The University of Texas at Austin
Petroleum and Geosystems Engineering
Cockrell School of Engineering

BeicipFranlab

Bureau of Economic Geology

Resampling from Reservoir Analog Models

Michael Pyrcz
Hildebrand Department of Petroleum and Geosystems Engineering, University of Texas at Austin

Jake Covault
Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin

Nicolas Hawie
Beicip-Franlab

Heehwan Yang
Hildebrand Department of Petroleum and Geosystems Engineering, University of Texas at Austin)

Overview

- Resampling from Reservoir Analog models as a method to learn about the subsurface
  - better utilizing geological process information

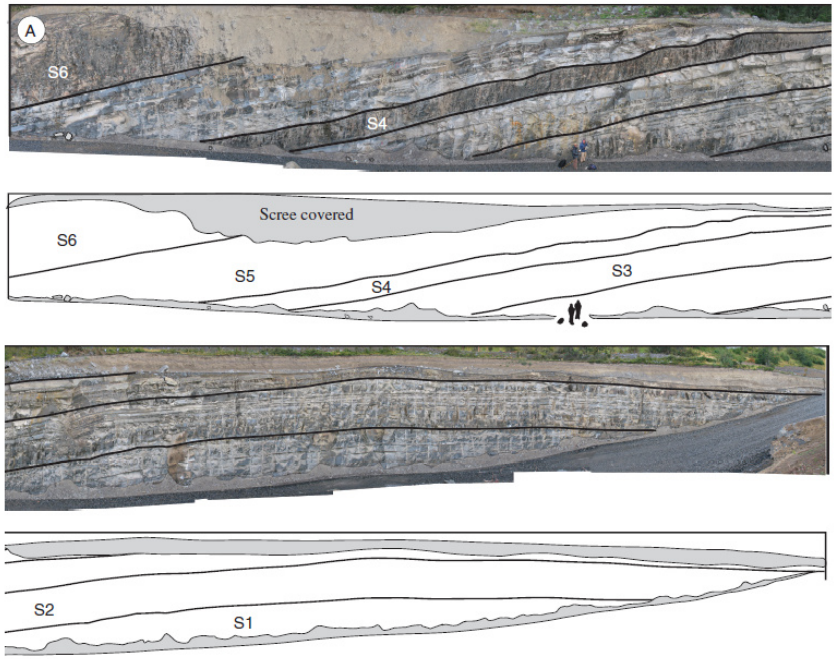
- **Topics:**
  - **The Problem**
  - **What has Been Done?**
  - **Opportunity**
  - **Example**
  - **Discussion**
  - **Future Work**

- We are just getting started with a partnership between process modeling, stratigraphy and geostatistics / reservoir modeling.

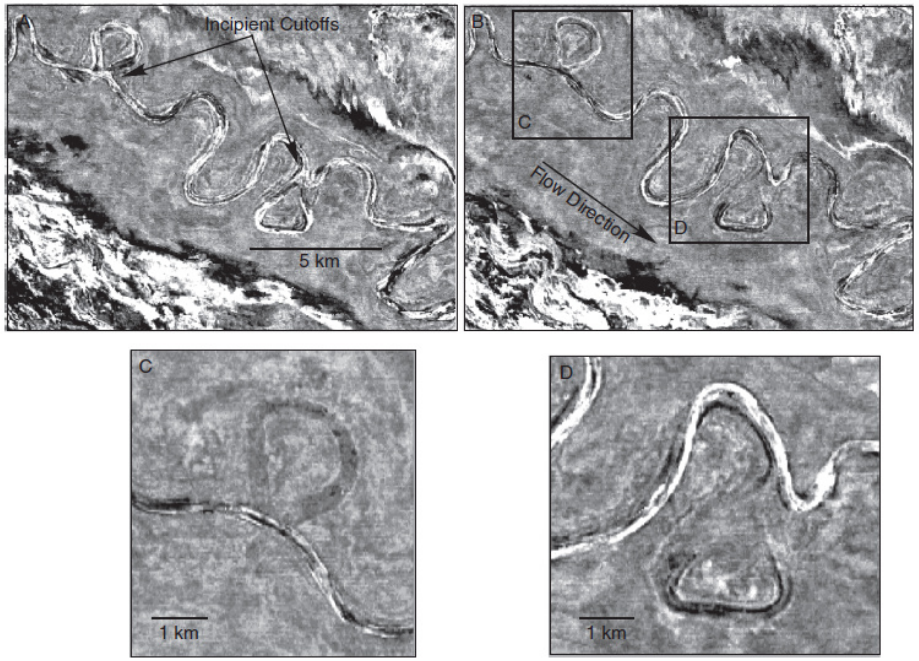
Definitions

- Reservoir Analog Models
  - A numerical representation of the features anticipated in a target reservoir
  - May originate from concepts, detailed mapping, process-based models, proxy models, experimental stratigraphy, shallow seismic, outcrop, mature fields etc.
  - Reasonable analog, but unconditional to the information available in the target reservoir
- Resampling
  - Extracting samples from a reservoir analog model
  - May mimic the information gathering of the target reservoir
  - Requires summarizations with metrics
- Stationarity
  - The statistic / metric of interest is the same over an area of interest

Problem #1 – Improved Geological / Geophysical Integration



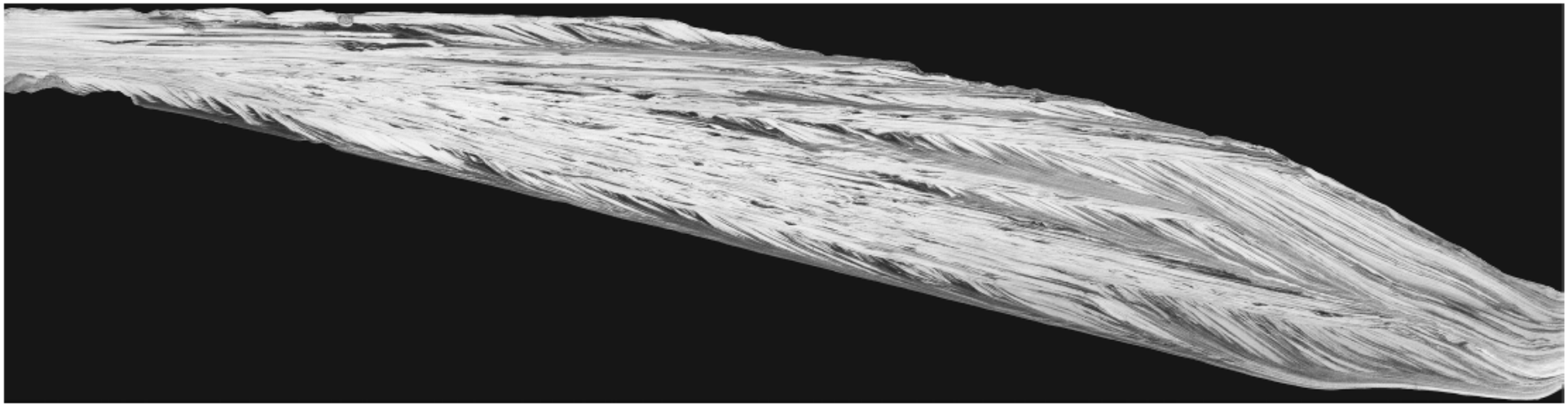
Photomosaic and line drawing trace from Punta Barrosa Formation, sheet complex (Fildani et al., 2009)



Shallow seismic Desoto Canyon offshore Mississippi Delta (Posamentier, 2003).

- Difficulty in imposing architectural complexity from geological concepts into reservoir model for practical workflows that account for uncertainty.

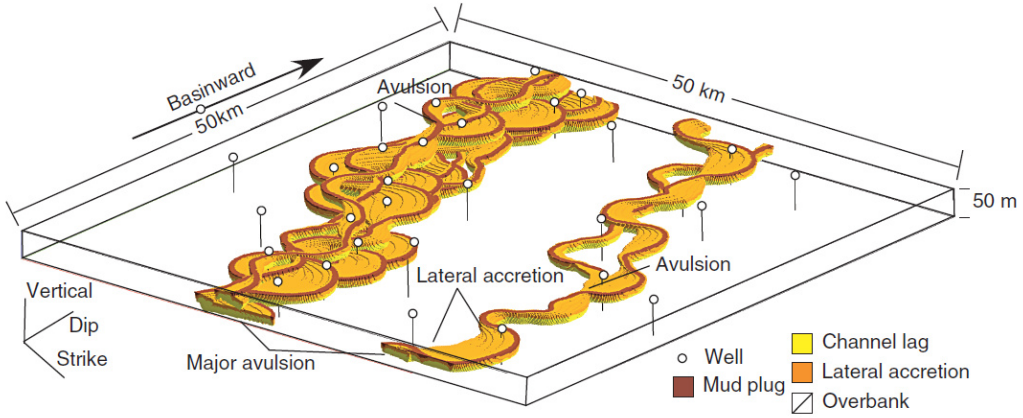
Problem #2 – Inability to Condition Physics-based Models



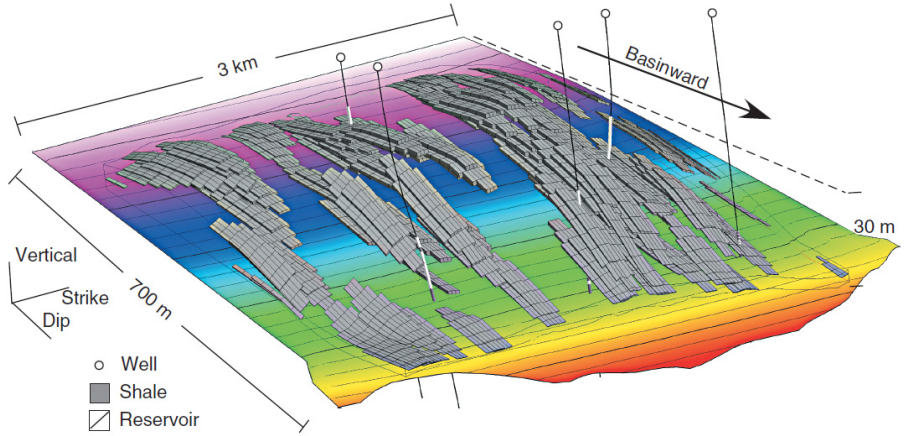
A Dip Section from the Experimental EarthScape (Jurassic Tank) Experiment from Saint Anthony Falls Laboratory. The details of this experiment are available in Paola et al. (2001).

