Space-Time Dynamics of Delta Evolution and Implications for Stratigraphy

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Overview

In depositional systems, channels migrate from one location to another causing erosion and deposition at any given point in the domain. The duration of depositional and erosional events, as well as their magnitudes leads to the formation of the stratigraphic record. In this study, we use high-resolution temporal surface elevation data from a controlled physical fan/delta experiment to quantify the probability distributions of the processes that govern the evolution of channelized depositional systems. Heavy-tailed statistics of erosional and depositional events are documented indicating that a small, but significant chance exists for the occurrence of extreme events. It is also shown that the duration of inactivity, when neither deposition nor erosion occurs, follows a Truncated Pareto distribution whose truncation scale is set by the characteristic avulsion time scale of the mean channel depth in the system. The erosional and depositional events have an upper bound that coincides with the maximum channel depths of the system indicating that the channel depths act as a first order control on the evolution of the system. Further, it is shown that the heavy-tails in the magnitudes of the erosional and depositional events are not preserved in the stratigraphic record thicknesses, resulting in an exponential distribution for the bed sediment thickness distribution.

A. Experimental Setup and Variables Studied

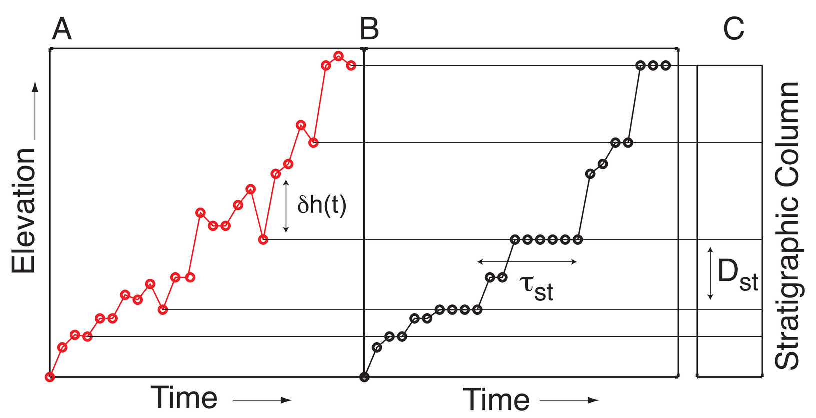
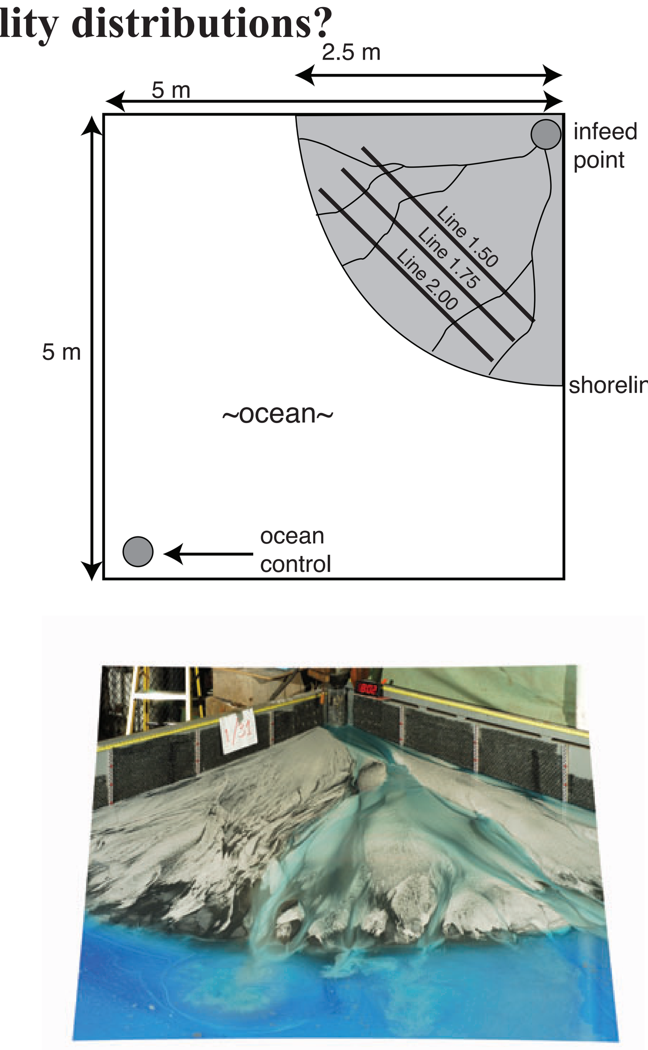


