

Understanding Flow Behavior in Carbonate Reservoirs from Facies-Based Earth Models

By

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Abstract

Reservoir models attempt to mimic the distribution of reservoir properties in subsurface systems, and in carbonate reservoirs should capture geologically meaningful and realistic heterogeneity. In this study, we explore grainstone-dominated systems. On the basis of modern analogs from the Bahamas, grainstone shoals are modeled with linear or crescent-shaped bars, and include barcrest, barflank, and island facies.

A series of flow experiment studies investigate the impact of a variety of model input parameters on different measures of flow performance. The first study focuses on using three different modeling techniques: SGS, a non-facies-based method using a continuous variogram; SIS, a facies-based method using an indicator variogram, and MPS, a facies-based method using a training image and facies probability cube. The second study considers the impact of reservoir facies percent on flow behavior and how this changes with different modeling methods and different facies geobody shapes. The third study is a Plackett-Burman experimental design varying a) proportions of reservoir facies vs non-reservoir facies, b) proportions of barflank/barcrest reservoir facies, c) dimensions of facies geobodies, d) dissolution or cemented diagenetic zones, e) stratigraphic cyclicity f) the porosity histogram, g) the permeability transform, and h) spatial distribution of reservoir facies (distributed across platform vs. localized).

Each model was tested using reservoir simulation and considered different development scenarios. Models were compared on the basis of static measures of OOIP, reservoir connectivity, and permeability heterogeneity and on the basis of dynamic measures of recovery factor vs. time, recovery factor vs. pore volumes injected, net present oil, cumulative oil produced, and water breakthrough time.



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Introduction

Using experimental design, we examine the uncertainty in input parameters on flow performance using Multiple Point Statistics for a synthetic carbonate platform.

■ The **objectives** of this study are to:

- Assess the value of **facies-based** models
- Explore **stratigraphic and textural uncertainty** in grainstone-dominated carbonate systems

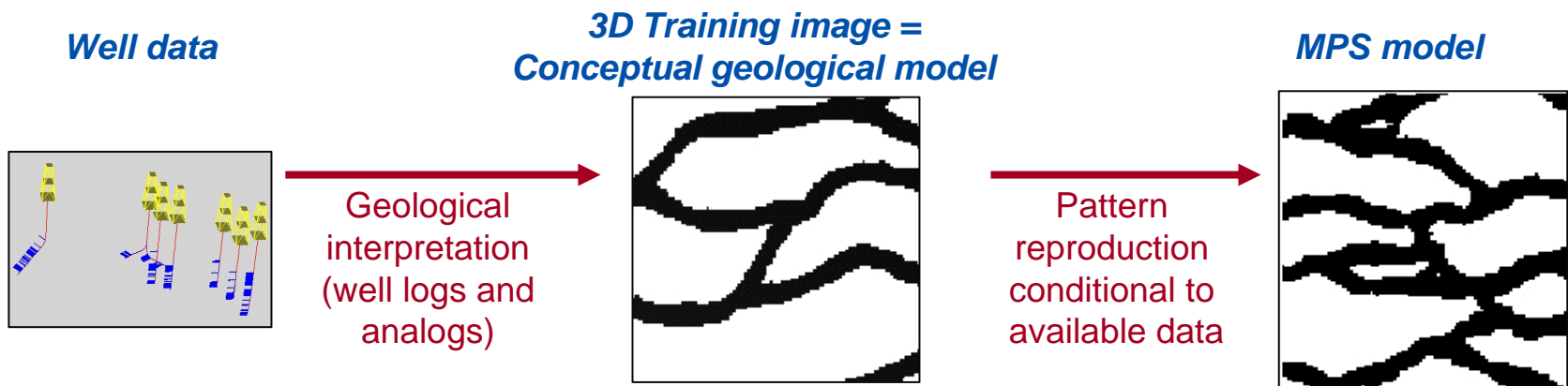
■ Methodology includes using:

- **Modern analogs** from the Bahamas for training images
- **Subsurface data** for reservoir properties
- A workflow combining **Multiple Point Statistics (MPS)** simulation and **Facies Distribution Modeling (FDM)**, and **streamline simulation**

Multiple Point Statistics (MPS)

MPS is an innovative reservoir facies modeling technique that uses conceptual geological models as 3D training images to generate geologically realistic reservoir models:

- Ability to reproduce “shapes” of object-based algorithms
- Speed, flexibility and easy data conditioning of variogram-based algorithms



What is a Training Image

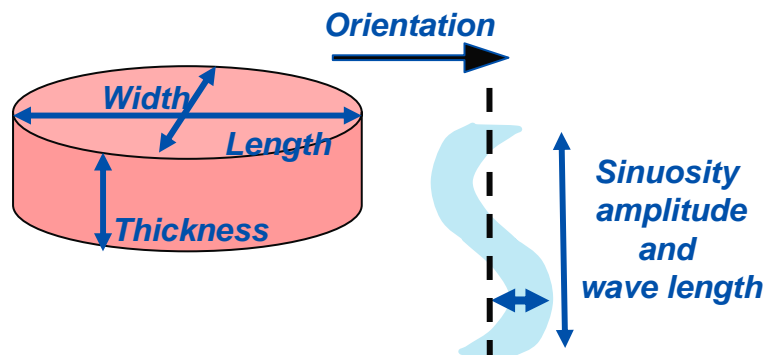
The 3D training image is a rendering of the geological model that defines relative facies body dimensions and shapes, as well as associations between facies

First describe geometry of each facies:

- Define map view and cross-section shapes:

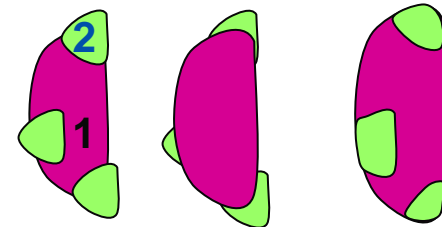


- Define dimensions, orientation, sinuosity:

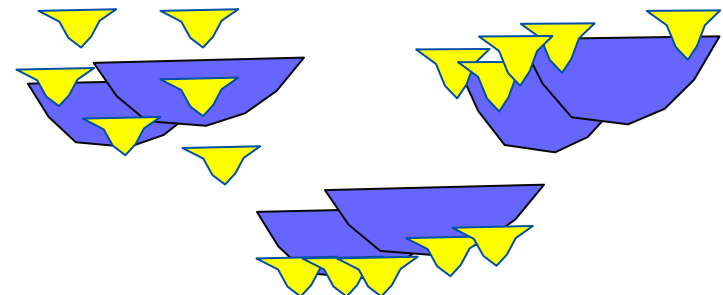


Then specify relationships between facies:

- Define Facies erosion rules:

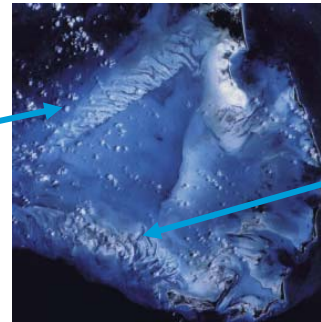
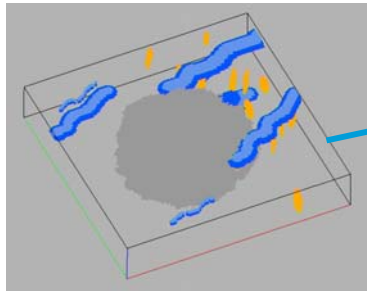


- Define vertical and/or horizontal constraints:

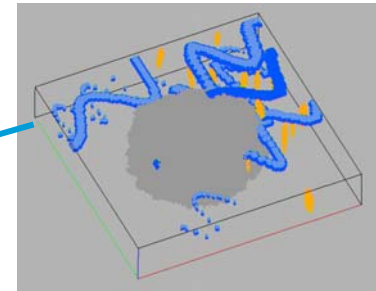


Examples of Carbonate Training Images

Linear Bars

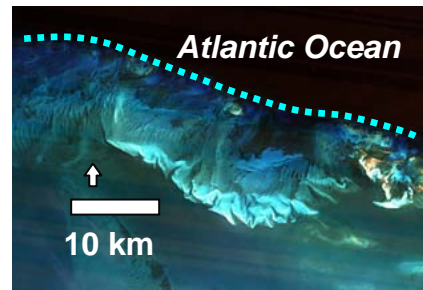
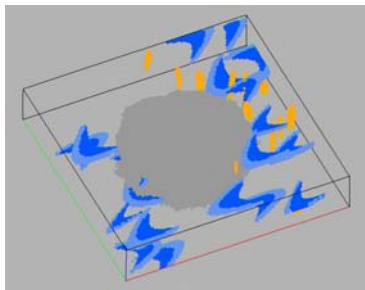


Sinuuous Bars



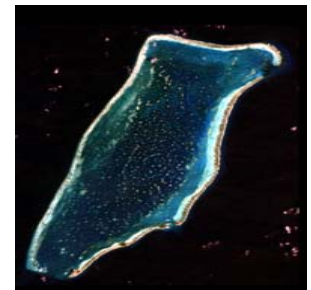
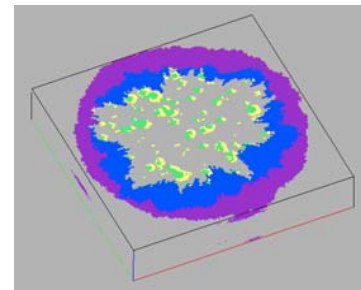
Modern Analog: Berry Islands, Great Bahama Bank, Bahamas

Crescent-Shaped Bars



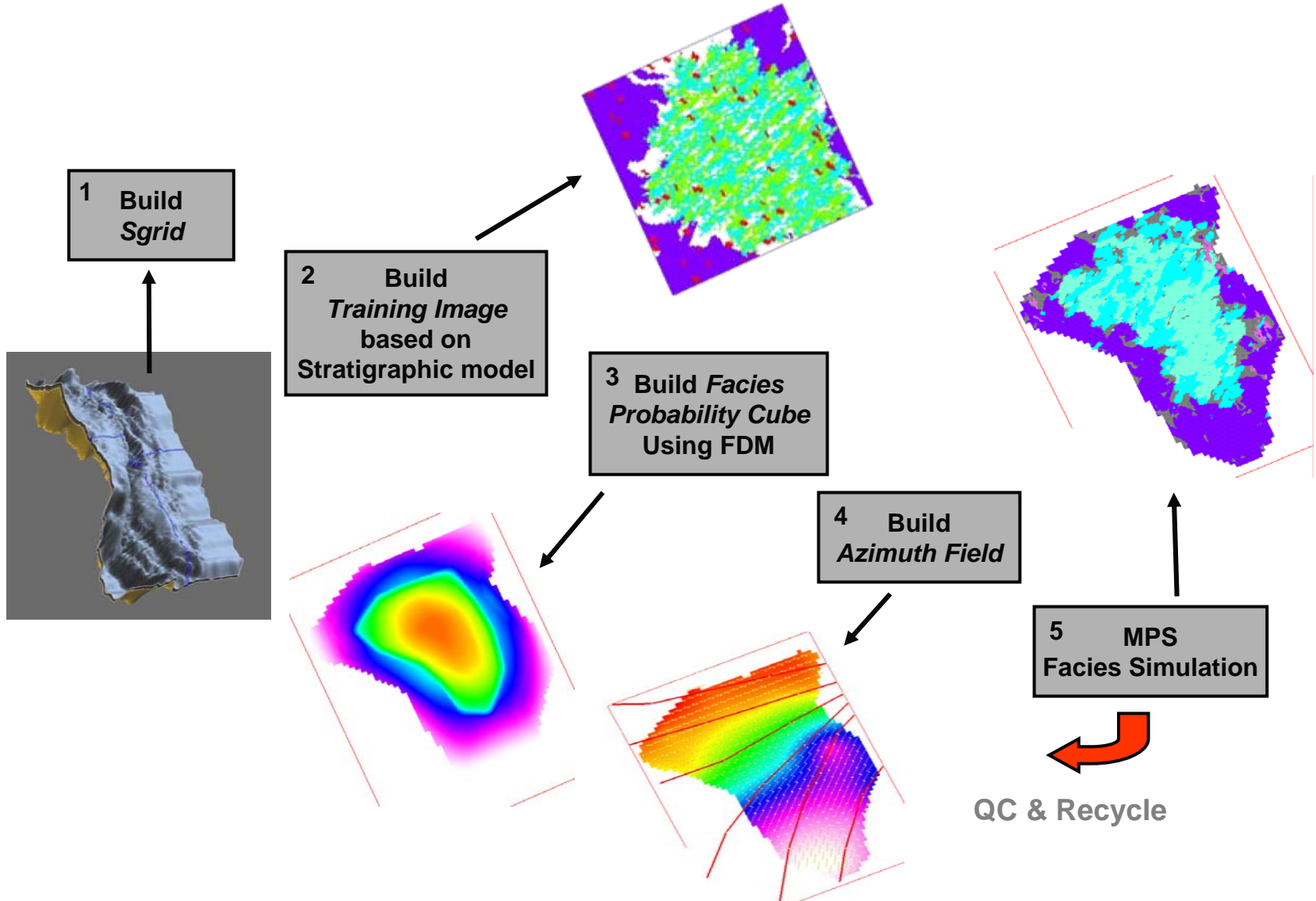
Modern Analog: Lily Bank, Little Bahama Bank, Bahamas

Reef-Rimmed Platform



Modern Analog: Glovers Reef, Belize

MPS/FDM Reservoir Modeling Workflow



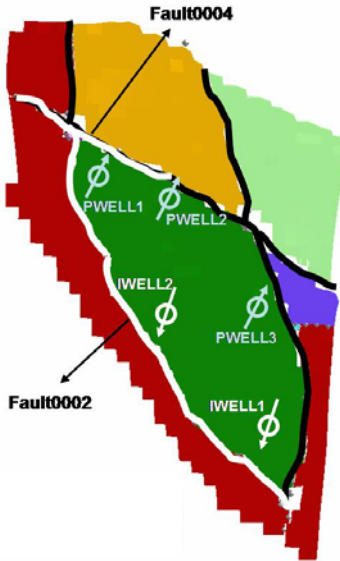
Carbonate Reservoir Modeling Study

Givens for study:

- Models are **facies-based**
- Geologic setting is **grainstone-dominated platform** consisting of barcrest, barflank, and island reservoir facies and a background facies.
- There are **5 delineation wells**. Facies and porosity data are generated in the wells, and all models are conditioned to that data.
- All models are simulated assuming a **waterflood** recovery mechanism.
 - Different well counts and different well patterns are considered.
 - Results of the simulation have been analyzed with respect to a range of measures (RF vs time, RF vs PVI, NPV, CumOil, etc).

Experimental Design Workflow

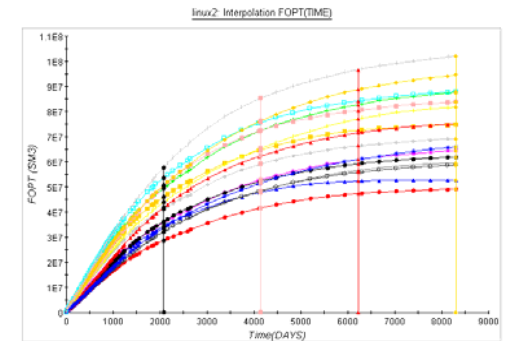
Experimental designs are protocols that provide maximum information about a problem with the minimum number of experiments. Plackett-Burman is a *Screening Design*.



