Outcrop to Subsurface Reservoir Characterization of the Lower Mesaverde Group, Red Wash Field, Uinta Basin and Douglas Creek Arch, Utah and Colorado*

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Search and Discovery Article #50995 (2014)**
Posted August 11, 2014

*Adapted from oral presentation at AAPG Annual Convention and Exhibition, Houston, Texas, April 6-9, 2014
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Abstract

The Mesaverde Group within the Uinta Basin produces oil and natural gas from unconventional fluvial sandstone reservoirs. This study addresses the stratigraphic architecture and connectivity of fluvial reservoirs through a combination of outcrop analysis and static and dynamic modeling of equivalent reservoirs. The Cretaceous Mesaverde Group in outcrop and at Red Wash field, Uinta Basin, Utah, serves as an excellent outcrop analog and consists of a succession of fluvial channel sandstones, crevasse splays, floodplain mudstones, and paludal coals that were deposited by meandering- and braided-river systems within coastal- and alluvial-plain settings. Fluvial reservoir bodies are inherently heterogeneous at a range of scales. To analyze the range of spatial variability and to aid in constraining subsurface reservoir models, field descriptions including hand-held spectral-gamma-ray measurements were acquired for four stratigraphic sections (total footage= 650 ft; 198 m) from lower Mesaverde outcrops (near Dinosaur, Colorado). Detailed core descriptions yield facies, facies associations, and architectural elements present within the subsurface at Red Wash Field for comparison to outcrop. The outcrop/core observations and statistics, combined with fluvial sandstone-body statistics from three additional localities (Douglas Creek Arch), and subsurface well data are used to reconstruct local depositional styles, to aid in subsurface correlation, and to condition multiple-point geostatistical models (i.e., multipoint statistics – MPS) of fluvial reservoirs at Red Wash Field. Geologically constrained, well-log-based electrofacies are estimated in non-cored wells using a k-nearest neighbor approach combined with outcrop-based thickness criteria. Three-dimensional models of architectural elements, porosity, and permeability show the spatial variability of reservoir properties and are used to evaluate static and dynamic connectivity across the field and stratigrapically. Static modeling and dynamic-simulation results explore the significance of crevasse splays and channel-sandstone bodies (fluvial bars) on reservoir connectivity and effective well spacing.

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AAPG ACE 2014 – Houston, Texas, April 8th, 2014

Reservoir Characterization
and Modeling Laboratory

RCML

Acknowledgements

Mark Longman
Russ Griffin
John Still
Greg Gromadzki

Rex Cole
Chris Beliveau
Dan King
Kevin Toeneboehn

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Williams Fork Consortium Sponsors

Outline

- **Introduction**
  - **Research focus, study area, geologic history**
- **Outcrop Analysis**
  - **Facies associations and paleocurrent data**
- **3-D Reservoir Modeling**
  - **Modeling techniques and workflow**
- **Fluvial Reservoir Connectivity**
  - **Analysis and results – well-based connectivity**