Figure A1: *Schematic showing the building of the stratigraphic column from the elevation time series. The variables used for representing the stratigraphic column and the elevation increments are also defined.*

1. The primary aim of this study is to address 1) which probability distributions describe the processes that govern the depositional dynamics of the system and how are they preserved in stratigraphy and 2) to what degree do physical mechanisms constrain the occurrence of extremes and how are they reflected in the probability distributions?



Notation

$h(t)$	Elevation time series
$\delta h(t)$	Elevation increments in time
D_i	Magnitudes of deposition ($\delta h(t) > 0$)
E_i	Magnitudes of erosion ($\delta h(t) < 0$)
D_e	Magnitude of depositional events
E_e	Magnitude of erosional events
τ_d	Periods of continuous deposition
τ_e	Periods of continuous erosion
τ_i	Continuous periods of inactivity ($\delta h(t) = 0$)
D_{st}	Bed thickness
τ_{st}	Time interval demarcating bed thickness

Figure A2: *Definitions of the variables studied in this work along with their notations (left panel), schematic of the experimental facility and the data used in this study corresponds to the Line 1.75 (top right panel). Also shown is the snapshot of the experimental run (bottom right panel).*

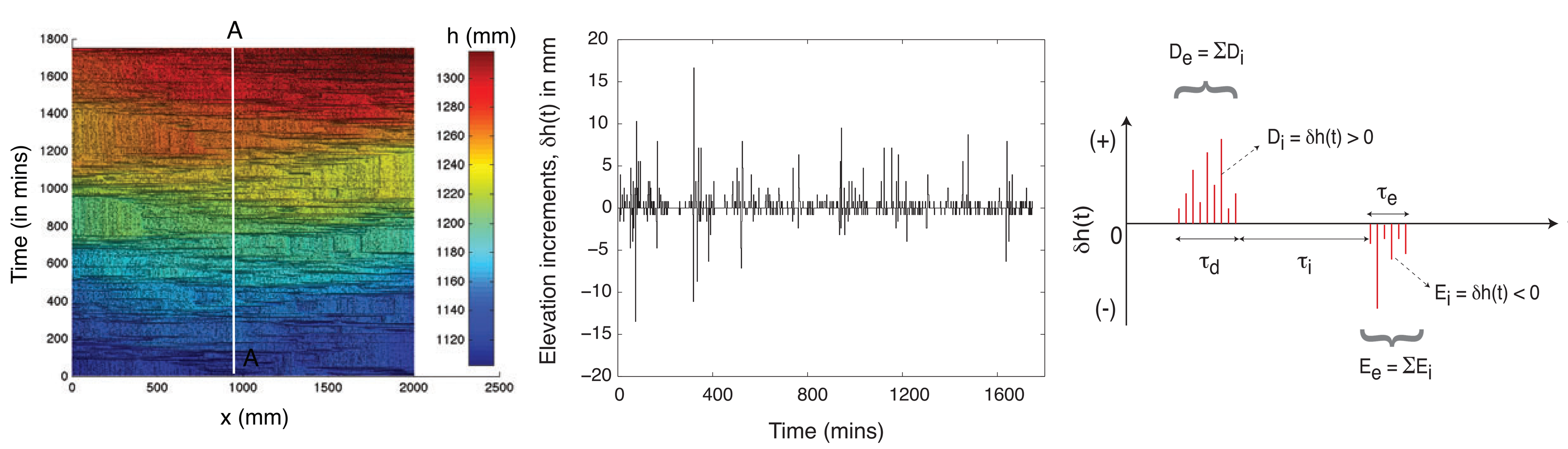


Figure A3: *Data collected from the experimental facility which corresponds to the Line 1.75 in Figure A2 (left panel). Elevation increments in time of the transect A-A (middle panel) and the schematic showing the definitions of the erosional and depositional magnitudes along with the time-scales involved in the system.*

