

Deltaic Network Growth and Stratigraphy through a Rule Based Geometric Model*

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Search and Discovery Article #41674 (2015)**

Posted August 31, 2015

*Adapted from oral presentation given at AAPG 2015 Annual Convention and Exhibition, Denver, Colorado, May 31 – June 3, 2015

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Abstract

We introduce a unified geometric model in which the short-term fluvio-deltaic processes generating discrete sedimentary bodies and long-term basin evolution coexist. Geometric aspects of delta channel networks and their long-term internal stratigraphic arrangements of deltaic deposits present enormous intricacy in almost every aspect (delta shape and size, number of channels, shoreline shape, etc.). To simulate the planimetric growth of a deltaic network we employ a flexible algorithm based on a set of simple rules some of which are quantitatively anchored in physical processes while others are purely stochastic and connected to the physical process via observed field correlations among various terms (e.g., Syvitski, 2006). The model generates distributary networks in which planform of individual channels emerge from a correlated random walk algorithm through successive addition of short segments (piecewise). Each segment involves a small direction deflection, partly correlated to the previous deflection. Frequent bifurcations result in dense, anabranching channel patterns while more representative deltaic networks are obtained using a small probability bifurcation value (0.01 to 0.05). The proposed network growth model can yield distributary networks of significant morphological variation in terms of shapes, channel planforms, or channel density. The comparison between model outcomes and field analogs will be through a series of metrics such as planform shape of individual channels, delta shape, shoreline shape, or channel density distribution. Long term, a kinematic basin filling mass conservation model is used to render large-scale strata arrangements, which under constant sediment supply and sea level conditions consists of monotonous parallel topset and foreset packages. Varying the external forcing factors (i.e., sea level, subsidence) yields complex stratal arrangements reflecting the effects of transgression and incision. We argue that this hybrid approach driven by simple rules is suitable for investigating complex systems. By aggregating only few simple rules, due to the random terms built in, this type of model creates complex landscape patterns via randomness built in (e.g. Murray & Paola, 1994). Using simple rules also enables scenario testing and makes it easier to understand the important controls on the stratigraphic outcome.

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Swenson, J.B., C. Paola, L. Pratson, V.R. Voller, and A.B. Murray, 2005, Fluvial and marine controls on combined subaerial and subaqueous delta progradation: Morphodynamic modeling of compound-clinoform development: *Journal of Geophysical Research*, v. 110/F2, p. 2-16.

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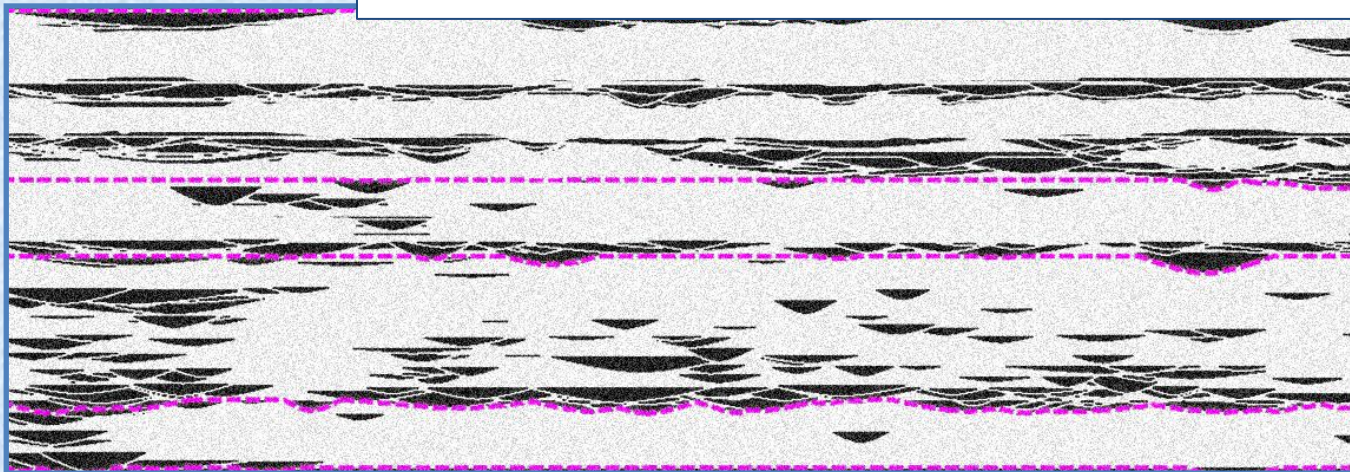
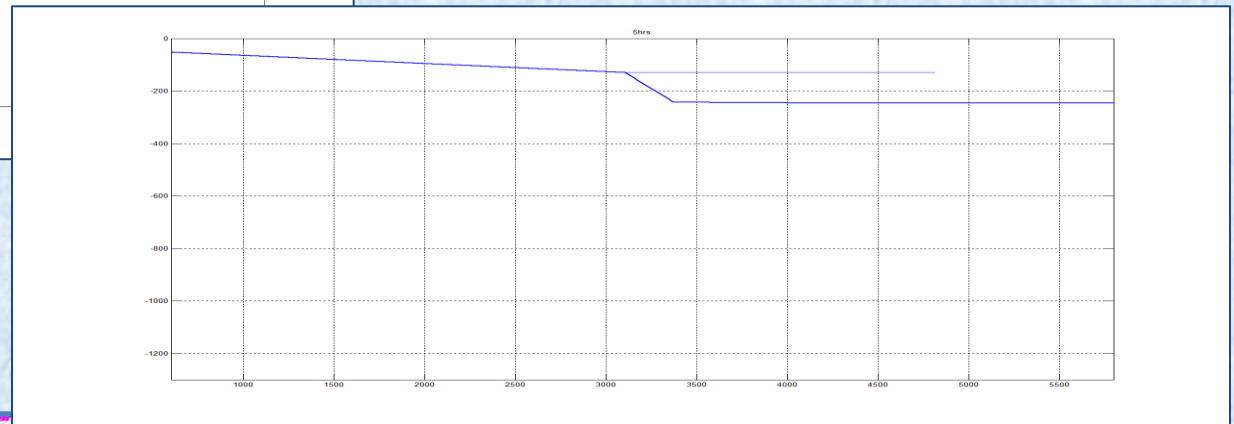
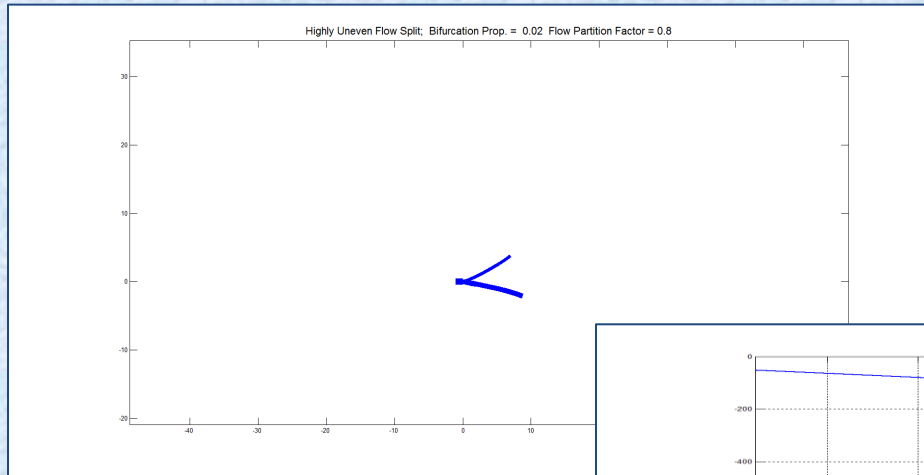
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AAPG Annual Convention and Exhibition
Denver, 2015



Surface Model + Basin Evolution > Stratigraphy



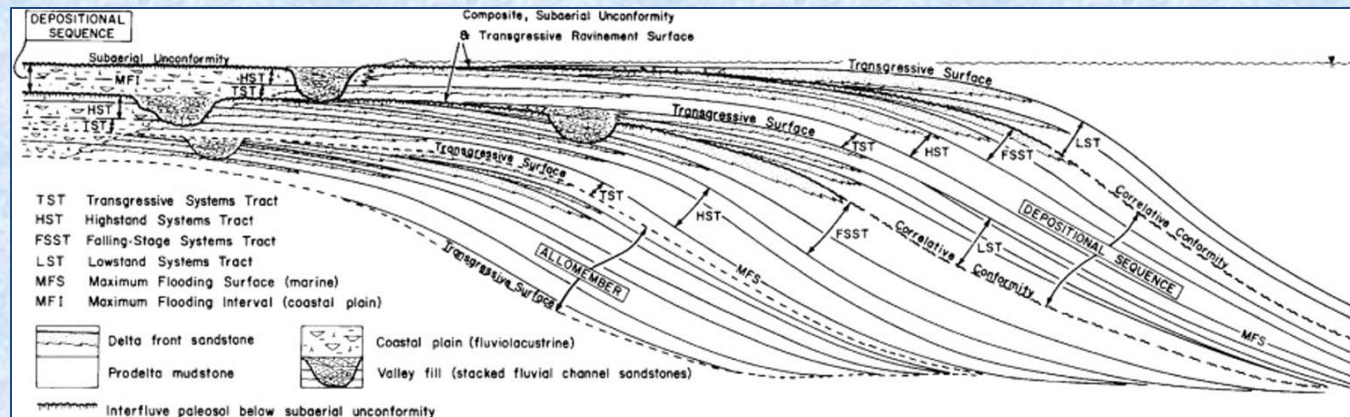
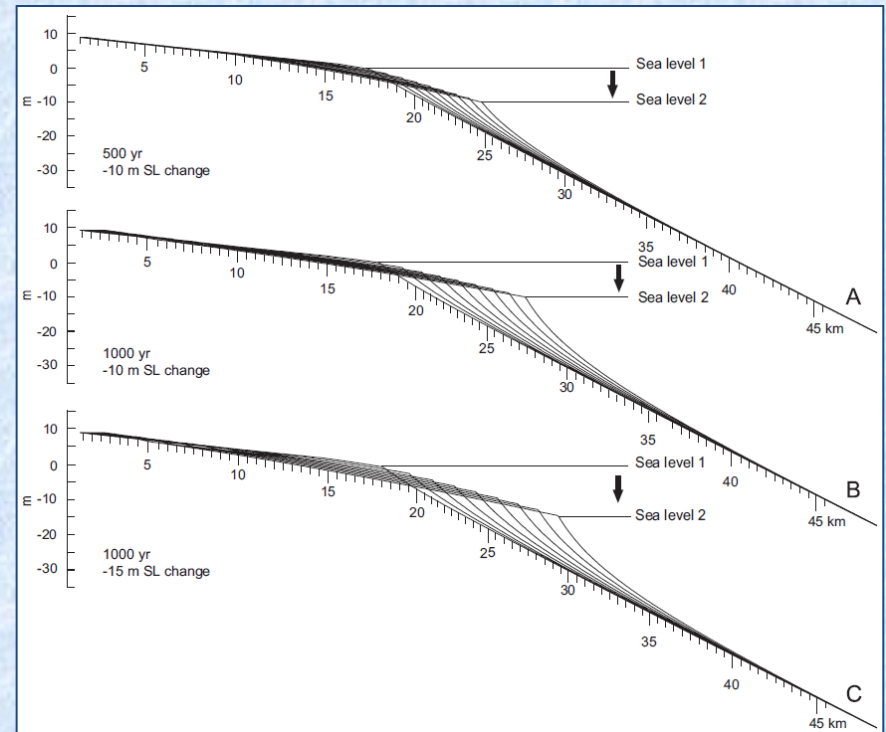
Cross-shore Models & Interpretation

2D Cross-shore models examples:

- Muto, Steel, Swenson, 2007
- Kostic and Parker, 2003
- Swenson, 2005
- Lorenzo-Trueba et al., 2009
- Hoogendoorn et al., 2008 - DELTASIM

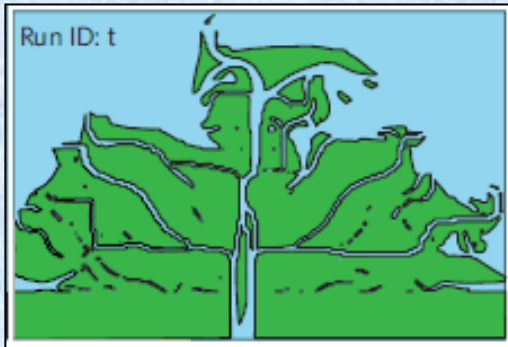
Sequence Stratigraphy

mostly cross-shore interpretation



3D Channel Resolving Deltaic Models - Examples

Delft 3D - Edmonds and Slingerland (2009)



“Reduced Complexity Models”

Liang et al (2014, 2015)

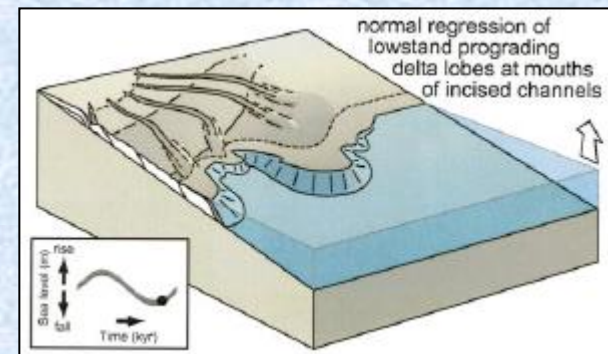


Seybold et al (2007)



Ritchie, Hardy, Gawthrope (1999; 2004a; 2004)

Simple, Large Scale (lobe)



PHYSICAL EQUATIONS

RULE BASED

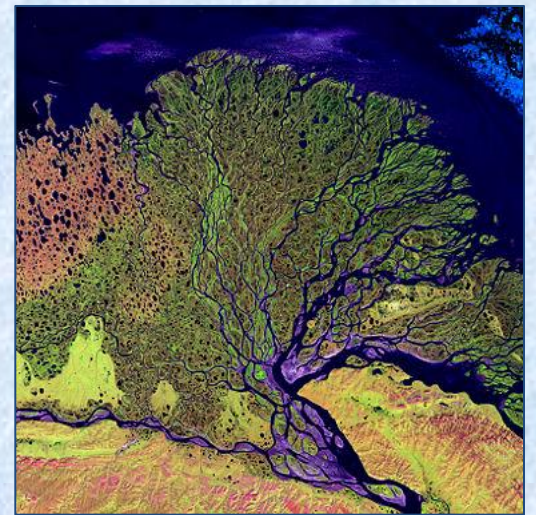
A New, Simplified Approach To Modeling Deltaic Networks

Objective:

Develop a model based on a minimal set of rules that can:

- Render distributary channel networks arrangements, representative for a wide variety of river deltas
- Be combined with basin-scale stratigraphic models
- Execute reasonably fast and allow scenario testing

Deltas exhibit a tremendous variability in size, morphology, channel networks

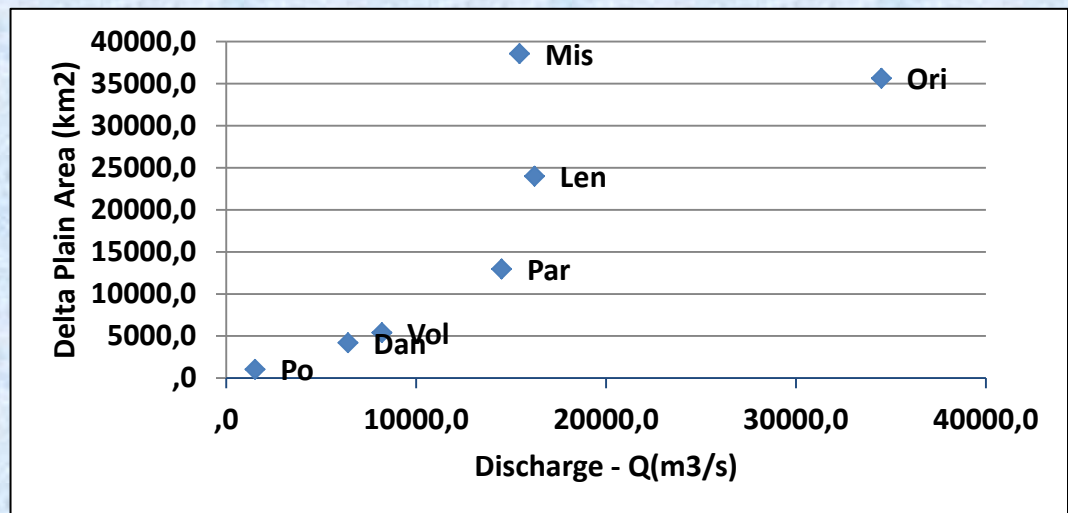


Deltas display morphological variation in almost every aspect

- Size / Shape,
- Number of Channels,
- Number of Bifurcations
- Land to Water Ratio
- **Channel Planforms**
- **Network Geometry**
- Island/Channel Patterns
- Shoreline Shapes

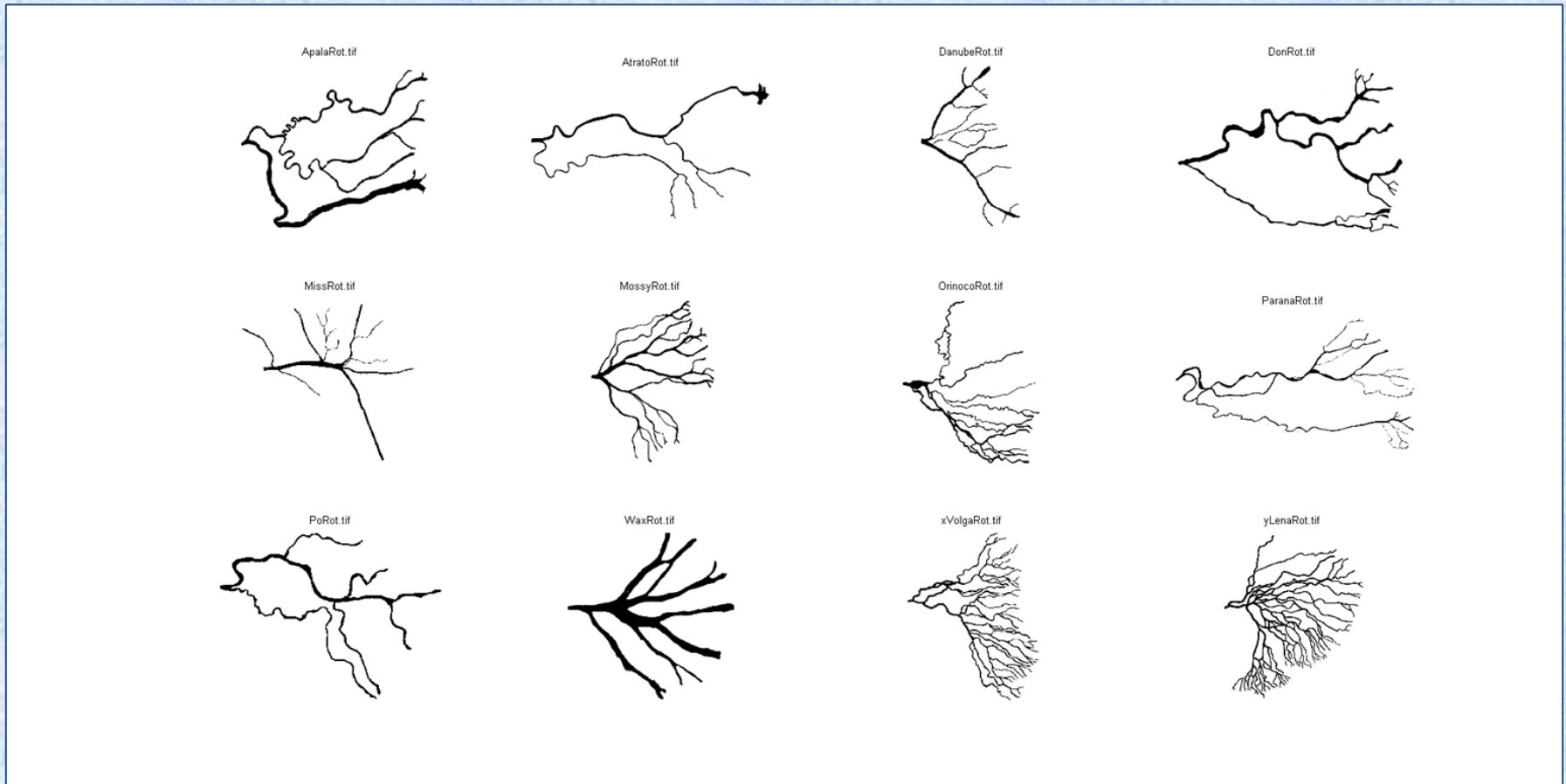
Syvitski (2006) - Investigation of many parameter on a large data set (55 deltas) reveals very few correlations:

- *Area \sim Water discharge*
 - *Gradient \sim Volume of sediment influx*
 - *Number of Channels \sim maximum monthly discharge*
- ... none of which tell us much about channel network geometry in the absence of scale.



