Shredding of Environmental Signals by Autogenic Transport Fluctuation*

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Search and Discovery Article #50302 (2010)
Posted August 13, 2010

*Adapted from oral presentation at AAPG Annual Convention and Exhibition, New Orleans, Louisiana, April 11-14, 2010

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Abstract

Sediment transport is an intermittent process. Even under perfectly steady boundary conditions, sediment flux in systems as diverse as rivers and rice piles undergoes wild fluctuations as a result of the inherent nonlinear dynamics of transport. This variability confounds geologic interpretation and prediction: “mean” transport rates may be dominated by rare but extreme events such that short-term measurements are not directly comparable to longer-time integrated measurements; and autogenic erosion and deposition events may be mistaken for changes in climate and tectonics where their temporal and spatial scales overlap. We hypothesize that the presence of a strong process threshold, and a high degree of internal friction (or “stickiness”), are sufficient conditions to generate intermittent sediment transport behavior. We present experimental data showing similarities in transport fluctuations from three very different systems: gravel bed load transport in a large flume, avalanching in a table- top pile of rice, and shoreline fluctuations in an experimental river delta. Numerical models reproduce these fluctuations, and are used to explore both their origin and also their influence on environmental perturbations. We impose an environmental perturbation on our model systems in the form of cyclically-varying sediment supply. Physical and numerical experiments demonstrate that these external signals are destroyed when their time and magnitude scales fall within the range of autogenic fluctuations. Thus, sediment transport can act as a noisy, nonlinear filter that “shreds” signals of environmental forcing so that they are not merely masked but entirely lost. Results suggest that the nonlinear dynamics of sediment transport sets a hard lower limit on our ability to resolve environmental forcing in sedimentary systems. We suggest that Earth's sedimentary archives could be dominated by transport “noise” on time scales up to ~10 kyr. This time scale range overlaps in particular with known climatic time scales, meaning that in many systems the physical signature of these signals may be lost. The ubiquity of autogenic sediment storage and release in river systems, however, suggests a new interpretation for common stacking patterns of stratigraphic sequences.

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Shredding of environmental signals by autogenic transport fluctuations

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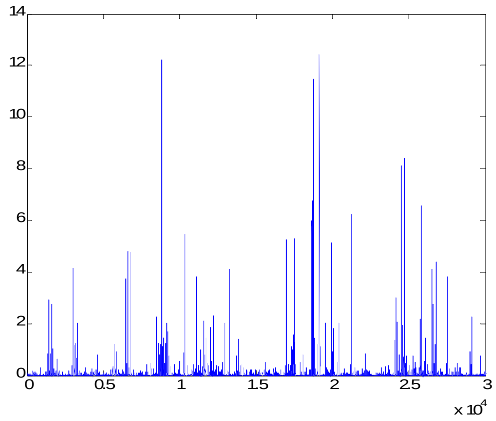
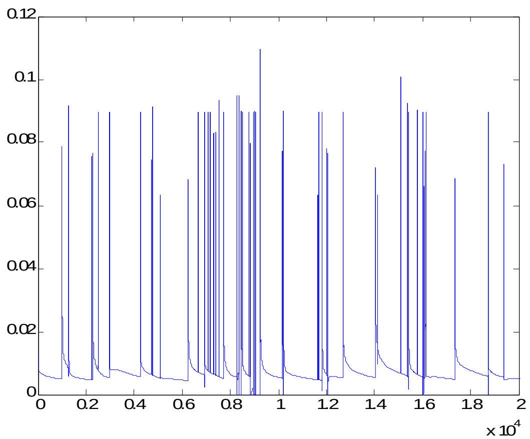
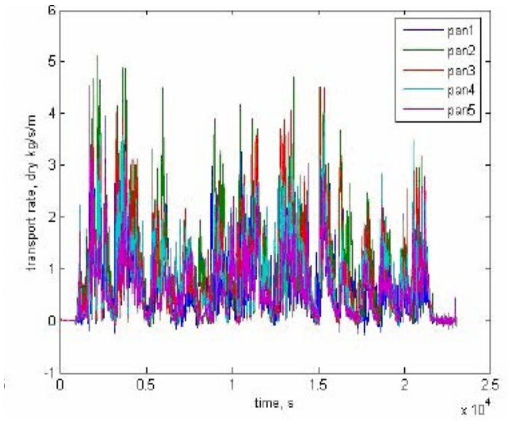
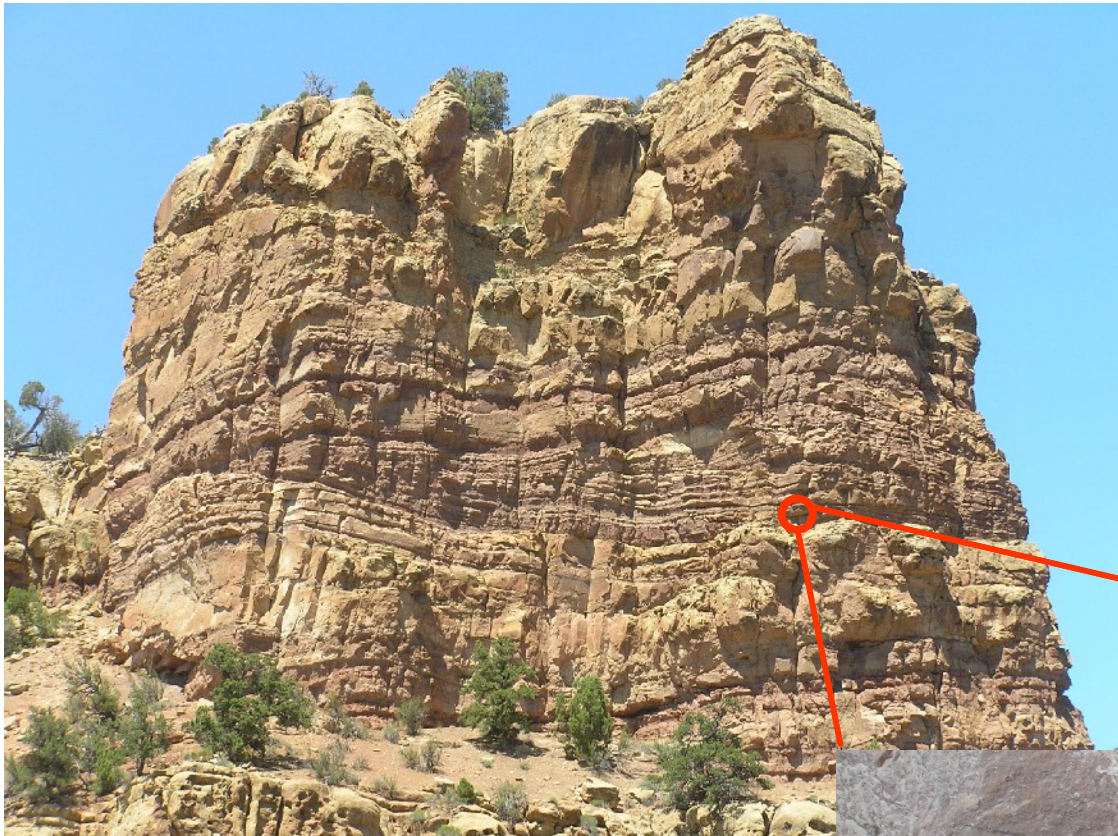






