete wave dominance: $\xi \rightarrow 1$

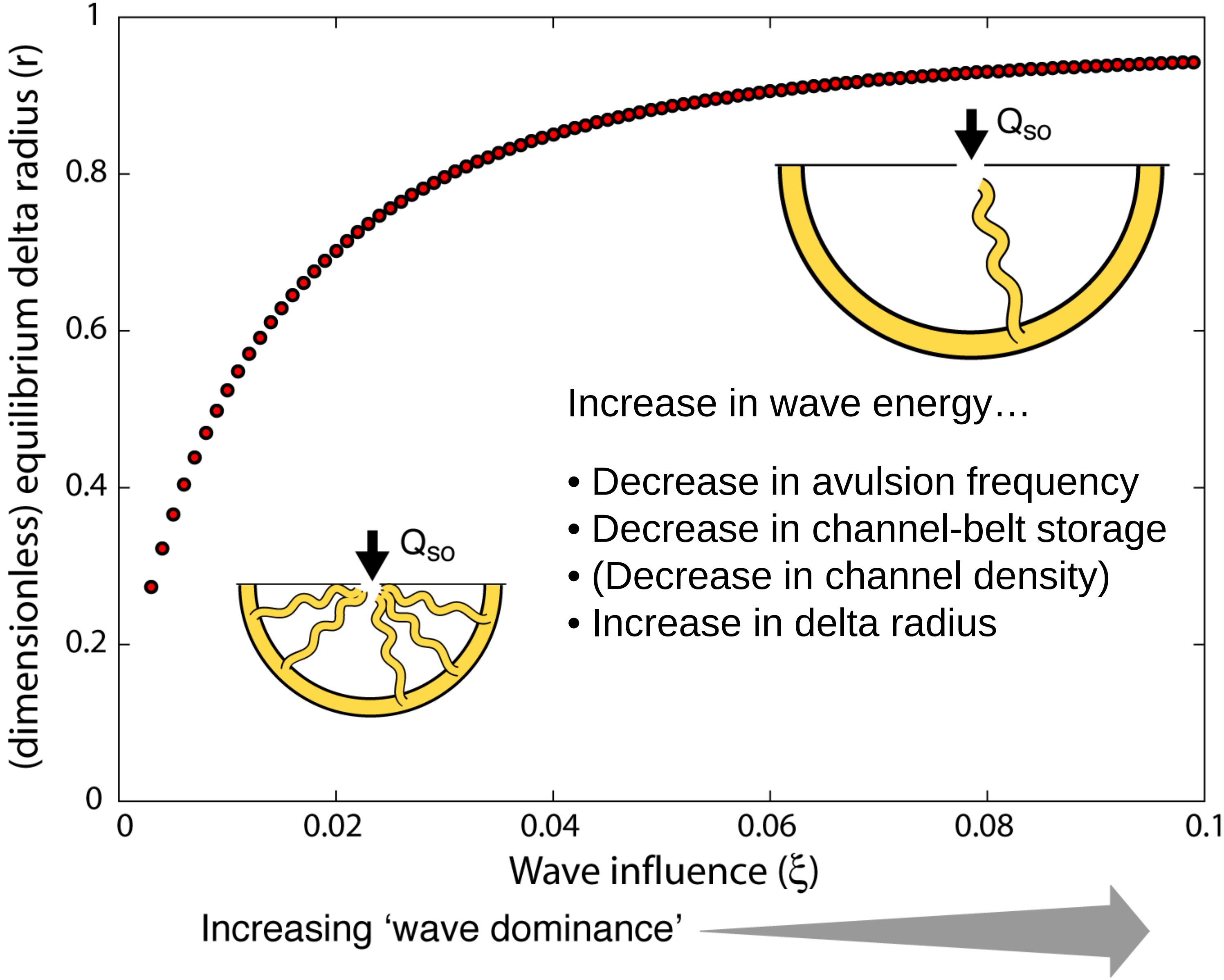
Strong wave influence: $\xi \sim 0.1$