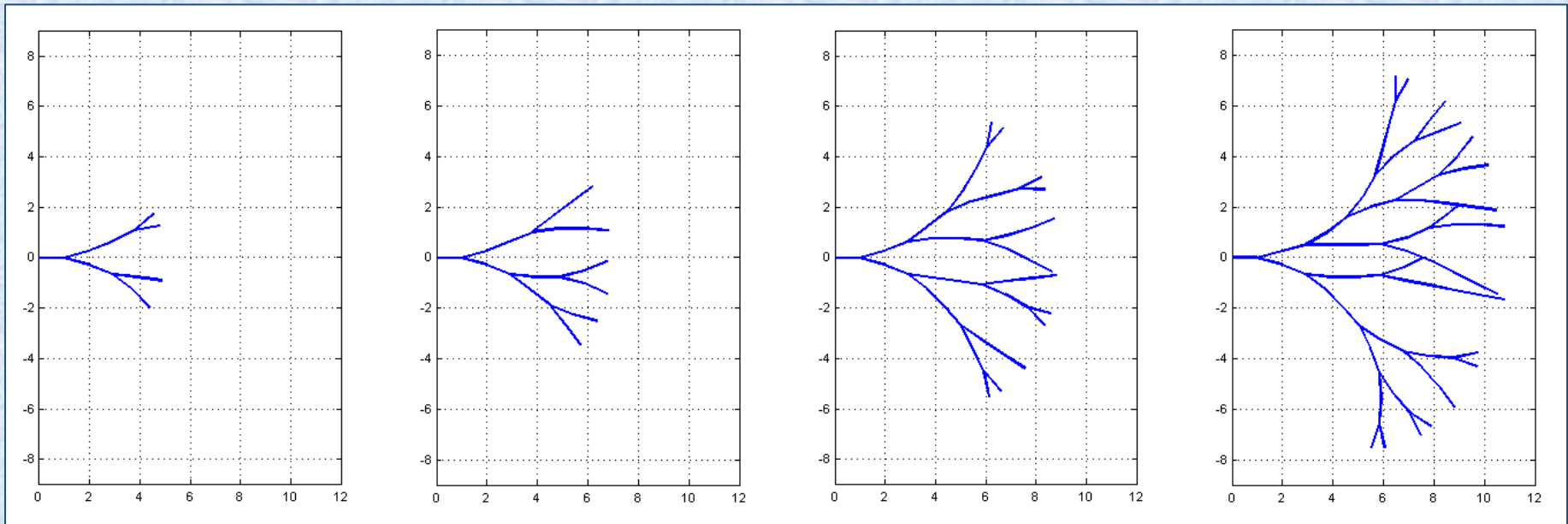
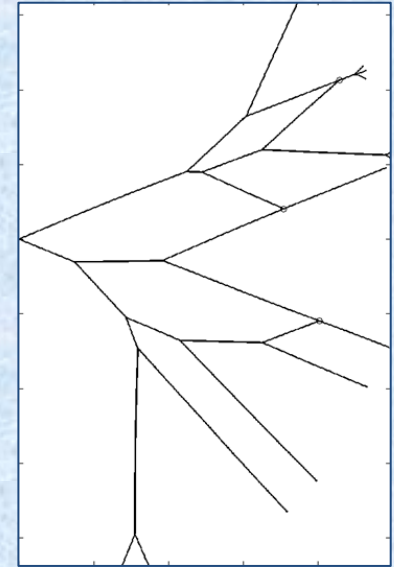
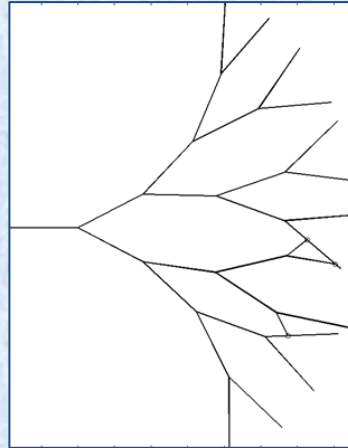
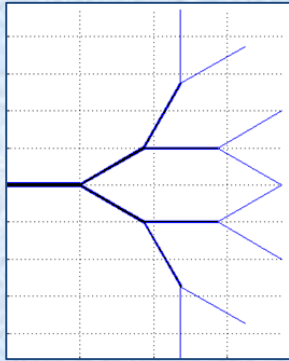
Exploring internal deltaic topology- or lack thereof

*“...it seems unlikely that “deltas worldwide will exhibit strong internal similarity, beyond the possible **fractal** nature of the channel network”
(Edmonds et al - 2011)*

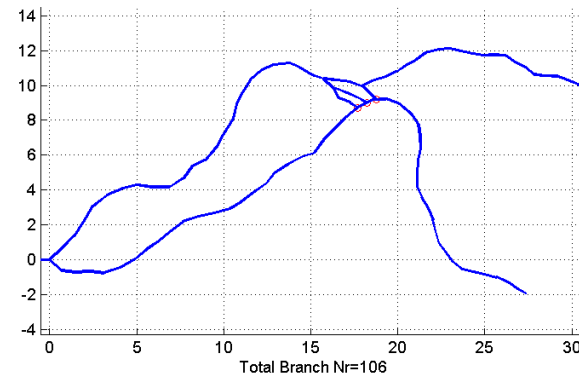
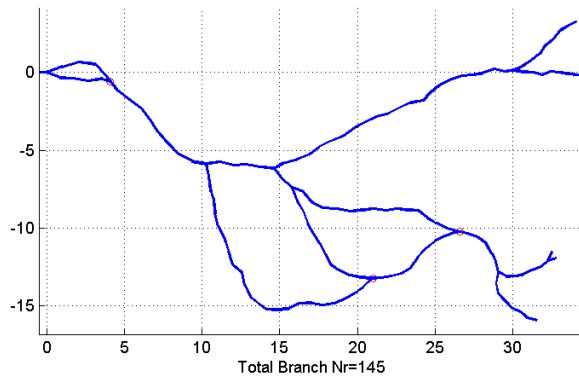
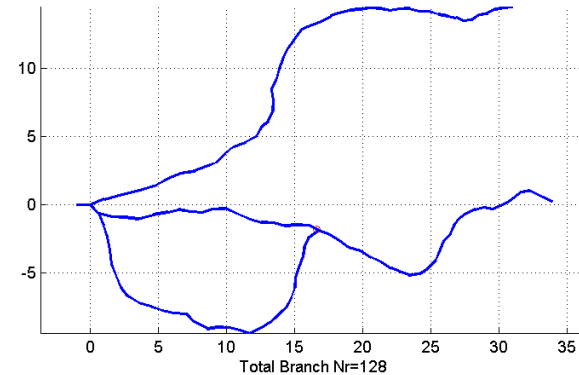
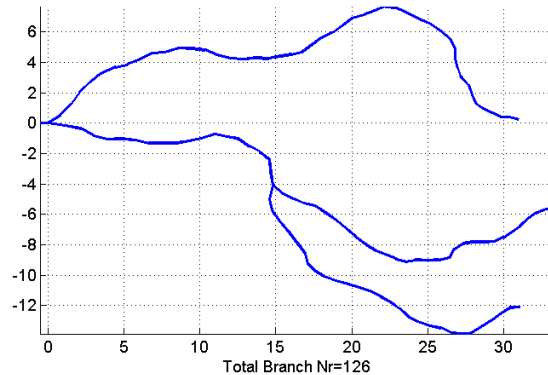


...different from tributary networks that show universal topologic laws (i.e., Horton's)

Network Generation - (2D)

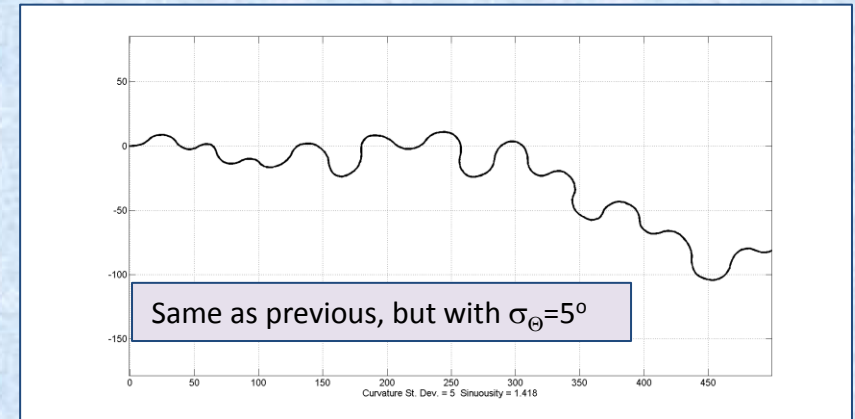
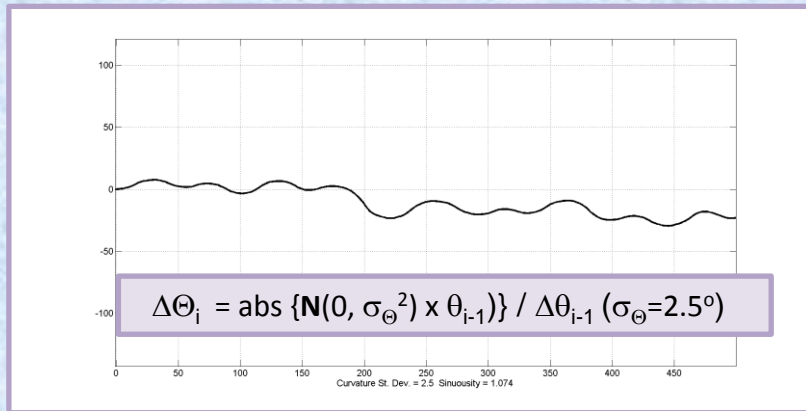
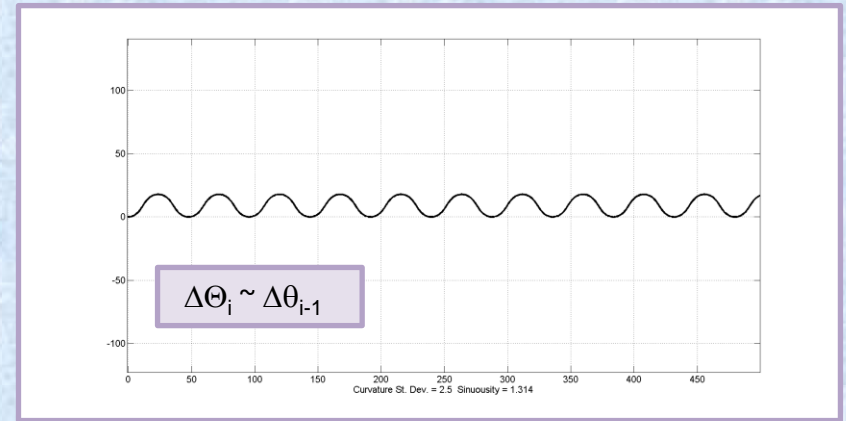
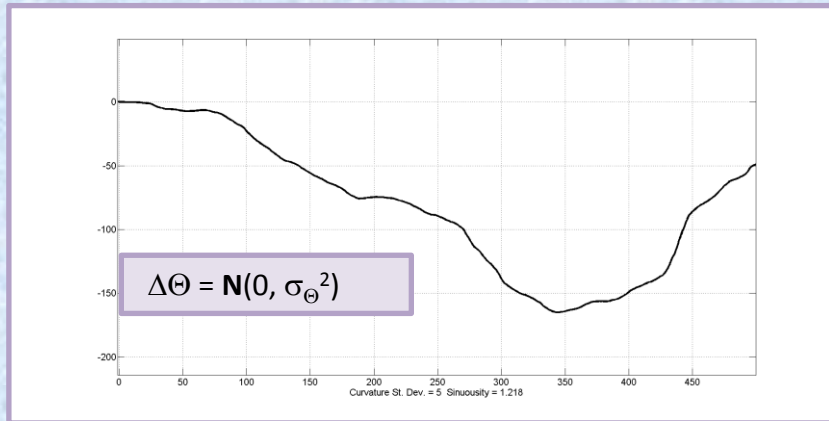


More representative networks can be obtained using a piecewise, random walk approach:

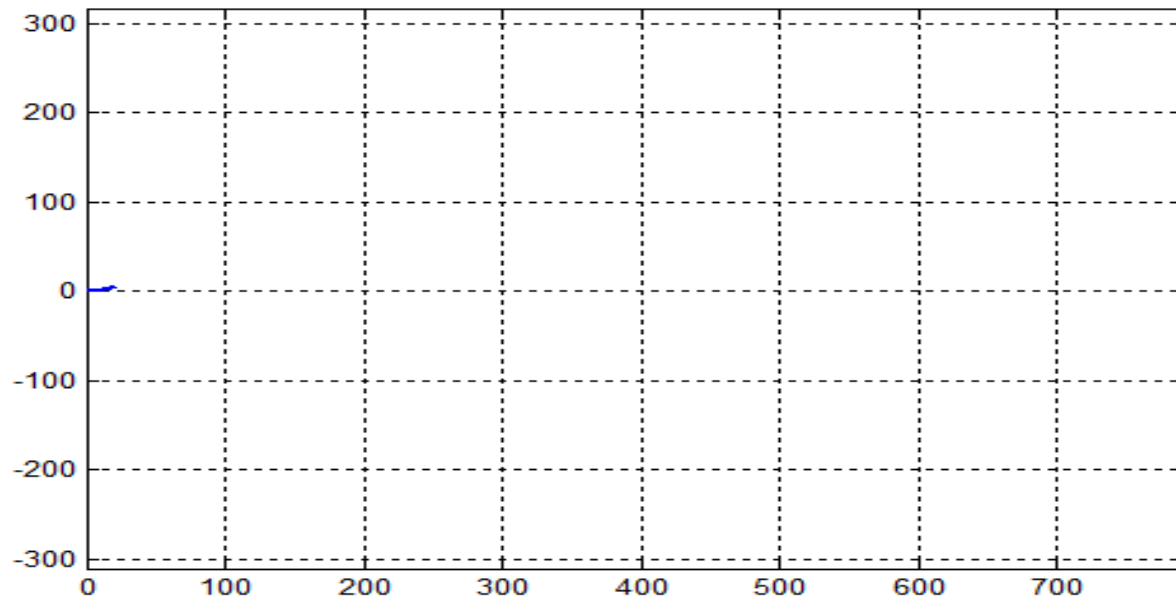


Examples of channel planform:

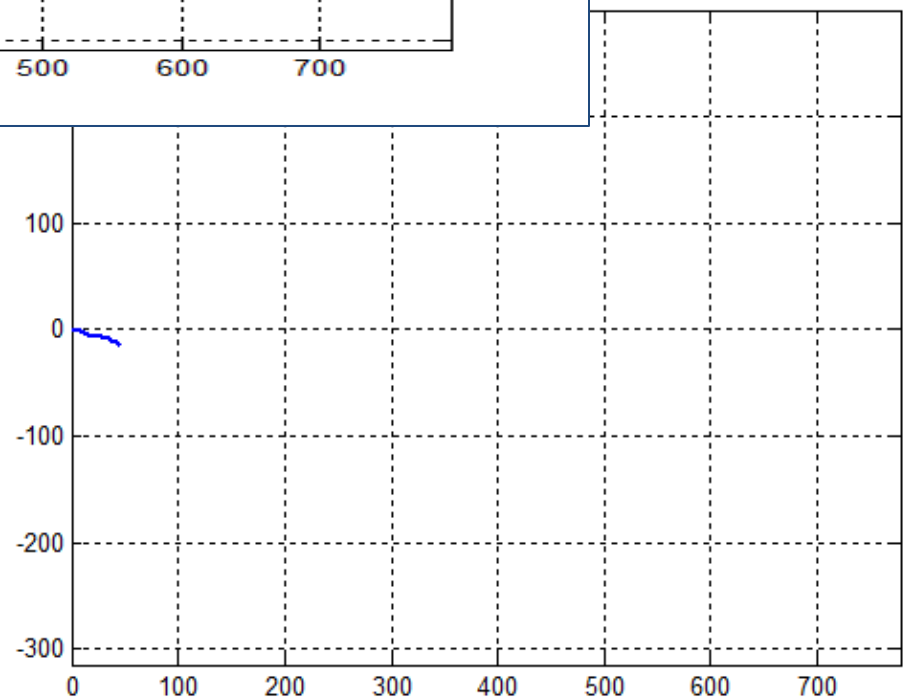
Random, Fully correlated, Partly correlated