How does sediment move sedimentary systems? – ***Intermittently***

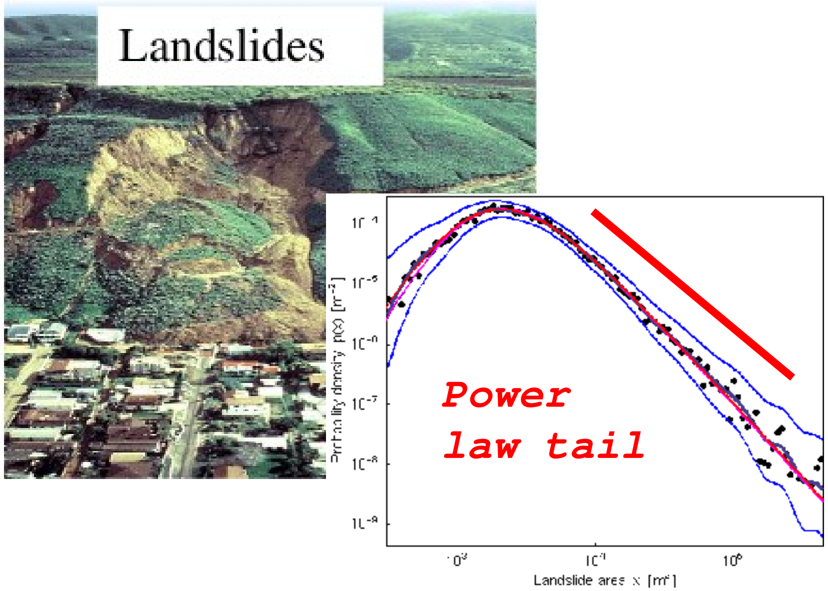


Interpreting environmental history from sedimentary deposits

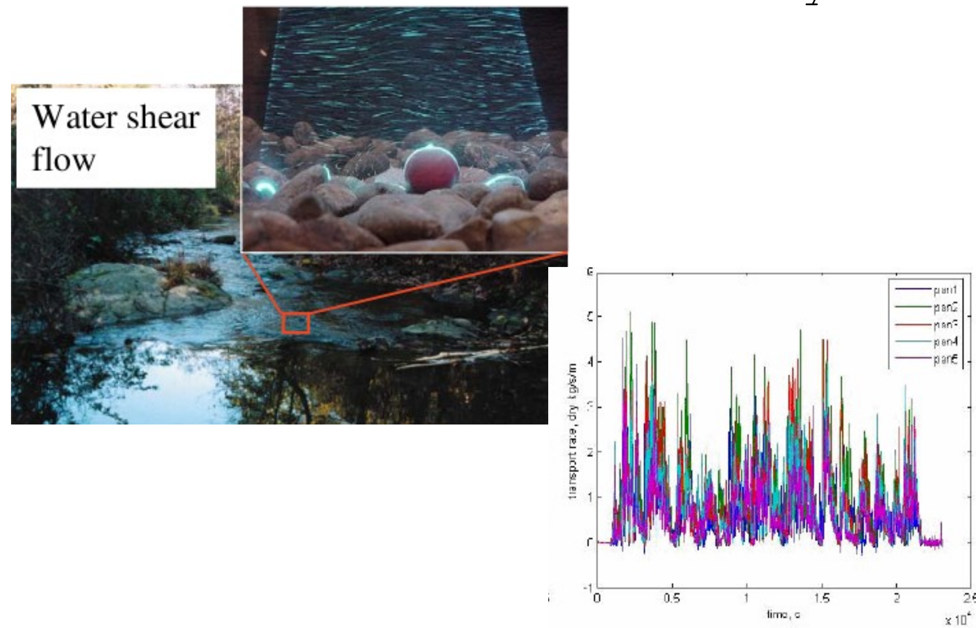
Intuitively, we look at small-scale deposits as local events, and large-scale events as climate/tectonics

→ Can we formalize this?

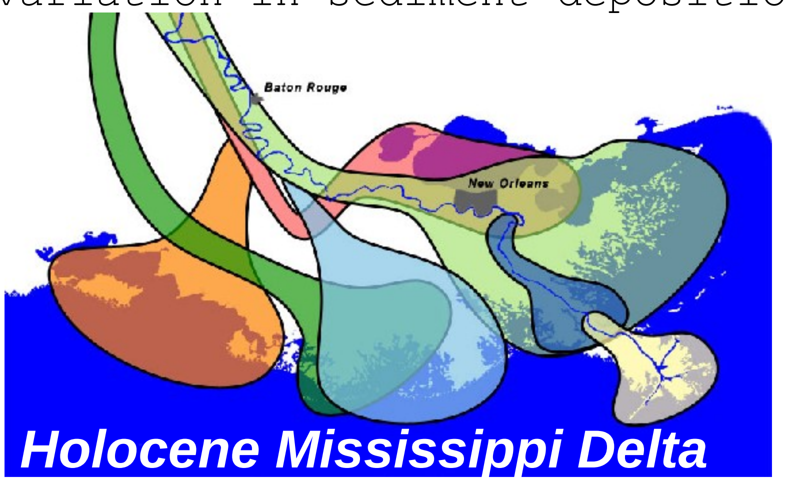
Intermittent, spatially variable sediment supply to rivers.



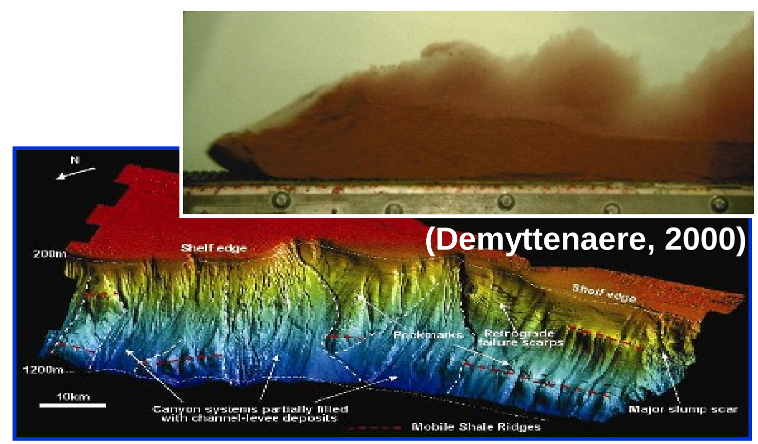
Bed load transport rates are intermittent – even under steady flows.