B. Which probability distributions describe the surface dynamics?

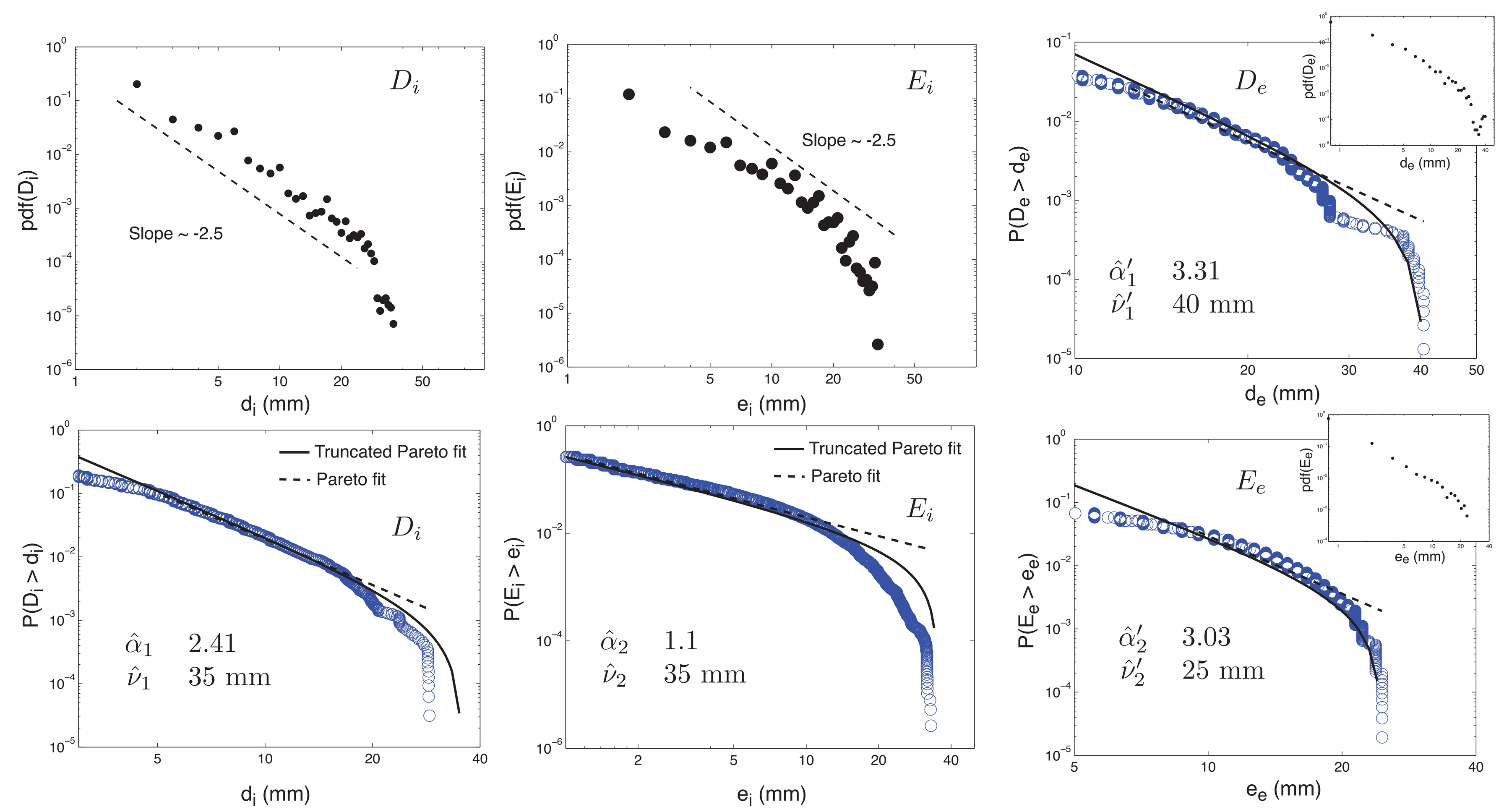


Figure B1: *Probability density functions and the probability exceedance plots of magnitudes of deposition (left panels) and erosion (center panels) along with their best fit Pareto and Truncated Pareto distributions. Probability exceedance plots of depositional events (top right panel) and erosional events (bottom right panel) along with their best fitting Pareto and Truncated pareto distributions. Notice that the random sum of random variables results in a thinner tail for the depositional and erosional events.*

1. Truncated Pareto distribution, a heavy-tailed distribution with a finite scale truncation, was found to describe the processes that govern the surface dynamics of the deltaic surface:

$$f(x) = \frac{\alpha\gamma^{\alpha}x^{-\alpha-1}}{1-(\gamma/\nu)^{\alpha}} \qquad P(X > x) = \frac{\gamma^{\alpha}\left(x^{-\alpha}-\nu^{-\alpha}\right)}{1-(\gamma/\nu)^{\alpha}}$$

α tail index

ν truncation parameter

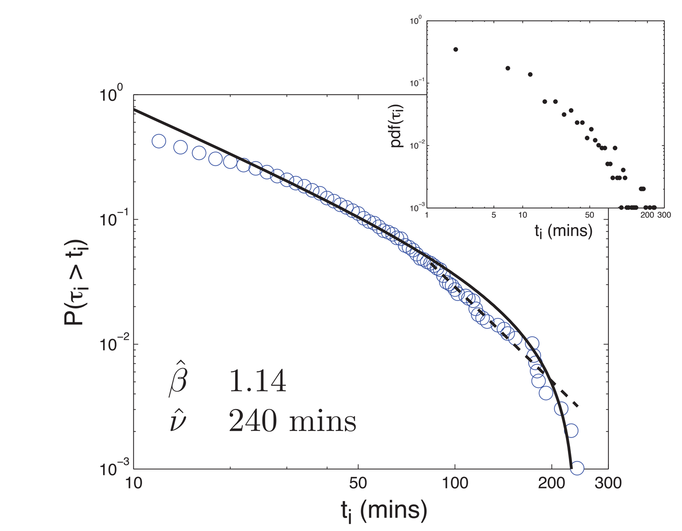


Figure B2: *Probability exceedance plot of the waiting times with their best fit Pareto and truncated Pareto distributions.*

C. What physical mechanisms control the truncation scales?

1. The maximum channel depths that were observed in the system were of the magnitude of 35 mm (see Figure C1) and the mean channel depths were around 20 mm.

2. It can be seen that the truncation scales on the erosional and depositional magnitudes as well as their magnitudes is set by the maximum channel depths in the system.

3. The dominant time scale in the system was that of inactivity, when neither deposition nor erosion occurs, and the truncation scale should be set by some characteristic avulsion time scale.