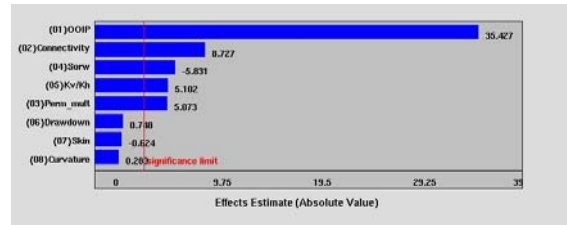
Reservoir Description

Name	Low Value	Low Label	Mid. Value	Mid. Label	High Value	High Label
1 Parameter 1	-1	Low	0	Middle	1	High
2 Parameter 2	-1	Low	0	Middle	1	High
3 Parameter 3	-1	Low	0	Middle	1	High
4 Parameter 4	-1	Low	0	Middle	1	High
5 Parameter 5	-1	Low	0	Middle	1	High
6 Parameter 6	-1	Low	0	Middle	1	High
7 Parameter 7	-1	Low	0	Middle	1	High
8 Parameter 8	-1	Low	0	Middle	1	High

Design of Experiments

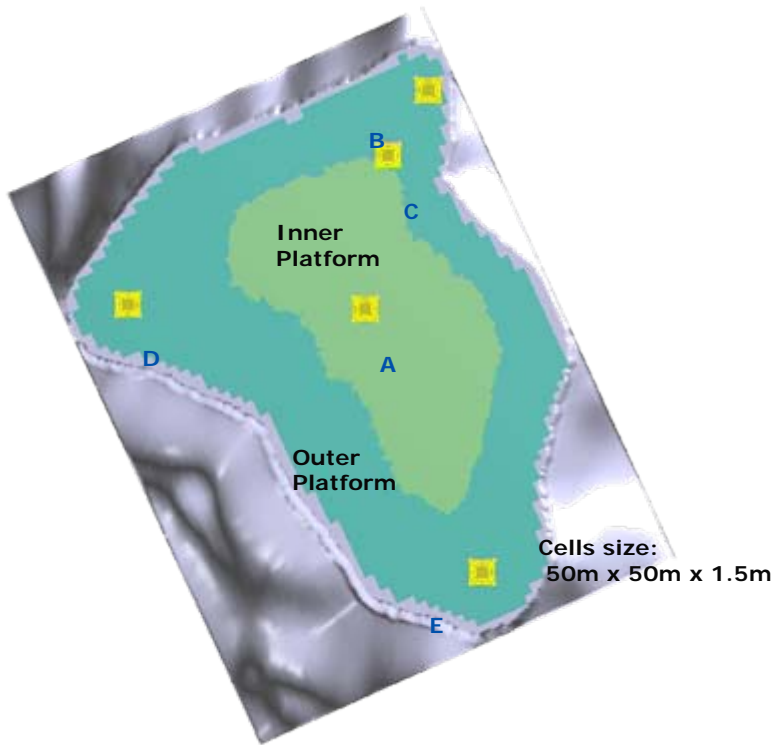


Recovery Profiles

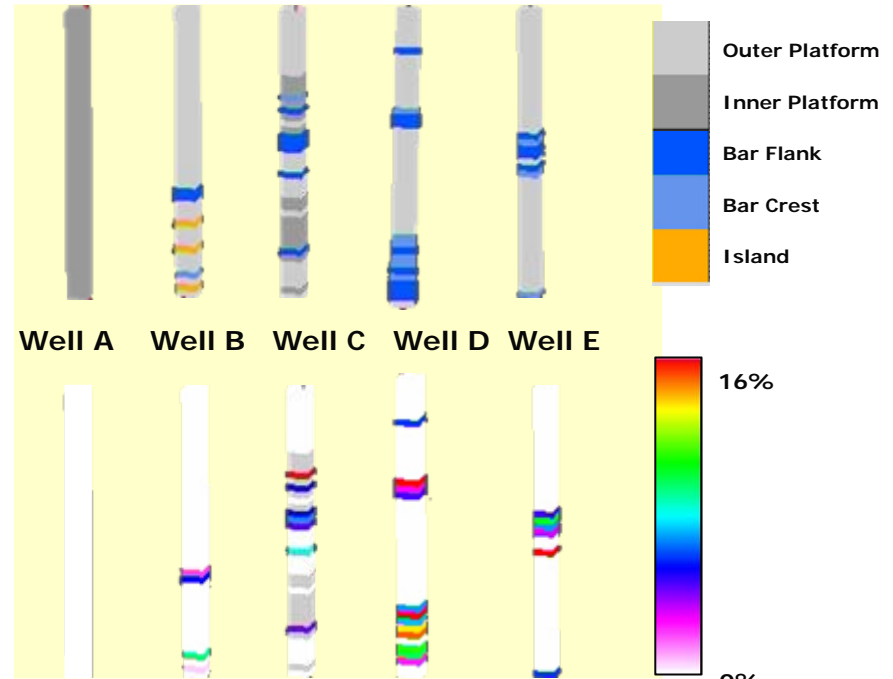


Ranking of Parameters

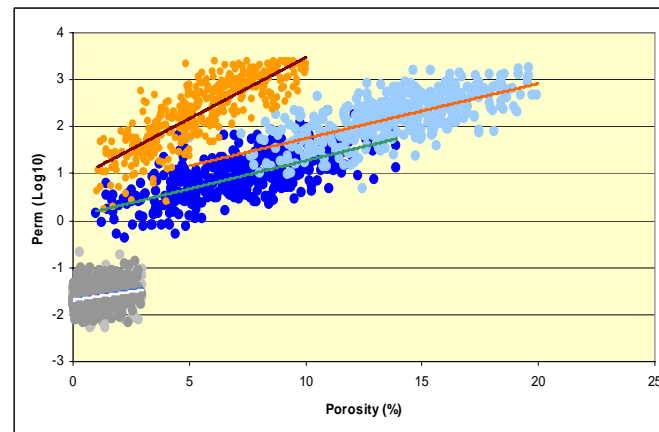
Sgrid and Conditioning Data



Facies Data



Porosity Data

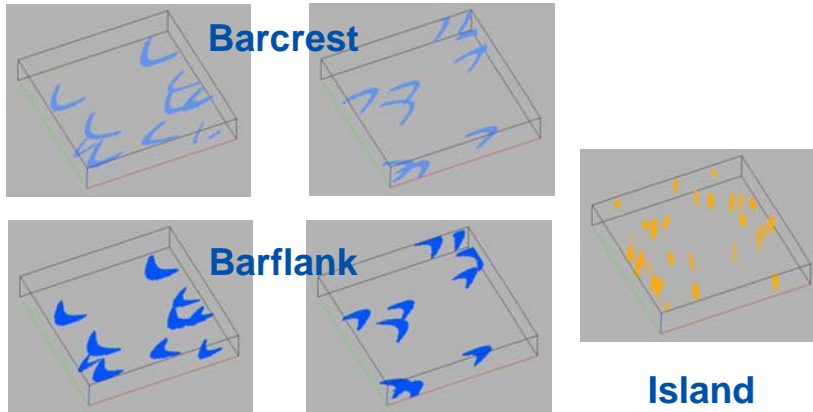


Input Permeability Cloud

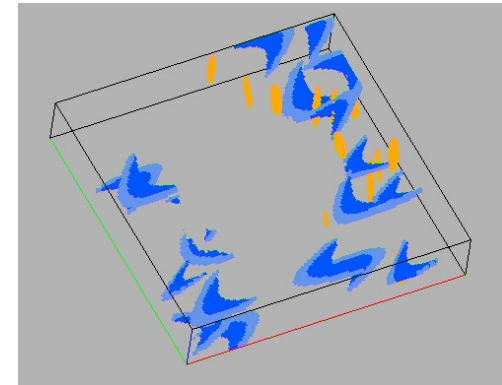
Training Image Generation Workflow: Grainstone Shoal-Crescent Bars