Avulsion – temporal and spatial variation in sediment deposition.

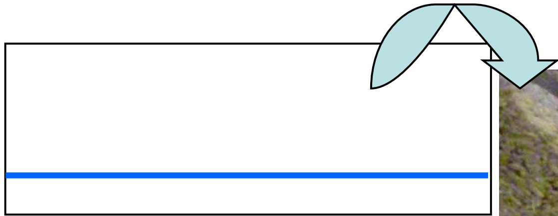


Turbidity currents are infrequent and catastrophic.



What do these systems have in common? – *Threshold dynamics.*

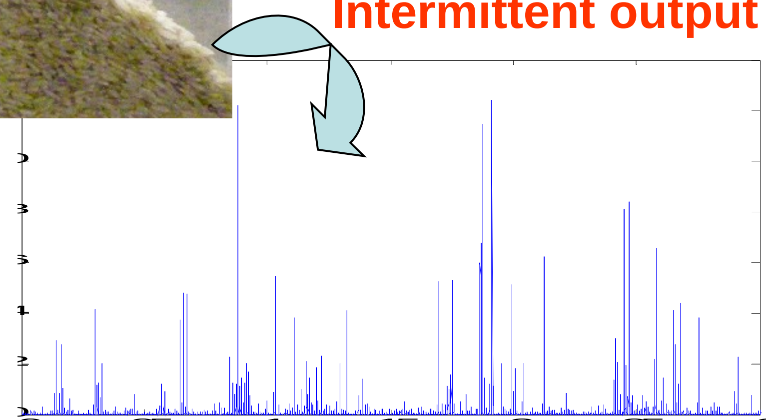
Thresholds and randomness – the rice pile.

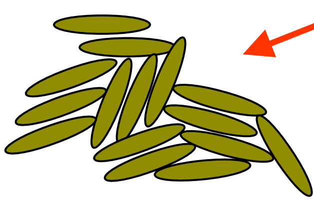


Steady input

Deposit of a rice pile is constructed from this output (think gravel transport, debris flows).

Intermittent output



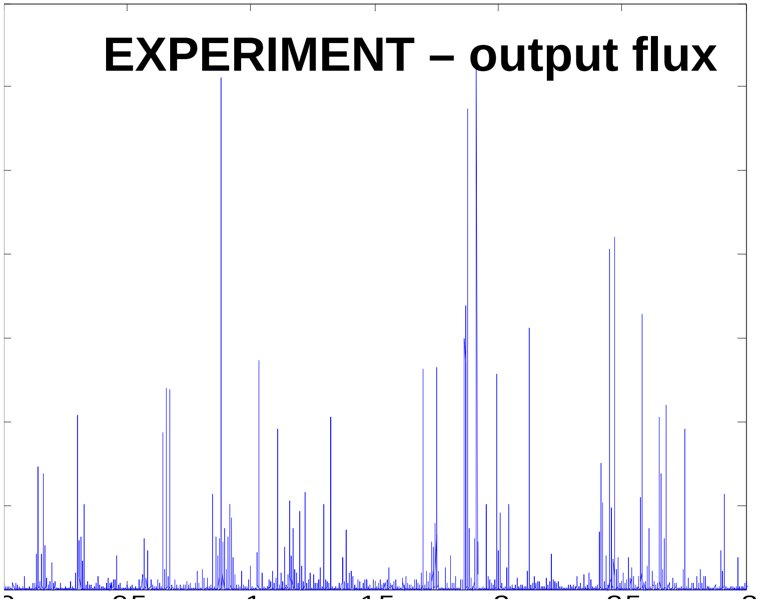


Steps of all sizes form in profile (storage)

→ "Bed forms"

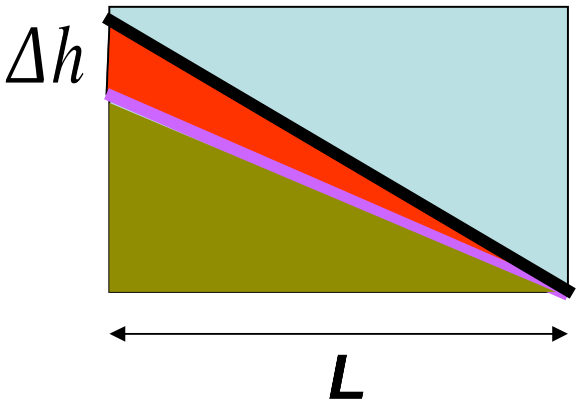
Threshold exceedance causes failure (release)

Rice Pile – Results

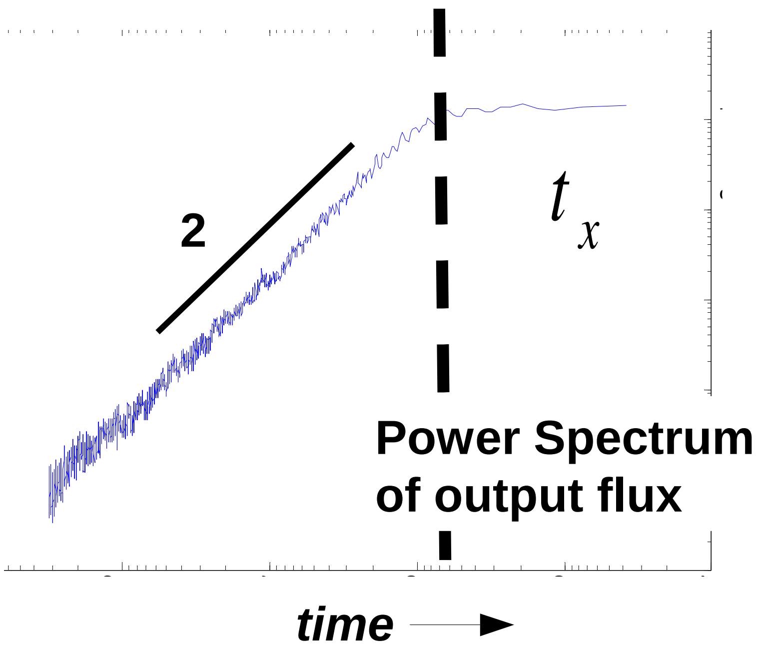


Fluctuations over a wide range of scales

Variability saturates at $t = t_x$



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

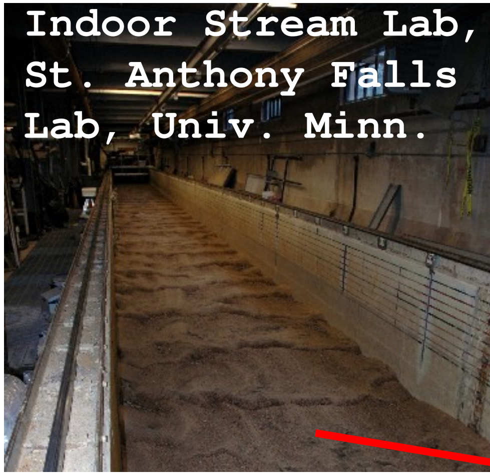


Magnitude of fluctuations increases as power law function of time
– nonlinear regime.