- Difficulty in imposing local conditioning on physics-based, experimental stratigraphy or process-mimicking models.

What Has Been Done?



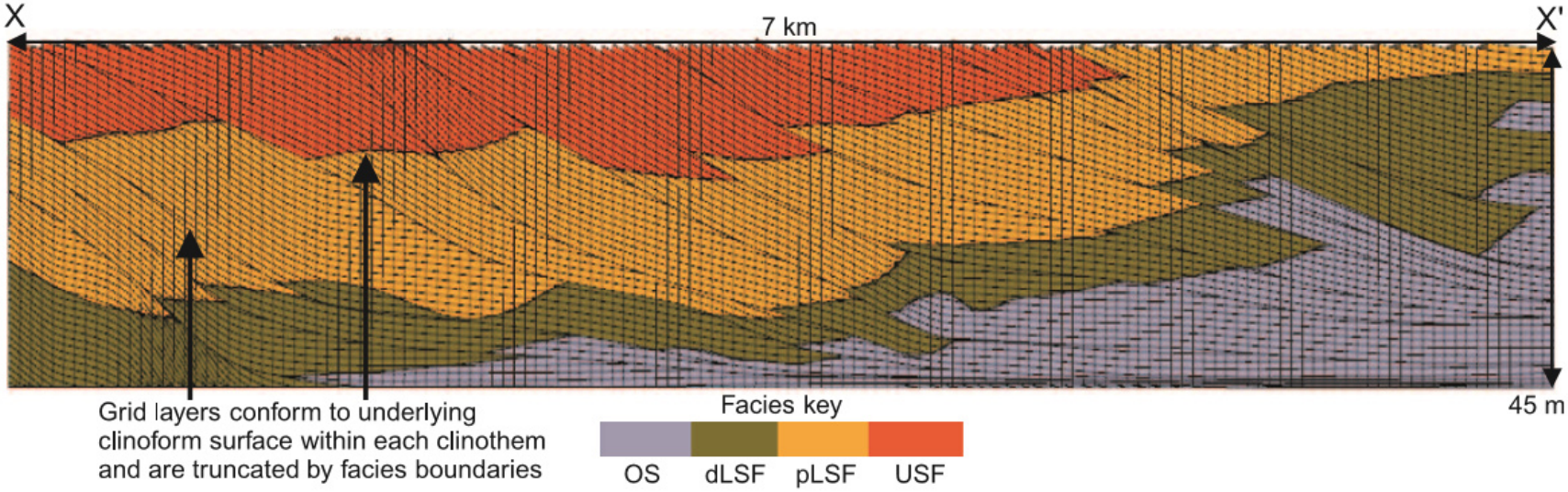
An Event-Based model with avulsion and meander migration (Pyrcz and Deutsch, 2014).



An object-based mud drape model for a deltaic setting (Pyrcz and Deutsch, 2014).

- Use of Currently Available Geostatistical Methods
  - Object-based, Multiple-point based, Rule-based
  - Improvements are being made, models are improving

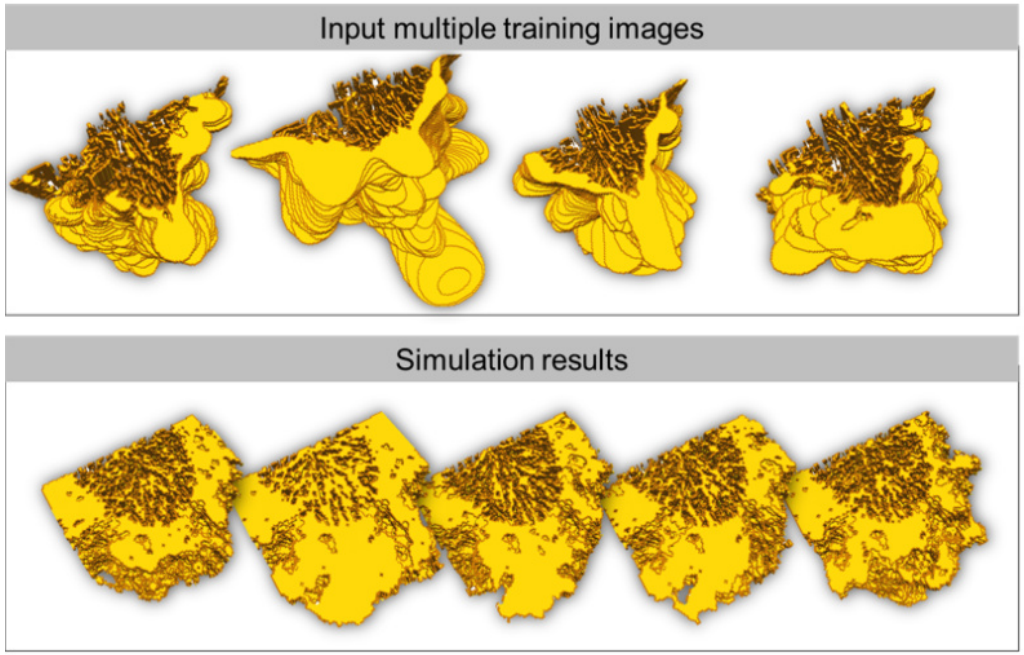
What Has Been Done?



Two-dimensional section through facies model showing grid and facies to capture complicated clinoform geometry (Sech, Jackson and Hampson, 2009).

- Sketch-based Models
  - Flexible, interactive, updatable use of gridding and trends
  - More should be done to account for uncertainty

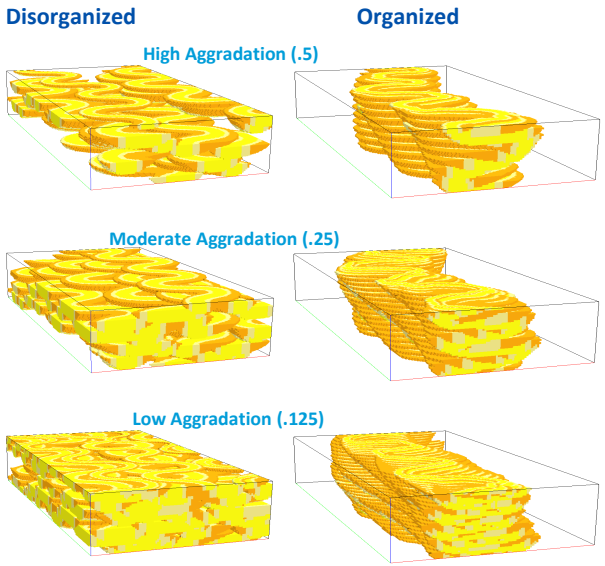
What Has Been Done?

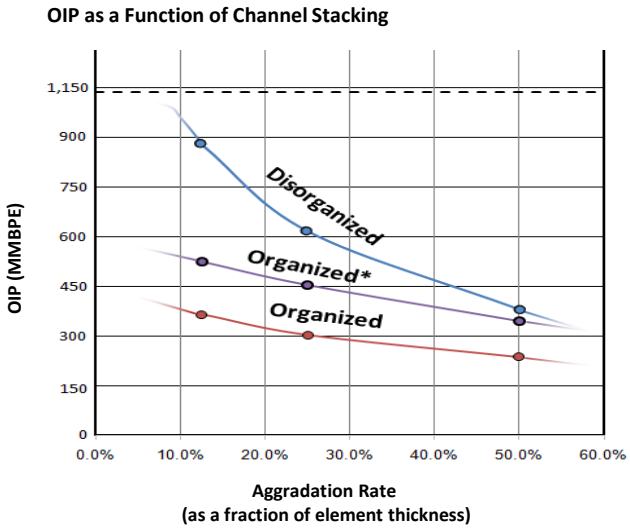


MPS with process-based models (Aarnes and Hauge, PIs), image from the Norwegian Computing Center project description (https://www.nr.no/en/projects/process-models).

- Extract Statistics from Physics-based Models
  - Proportions, trends, spatial continuity (variogram), training image

Previous Work to Learn from Numerical Analog Models?





Resampling from reservoir analog models to constrain reservoir volumes (Pyrcz, McHargue, Clark, Sullivan, Strebelle, 2012).

- Resampling Learning from the Models
  - Inference: physical constraints on the various model features / parameters
  - Prediction: range of uncertainty constraints on model response / outputs.