4. Avulsion time scale can be calculated by using the following relationship:

$$T_A = \frac{\eta}{\sigma_A}$$

T_A	Avulsion time scale
η	Channel depth
σ_A	Net aggradation rate

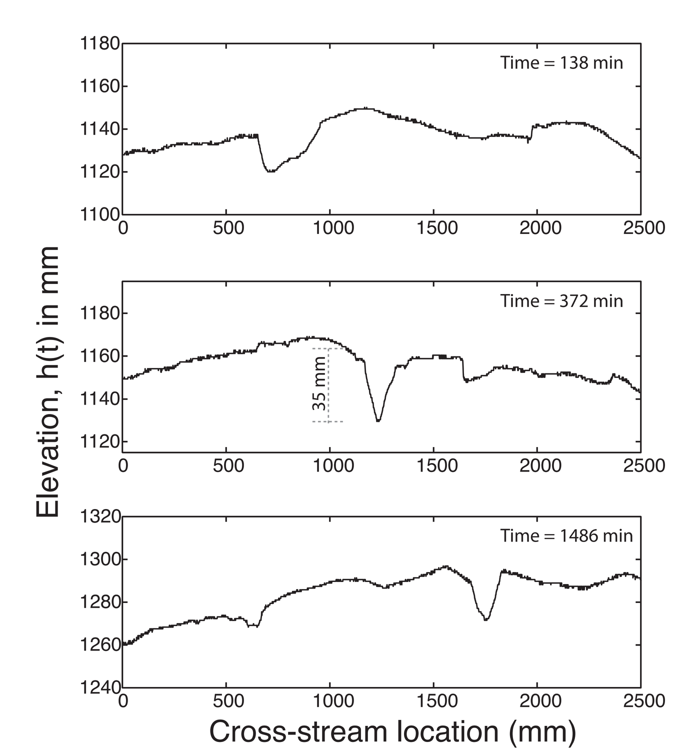


Figure C1: *Elevation cross-sections showing the deepest channels that appeared in the system during the experimental run. The middle panel shows the deepest channel whoch was 35 mm.*

5. The avulsion time scale of the periods of inactivity correspond to the characteristic avulsion time scale of the system (independently estimated) thus indicating that channel depths act as a first-order control on the truncation scales of the deltaic system.

D. Do the extremes of surface processes get preserved in stratigraphy?

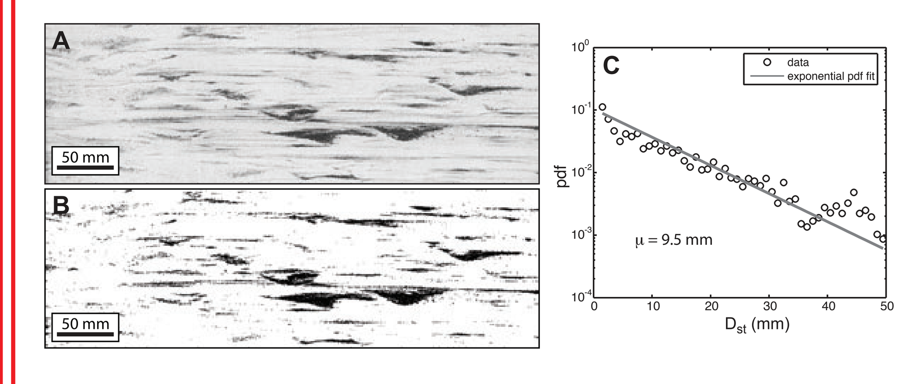


Figure D1: *Information defining distribution of bed thicknesses for DB-03 experiment generated from images of physical stratigraphy. A) Photograph of approximately 0.14 m of stratigraphy generated during DB-03 experiment. Stratigraphic section is located approximately 1.75 m from source. B) Facies map of stratigraphy where white pixels represent quartz deposits and black pixels represent coal deposits. C) PDF of Dst shown in semi-log space generated from deposit facies map. Linear decay of bed thicknesses in semi-log space suggests exponential.*

1. Bed thicknesses can be viewed as the difference of depositional and erosional events, which are random sums of the random variables, magnitudes of deposition and erosion, respectively.

$$D_{st} = \sum_{i=1}^{\tau_d} D_i - \sum_{i=1}^{\tau_e} E_i$$

2. Through numerical simulations we show that when the elevation fluctuations have a symmetrical PDF, the resulting bed thickness distribution is exponential. However, only when there is asymmetry in depositional and erosional magnitudes, the resulting bed thickness distribution deviates from exponential and follows a power-law PDF.