Highly Corr. (RW) Channel; Def. Angle STD = 5; Corr. Factor = 0.99



D = 5; Corr. Factor = 0.6



Effect of correlation factor
High (top) vs Low (bottom)

Basic Rules For Individual Channels

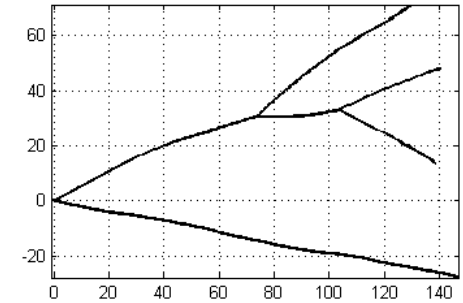
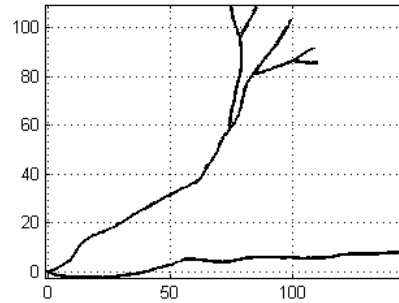
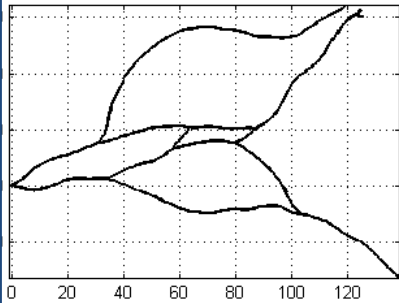
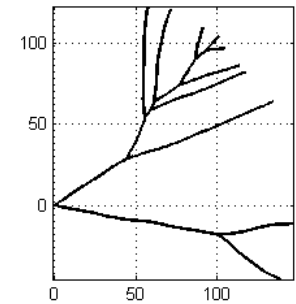
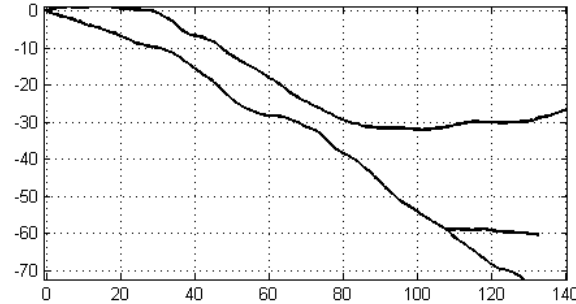
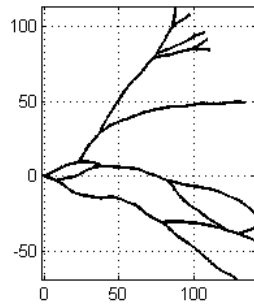
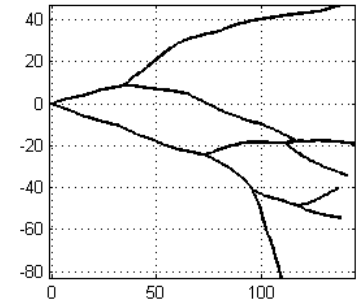
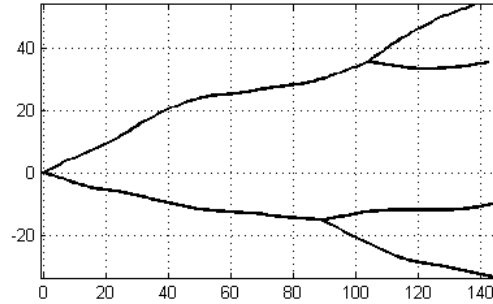
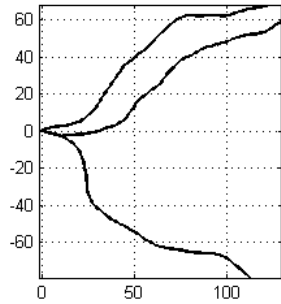
1. $\Delta\theta = \mathbf{N}(0, \sigma_\theta^2)$ Deflection Angle - Normal Distribution [0.5 – 5]
2. $u_i = \mathbf{U}(0, 1)$.
 $\Delta\theta_i = \mathbf{N}(0, \sigma_\theta^2)$, if $u_i > C_d$ [0.6 – 0.9]
 $\Delta\theta_i = \text{abs}(\mathbf{N}(0, \sigma_\theta^2) \times \Delta\theta_{i-1}) / \Delta\theta_{i-1}$, if $u_i < C_d$
3. $\theta_i = (1 - k_m)(\theta_{i-1} + \Delta\theta_i) + k_m \theta_m$ (Directional Stability – “Bias”) [0.001-0.01]

Similar previous work on single channel centerline:

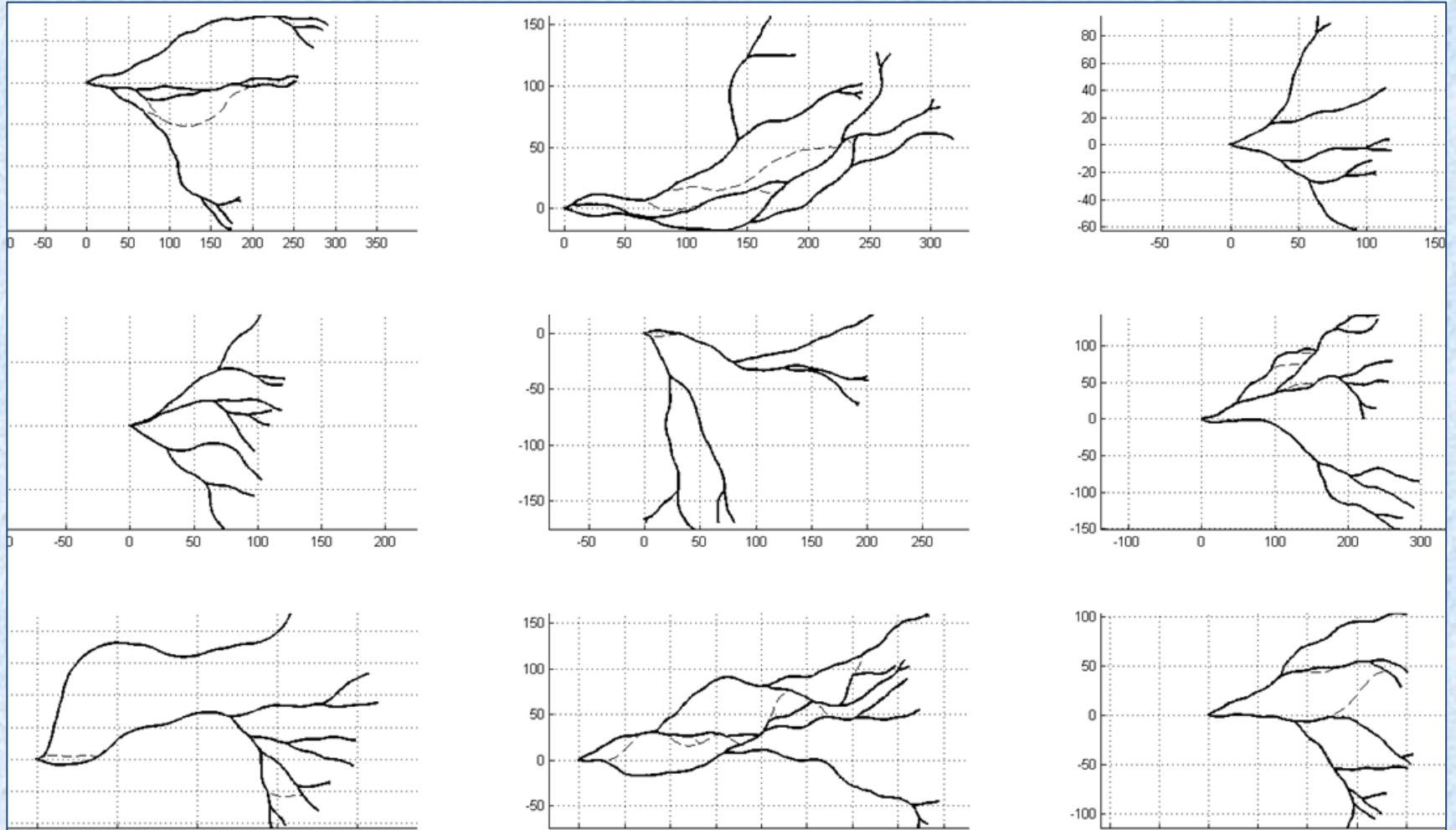
- Thakur and Scheidegger, 1968).
- **Surkan and van Kan (1969).**
- Ferguson (1976).

Such recursive methods can approximate well a wide variety of planforms in terms of sinuosity or orientation angle PDF but cannot faithfully capture higher order statistics (i.e., meander loops asymmetry) - Mariethoz et al (2013) .

“Random” Deltas - Examples



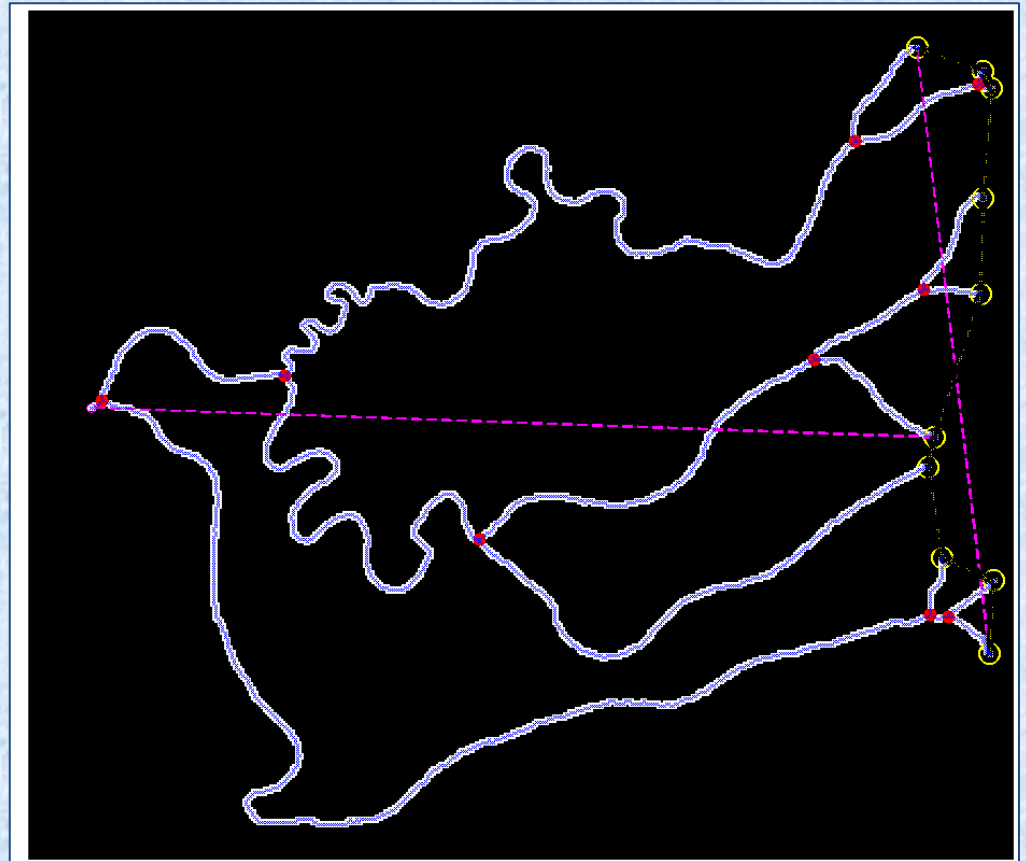
Model Results



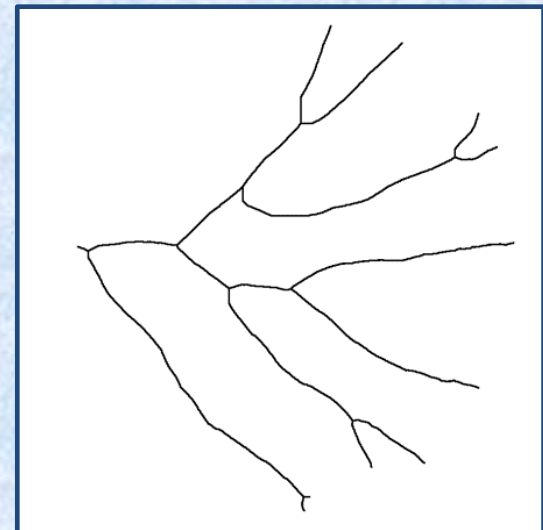
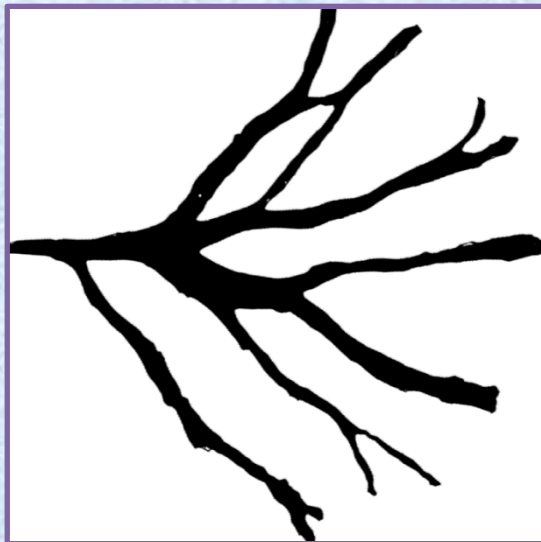
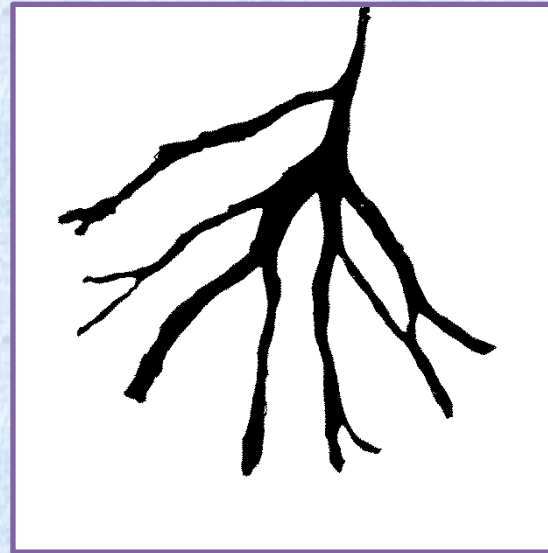
Comparison With Filed Deltas

Compare what?

- ~~Size~~
- ~~Number Of Channels~~
- Shape (wide vs narrow)
- Planform Sinuosity (PDF)
- **Distribution of Bifurcation Nodes from US to DS**
- **Reach Lengths (PDF)**
- **Dispersion of Outlets**
- ~~Shoreline Shapes~~