Proposal

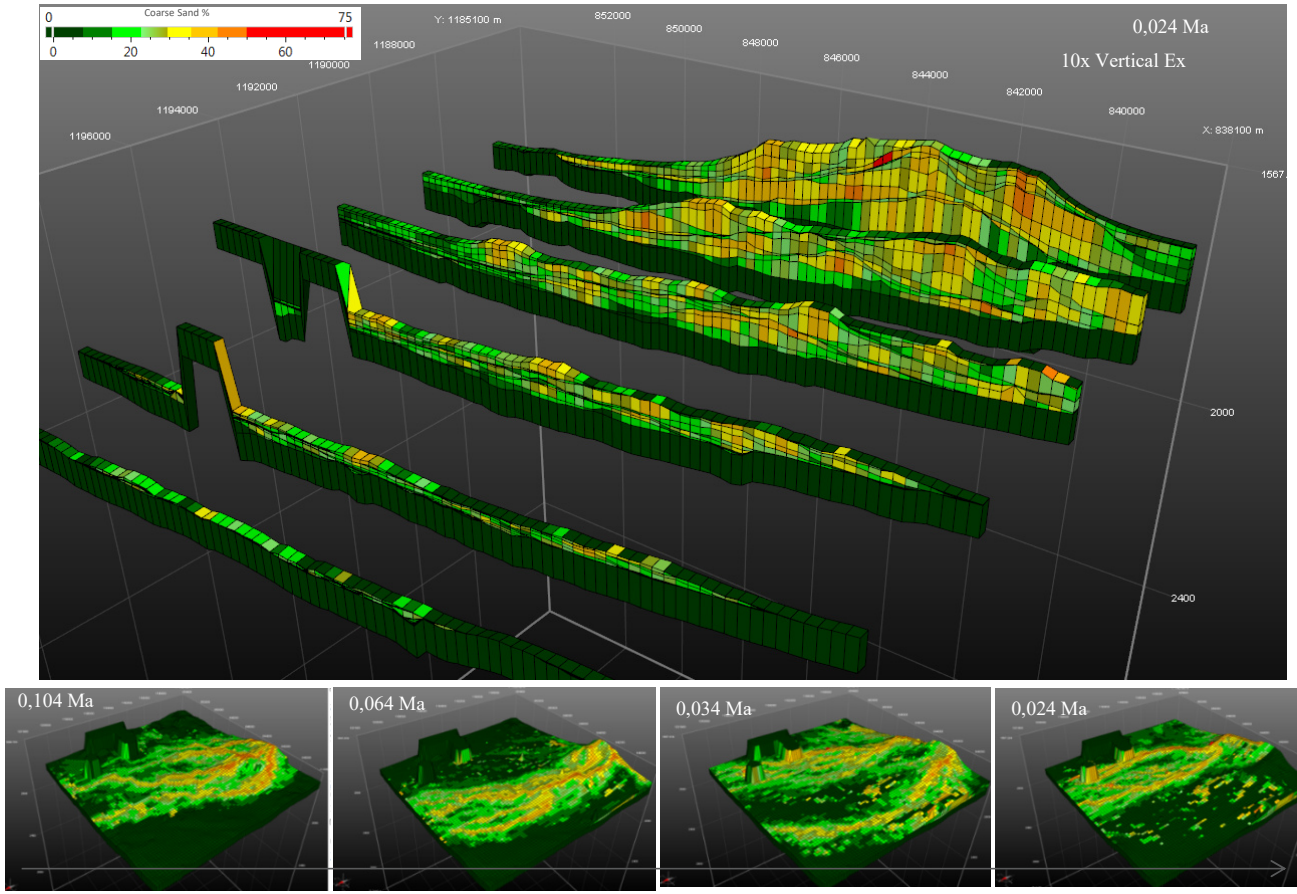
- Develop New Methods to Resample from Reservoir Analog Models
  - Learn / infer the fundamental relationships
  - Develop value of information models my simulating data collection

Opportunity

- Enhance the Inference / Integration in Reservoir Assessments
  - Learn from our modeling efforts
  - Feedback into modeling methods and outputs
- Better Leverage the Current and Emerging Numerical Models
  - Focus on the fundamental processes, complexity of the system without abstraction
  - Integration for more accuracy and reduce uncertainty

Example

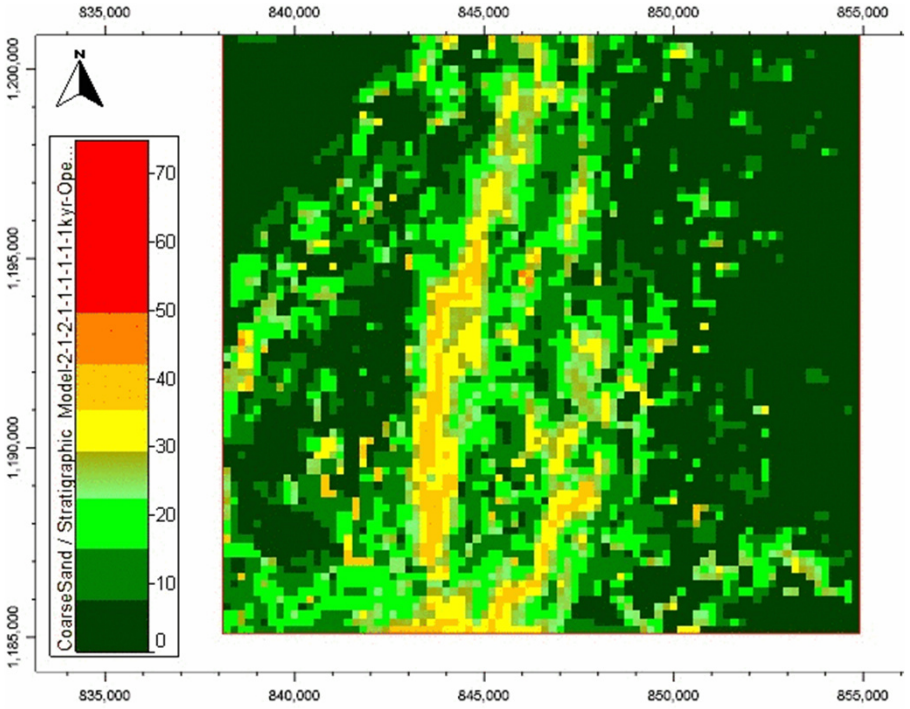
- DIONISOS Model
  - 17 x 17 km
  - 200 x 200 m cell size
  - Simulation age: 124ka – 24 ka.
  - Simulation time steps: 1,000 years.



DIONISOS forward stratigraphy model of Trinidad intra-slope fan (provided by Nicolas Hawie).

Example – What Will We Sample? What Questions?

- The Model is Purely Autogenic
  - Learn about the sedimentation rates locally, spatial analysis of sedimentation rates
  - Sedimentation rates will be related to reservoir architectures
    - Types of beddings, thickness of bedding, likelihood of barriers and baffles
    - Sedimentation Rate, Thickness of Accumulation and Sadler Effect in 1D/3D



DIONISOS forward stratigraphy model of Trinidad intra-slope fan (provided by Nicolas Hawie).

Example – What Will We Sample? What Questions?

- The Model is Purely Autogenic
  - Learn about the sedimentation rates locally, spatial analysis of sedimentation

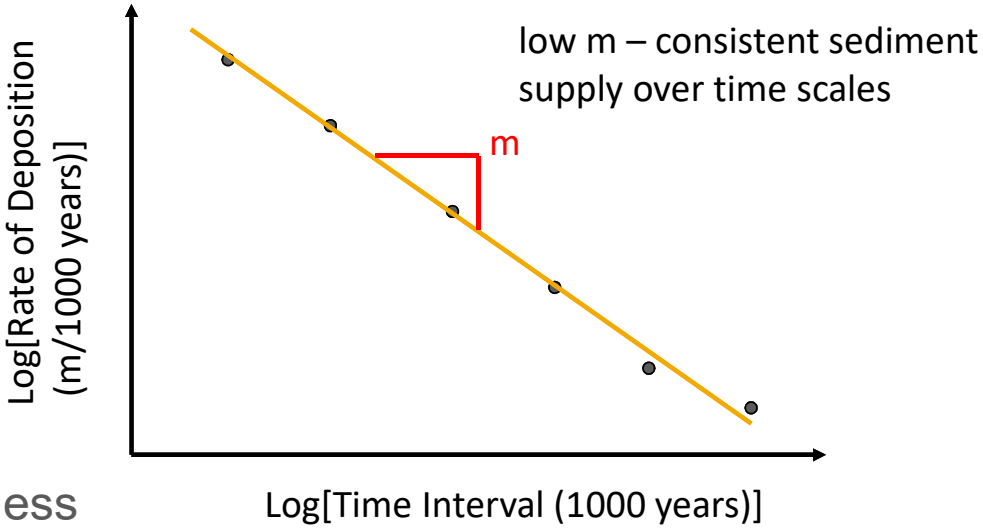
  - Sadler Effect (Sadler, 1981)
    - trend of falling mean rate with increasing time span (Sadler, 1981)
    - fit a power law, retain the exponent

$$r = Kt^{-m}$$

$$\log r = (-m) \cdot \log t + \log K$$

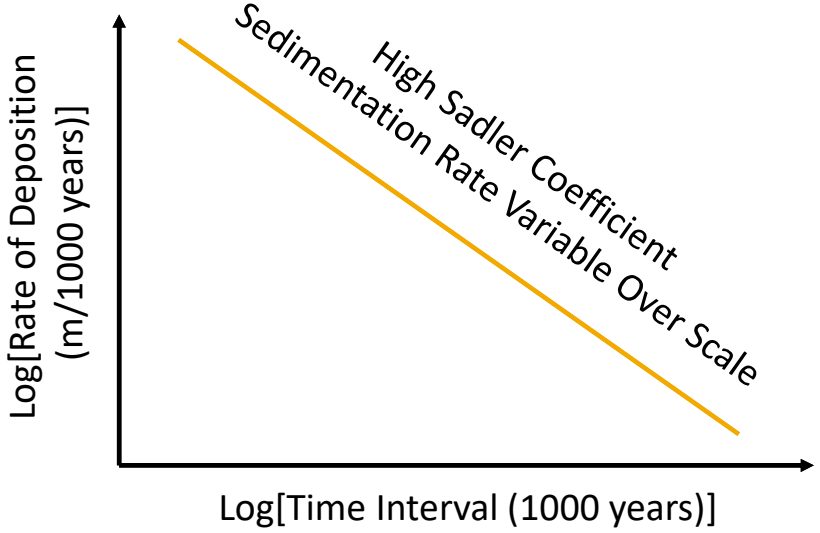
r= The rate of deposition
t= time
K= Constant
m = power law slope, "Sadler Coefficient"

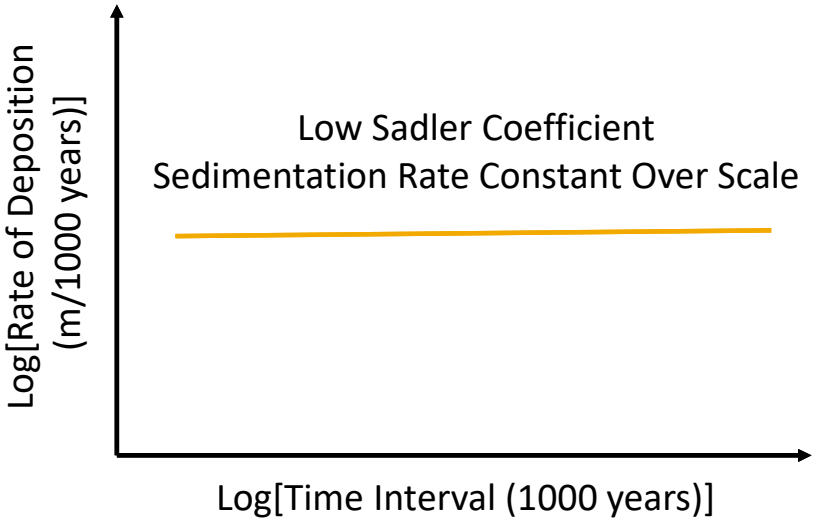
    - could have also considered completeness



Example – What Will We Sample? What Questions?