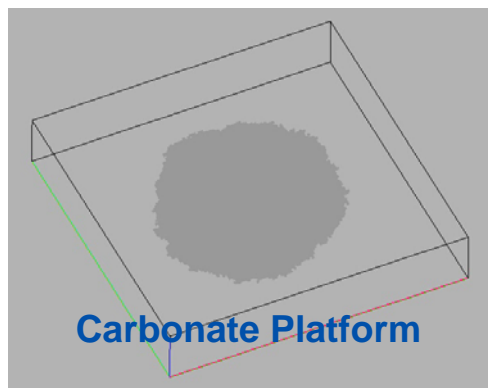
Step 1: Create Facies Files and Internal Facies Organization



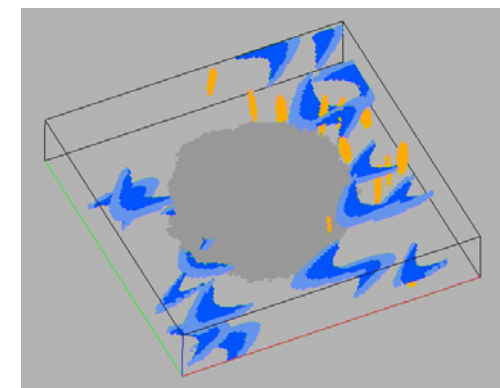
Step 2: Combine Facies Files in Outer Platform Region



Step 3: Create Carbonate Platform and Regions



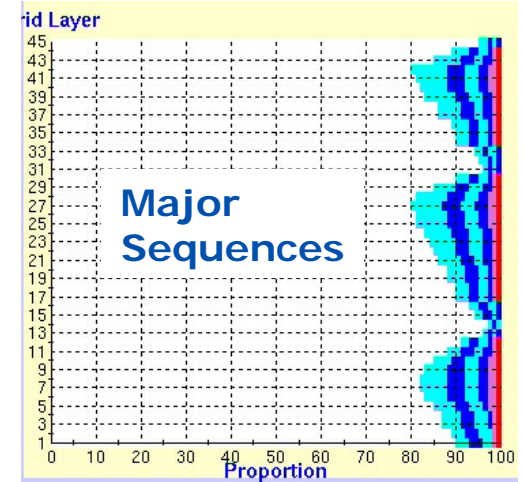
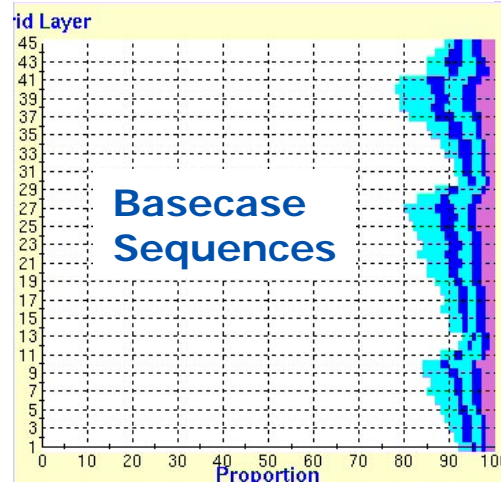
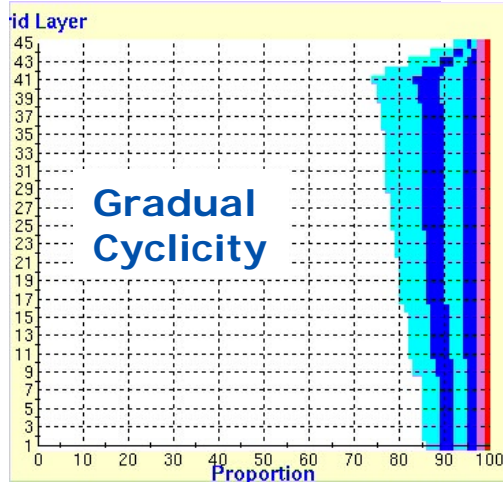
Step 4: Combine Training Images and Platform Regions



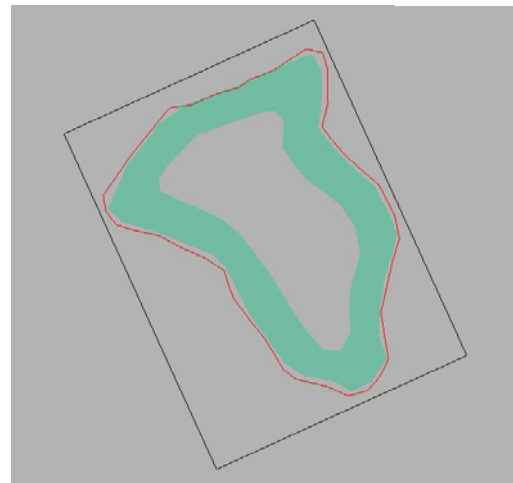
FDM Cube: Grainstone Shoals – Crescent Bars

Modern Analog: Lily Bank, Bahamas

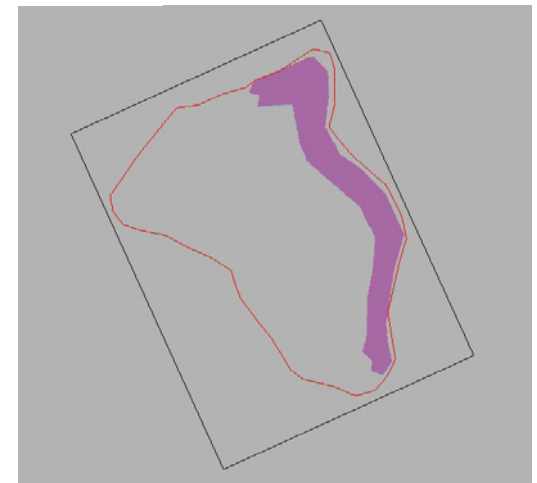
Vertical Proportion Curves



Map Depocenters



Barflank/ Barcrest Facies



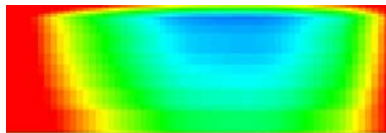
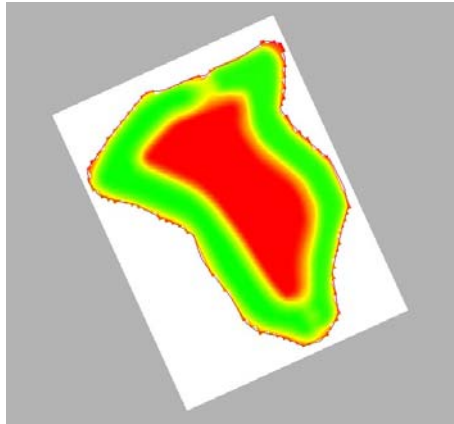
Island Facies