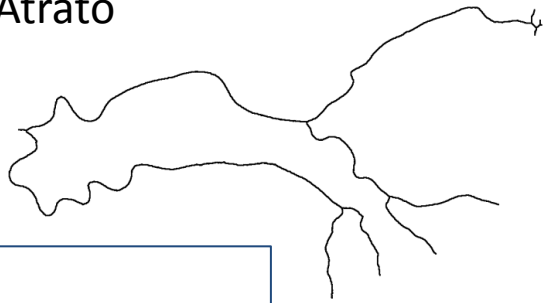


Skeletonize Filed Deltas

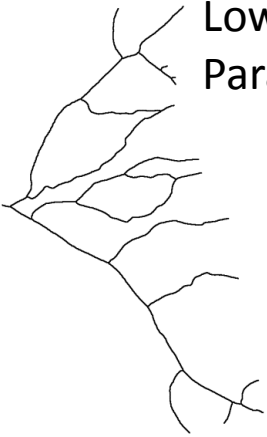


Set of Skeletonized, Dimensionless, Rotated Filed Deltas

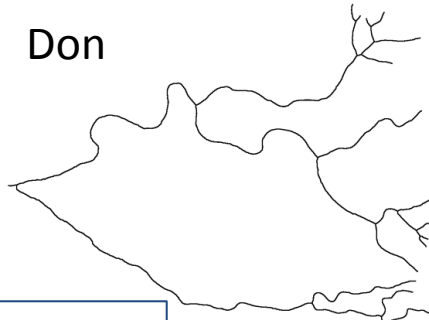
Atrato



Lower
Parana



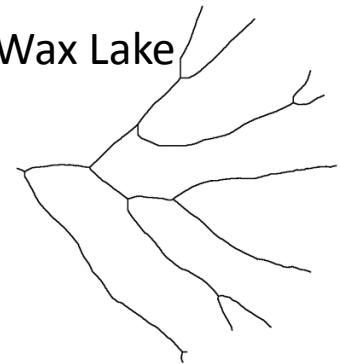
Don



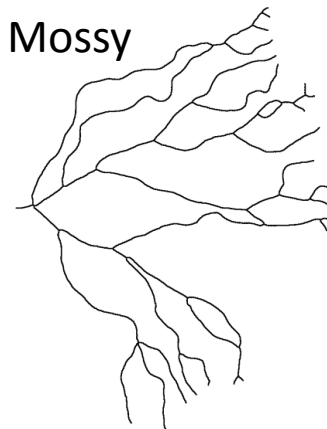
Mississippi



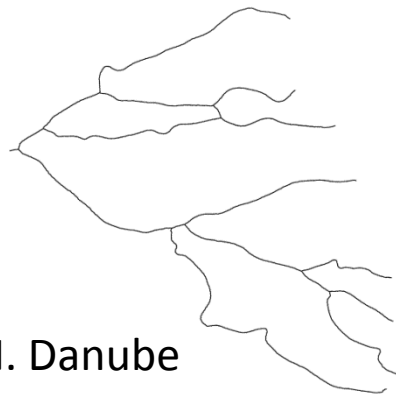
Wax Lake



Mossy

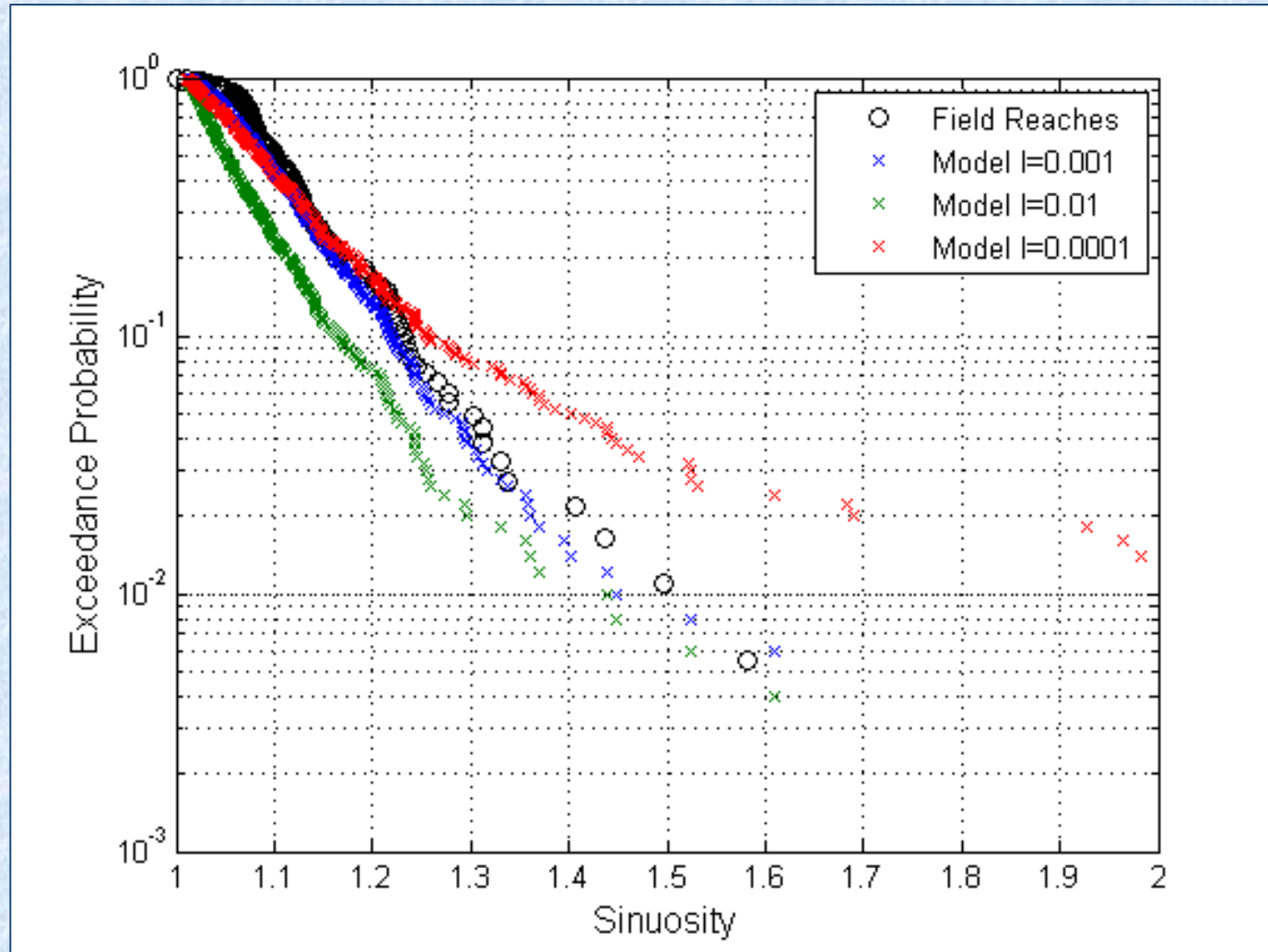


N. Danube

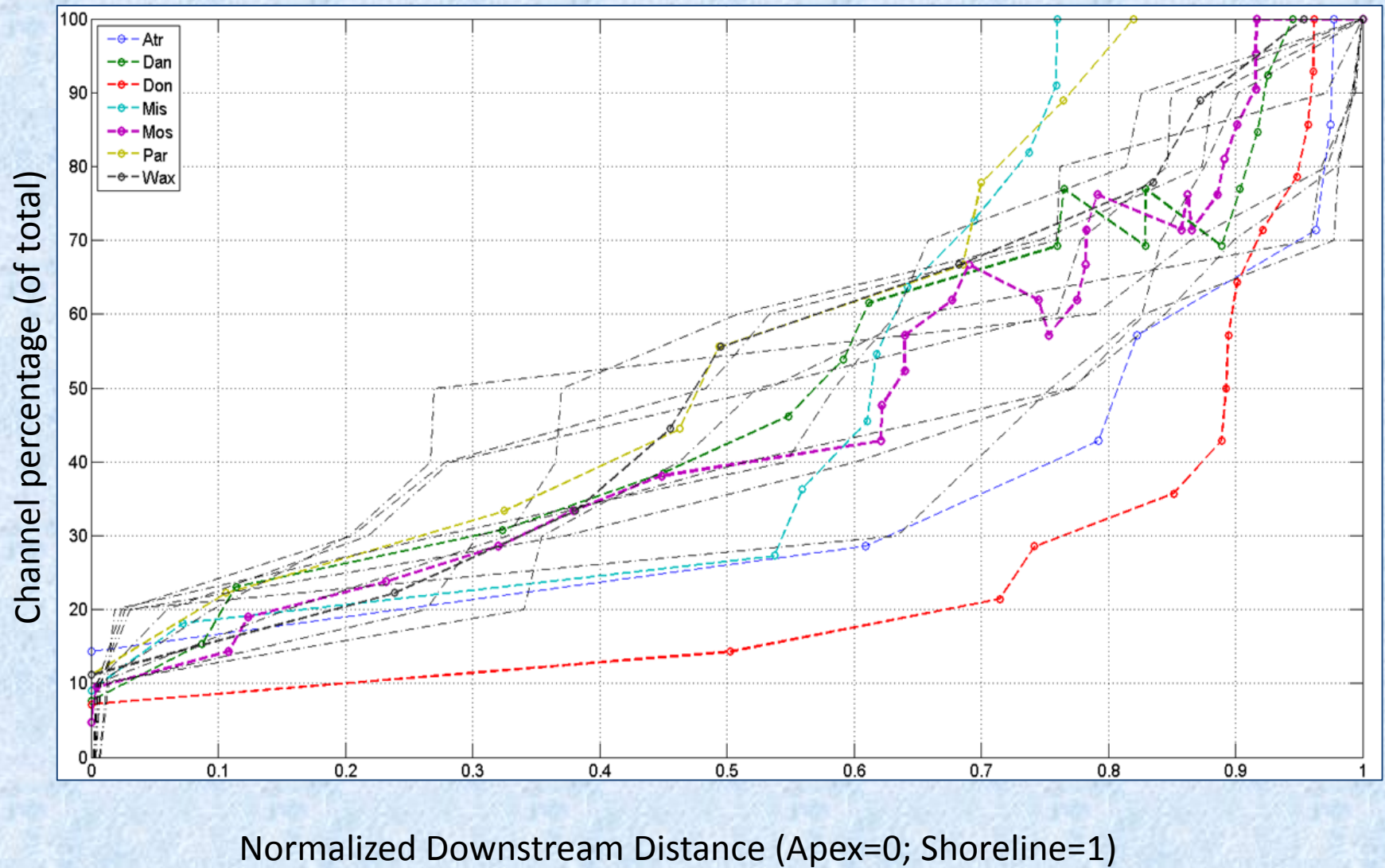


Sinuosity – Partial Conditioning

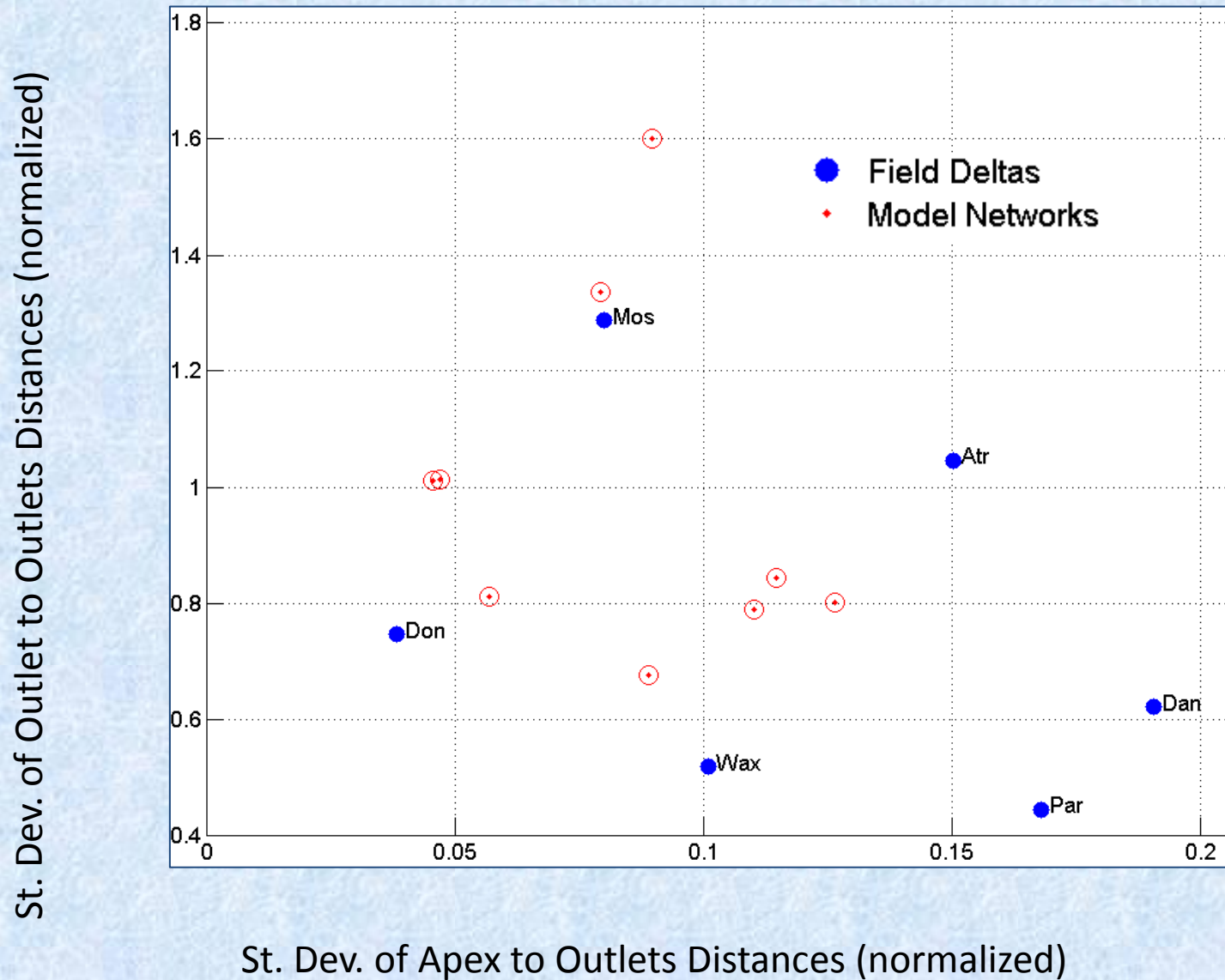
Main Direction Weight (“Bias”) $\sim 10^{-3} * \text{St. Dev. of Angle Deflection}$



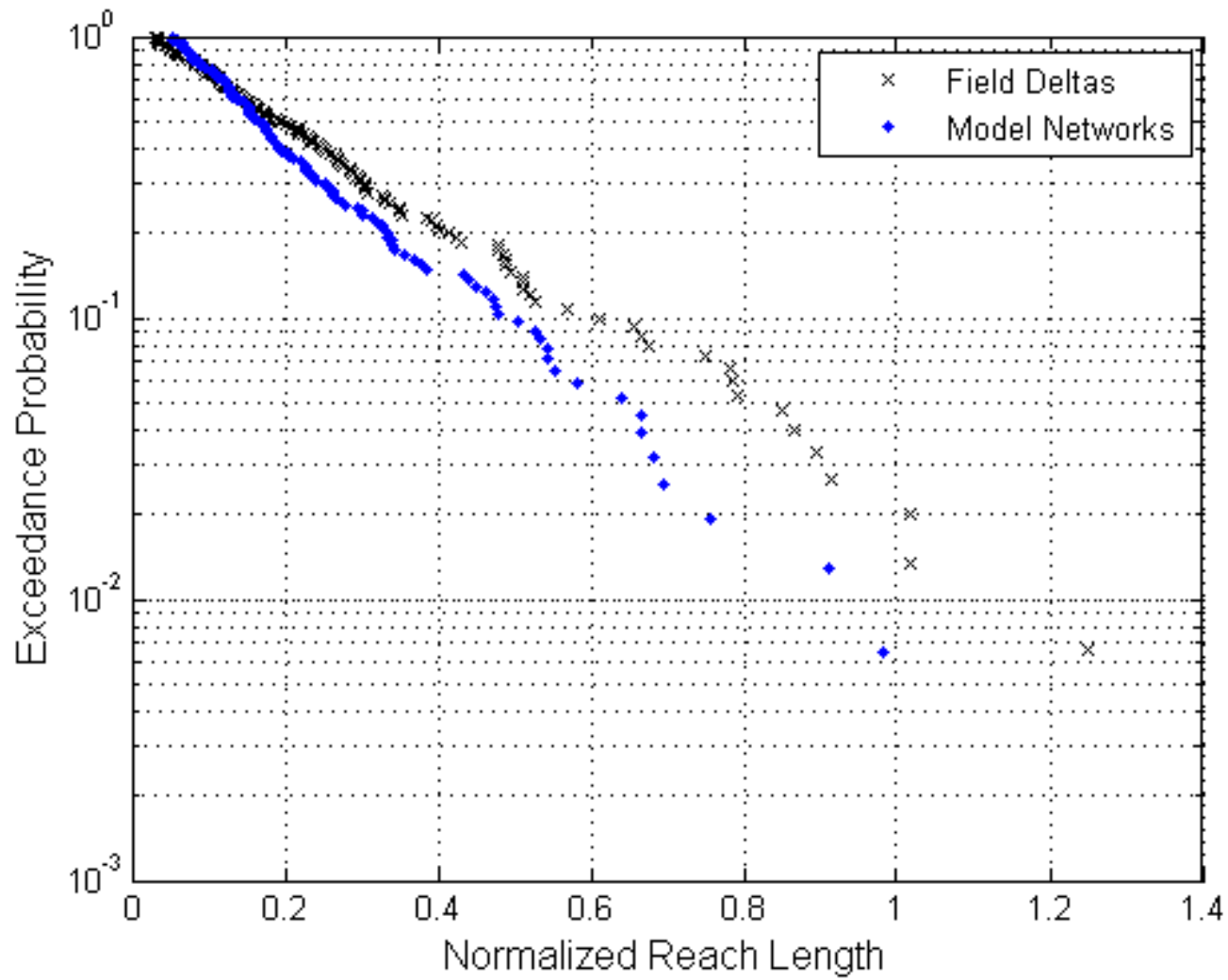
Increase in Channel Number from Apex to Shoreline