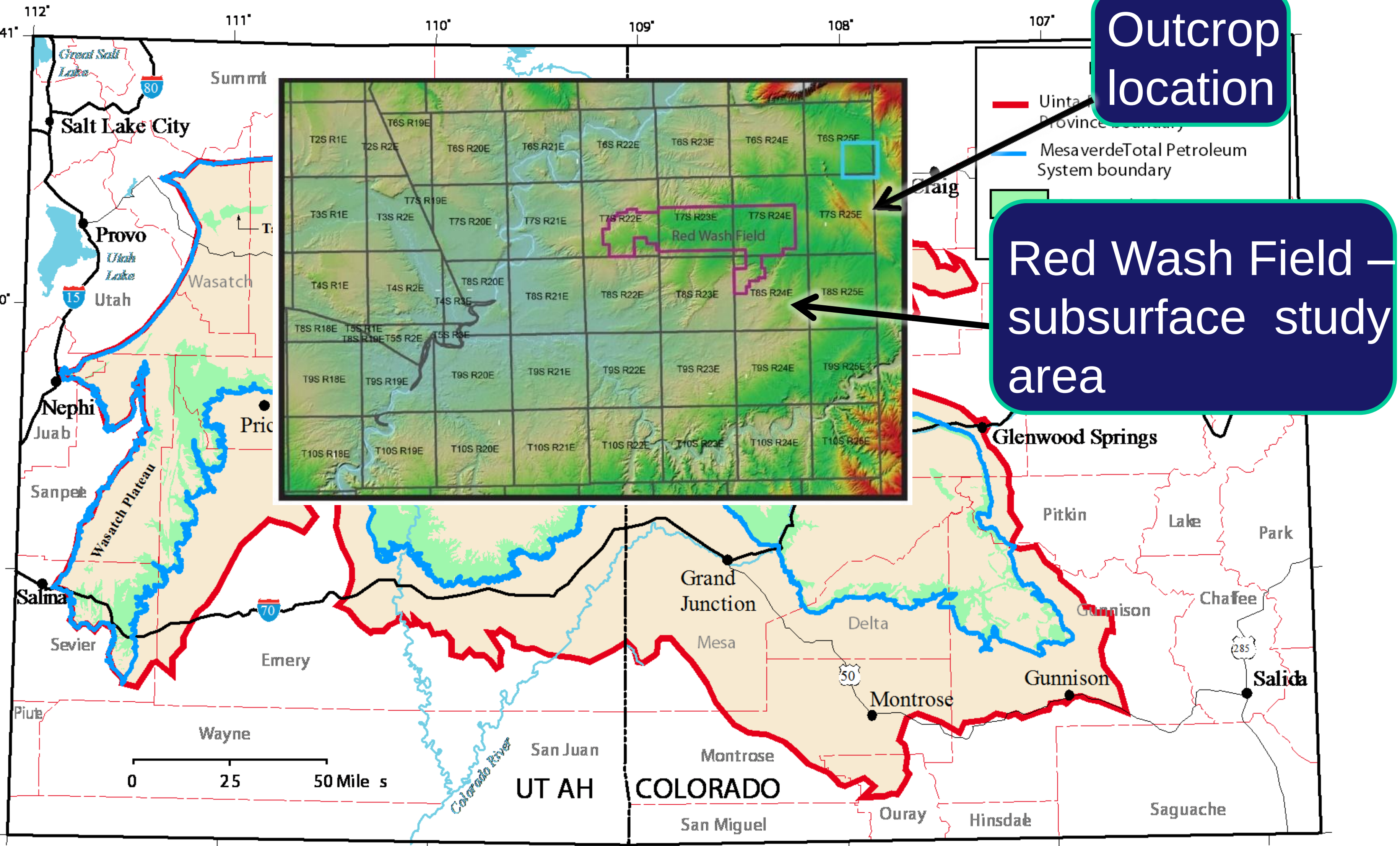
Research Focus

For the lower Mesaverde Group:

- What is the stratigraphic variability of sedimentary and reservoir properties (lithology, architectural elements, porosity, permeability)?

- How does static reservoir connectivity vary with well spacing, net-to-gross ratio, and sandstone-body type?