- Sadler Coefficient





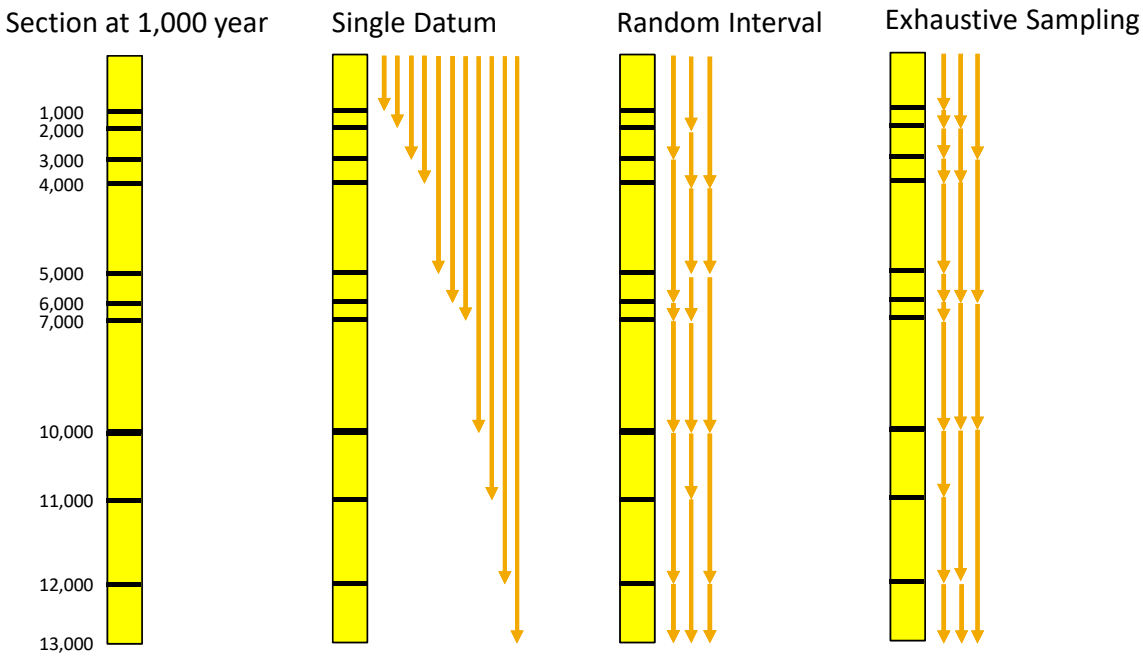
Example – How Do We Measure Sadler From an Analog

- In Natural Systems
  - Limited chronological control / exposure
- For a Numerical Analog Model
  - Perfect control at all locations of sedimentation rates at 1,000 year, 200 x 200 m resolution
- Methods:
  - Single Datum
  - Random Interval
  - Exhaustive Sampling

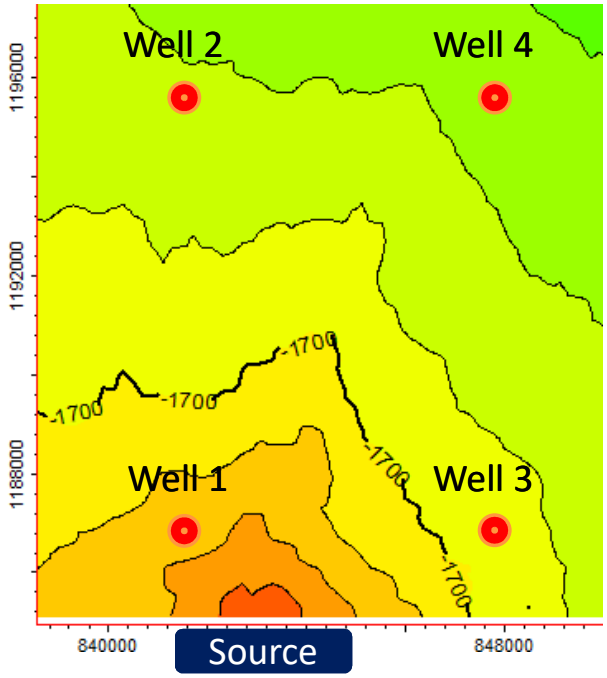
Example – How Do We Measure Sadler Form an Analog

- Comparison of Measurement Methods

- Single Datum
  - top datum to all interfaces
  - strong datum
- Random Interval
  - sequence of partial time control
  - limited exposure / missing data
- Exhaustive Sampling
  - all possible intervals
  - complete knowledge



Metrics Measured at 4 Distinct Locations

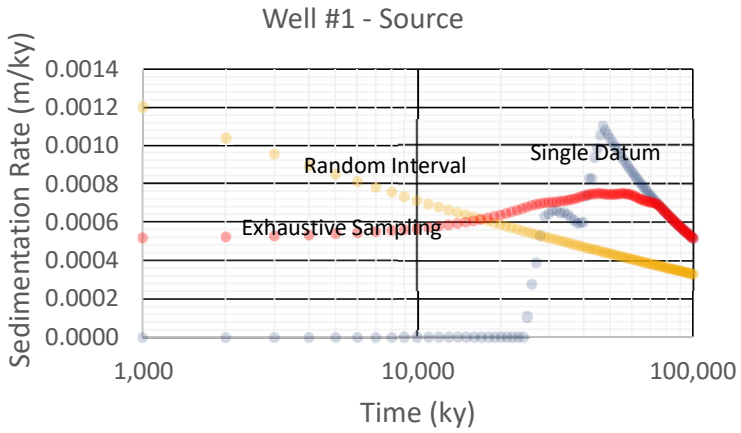


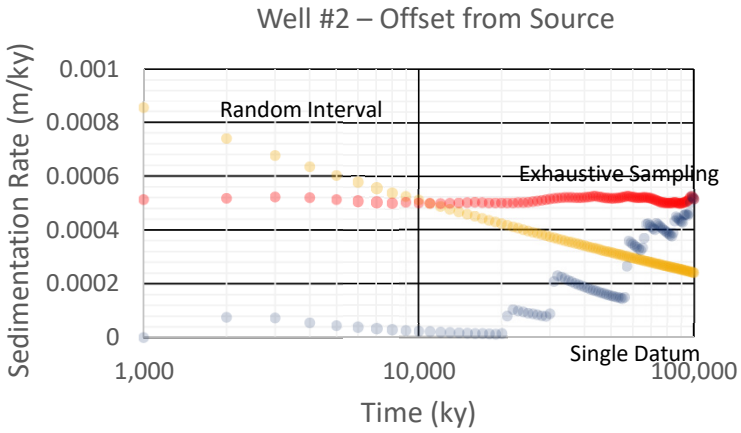
Model last surface elevation with source and resampled wells.

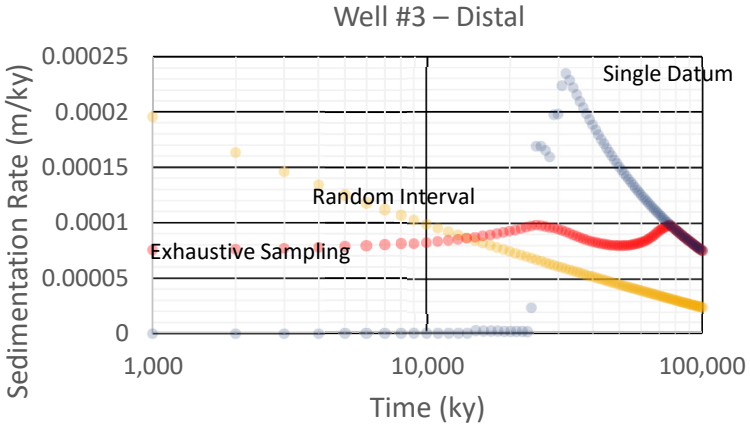
- Wells 1 – 4
  - 1: Source
  - 2: Distal
  - 3: Offset from Source
  - 4: Distal, Offset from Source
- Sampling at 4 locations in the model
  - Are the sedimentation rate related metric consistent?
  - What is the impact of location relative to source?