Channel Mouths (Outlets) Dispersion

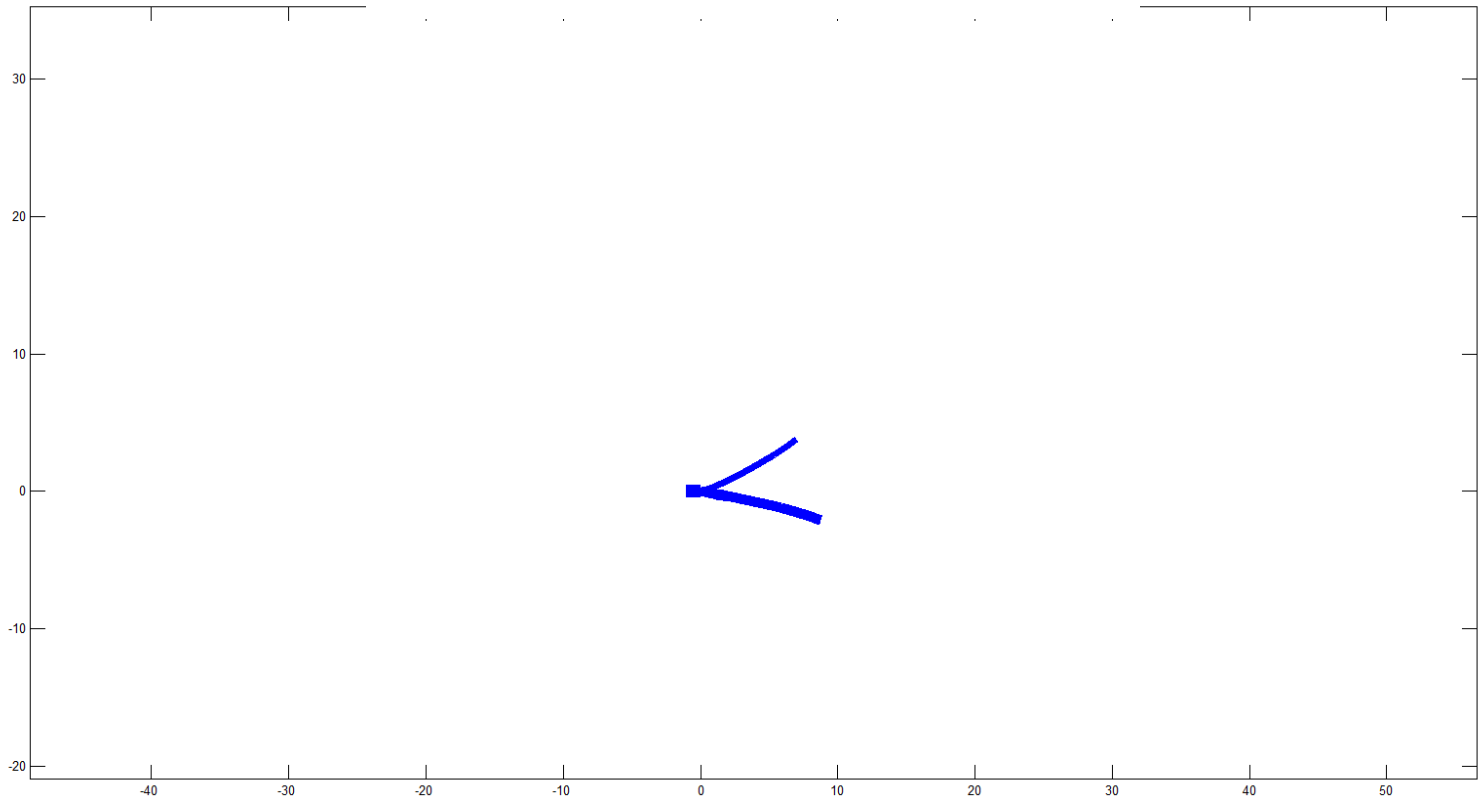


Distribution of Individual Reaches Lengths

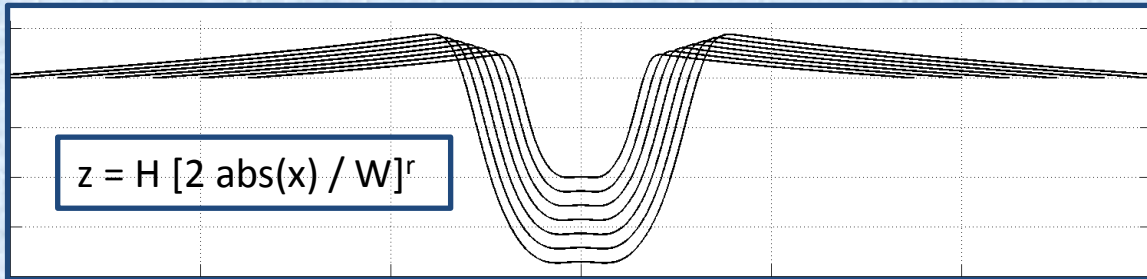


Where Next? Towards Building Stratigraphy

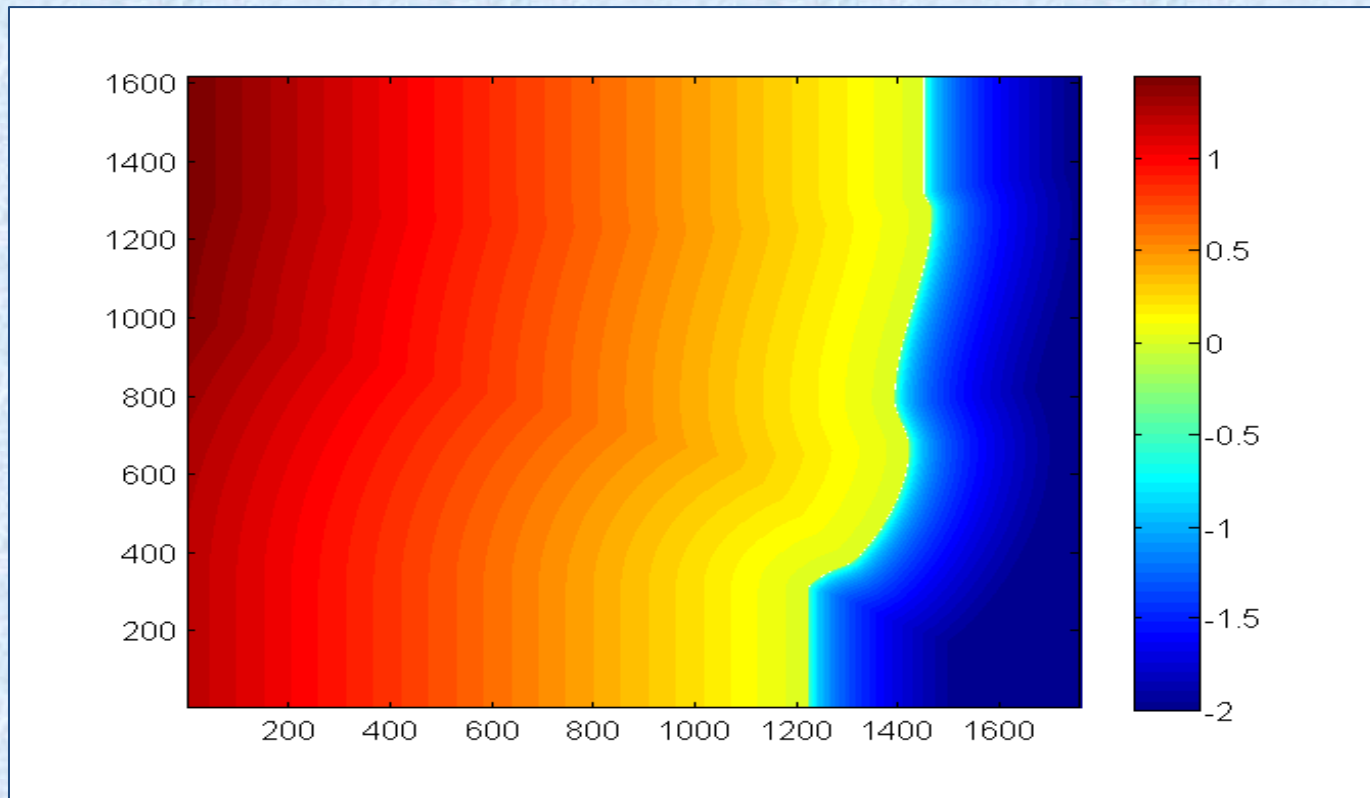
First step is assigning a width expression: $W \sim Q^{0.5}$



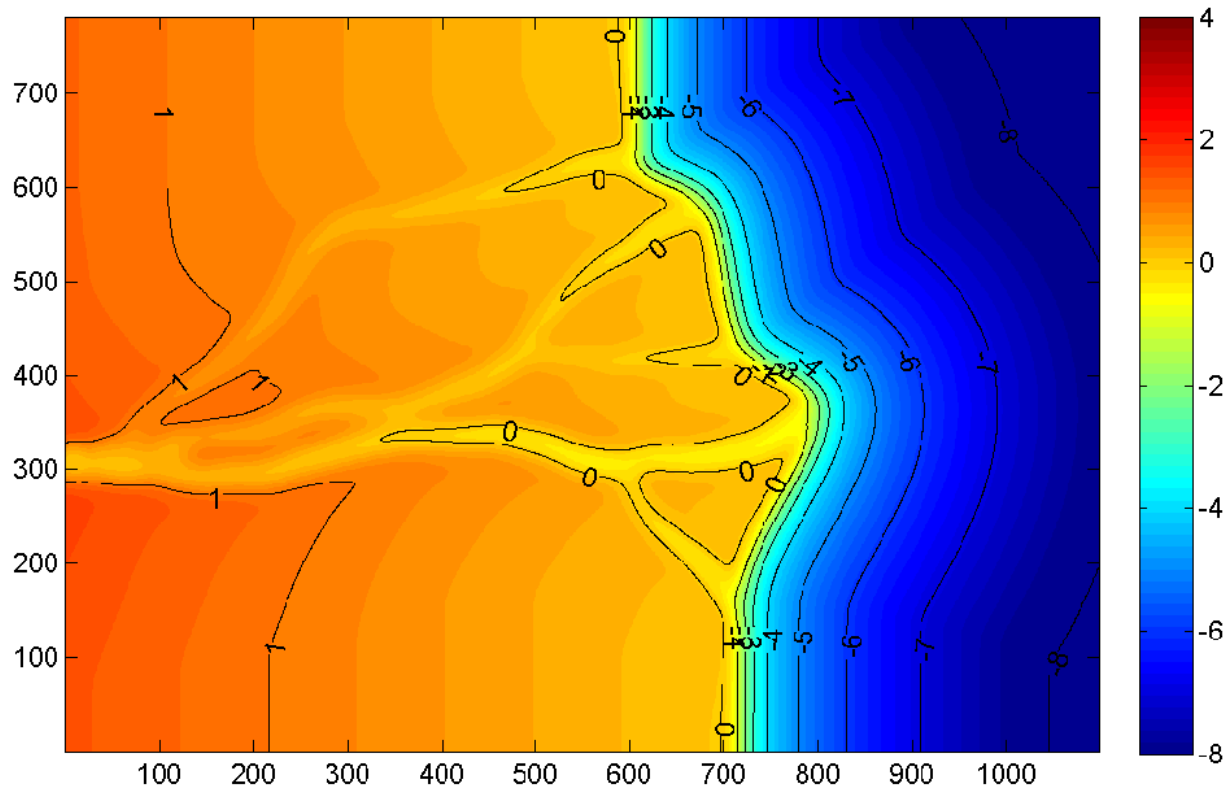
Channel/Levee shapes + Subaerial/Submarine surfaces



$r = 1$ - "V" shape;
 $r = 2$ - Parabolic ch. shape
 $r = 5 \sim 10$ - Wide ch. ($W \gg D$)
 $r \sim \text{Inf}$ - Rectangular shape

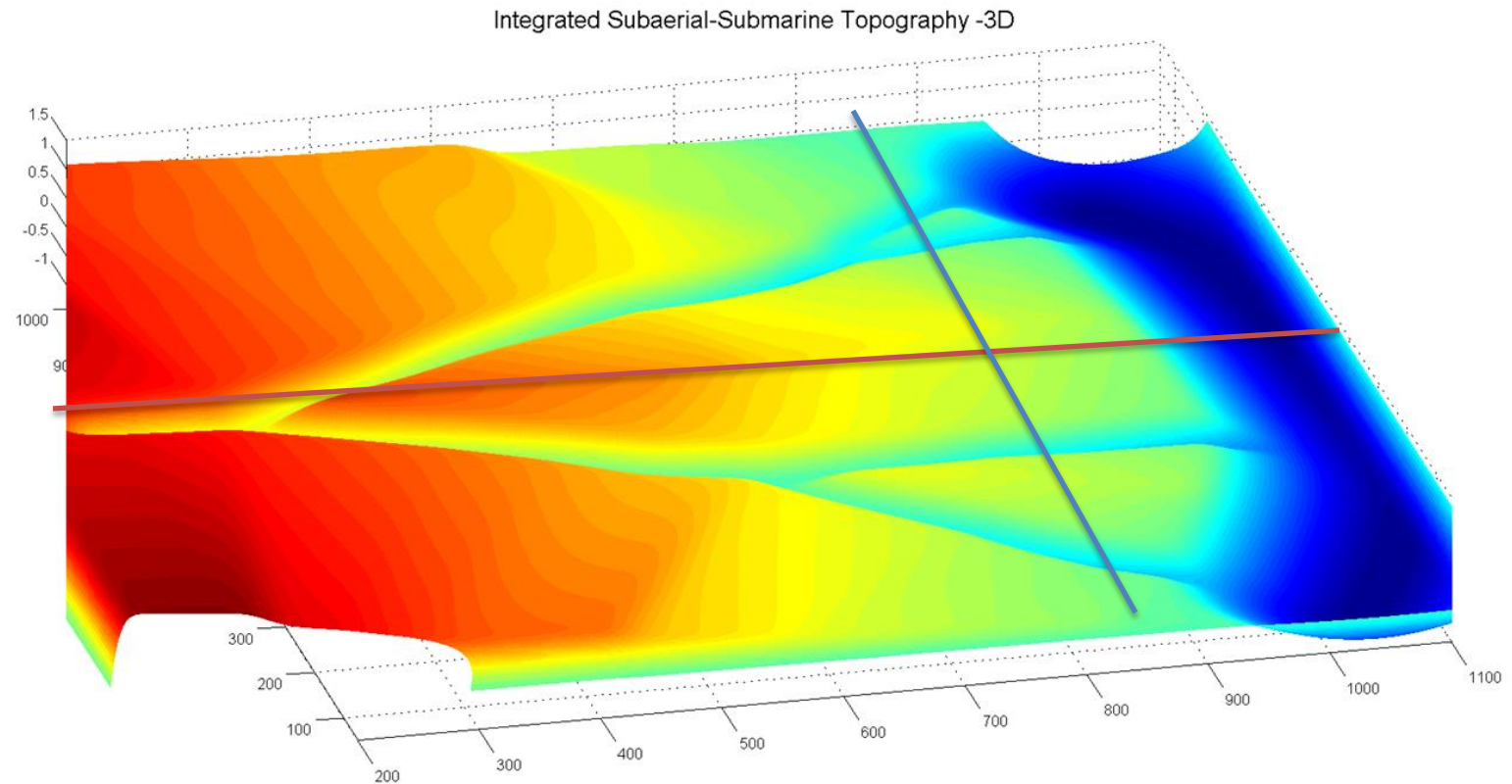


Dynamic Topography – Aggradation & Progradation

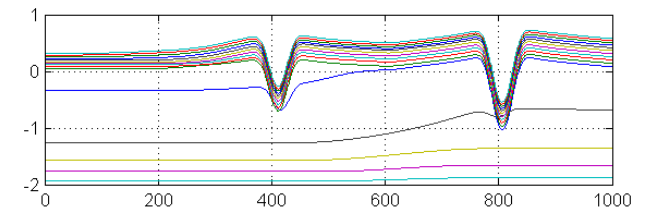
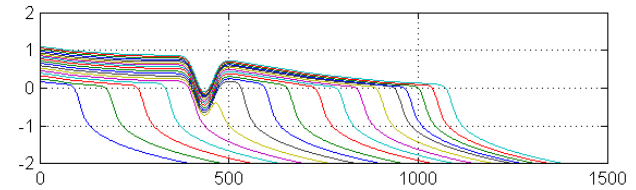
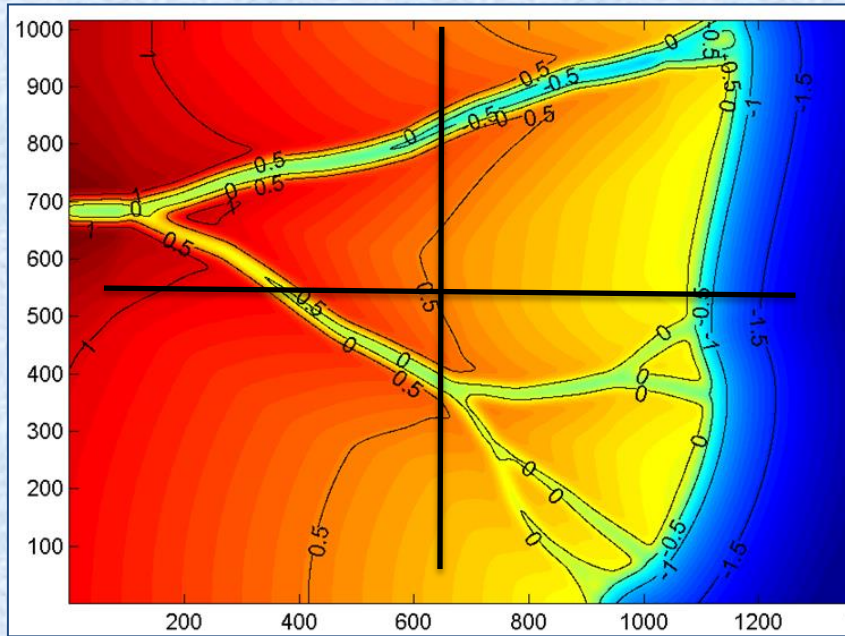


Animated GIF (view in slide show)

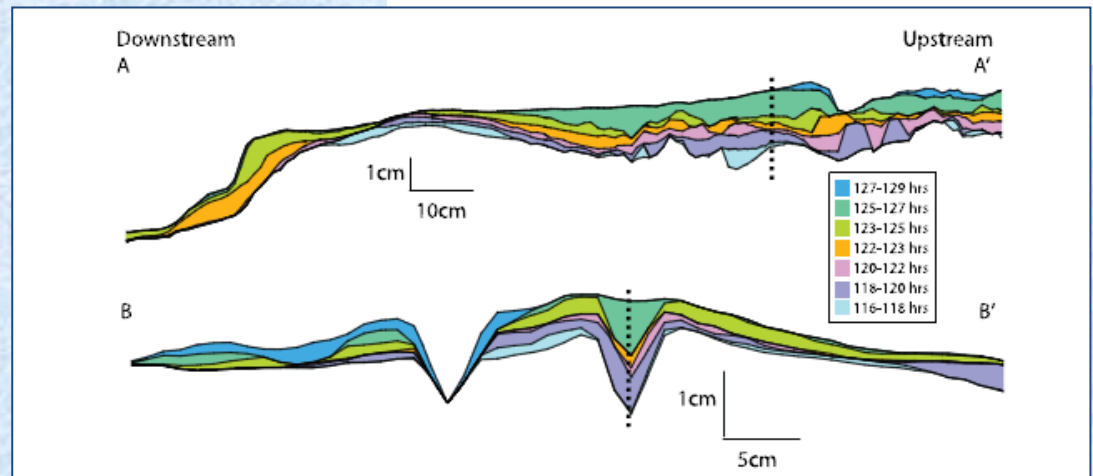
Results in 3D



Stratigraphic Result

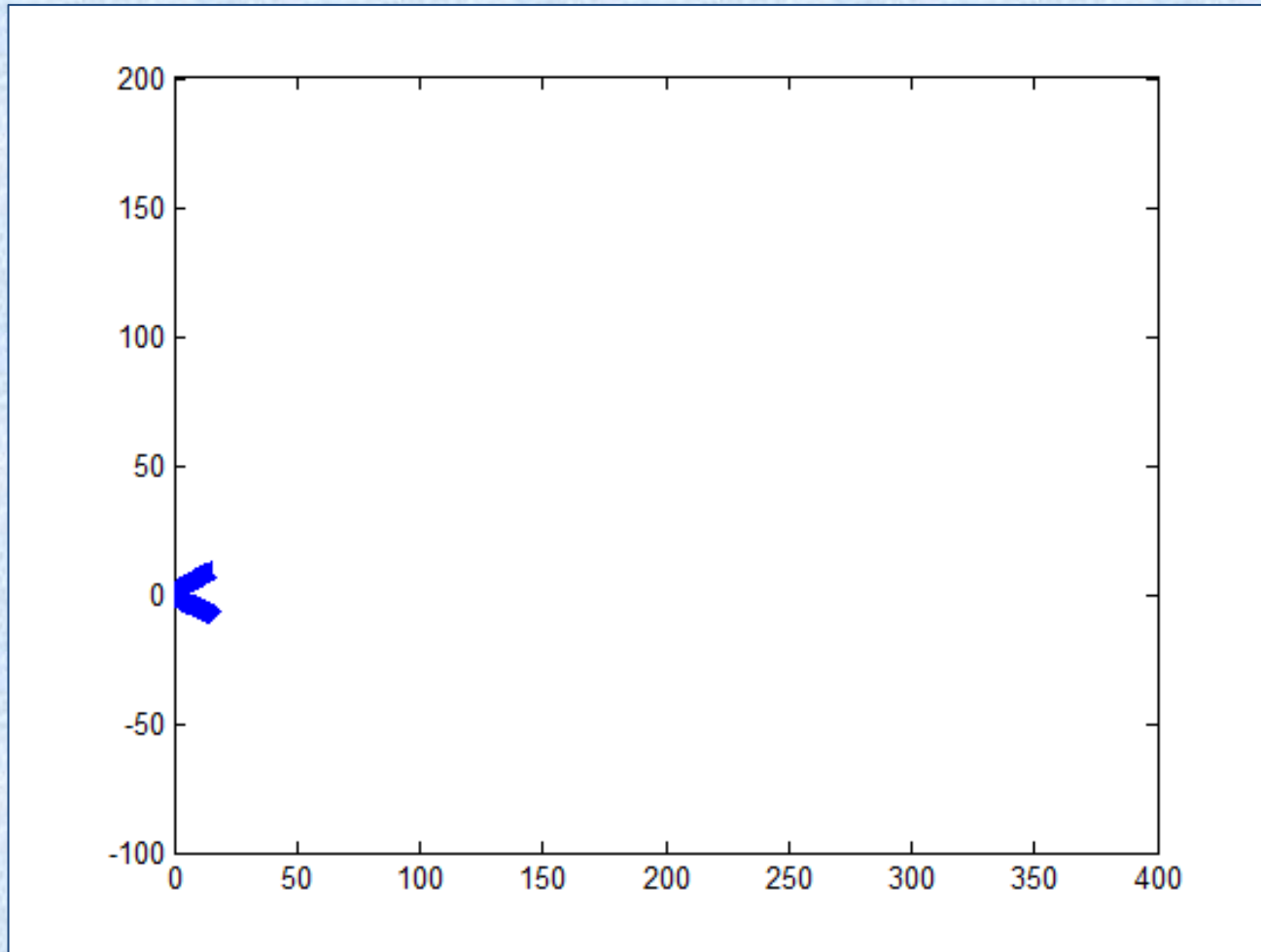


Cohesive Deltas: Longitudinal
and Cross Sections (Hoyal
and Sheets, 2009)