FDM Cube: Grainstone Shoals – Crescent Bars

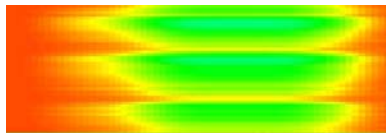
Modern Analog: Lily Bank, Bahamas



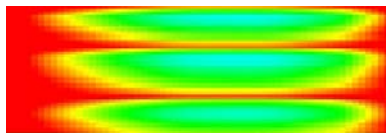
Background Facies



Gradual Cyclicity

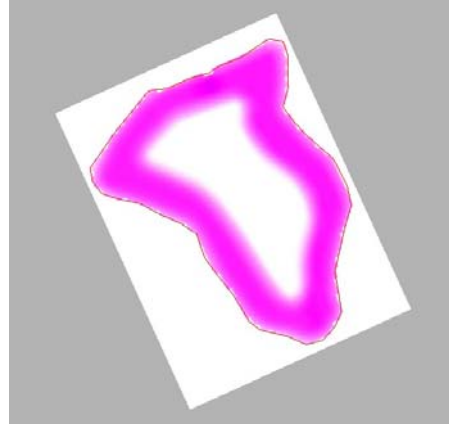


Basecase Sequences

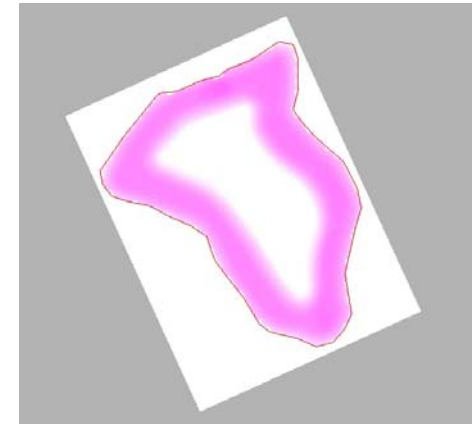


Major Sequences

Barflank Facies



Barcrest Facies



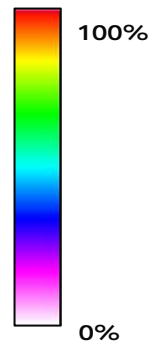
Gradual Cyclicity



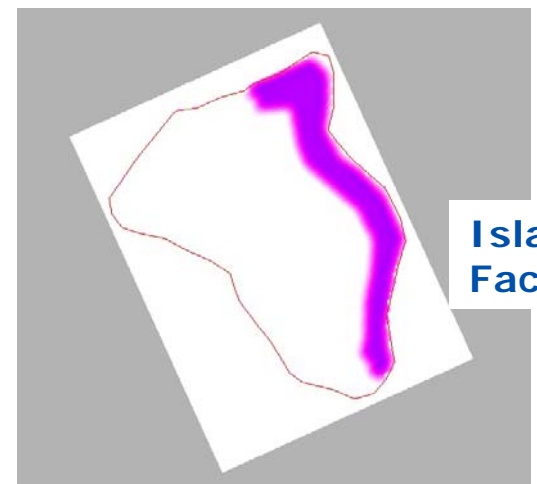
Base Case Sequences



Major Sequences



Probability of Facies Occurrence



Island Facies

Experimental Design Run Table

	\$RUN\$	\$crescent_size\$	\$crescent_ratio\$	\$distribution\$	\$cyclicality\$	\$poro\$	\$diagenesis\$	\$ktransform\$	\$res_quality_facies\$	
1	run1	large_crescent	narrow_crest	windward	major_seq	LCS		-1	HKtrans	high
2	run2	large_crescent	wide_crest	everywhere	gradual	LCS		-1	LKtrans	high
3	run3	small_crescent	wide_crest	windward	major_seq	HCS		-1	LKtrans	low
4	run4	large_crescent	narrow_crest	windward	gradual	LCS		1	LKtrans	low
5	run5	large_crescent	wide_crest	everywhere	gradual	HCS		-1	HKtrans	low
6	run6	large_crescent	wide_crest	windward	major_seq	HCS		1	LKtrans	high
7	run7	small_crescent	wide_crest	windward	gradual	LCS		1	HKtrans	low
8	run8	small_crescent	narrow_crest	windward	gradual	HCS		-1	HKtrans	high
9	run9	small_crescent	narrow_crest	everywhere	gradual	HCS		1	LKtrans	high
10	run10	large_crescent	narrow_crest	everywhere	major_seq	HCS		1	HKtrans	low
11	run11	small_crescent	wide_crest	everywhere	major_seq	LCS		1	HKtrans	high
12	run12	small_crescent	narrow_crest	everywhere	major_seq	LCS		-1	LKtrans	low
13	run13	mid	mid	mid	mid	MCS		0	mid	mid

Total number of runs = 13

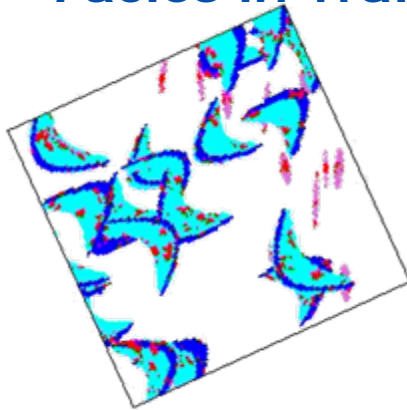
Close

Variables

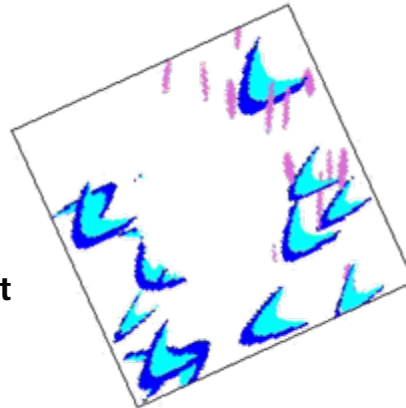
- Crescent Size
- Barflank/Barcrest Ratio
- Areal Distribution
- Cyclicality
- Porosity Histogram Overlap
- Diagenesis
- Permeability Transform
- Percent of Reservoir Facies

Plackett-Burman Experimental Design Variables

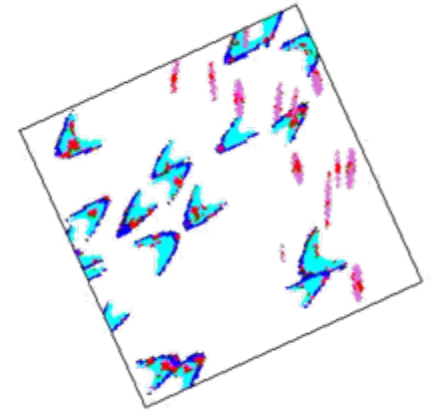
- Size and Ratio of Barcrest and Barflank Reservoir Facies in Training Image