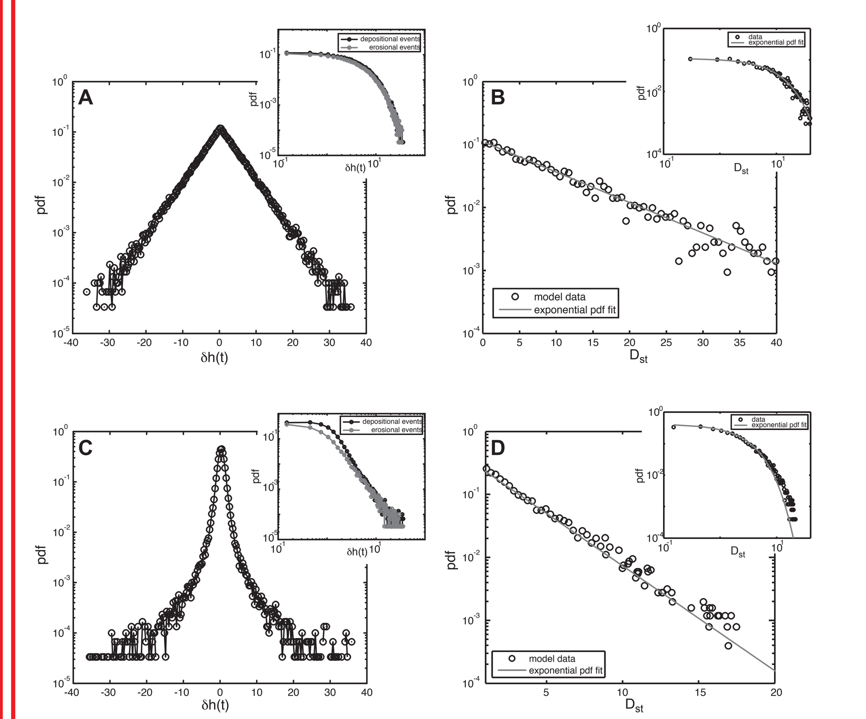


Figure D2: *Plots showing results from numerical simulations. PDFs of elevation fluctuations which are symmetrical (A) Laplace distribution and (C) Double Pareto distribution result in an exponential distribution for the resulting bed thickness distribution (as shown in B and D, respectively).*

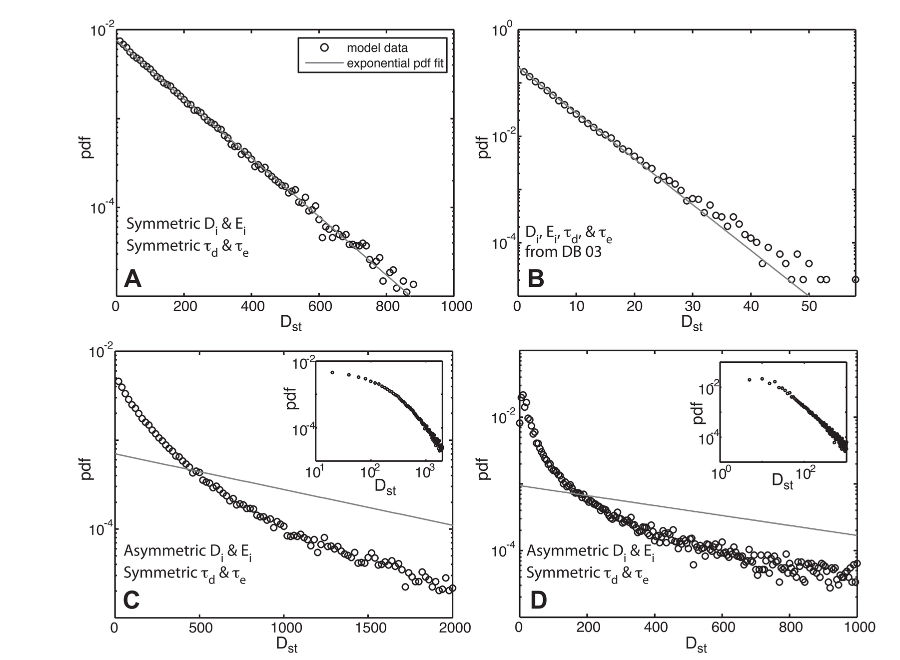


Figure D3: *Plots showing results from numerical simulations. It is to note that bed thickness distribution is exponential as long as the elevation fluctuations' PDF is symmetrical (thin or heavy-tailed). However, when the elevation fluctuations' PDF is asymmetrical the resulting bed thickness distribution deviates from an exponential distribution.*