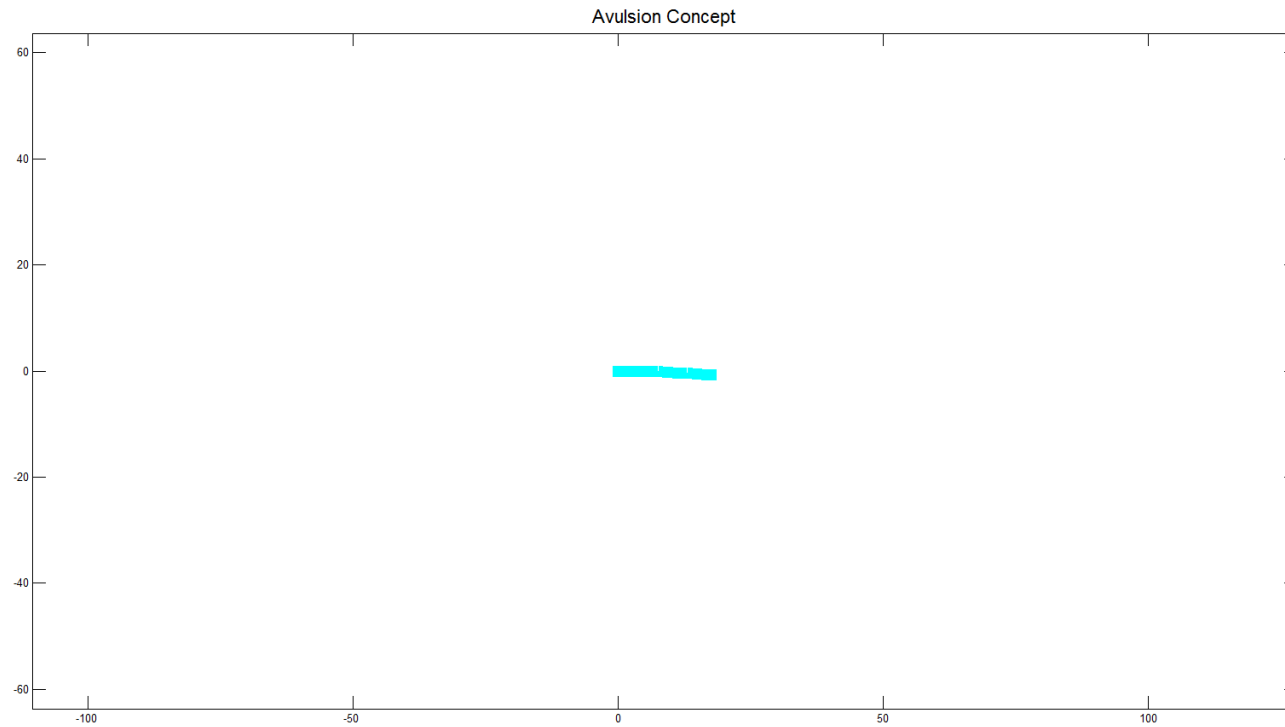


Steps towards a Morphodynamic Model

Low amplitude meanders with an early cutoff (self-rectifying) condition



Avulsion - Flow Path Switch - Concept



Conclusions

- Deltaic networks appear to lack of universal topologic and geometric relationships lending support to a rule based approaches that employ random variables.
- At the crux of proposed model is a method for drawing binary tree networks using constant segments and a low probability bifurcation value (~ 0.01) drawn from a uniform distribution.
- Equally important is the piecewise generation of channel planforms using a partly correlated random walk algorithm whose parameters can be conditioned to match the spectrum of the field observed sinuosity values.
- The model is adept at capturing the variability of deltaic channel arrangements embodied by a set of different field deltas
- This rule based approach has the advantages of simple and fast implementation as well as fast computations which enable efficient scenario testing and, through proper scaling conditioning against stratigraphic data.



EXTRA SLIDES

SHORT TERM – LONG TERM CONNECTIONS

As time frame is extended delta morphology/style can change substantially
How can we properly capture these changes?

Qualitative Cause – Effect relationships (examples)

- Impact of fine sediment onto delta morphology (Edmonds and Slingerland, 2009).
- Rate of avulsion - a function of sediment supply (Jerolmack and Paola, 2007).
- Avulsion rate - function of sea level change (e.g., Jerolmack, 2007).

Predictive relationships from Experimental and Field Data

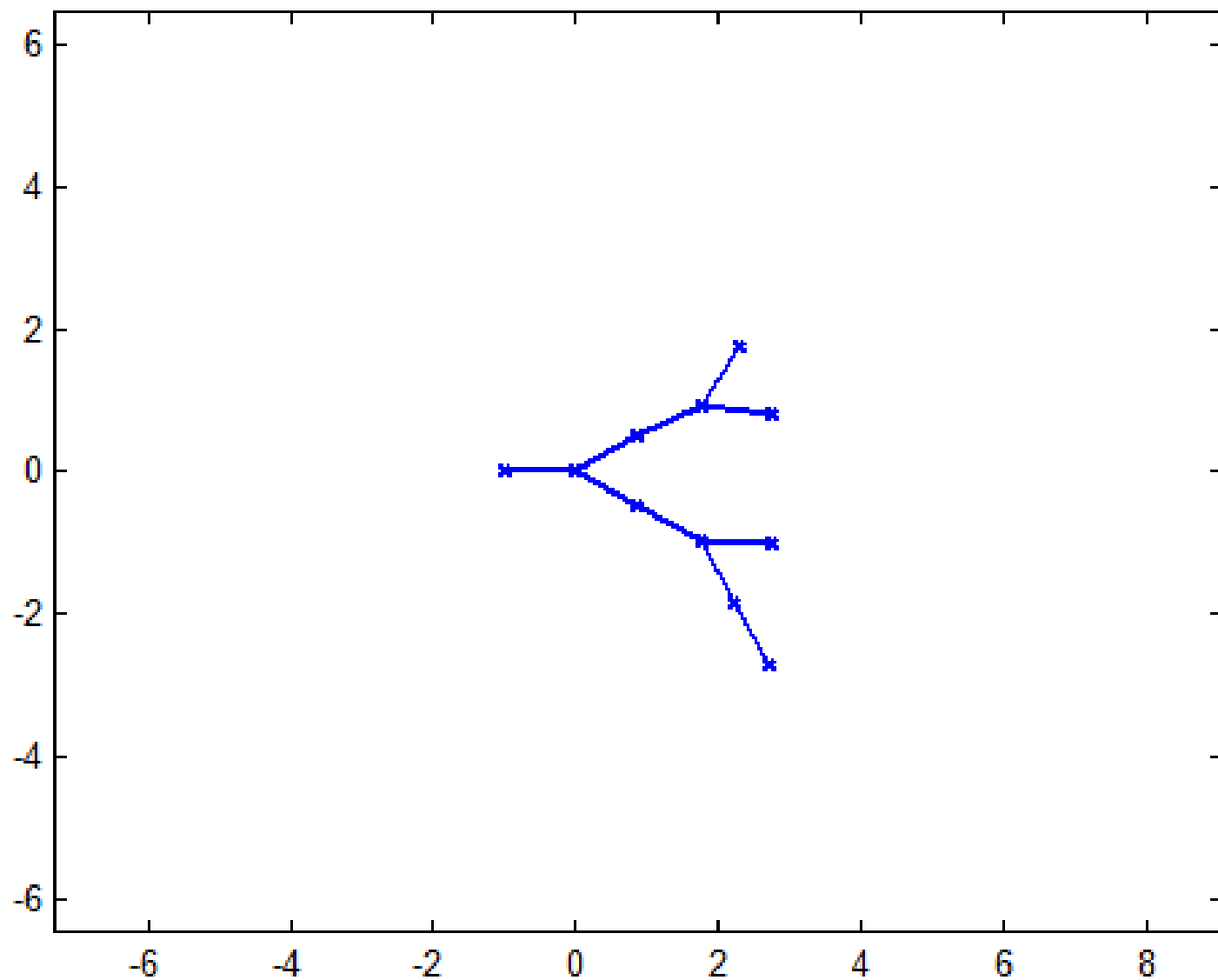
Relationships predicting: Surface “Reworking” Rate and Fraction of Channel Deposit

- $F_R \sim a [1 - \exp(-bt)]$ Modified after Wickert et al., 2013 (Eq. 14)
- $F_{\text{Ch.Deposit}} = F_{\text{ch}} + a (1 - F_{\text{ch}}) [1 - \exp(-b \cdot H/h')]$ Modified after Wickert et al., 2013 (Eq. 31)

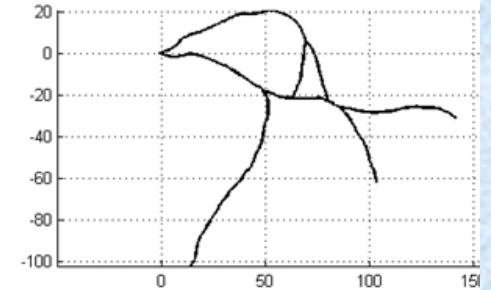
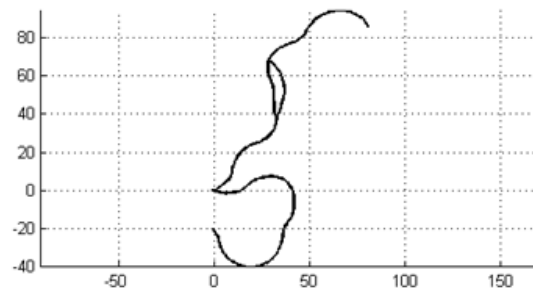
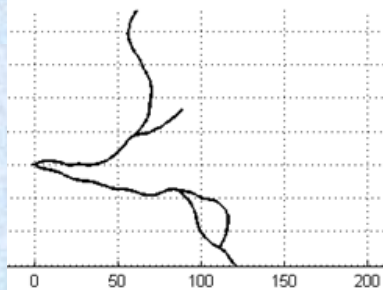
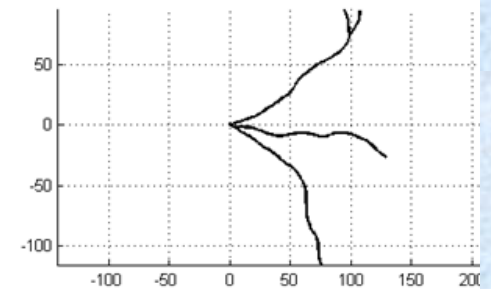
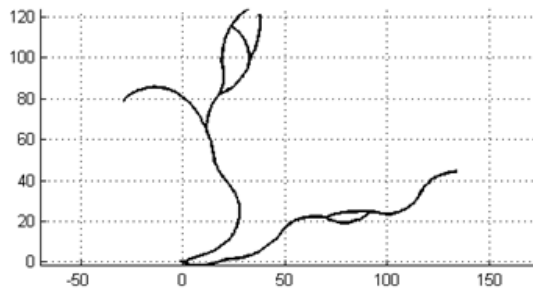
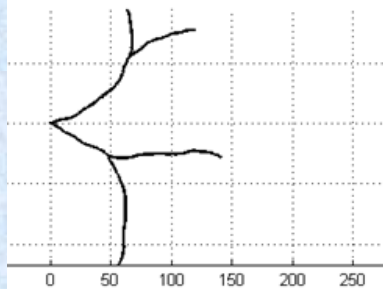
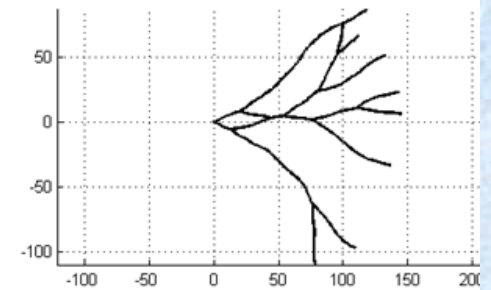
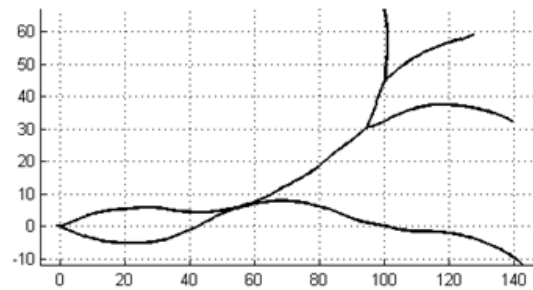
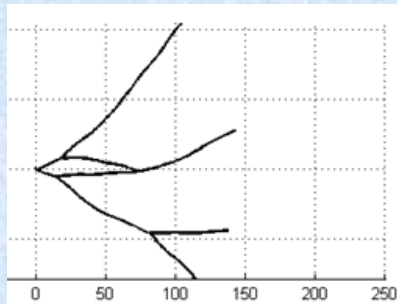
Relationships predicting Avulsion frequency = f(nr. Channels, Depth, aggradation rate)

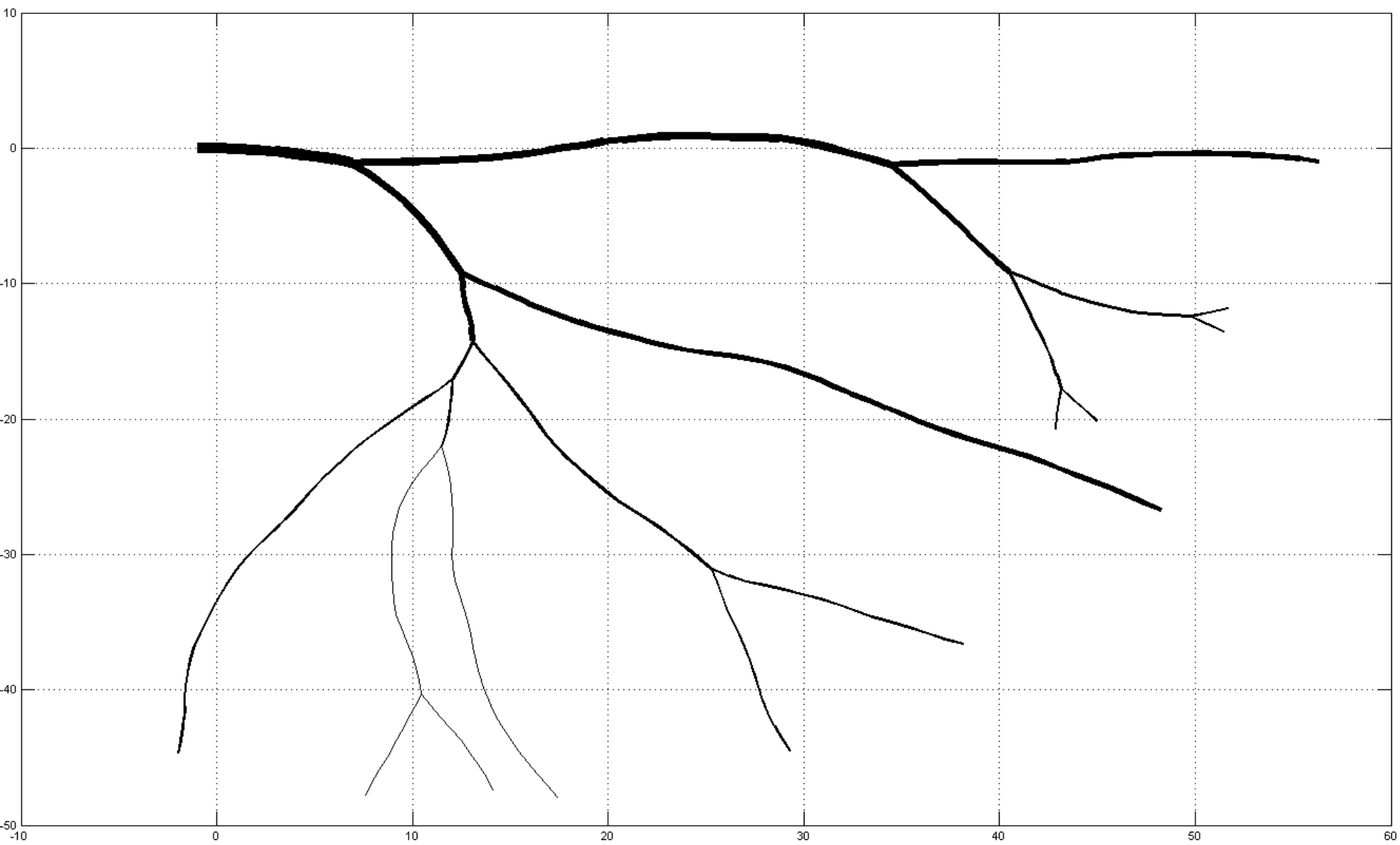
- $F_A = N \eta' / H,$ After Jerolmack & Mohrig, 2007 (Eq. 1)