Minimal wave influence: $\xi < 0.01$

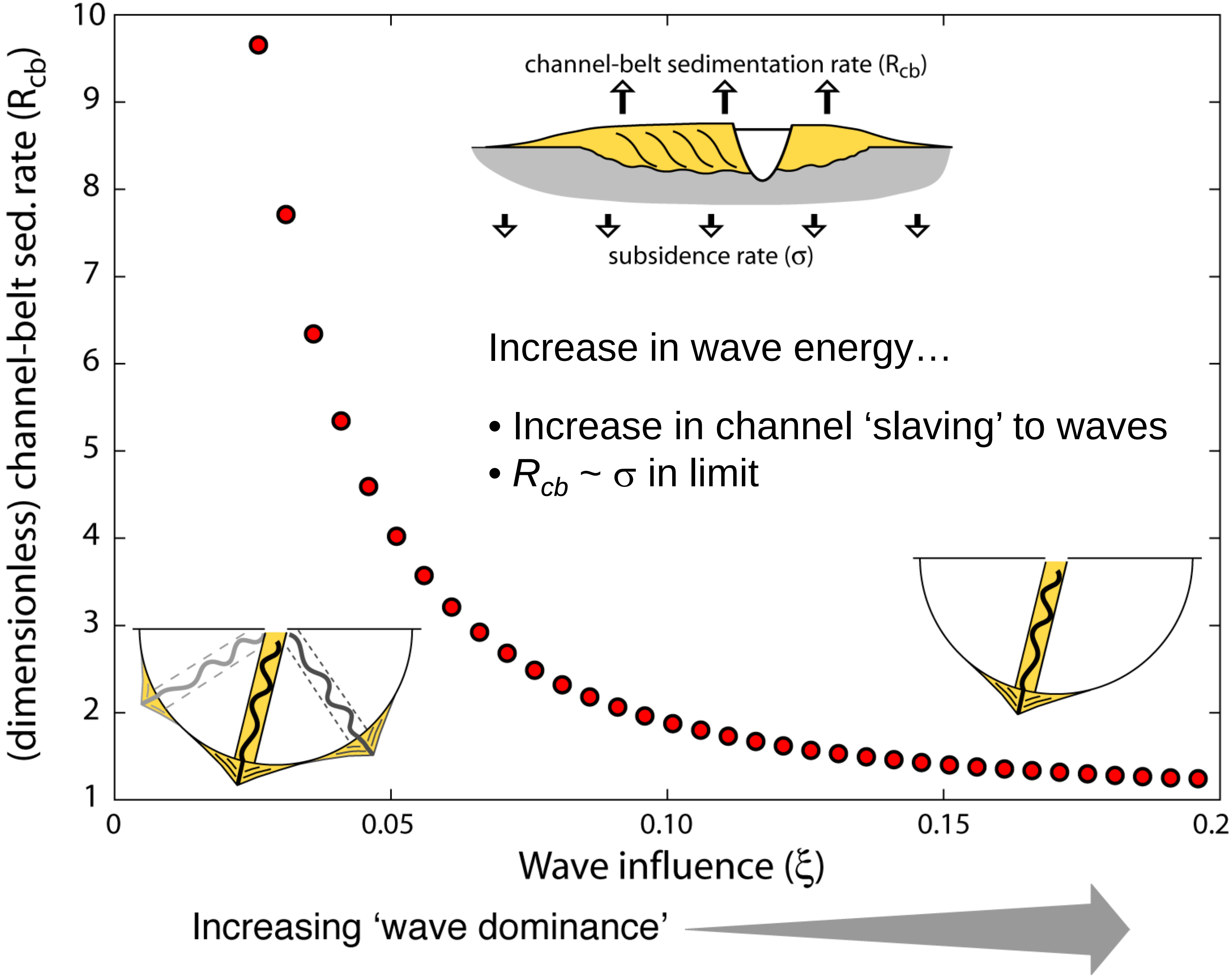
Channel residence time (τ) vs. wave energy (ξ)