E. Inverting stratigraphic records for information of surface dynamics?

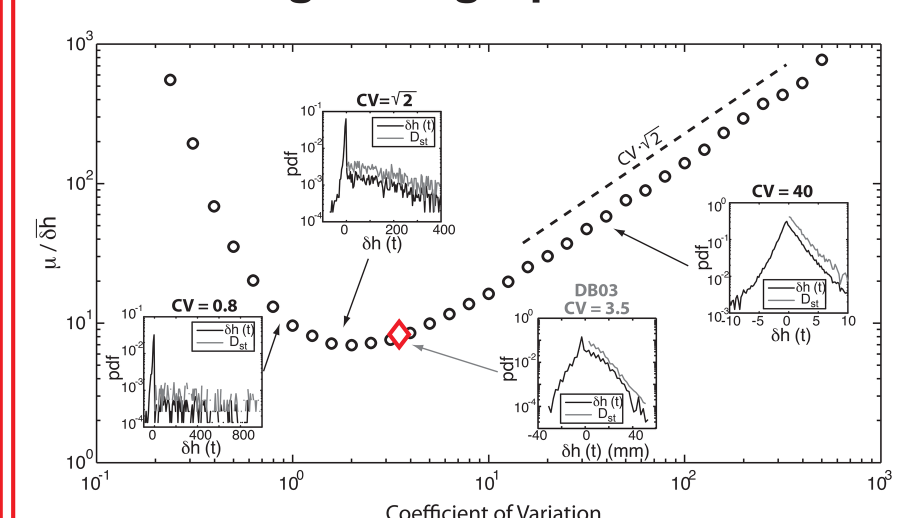


Figure E1: *Model results documenting relationship between coefficient of variation for surface elevation fluctuations and μ/δh generated from 1D synthetic stratigraphy models are shown with black open circles. Red open triangle indicates relationship between CV and μ/δh for DB-03 experiment. Insert plots illustrate shape of Kolmogorov increments, δh'(t), and resulting bed thickness, D_{st}, distributions for 1D models with 3 CV values. Distributions displayed in insert plots resulted from elevation increments.*

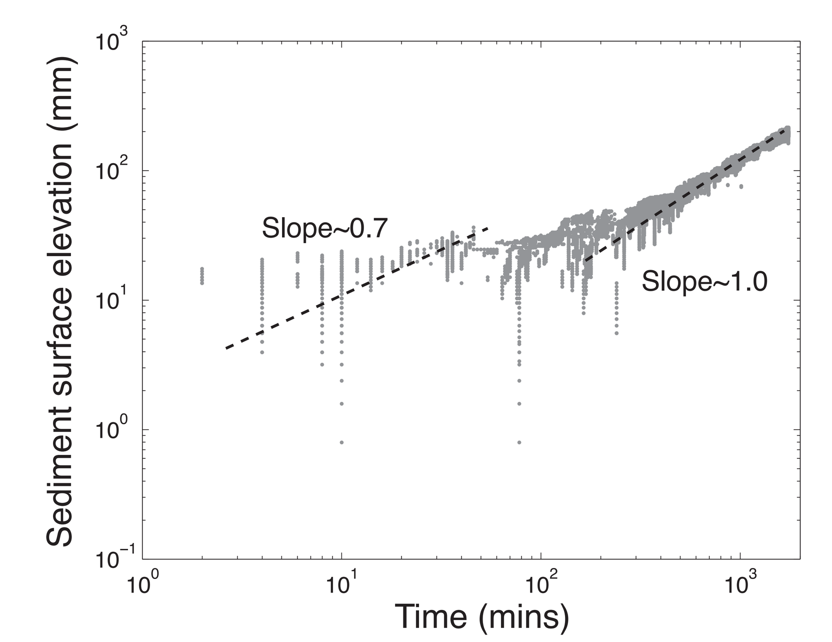


Figure E2: *Plot showing the growth of the sediment surface elevation of the stratigraphic column with time. Scaling of the sediment surface elevation of the stratigraphic column clearly shows the signature of the heavy-tailed hiatuses which manifest themselves as a scaling break in this plot.*

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