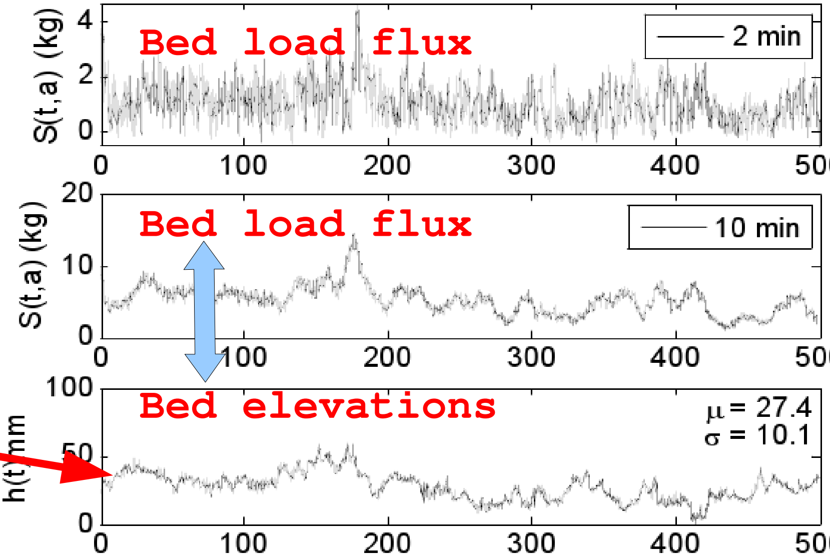
Largest avalanche determined by system size.

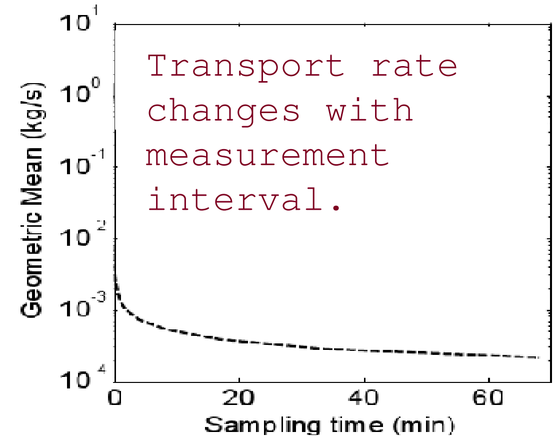
Timescale of largest avalanche scales w/ time required to fill critical wedge.

Bed load fluctuations in steady flow



[Singh et al., JGR-ES, 2009]





Fluctuations related to **storage and release of sediment in bed forms.**

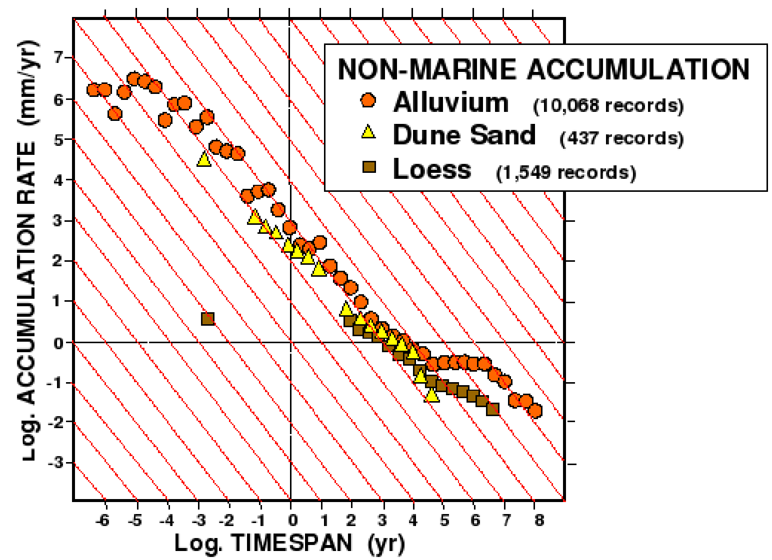
Transport fluctuations have **heavy tails.**

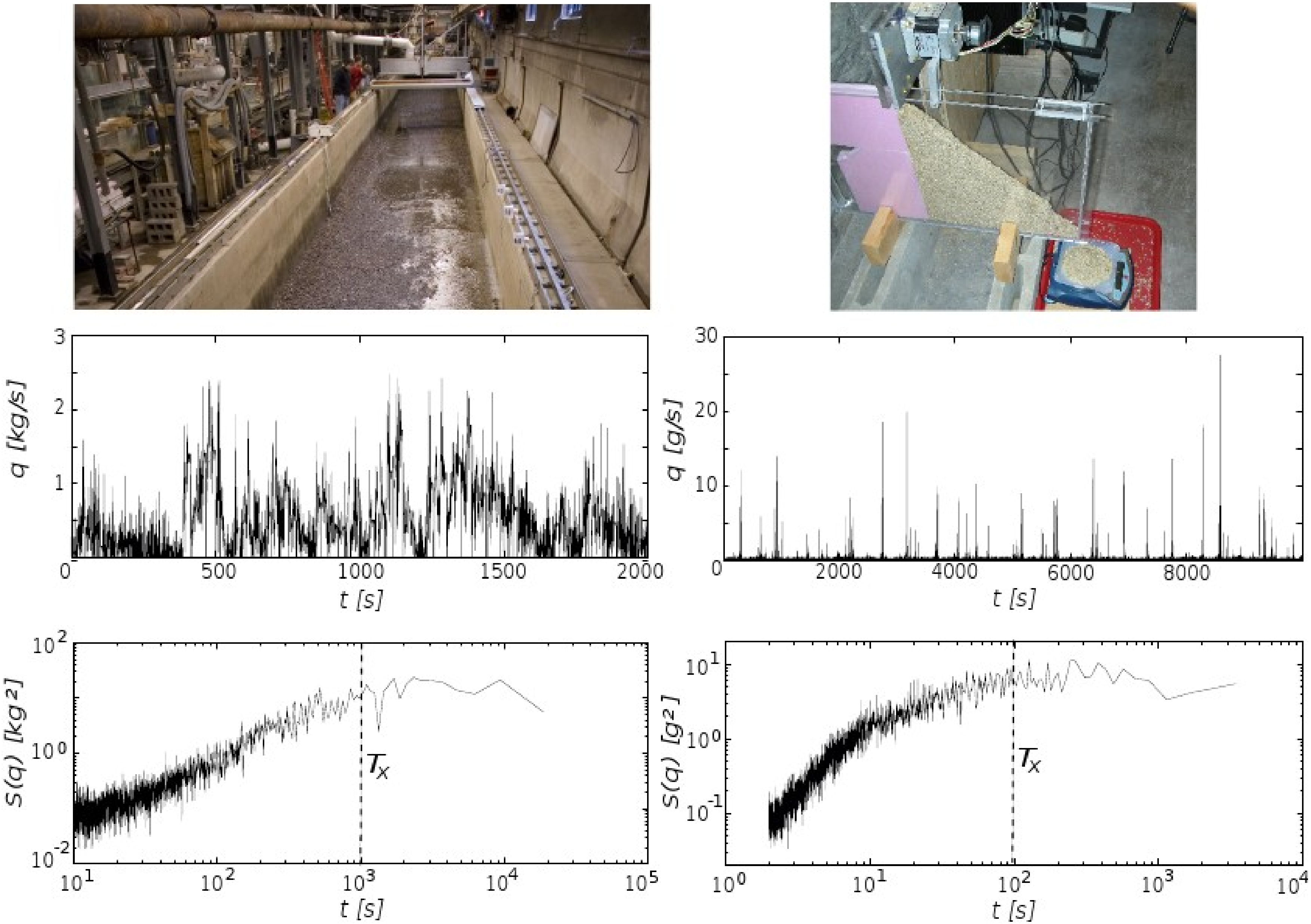
Longer wait – greater *P* of extreme event.