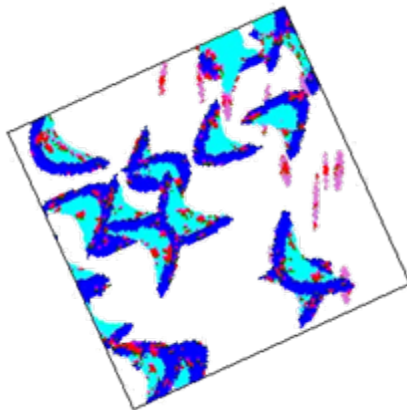
Large crescents with narrow crest



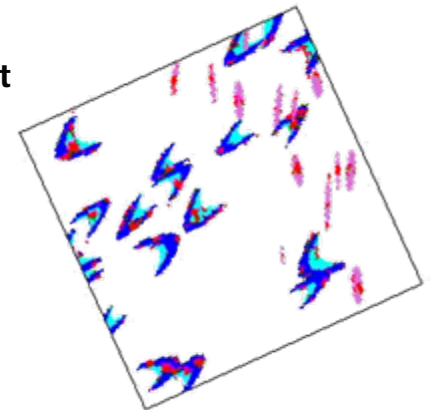
Mid-size crescents with mid-size crest



Small crescents with narrow crest



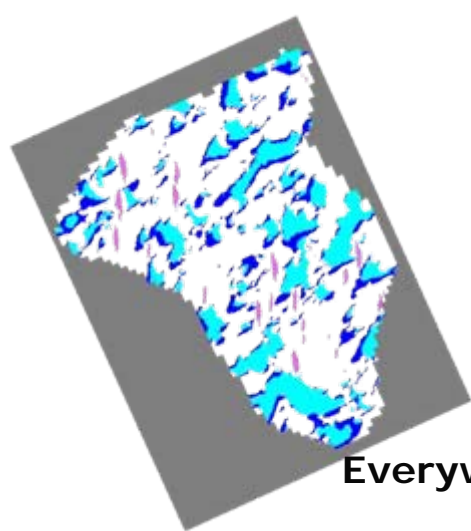
Large crescents with wide crest



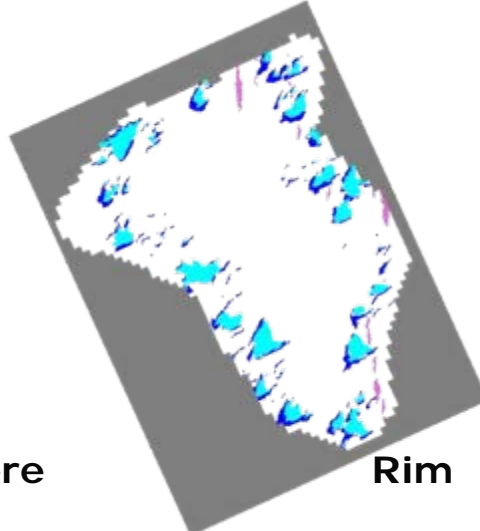
Small crescents with wide crest

Plackett-Burman Experimental Design Variables

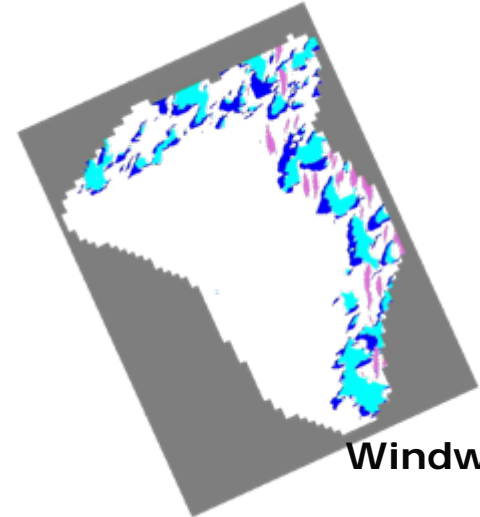
■ Distribution of reservoir facies



Everywhere

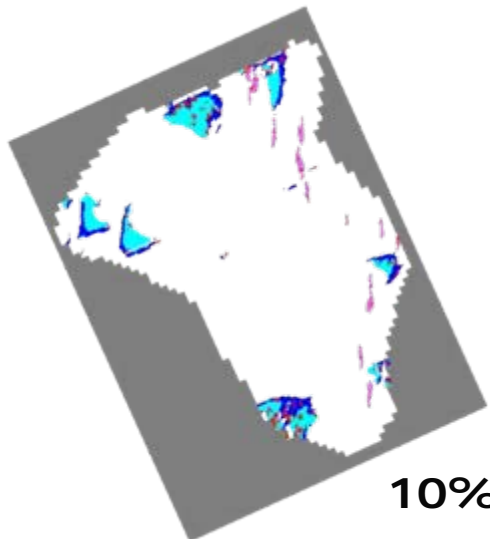


Rim

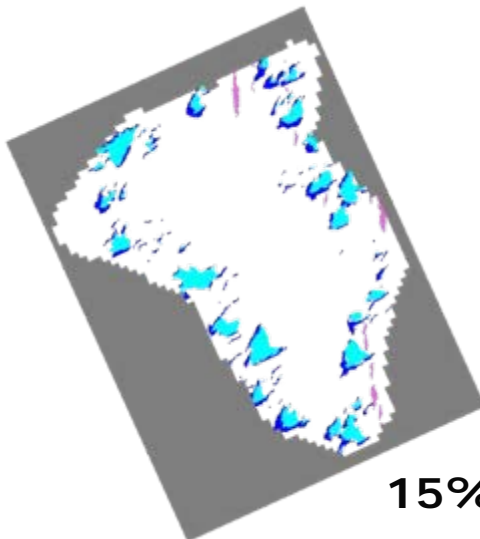


Windward

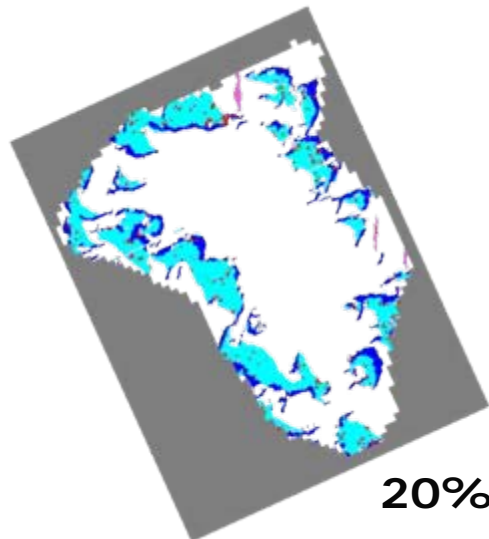
■ Percentage of total reservoir facies



10%



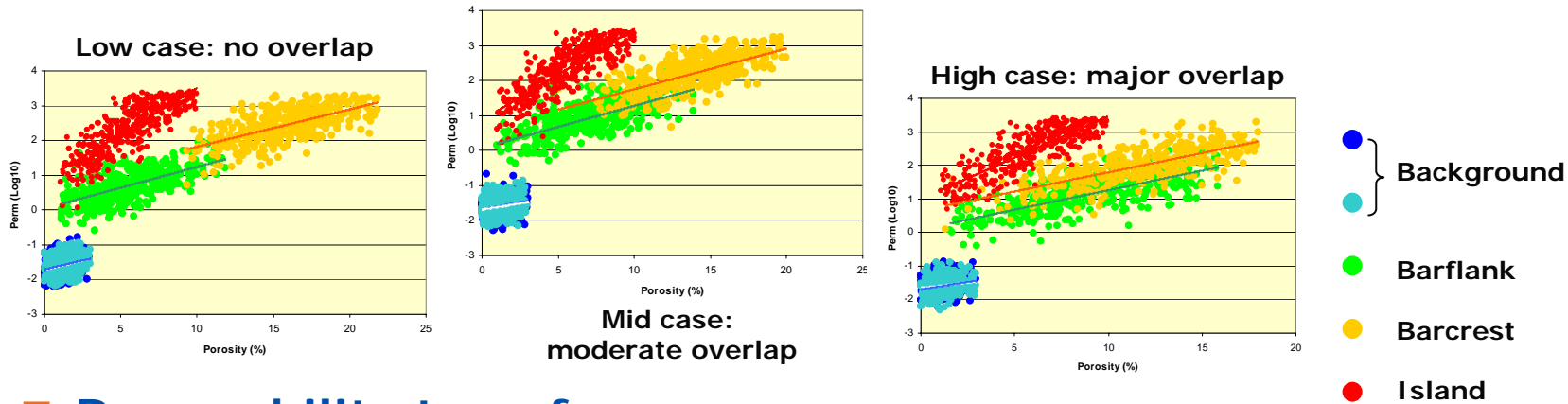
15%