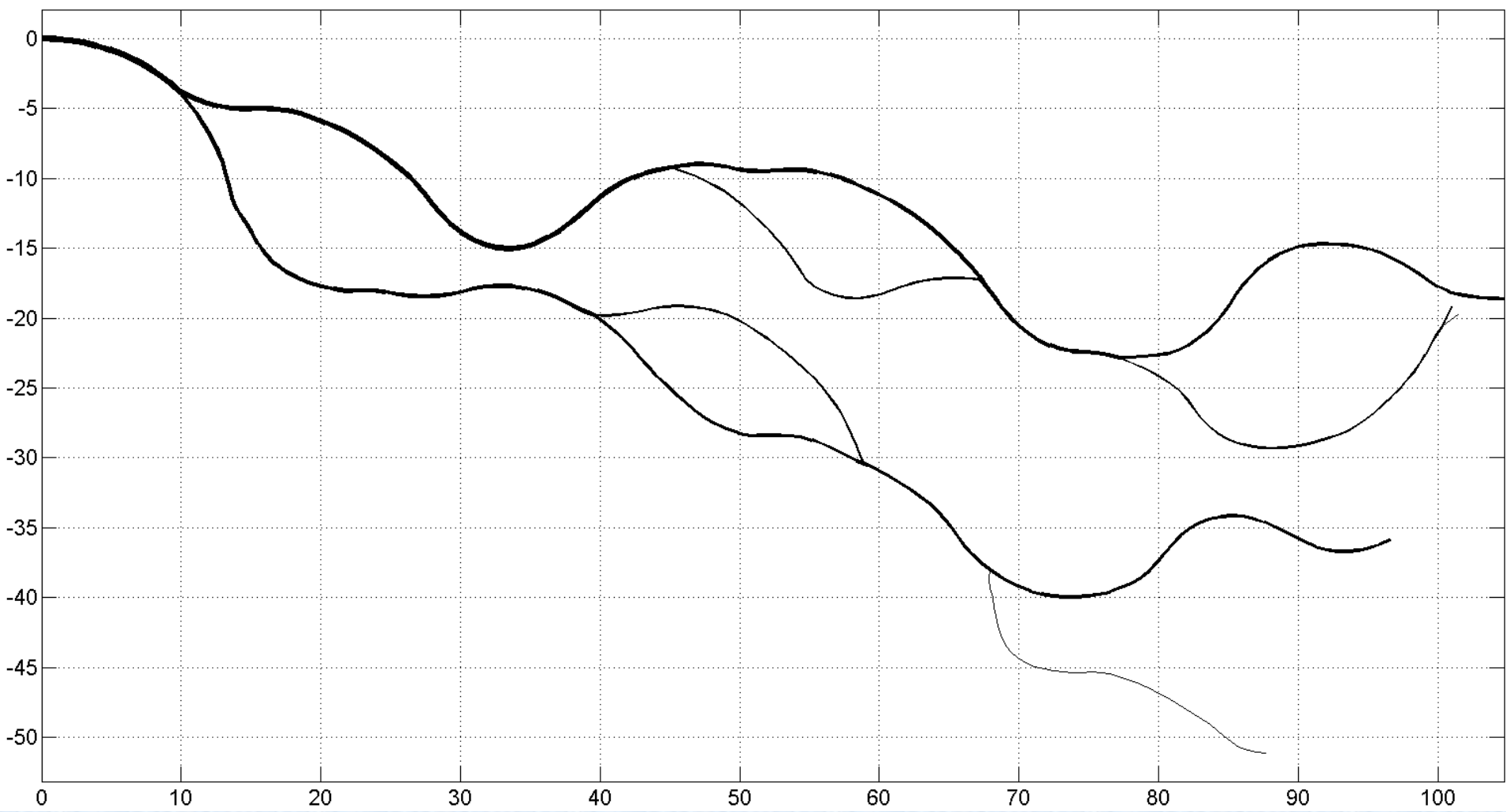
Simple Fractal Delta; Bifurcation Probability = 1

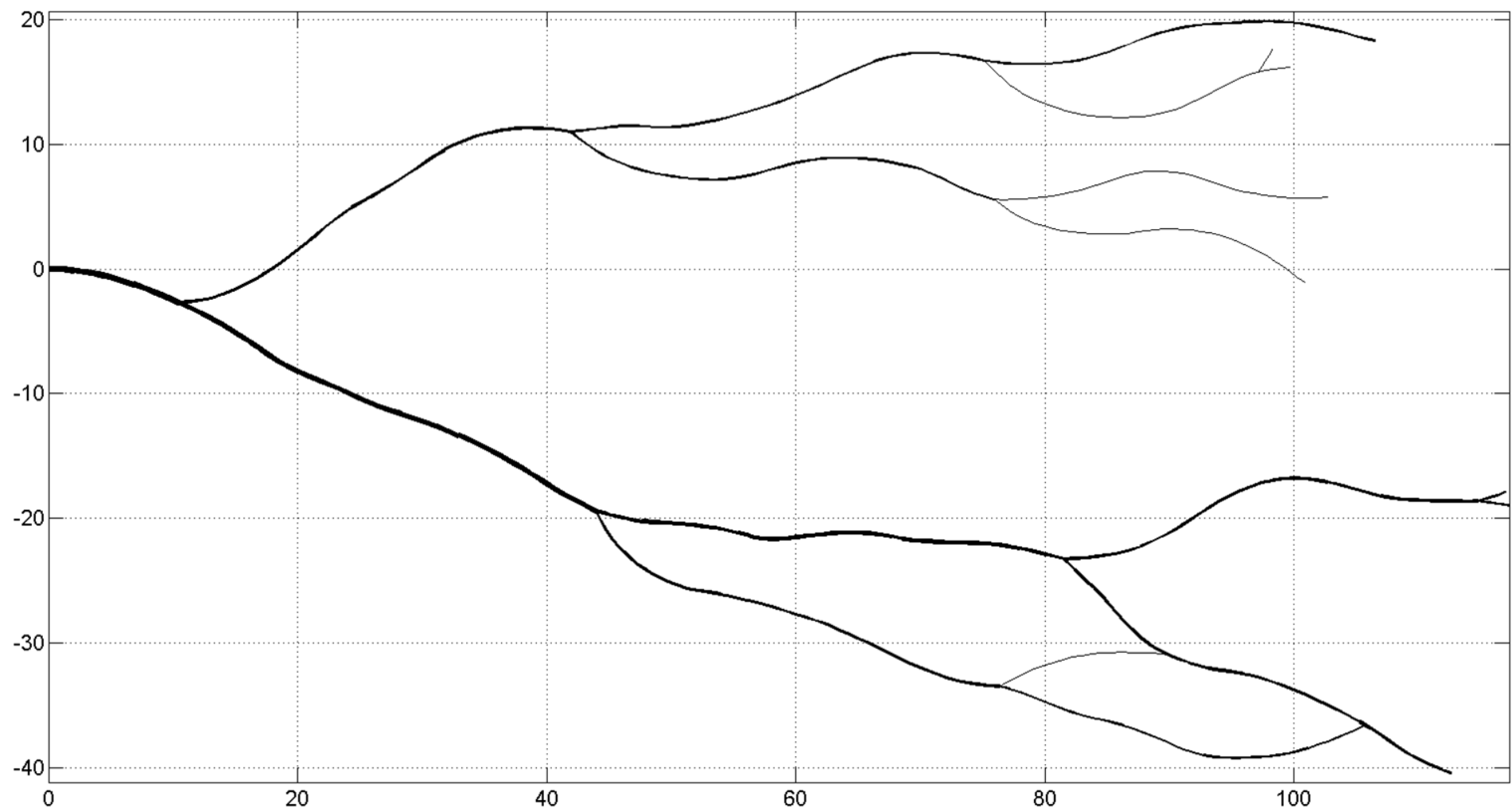


Basic Rules For Individual Channels

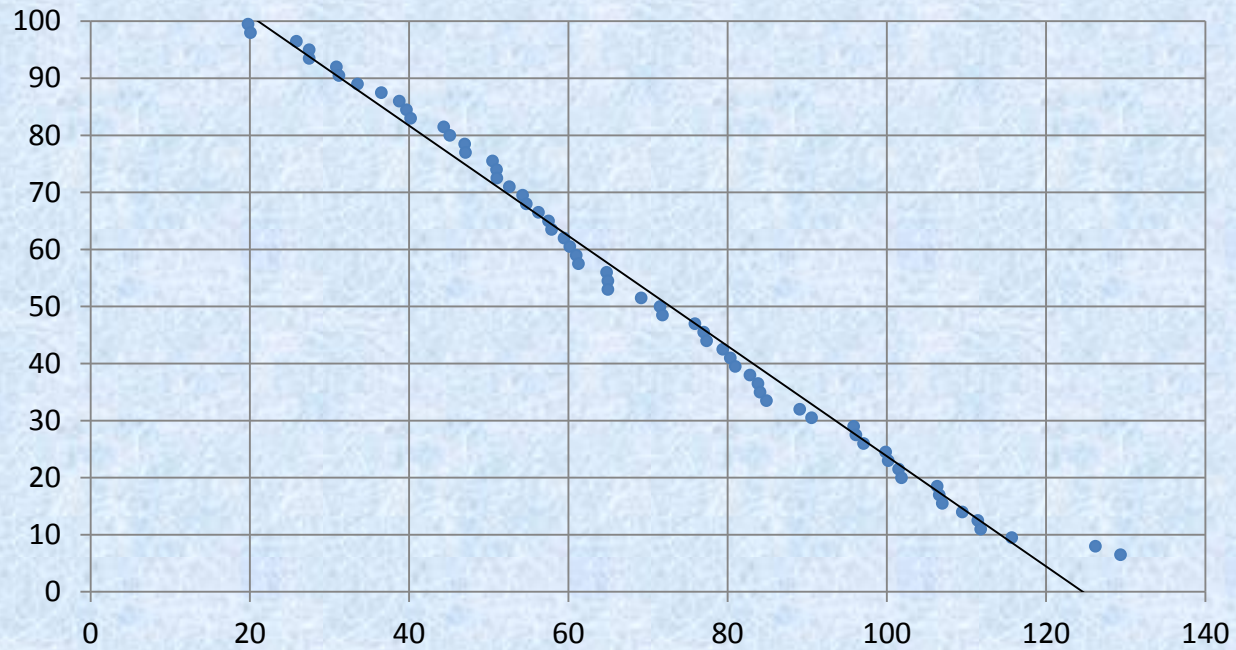




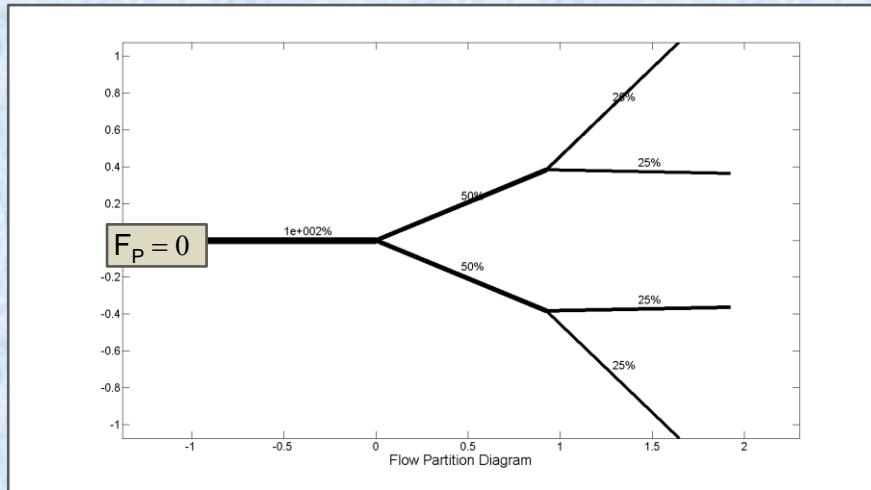




PDF of Bifurcation Angles (Average~70deg)



5. Flow partition effect on bifurcation geometry



Flow partition at bifurcation is handled through a flow partition factor F_P . Q_0 , the incoming flow is partitioned into a larger and a smaller flow:

$$Q_{\text{Large}} = (Q_0 + F_P \mathbf{U}_{(0,1)})/2$$

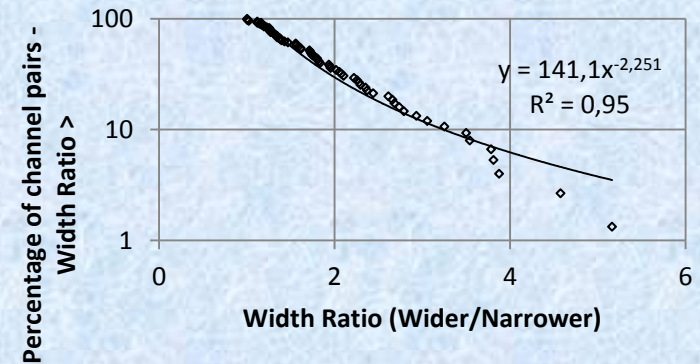
$$Q_{\text{Small}} = Q_0 - Q_{\text{Large}}$$

Where $\mathbf{U}_{(0,1)}$ is a uniform distribution.

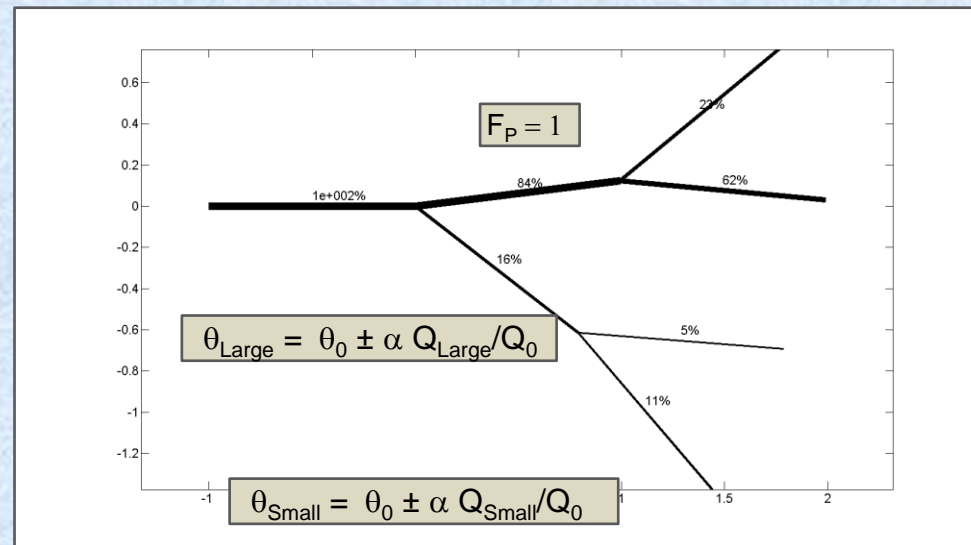
If $F_P = 0$, $Q_{\text{Large}} = Q_{\text{Small}}$

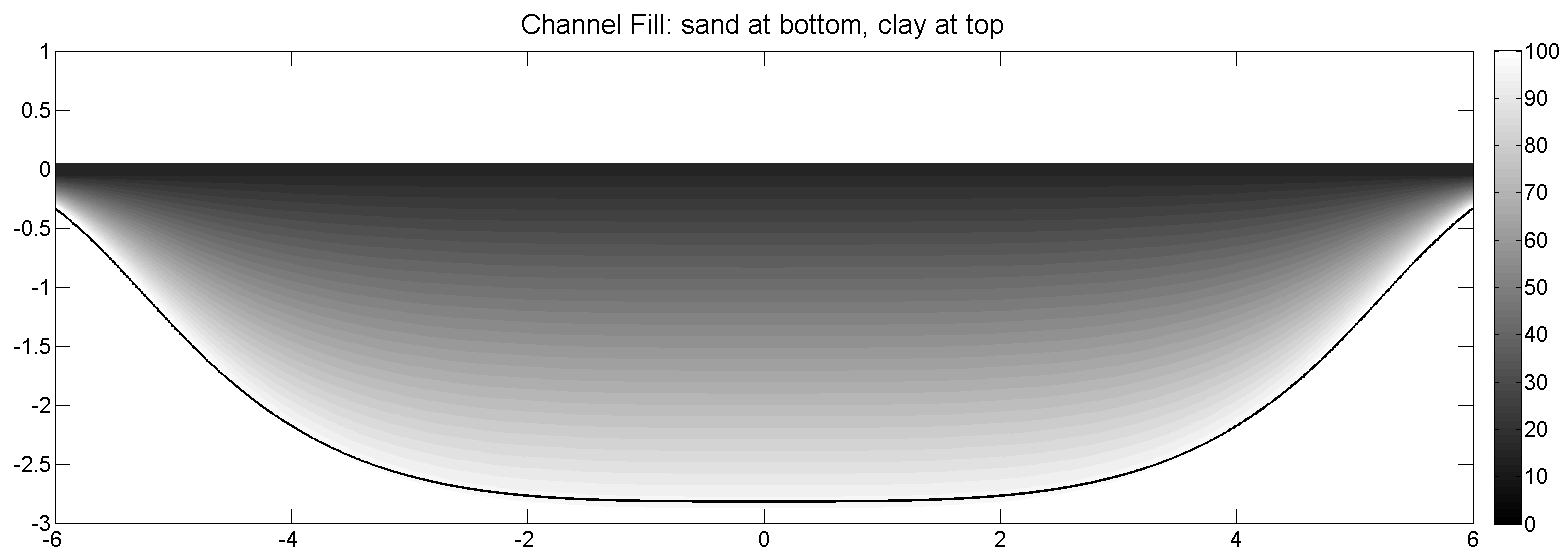
If $F_P = 1$, flow split can take any % values