Mean does not converge.

May explain sedimentation scaling in the geologic record.

Geologic deposition rates as a function of measurement interval, from Sadler

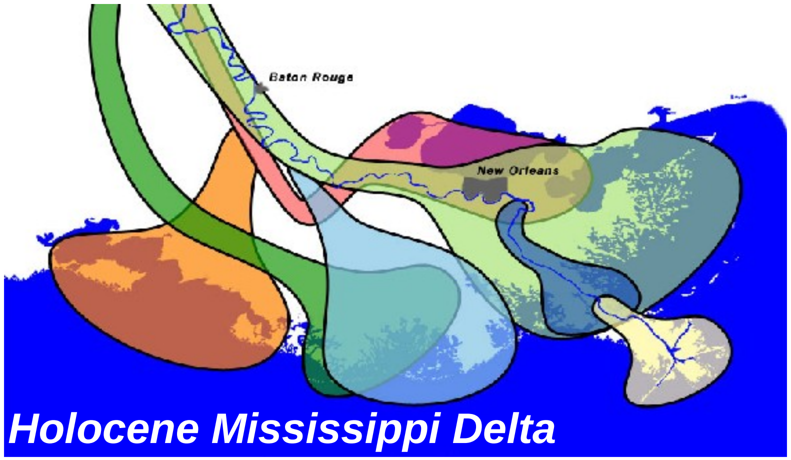




q [kg/s]
t [s]
q [g/s]
t [s]
S(q) [kg²]
T_x
t [s]
S(q) [g²]
T_x
t [s]

River avulsions – another threshold process

Avulsions occur due to ***deposition of channel above surrounding floodplain.***



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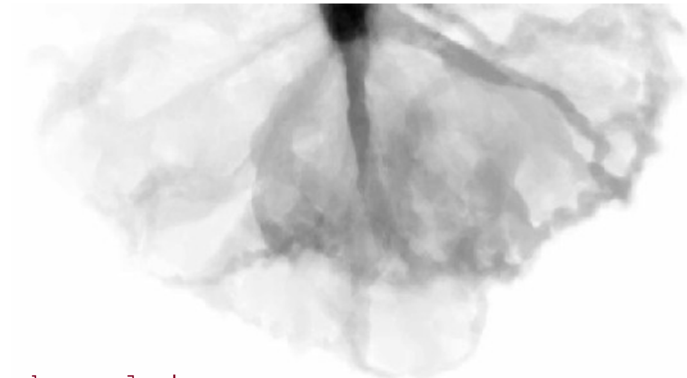
[Reitz, Jerolmack and Swenson, 2010]



Repeated avulsions:
1. Build channel networks on fans
2. Generate **spatial variability in deposition**

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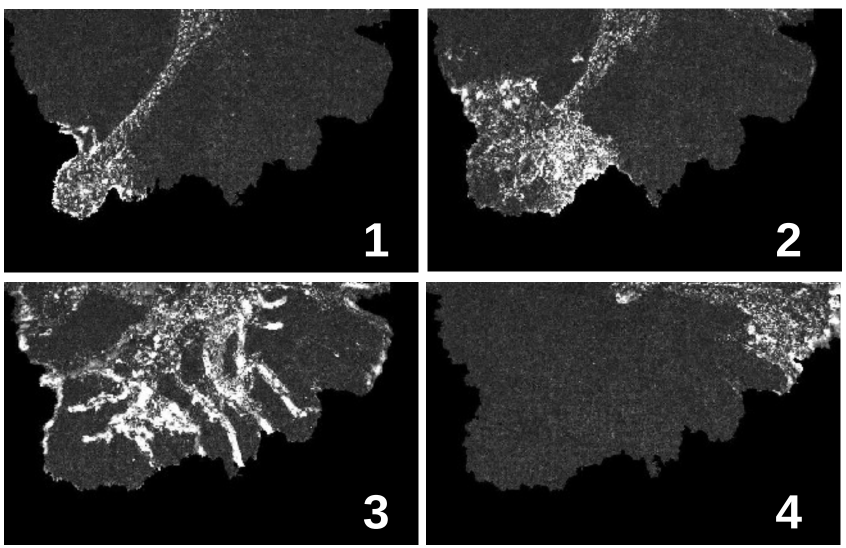
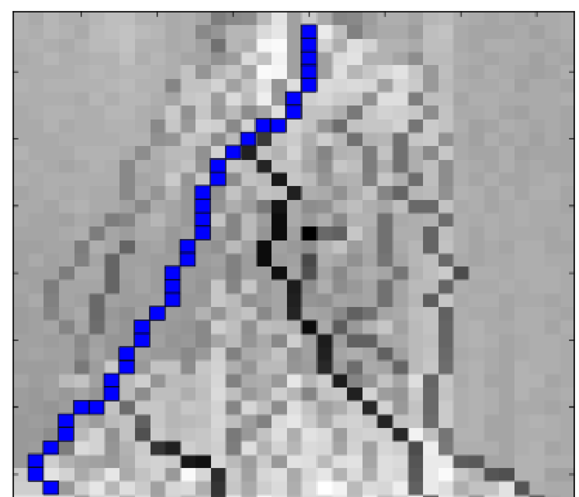