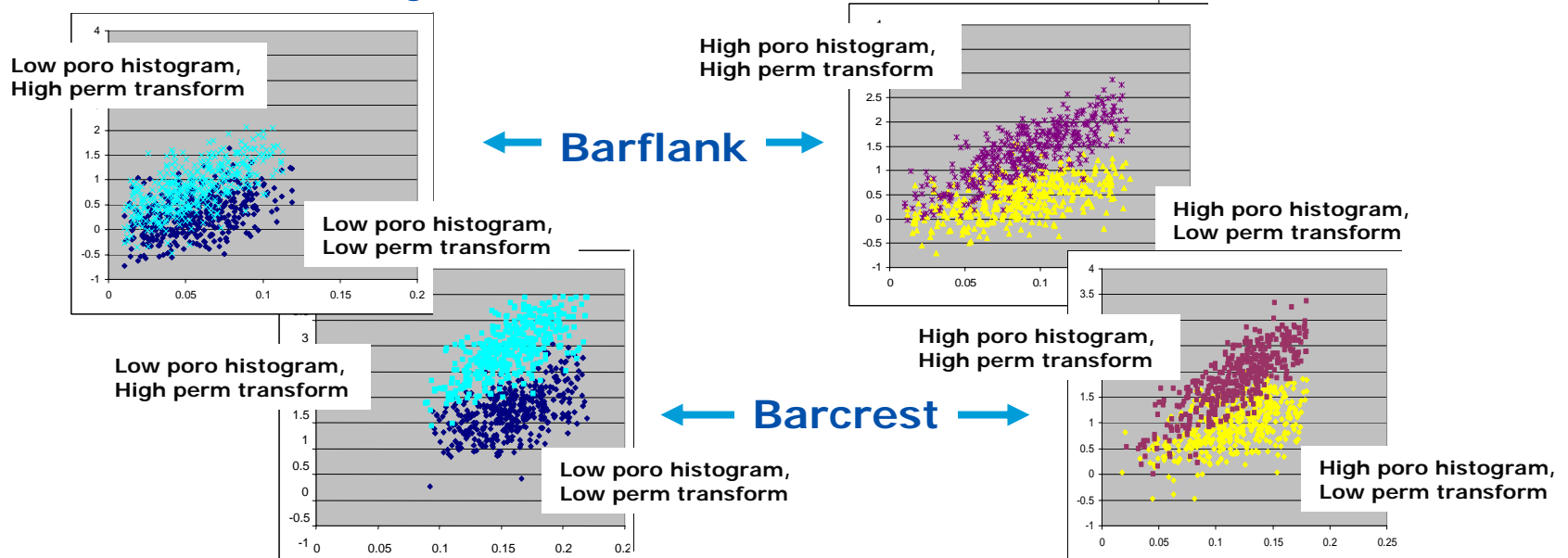
20%

Plackett-Burman Experimental Design Variables

Barflank/Barcrest Porosity histogram overlap



Permeability transform



Plackett-Burman Experimental Design Variables

■ Cyclicity



Low case: Major breaks between reservoir facies



Mid case: Minor breaks between reservoir facies



High case: No breaks between reservoir facies

■ Diagenesis

Diagenetic facies stochastically distributed within reservoir facies

● High case:

- ▶ Assumed significant dissolution
- ▶ Populated with high porosity and high permeability distribution

● Mid case:

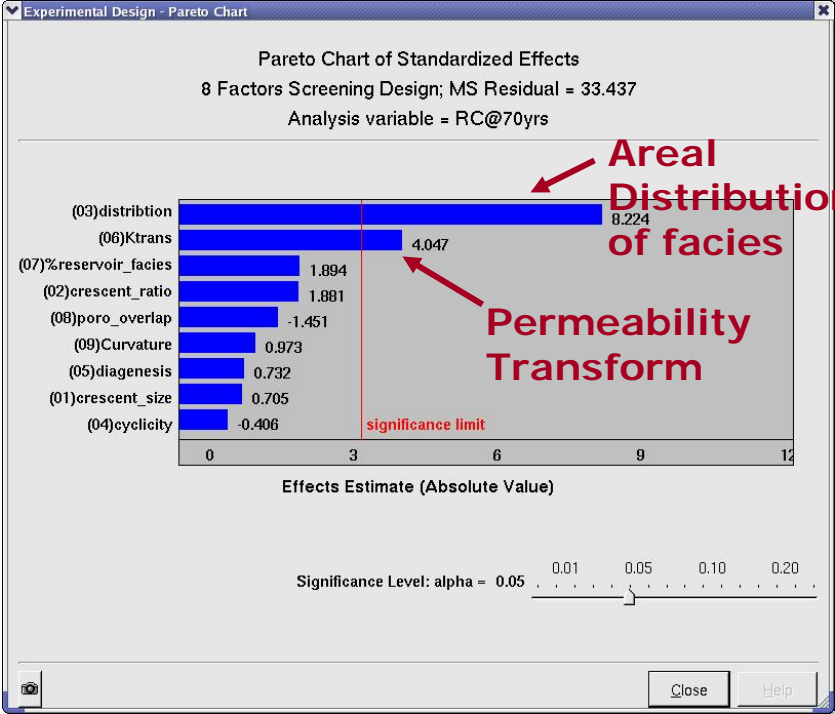
- ▶ No diagenetic overprint

● Low case:

- ▶ Assumed significant cementation
- ▶ Populated with no porosity or permeability