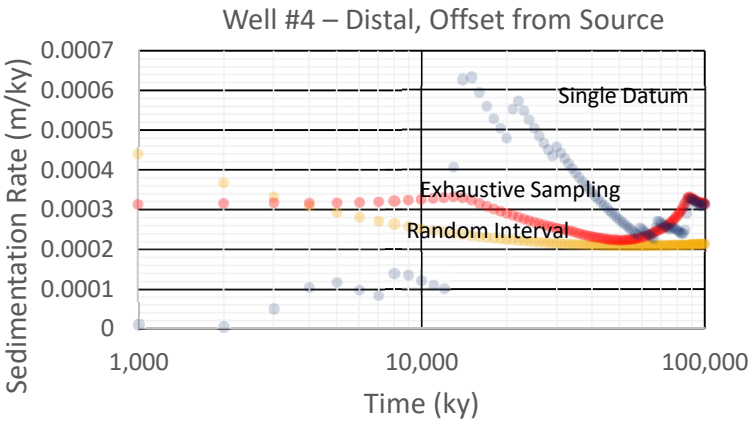
Sampling with Sadler Effect – Various Locations

- Observations:
  - Sensitivity to method
  - Exhaustive sampling averages out Sadler effect!
  - Lowest random interval result for distal, offset from source.
- Let's calculate the coefficient for every column
  - 2D map of coefficient

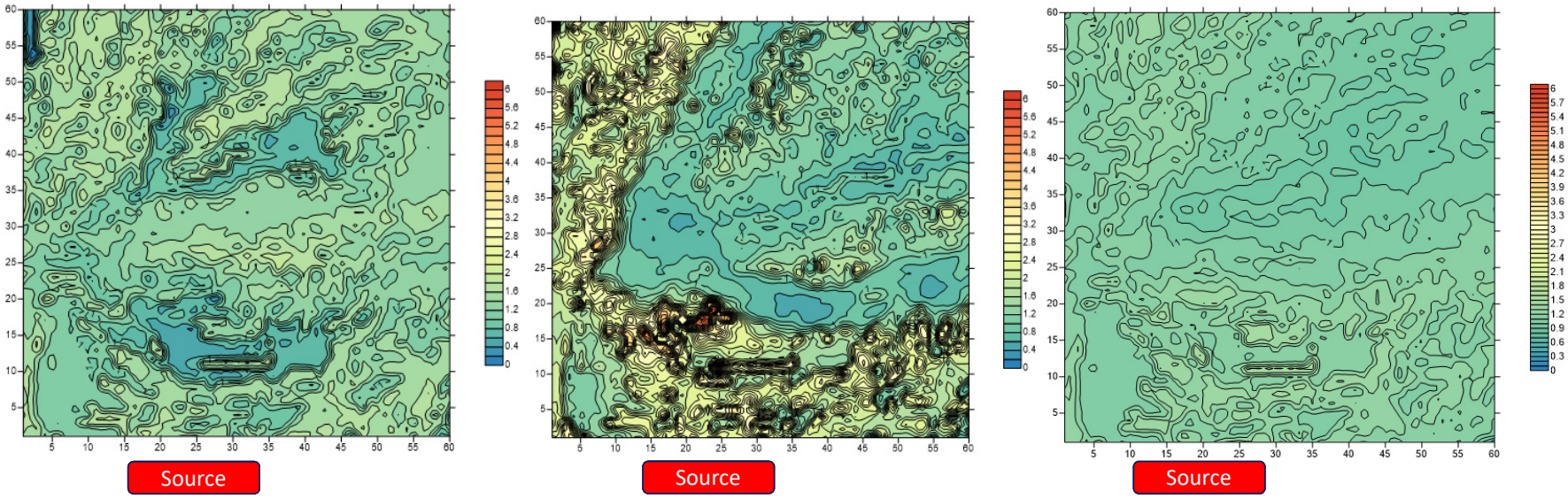








Sadler Coefficient Map



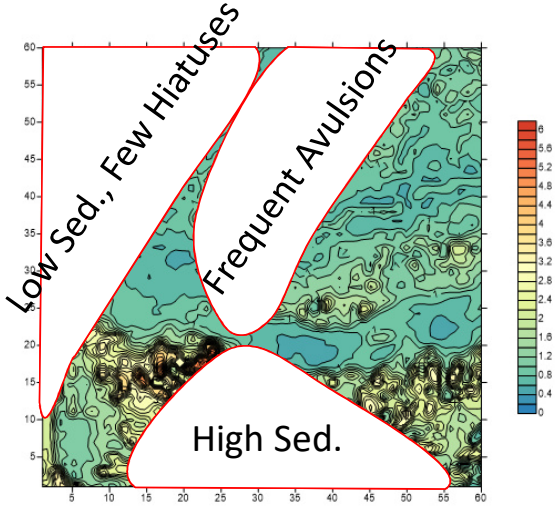
Exhaustive Sampling Method

Single-datum Method

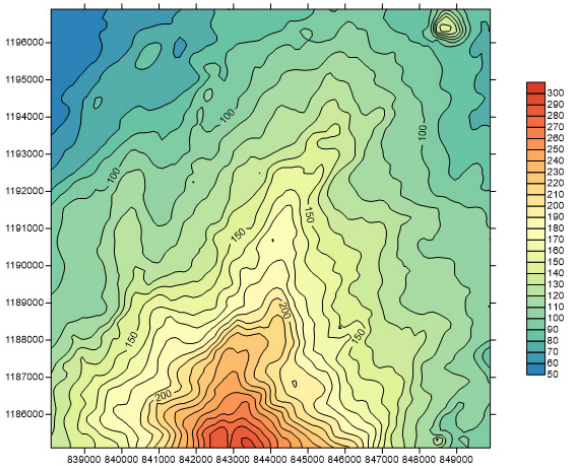
Random Interval Method

- Observations
  - Single datum is most locally sensitive
  - Controlled by proximal to distal variations and local avulsions frequency?

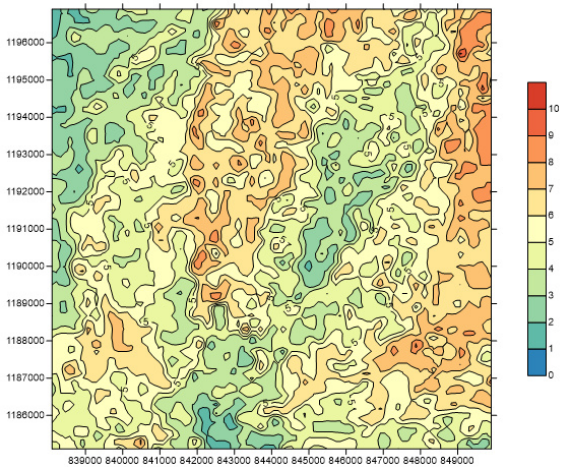
Sediment Thickness and Number of Hiatus (Completeness)



Single Datum Method



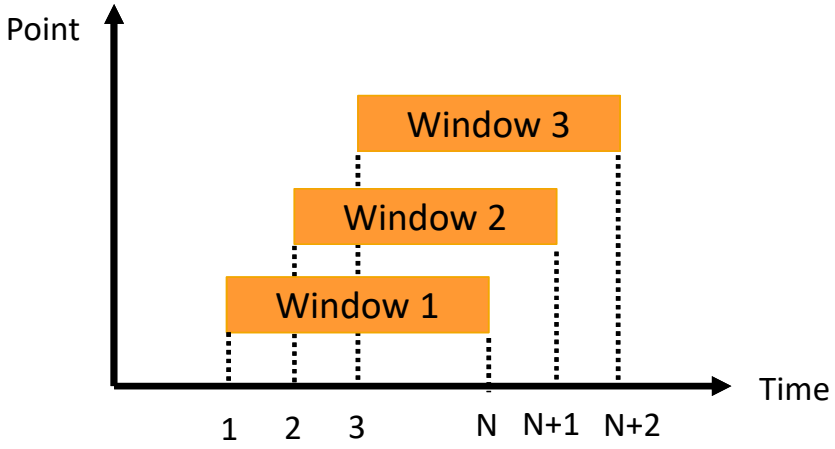
Total Thickness Over Entire Time Lag



Number of Hiatuses

- Checked if the previous results are related to total sedimentation and number of hiatuses (completeness)
- We see features from combination of total sedimentation and number of hiatuses.

Are the Sedimentation Related Measures Consistent Vertically?



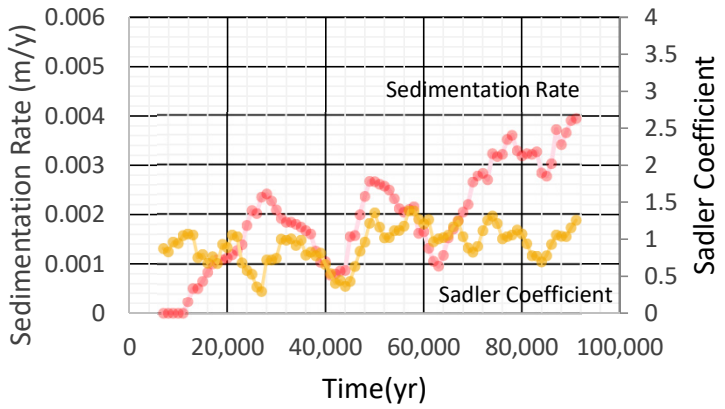
$$\overline{P_{SM}} = \frac{P_M + P_{M-1} + \cdots + P_{M-(n-1)}}{n} = \frac{1}{n}\sum_{i=0}^{n-1} P_{M-i}$$

$$\overline{P_{SM}} = \overline{P_{SM,prev}} + \frac{P_M}{n} - \frac{P_{M-n}}{n}$$

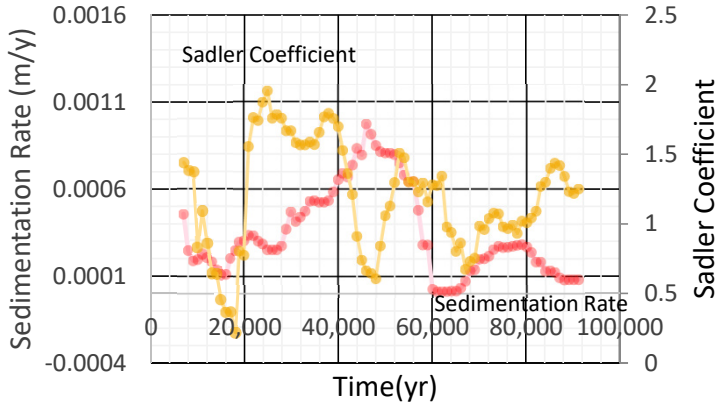
- Useful tool for calculating a trend model
- As the window moves through the model, new results are calculated using neighboring points when the model is nonstationary.