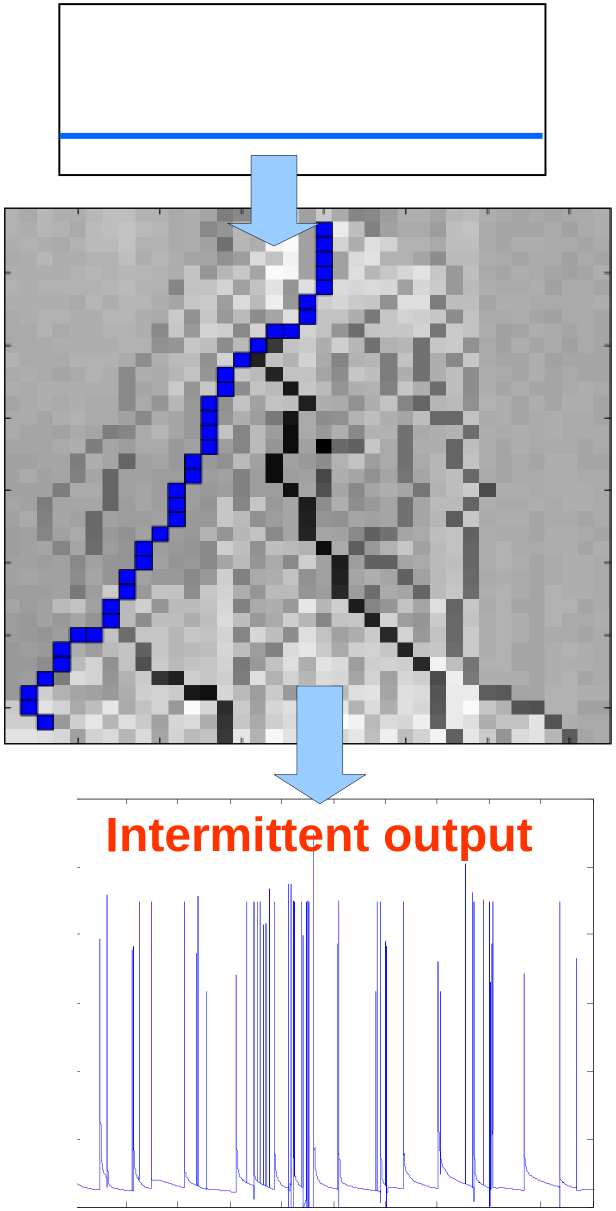
Threshold avulsion model
[Jerolmack and Paola, 2007]

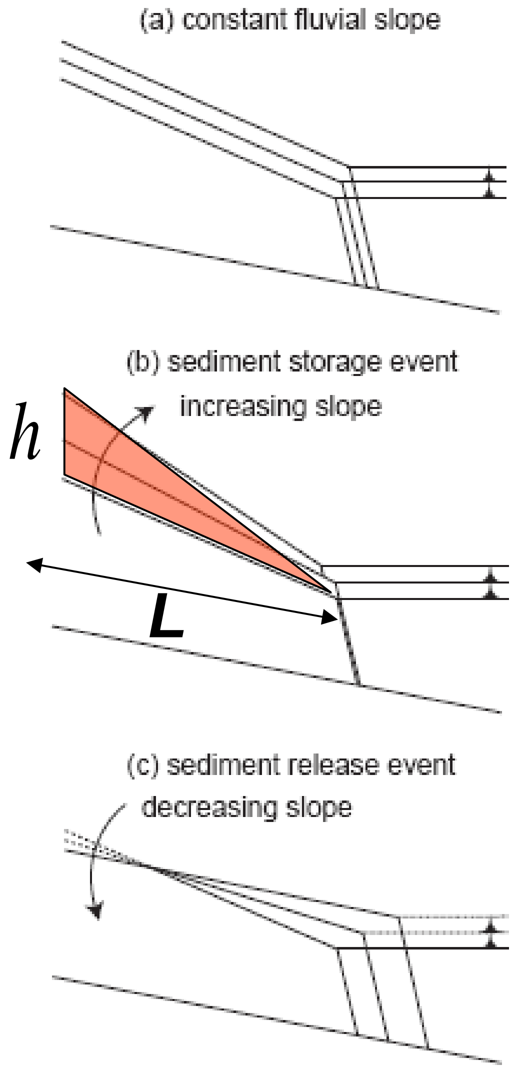


Avulsion:
Flow finds a new, steeper path.
– subject to constraint that –
Flow often reoccupies abandoned channels.

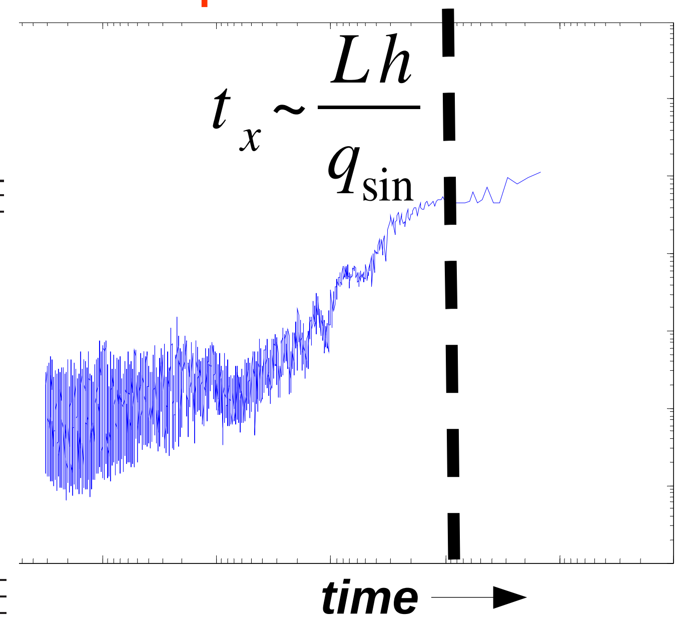
Threshold avulsion model - temporal fluctuations