Flow Simulations Results: Using Variable Distribution Parameter

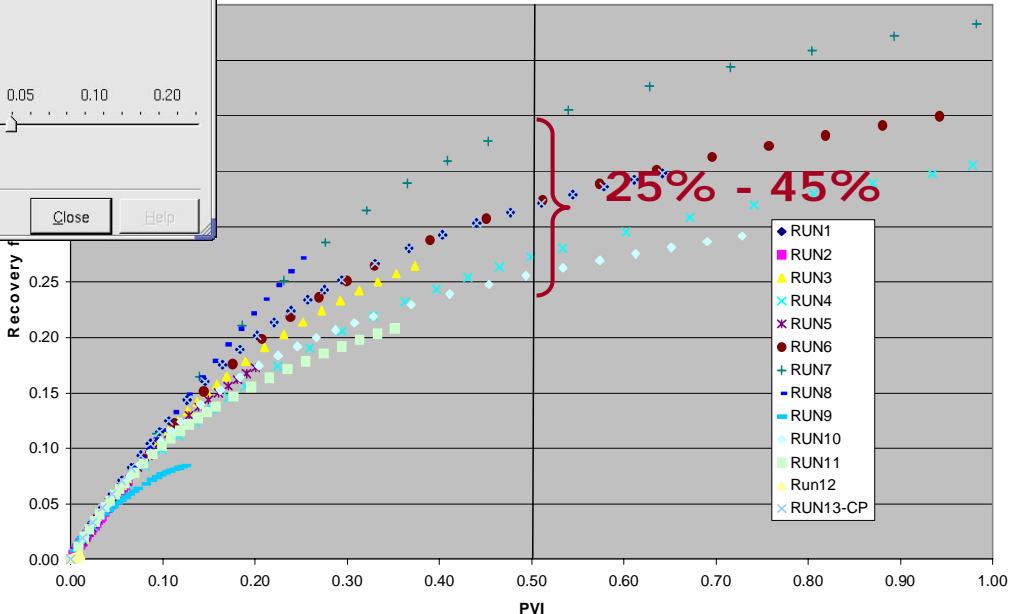


**Areal
Distribution
of facies**

**Permeability
Transform**

**Pareto Chart
of R_f @ 70yrs**

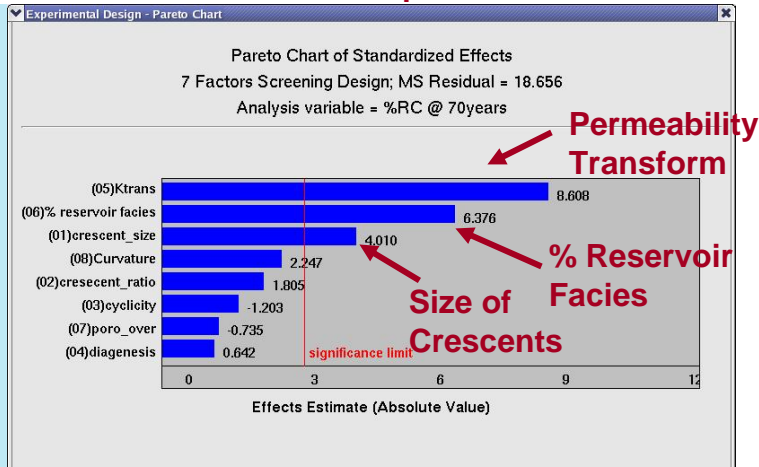
Sweep Efficiency at 0.5 PVI



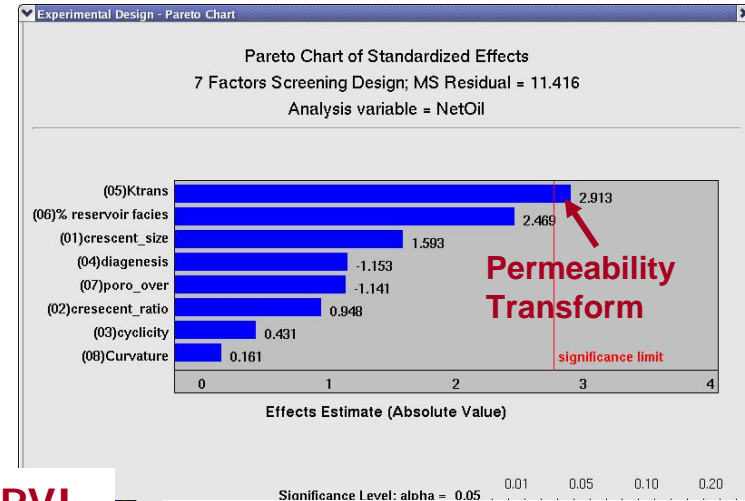
Flow Simulation Results: Rim Distribution



Pareto chart for R_f @ 70 years

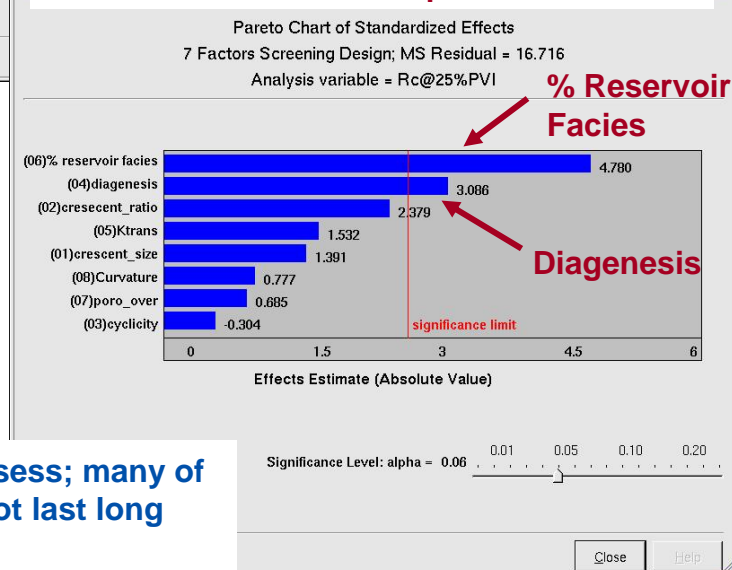


Pareto chart for Net Oil



Three clearly relevant parameters.

Pareto chart for R_f @ 25%PVI



NetOil shows all but one variable below the significance threshold.

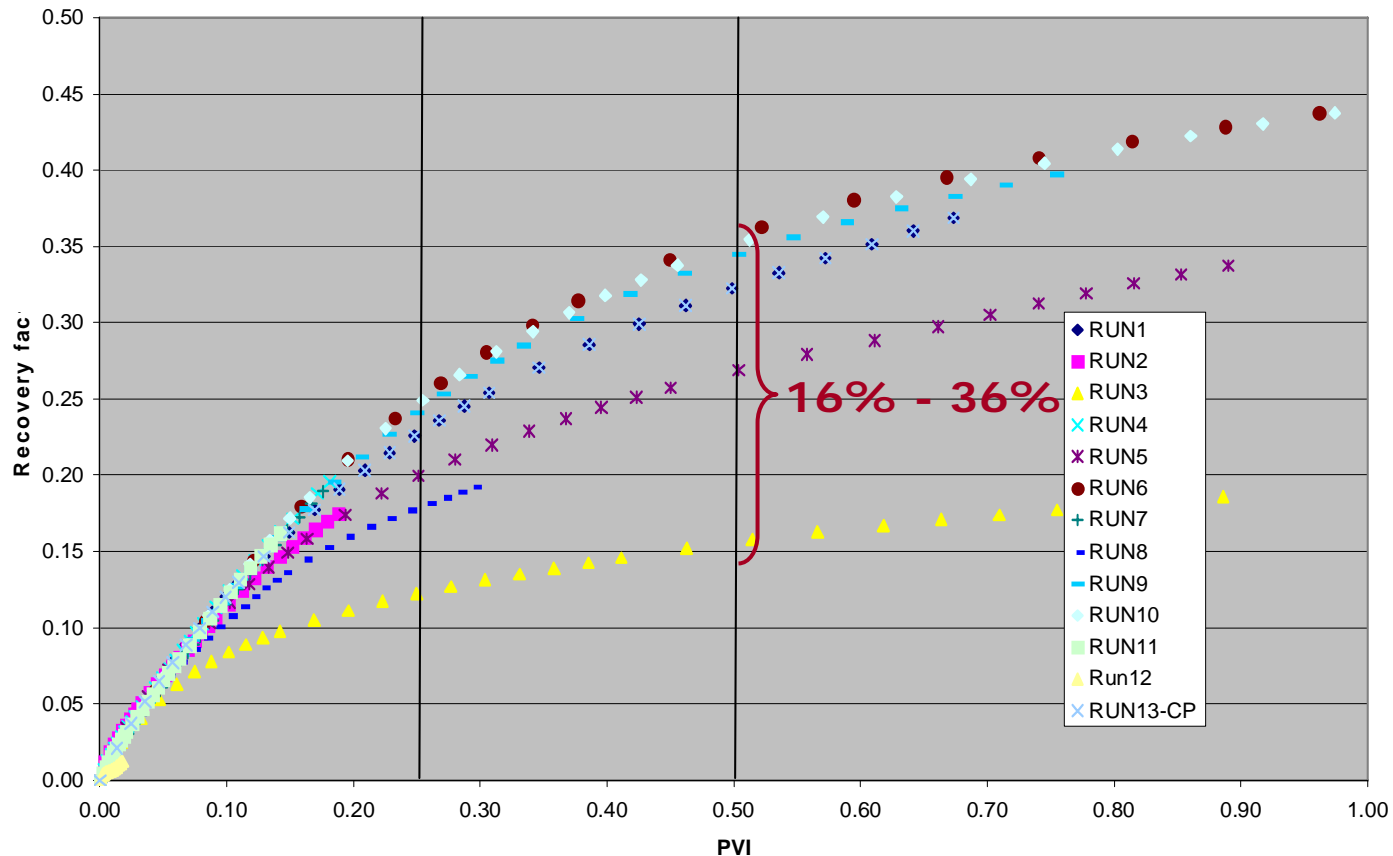
Difficult to assess; many of the runs do not last long enough

The permeability transform and the percent of reservoir facies consistently are the big hitters.

Flow Simulation Results: Rim Distribution



Sweep Efficiency at 0.5 PVI



■ Huge variation in the sweep efficiency curves and this is a conservative estimate of the variation. The performance of some models is so small that the curves could not be simulated to 0.5 PVI. The actual variation is over 30% in recovery.

Summary of Experimental Design Study

- Analyzed the effect of architectural and textural parameters on fluid flow in a synthetic grainstone-dominated carbonate platform
- Workflow used MPS/FDM to generate facies geobodies
- Areal distribution of reservoir facies shows a first-order impact on flow performance with respect to different measures of flow
- With areal distribution held constant, the most significant parameters were:
 - Absolute permeability values
 - Percent of reservoir facies
 - Size of reservoir facies geobodies
 - Ratio of barcrest to barflank facies