Width Ratio PDF for Bifurcating Branches Pairs

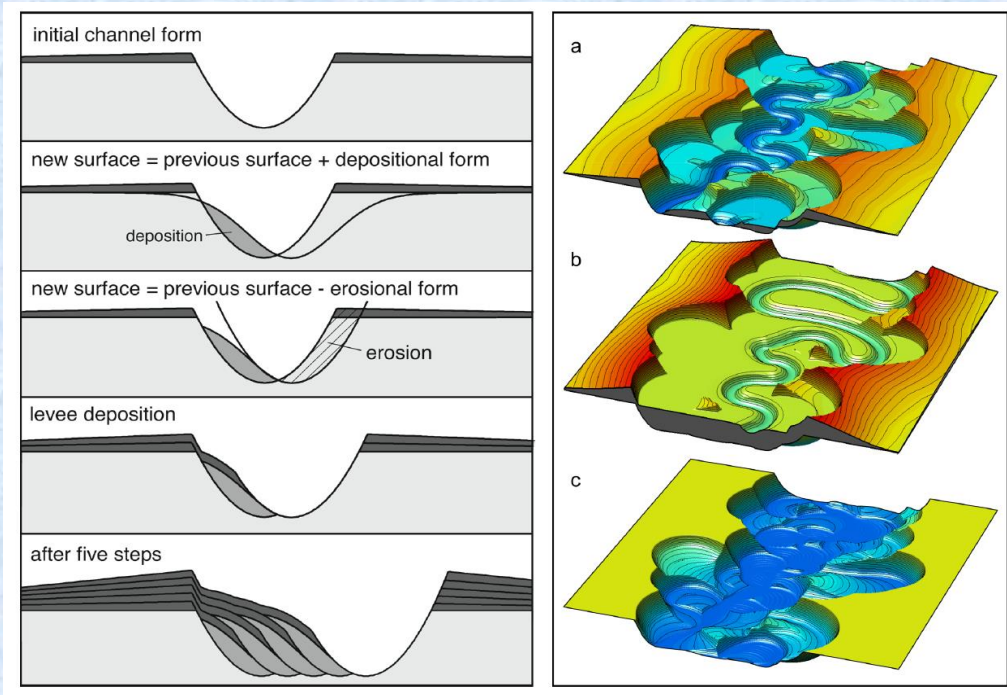


Data courtesy of Doug Edmonds



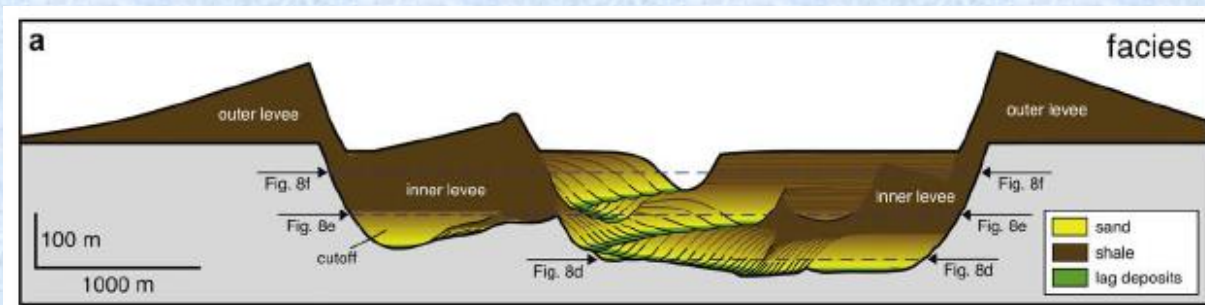


FROM SIMPLE PATTERNS TO COMPLEX RESULTS

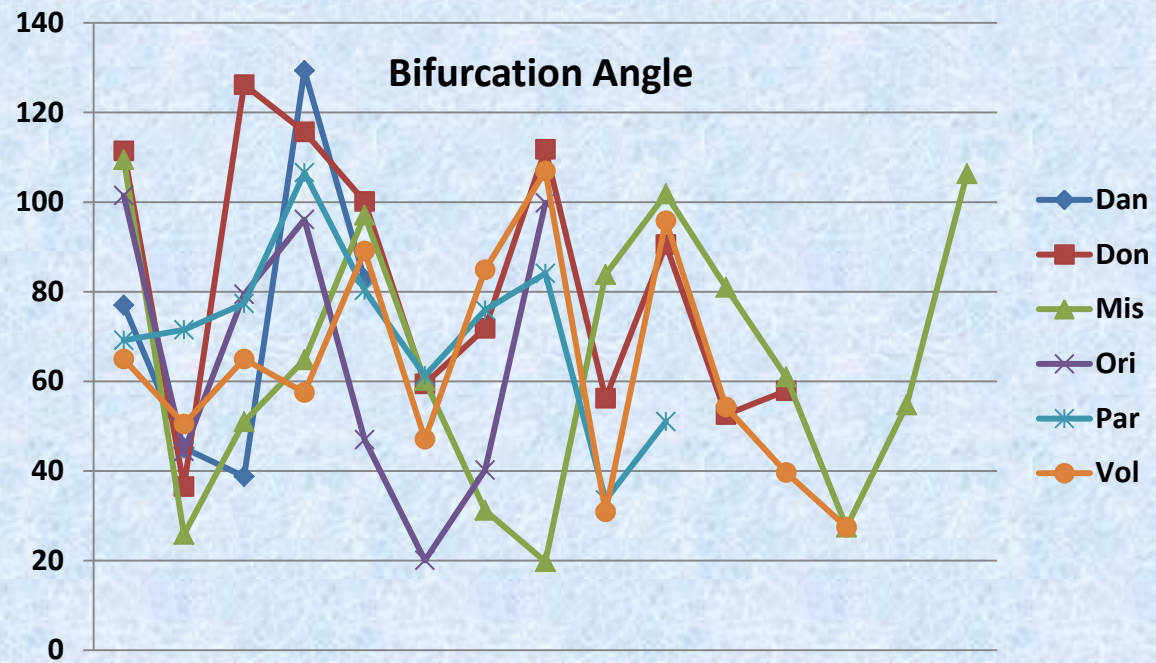


Complex results do not require complex input or many rules. Complexity can arise from aggregating few simple geometric patterns and few behavior rules. (e.g. Murray & Paola, 1994).

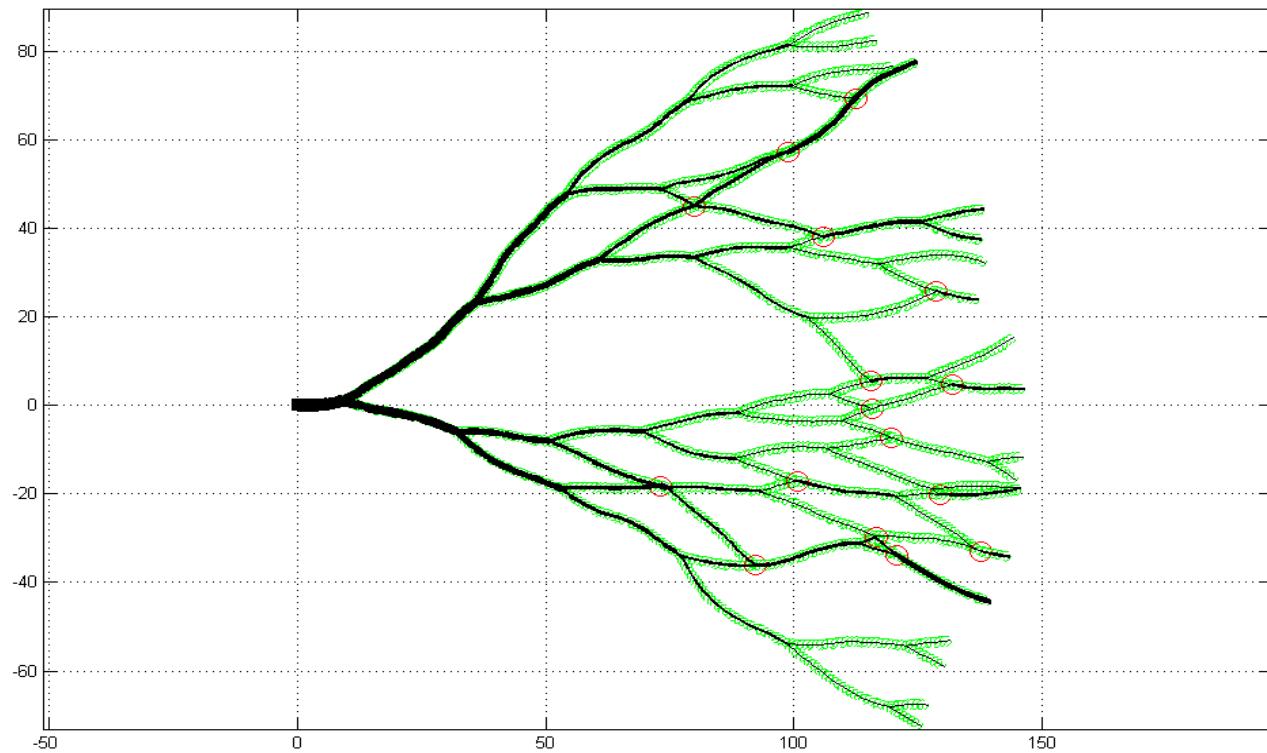
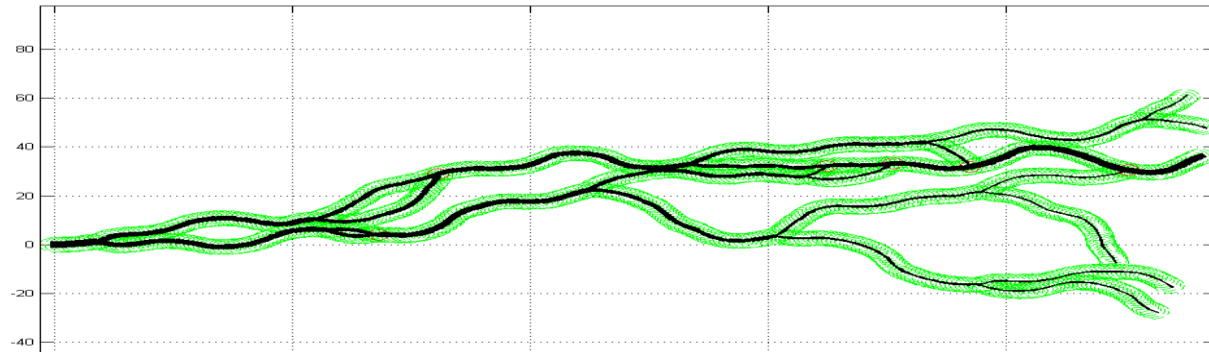
It is plausible that only a handful of geometric elements and kinematic rules are needed to generate representative geometric architecture.

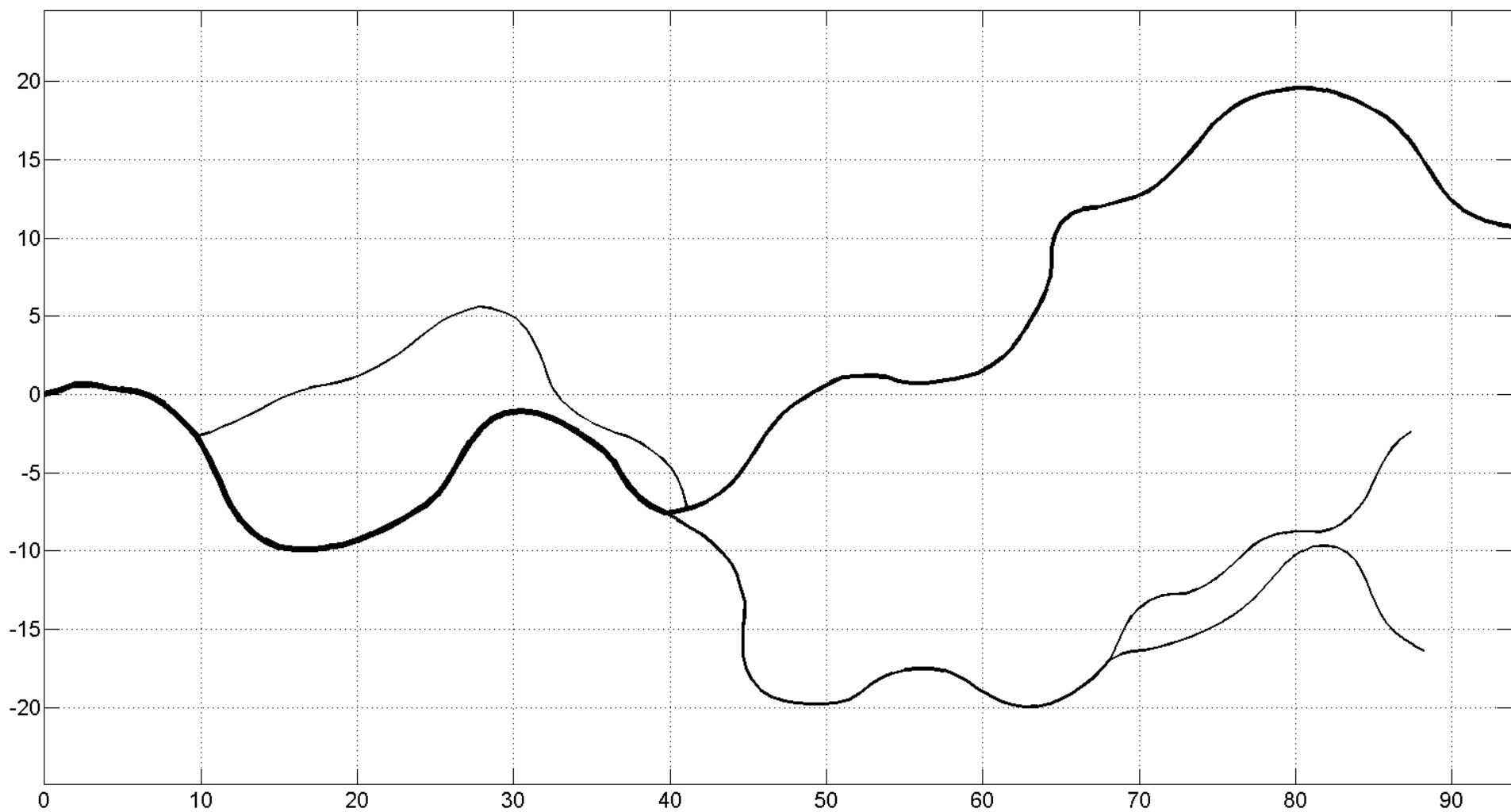


(Sylvester, Pirmez, Cantelli, 2011)

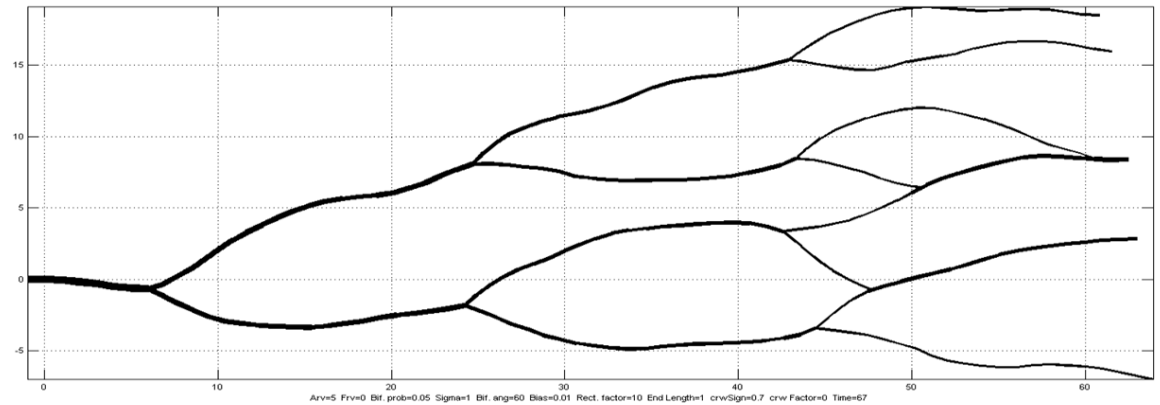
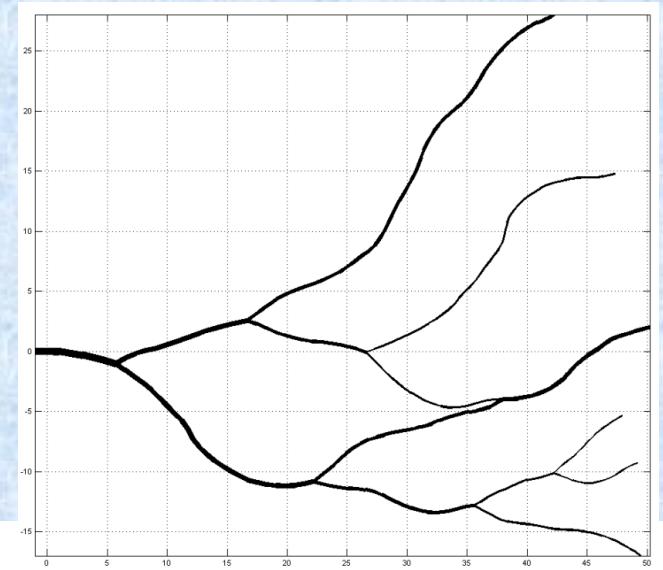
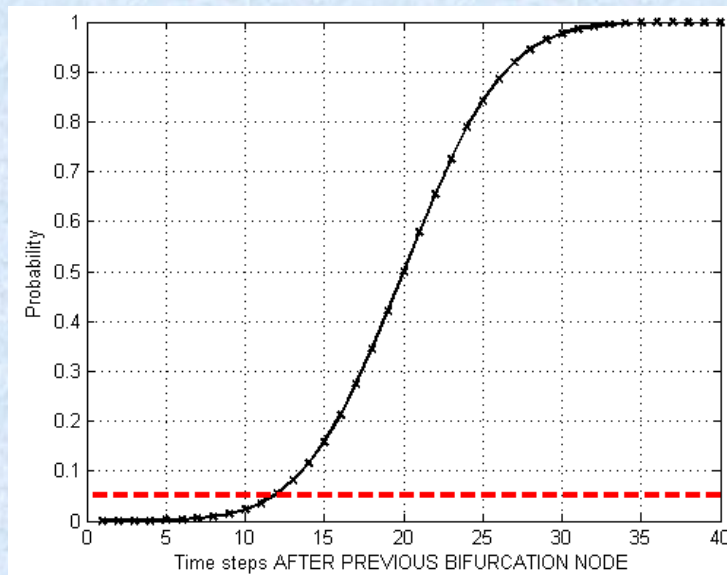


Effect of Main Direction Weight on Delta Shape (aspect Ratio): 0.01 vs 0.001





Bifurcation Length



Edmonds &
Slingerland (2007)