Moving Windows – Window Size: 15,000 years

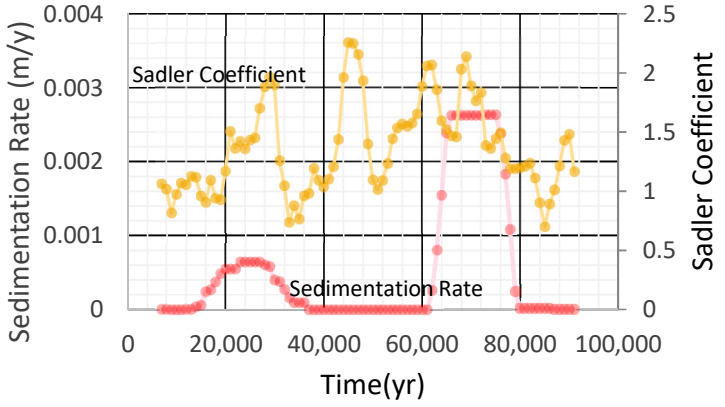
Well1



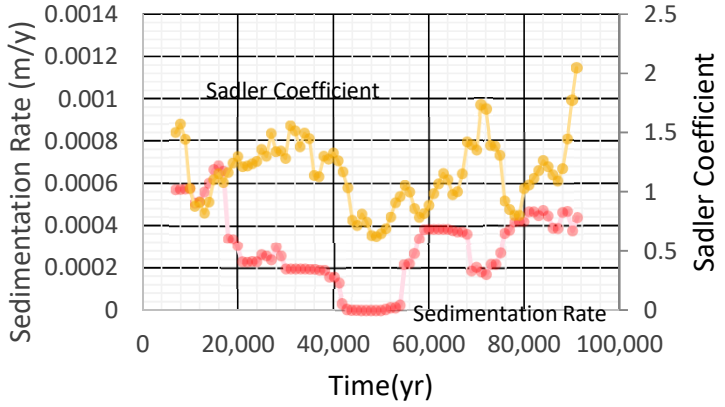
Well2



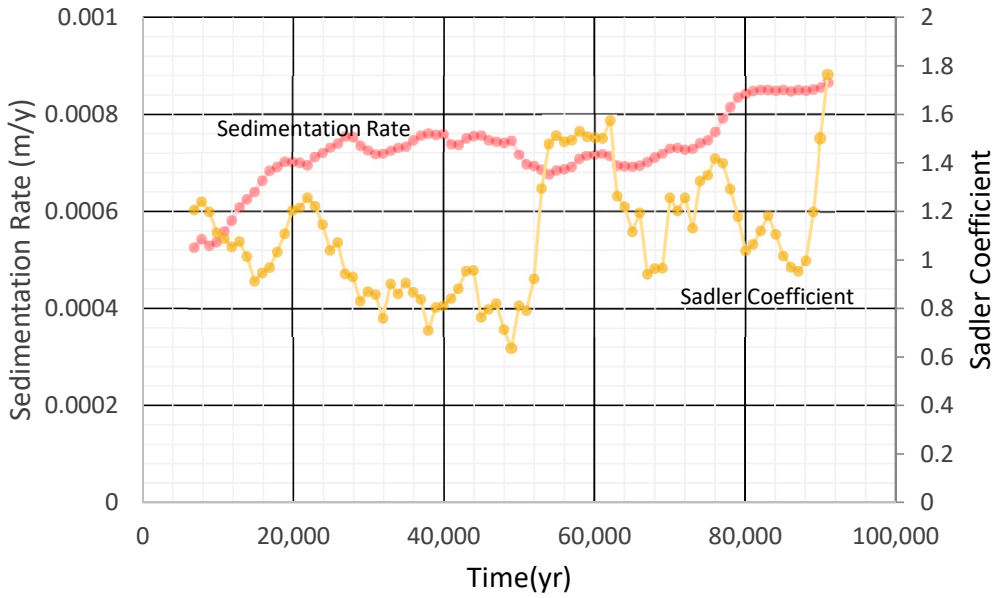
Well3



Well4



Moving Windows – Window Size: 15,000 years



Vertical trend over entire model with 15,000 years of moving window

- Significant vertical trends in Sadler coefficient

Discussion

- Opportunity to Resample from Reservoir Analog Models
  - 1D samples at vertical well locations
  - 2D maps at every column
  - 1D vertical curves from each stratigraphic layer

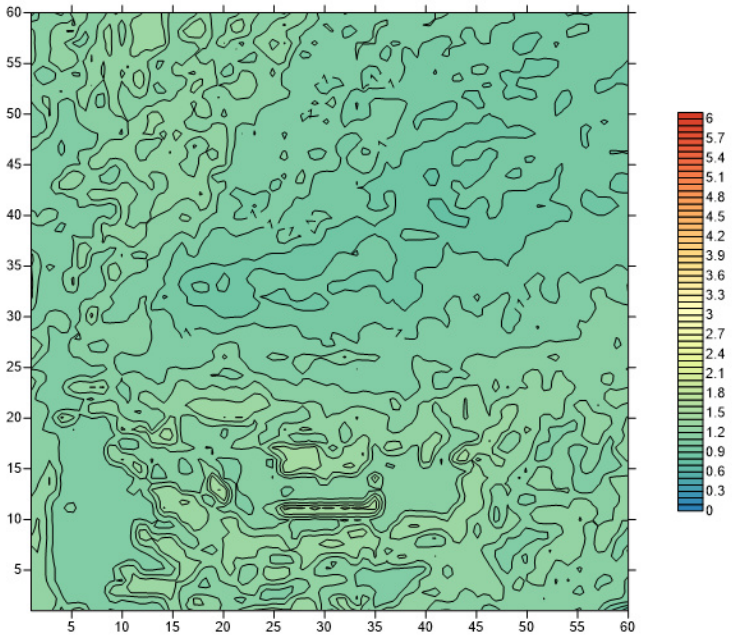
- Sedimentation Related Measures
  - Sadler is sensitive to calculation method
  - May provide indication of local heterogeneity
  - Demonstrate significant local variability even without allogenic forcing

Future Work

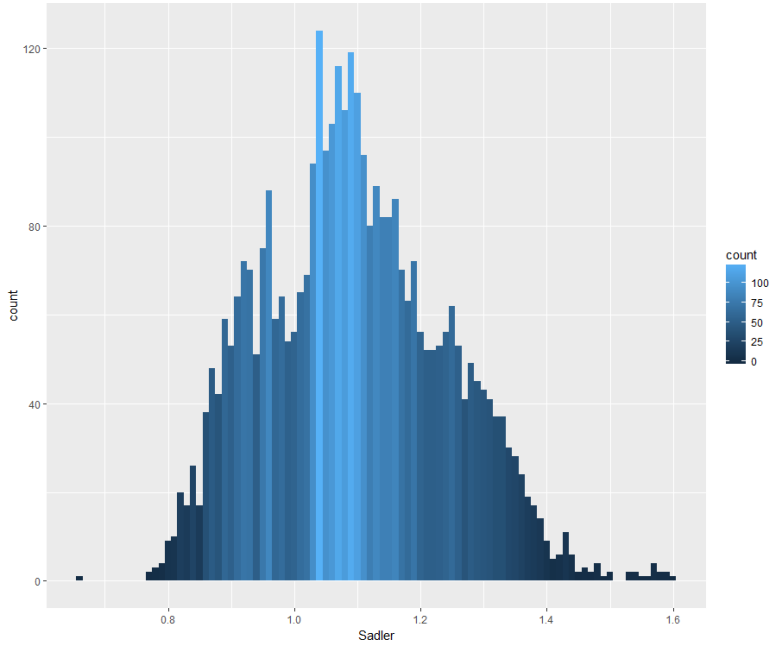
- Relationship Between Heterogeneity and Sedimentation Metrics
- Value of Information – How Many Wells to Predict?
- Sedimentation Metrics as a Reservoir Model Validation Tool

Back Up

Sadler Coefficient Map



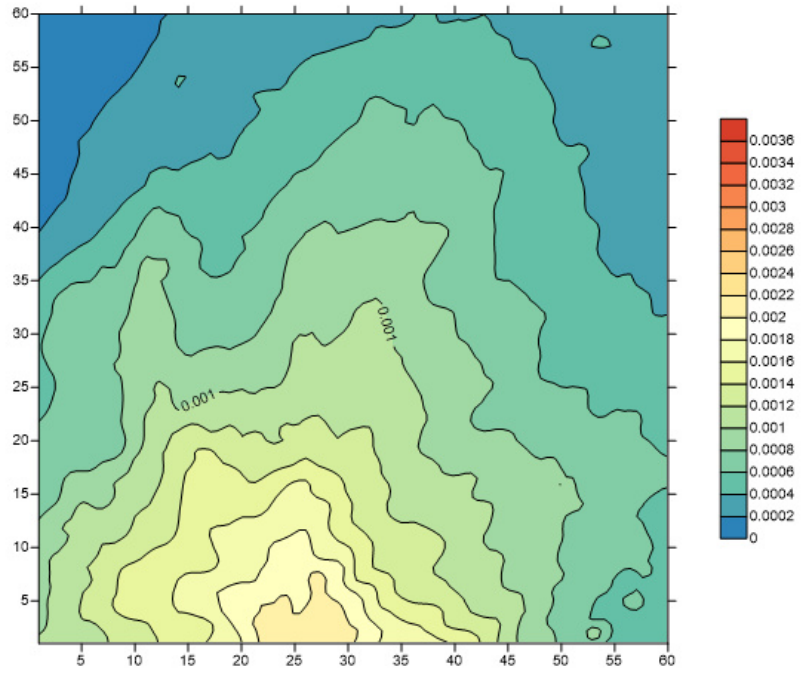
<Sadler Coefficient map of the entire model>



<Distribution of the Sadler coefficients of the entire model>

- The Sadler coefficient of the total model has the range from 0.66 to 1.60.