Steady sediment input





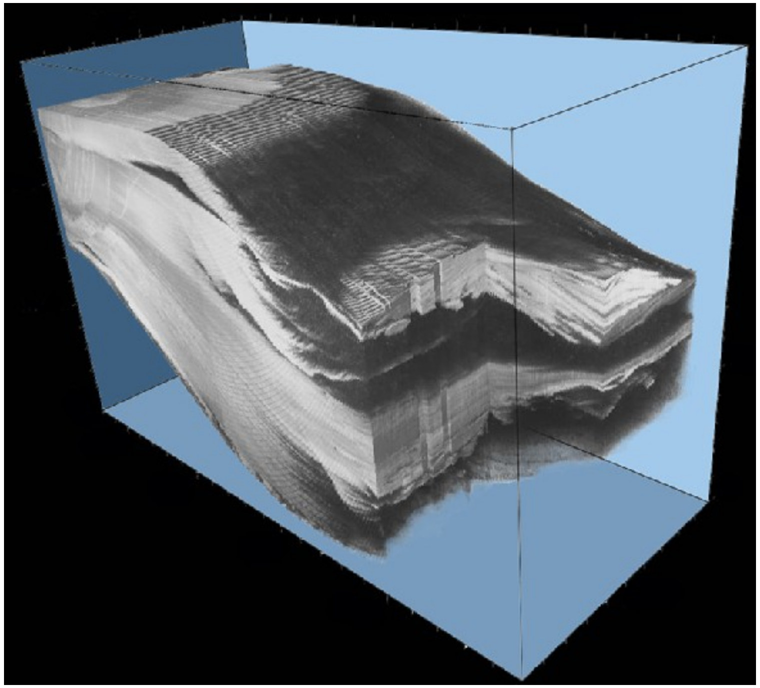
Power spectra of sediment efflux



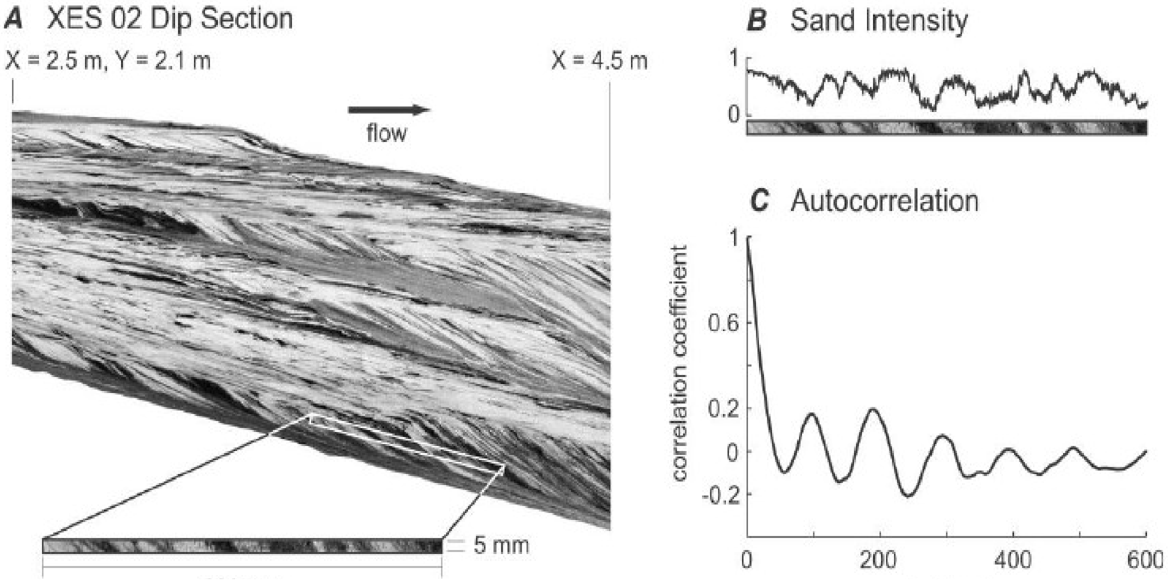
Storage – channels and floodplains store sediment within network.

Threshold – channel deposition causes avulsion (release).

Net effect – pulsing sediment transport, fluctuations across wide range of time scales.



A consequence of autogenic transport fluctuations - parasequences



[Kim and Jerolmack, 2008]

Sediment transport – a nonlinear filter

Environmental signal
(sediment supply, base level, etc.)

Sediment transport

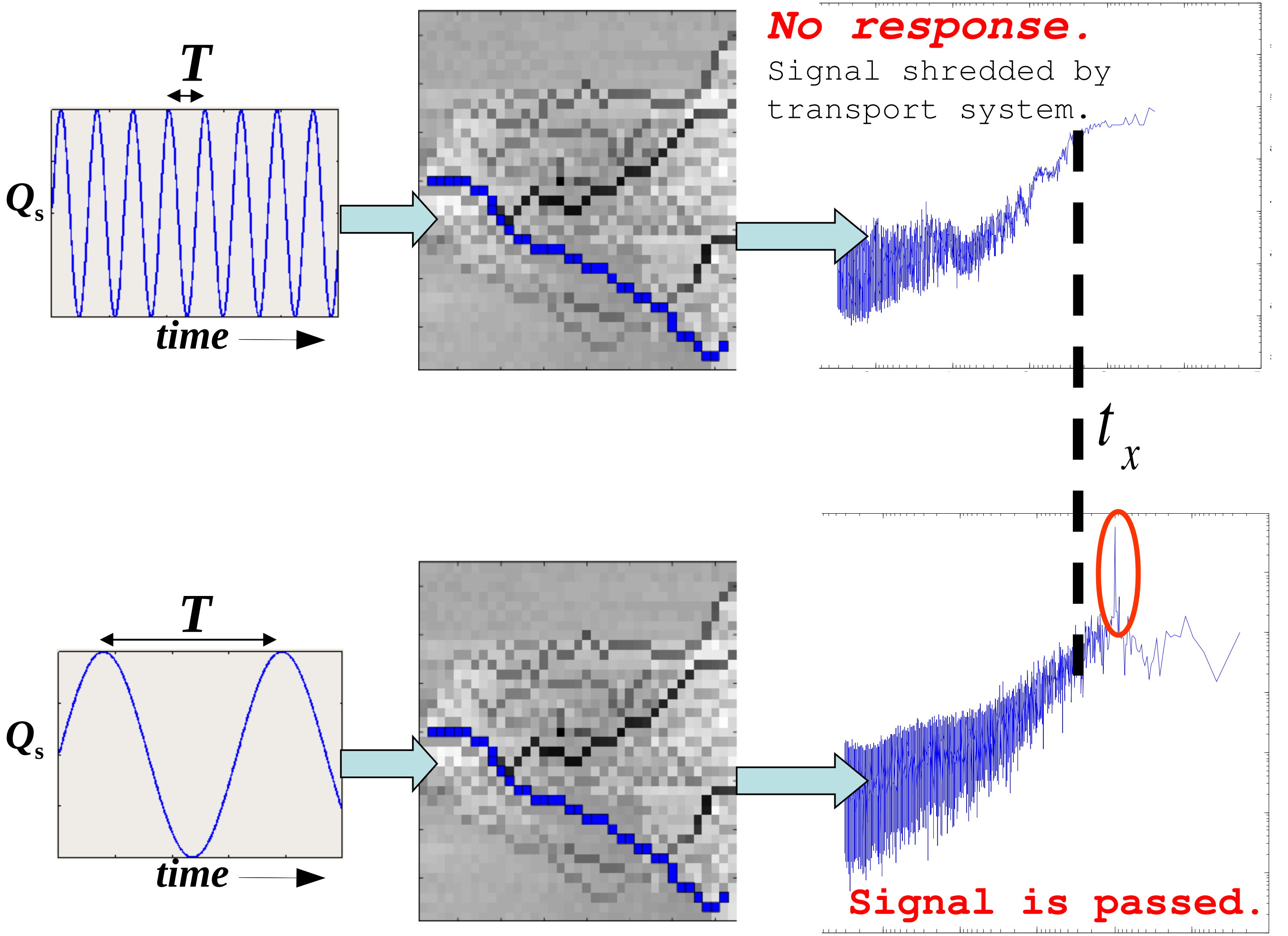
System response
(transport rate, deposits, etc.)