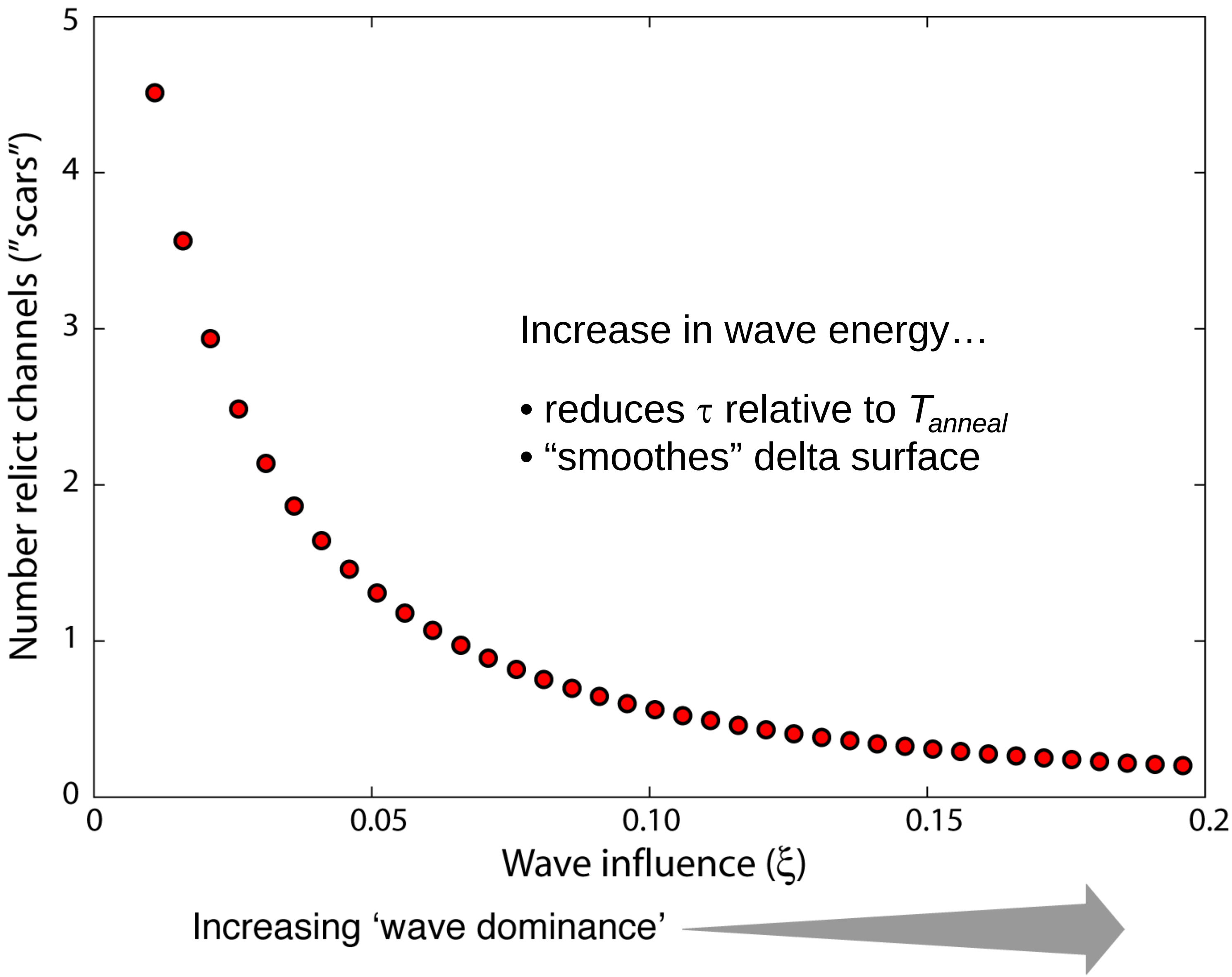
Equilibrium delta radius (*r*) vs. wave energy (ξ)



Channel-belt deposition rate (R_{cb}) vs. wave energy (ξ)



Number of channel scars (N_s) vs. wave energy (ξ)



Summary / Conclusions:

Simple model makes several testable predictions.

An relative **increase** in **wave energy** (ξ) should:

- Increase channel residence time (τ)
- Increase the equilibrium size (radius, *r*)
- Decrease the channel-belt aggradation rate (R_{cb})
- Decrease the number of channel scars (N_s)