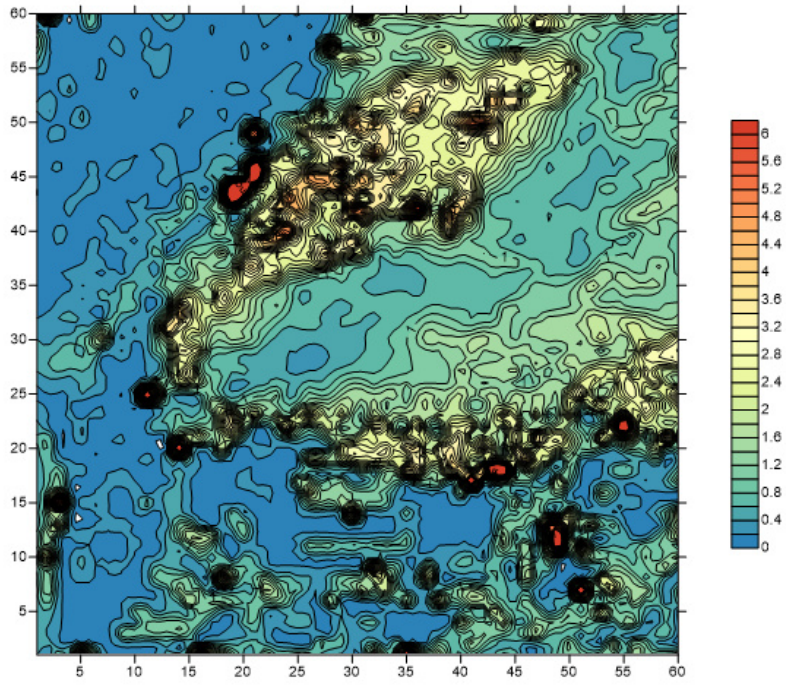
Average Sedimentation Rate Map



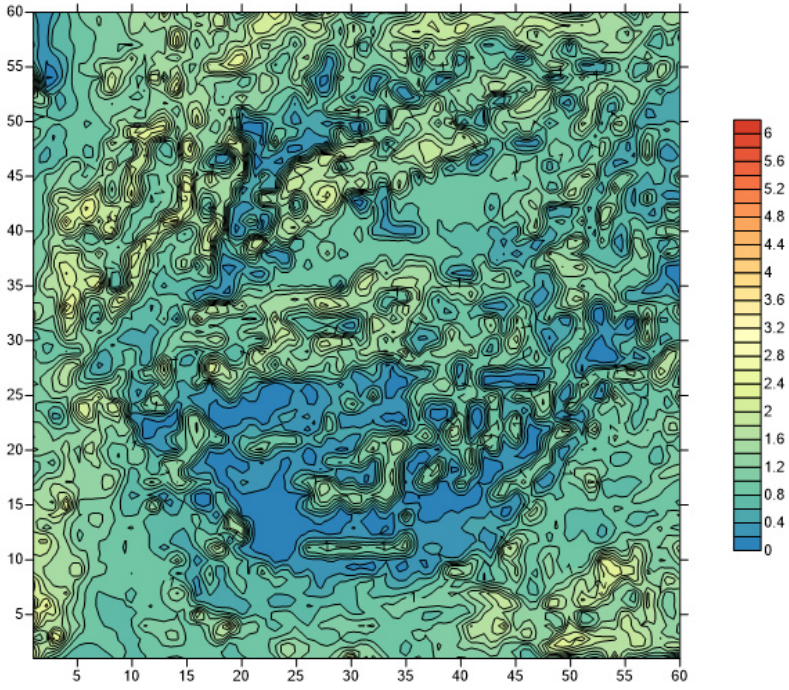
Total Model

- The sedimentation rates closest to the source are the highest.
- The sedimentation rates farther from the source are smaller.

Ages

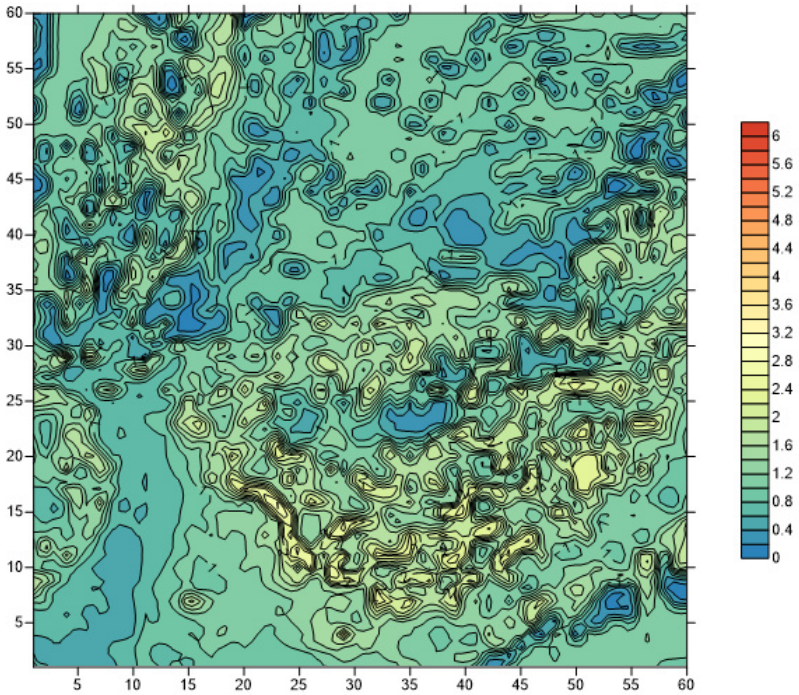


1,000 years to 23,000 years

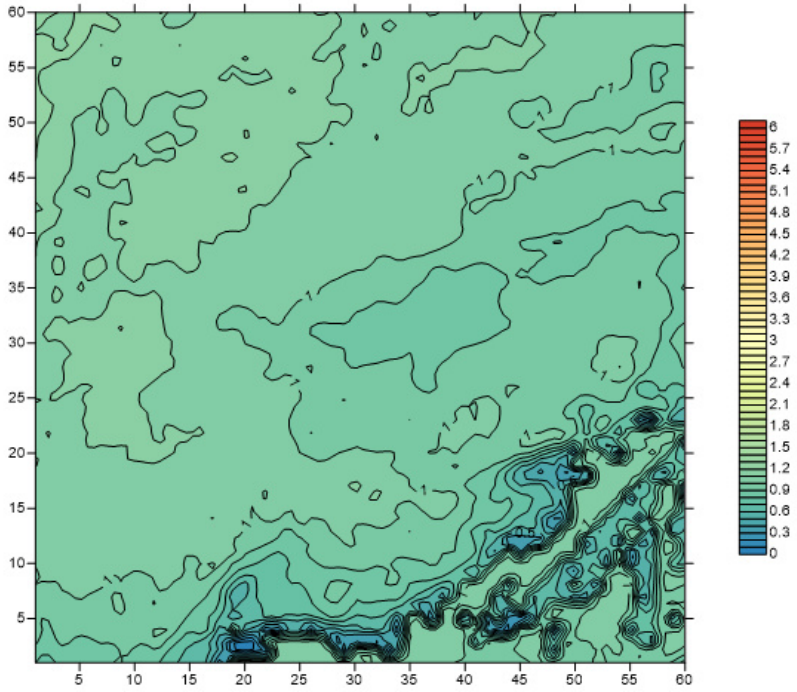


23,000 years to 36,000 years

Ages

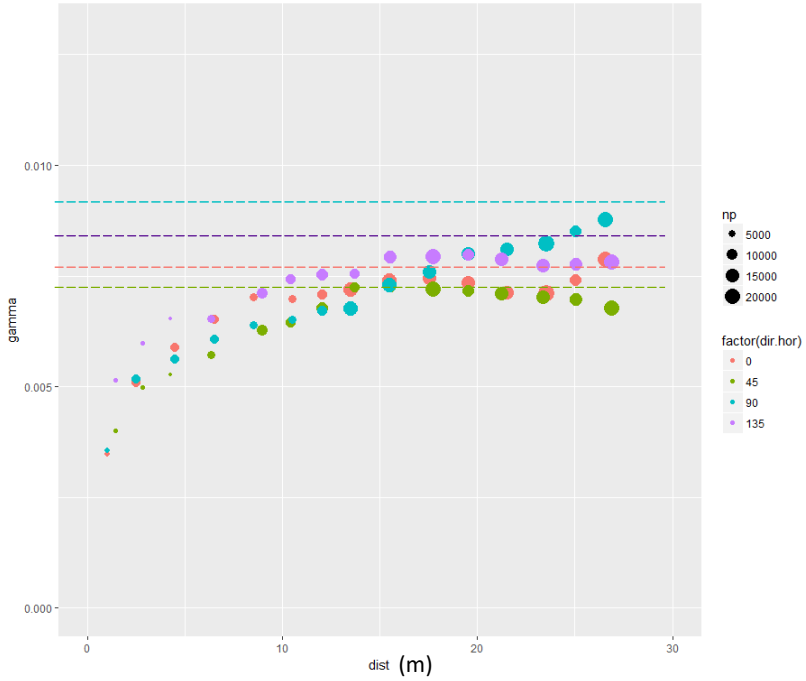


36,000 years to 54,000 years

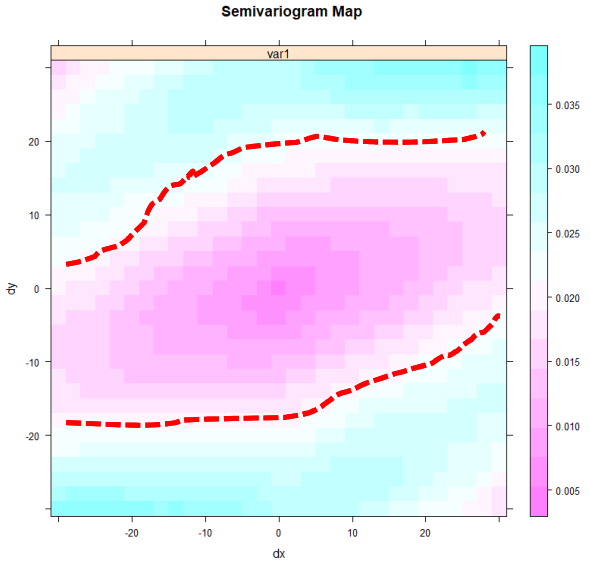


54,000 years to 101,000 years

Directional Variogram



<Variogram with different directions>

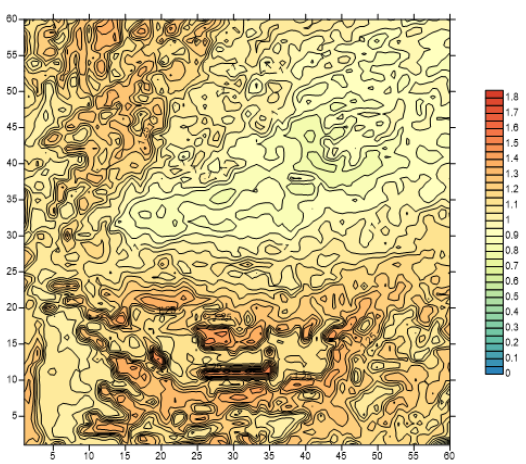


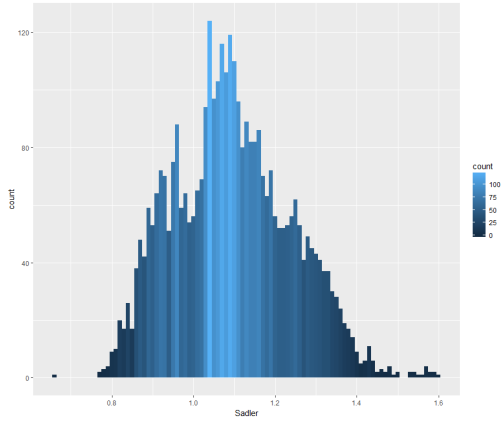
<Variogram Map>

- Calculated the variogram values for many different distances and directions.
  - Good for detecting directions of anisotropy.