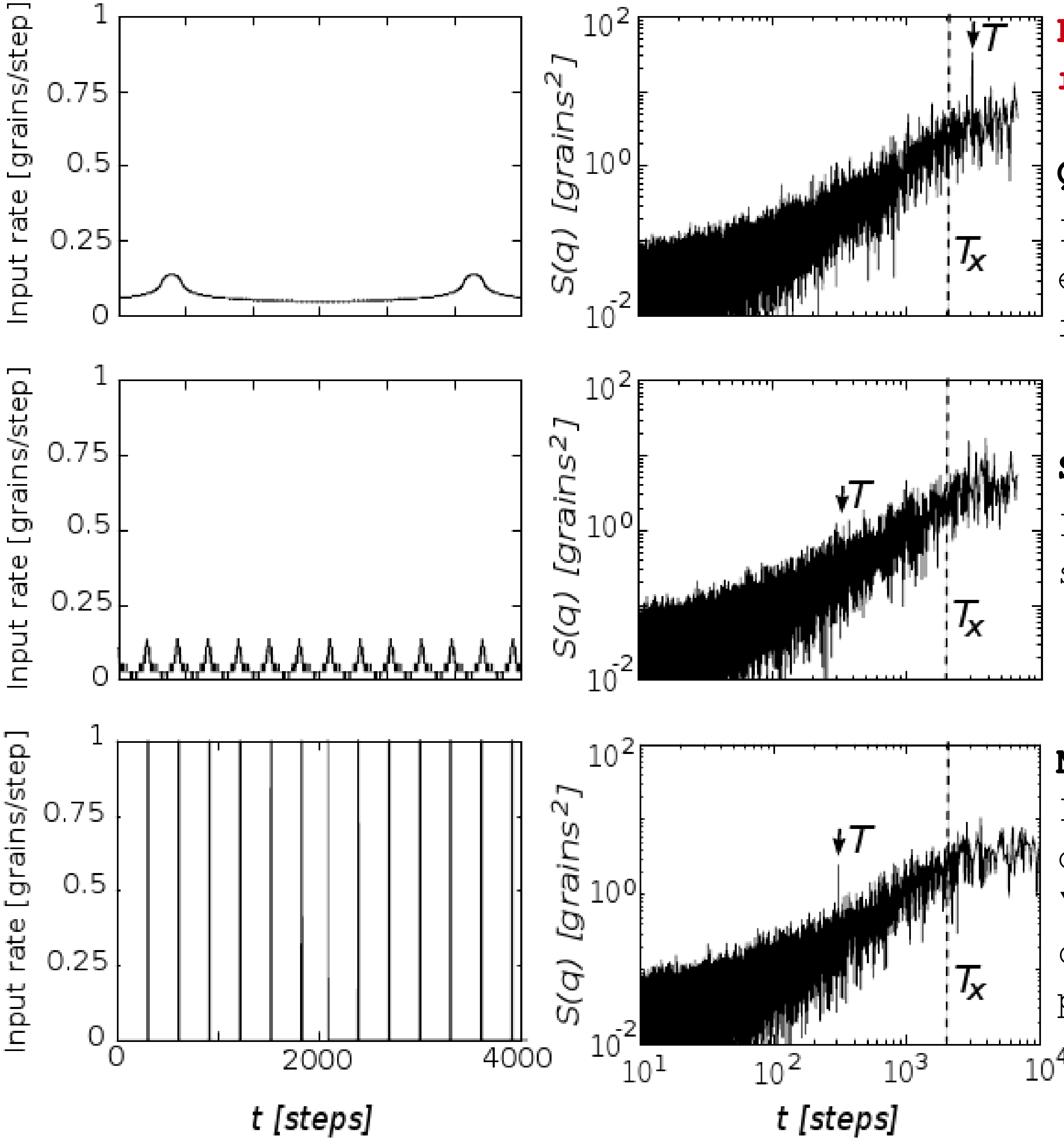
T < ***t*_x_:** $T < t_x$:

Period of perturbation less than timescale of largest fluctuation.

T > ***t*_x_:** $T > t_x$:

Period of perturbation greater than timescale of largest fluctuation.





Frequency-dependent response:

Quasi-steady ($T > T_x$)

Input varies slow enough that system responds.

Shredding ($T < T_x$)

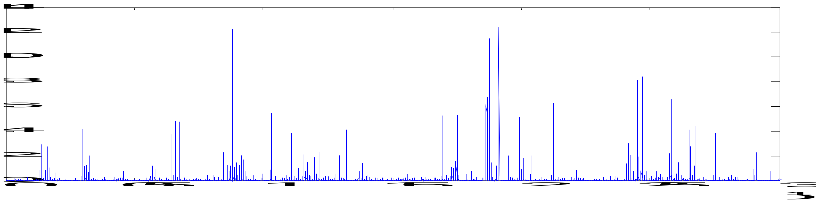
Input at one *f* smeared across many.

MAGNITUDE?...

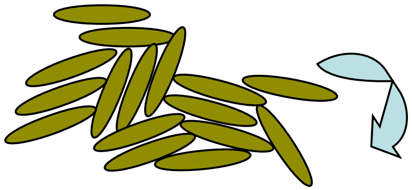
If input pulse overwhelms "buffering capacity", it will pass.

Conclusions - it's all about thresholds

- Steadily-driven sediment transport systems exhibit fluctuations across a range of time scales

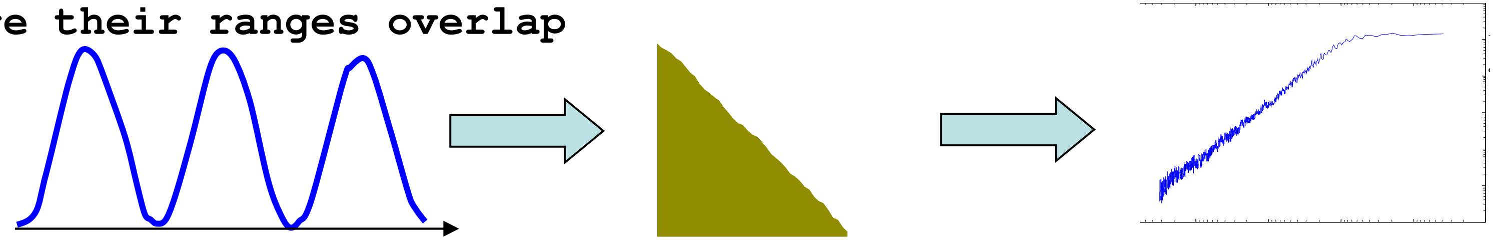


- Thresholds in transport introduce strong nonlinearity → storage and release



- Range of transport fluctuations may overlap with range of environmental forcing

- Internally-generated fluctuations may destroy environmental signals where their ranges overlap



- Nonlinear dynamics of sediment transport sets hard lower limit on temporal range of environmental signals that may pass through a system

Thank you
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