Scaling Effect

<Without Scaling Effect – 196.7m x 196.7m>

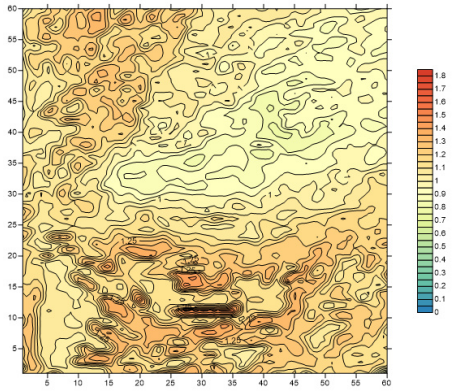


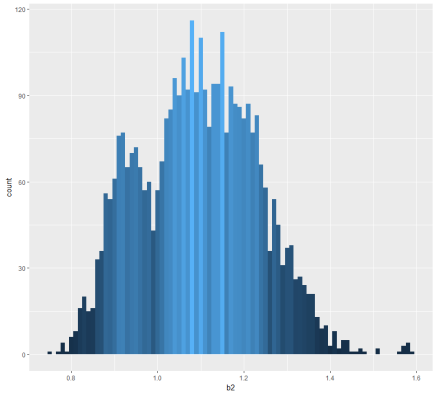


1 Block (γ=0.144506)

Scaling Effect

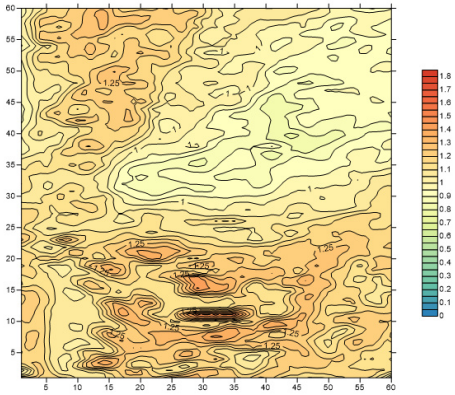
<393.3m x 393.3m >

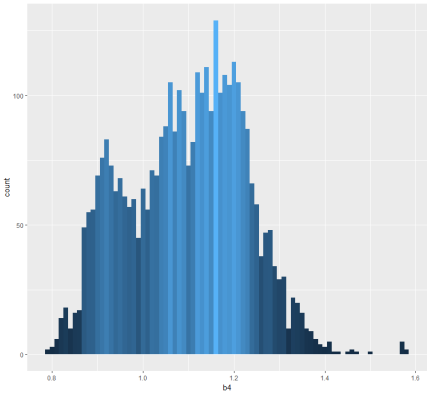




γ=0.136893

<786.7m X 786.7m>

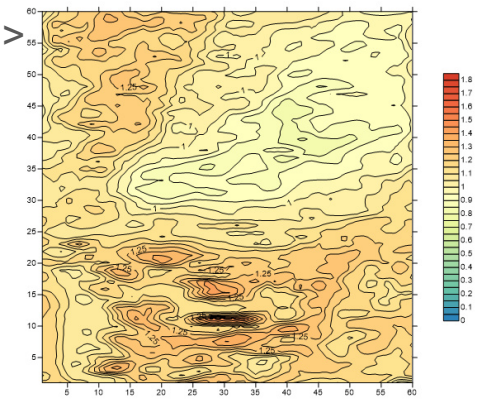


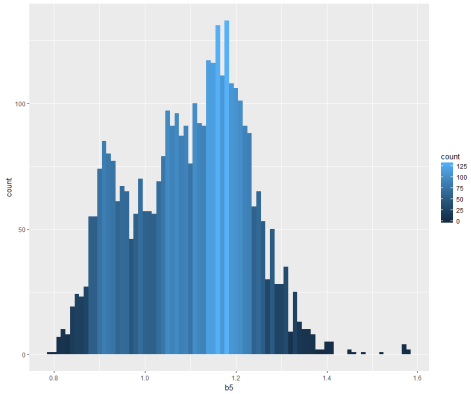


γ=0.130163

Scaling Effect

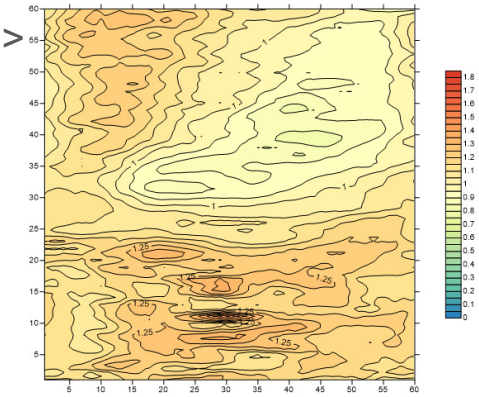
<983.3m x 983.3m >

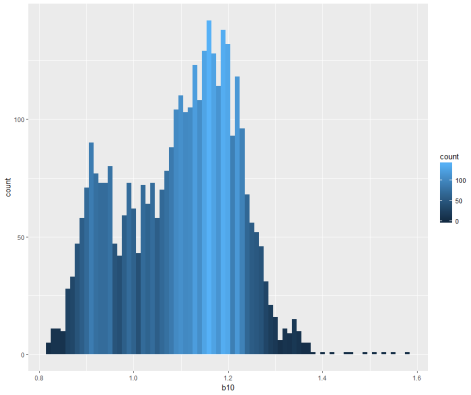




γ=0.128135

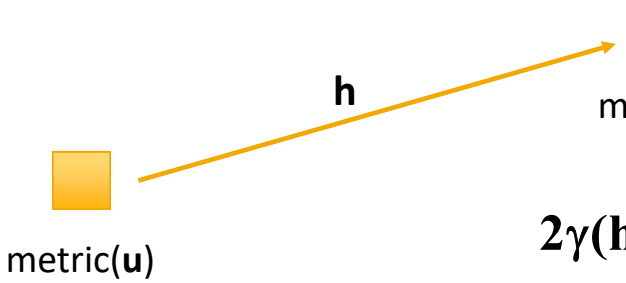
<1,966.7m X 1,966.7m>





γ=0.120959

What is the Spatial Continuity of Sadler Coefficient?

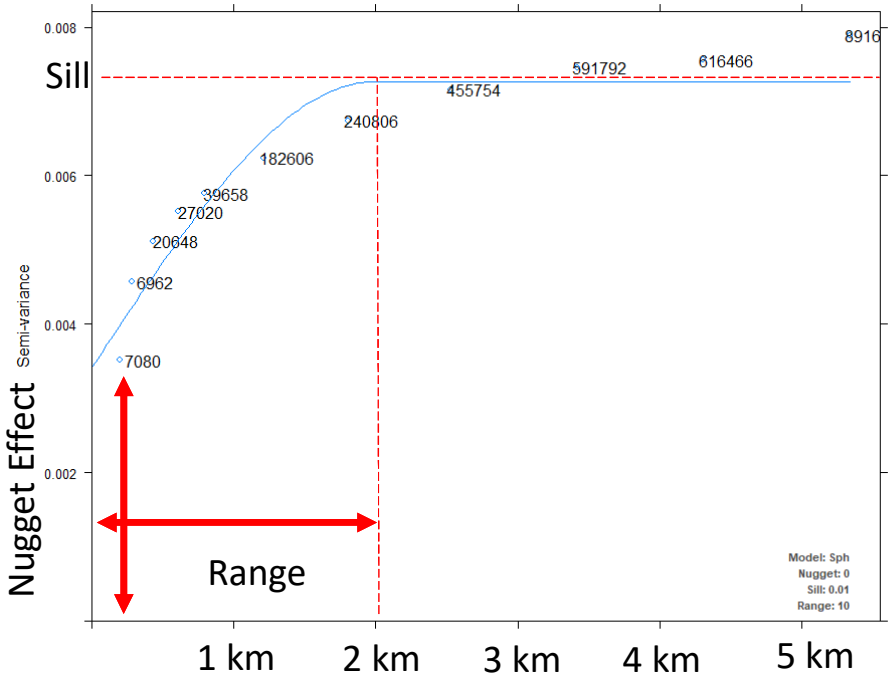


$$2\gamma(\mathbf{h}) = \mathrm{E}\{[\mathbf{Z}(\mathbf{u}) - \mathbf{Z}(\mathbf{u}+\mathbf{h})]^2\}$$

- Variogram: measure of spatial continuity
  - It gives a measure of difference over distance
- Prediction: variogram provides a predictive model
  - High spatial continuity, good prediction over distance

What is the Spatial Continuity of Sadler Coefficient?

- Variogram Model
  - 40% Nugget Effect – short scale variability noise, sampling issues
  - 60% Continuity – with a range of correlation to 2 km.



Variogram for Sadler Coefficient of The Entire Model