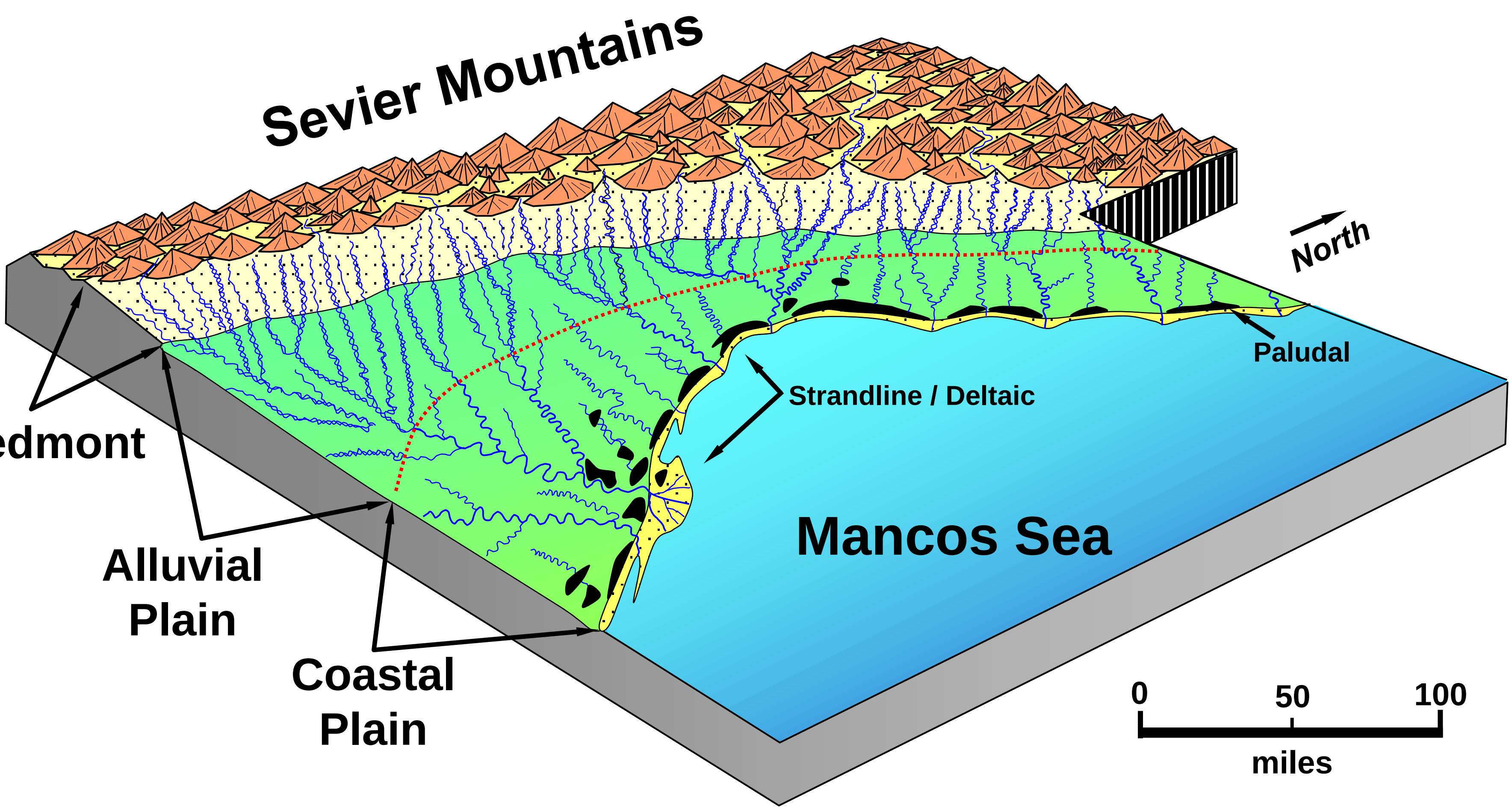
Study Area



Modified from Johnson and Roberts (2003)

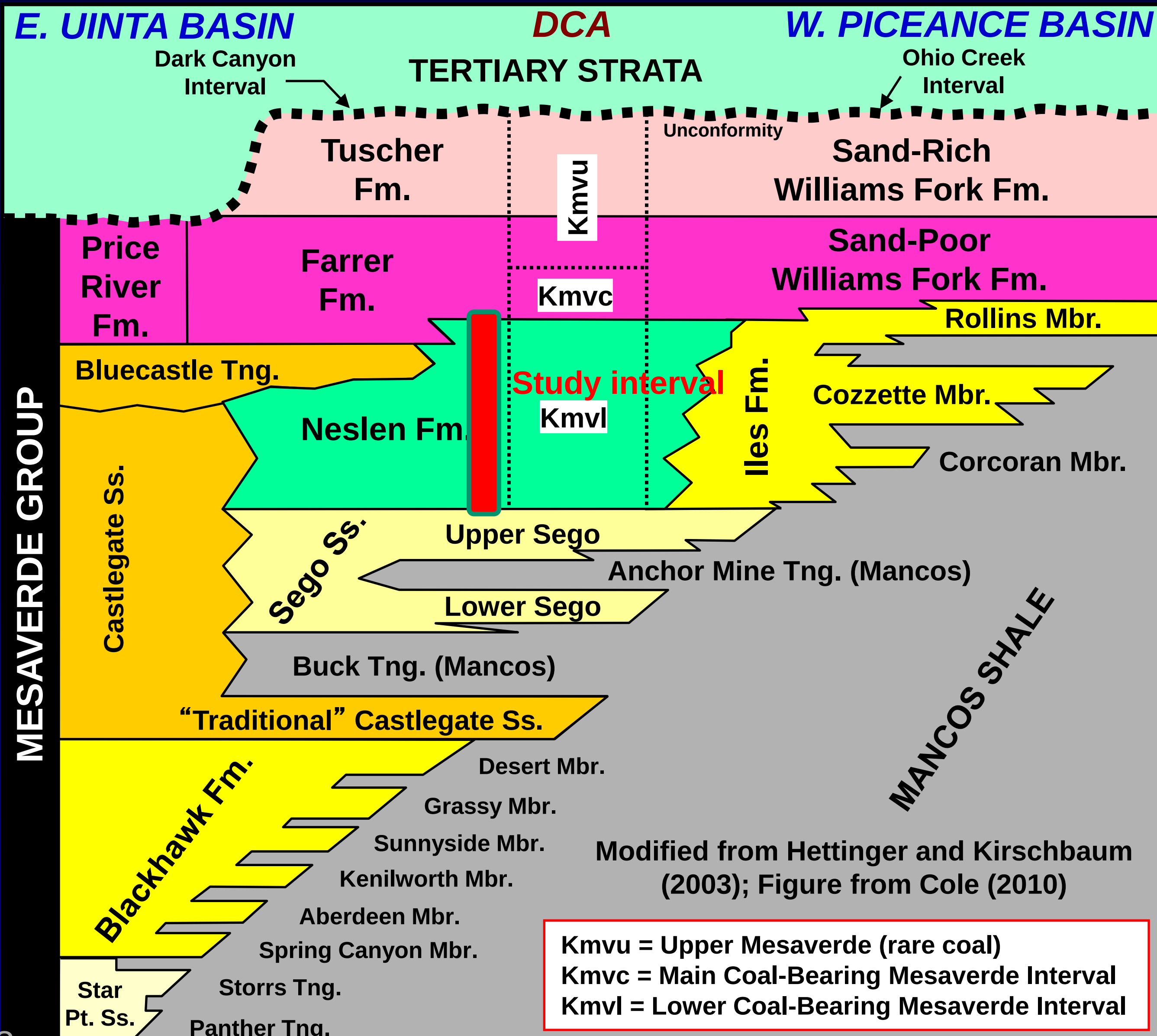
Geologic History

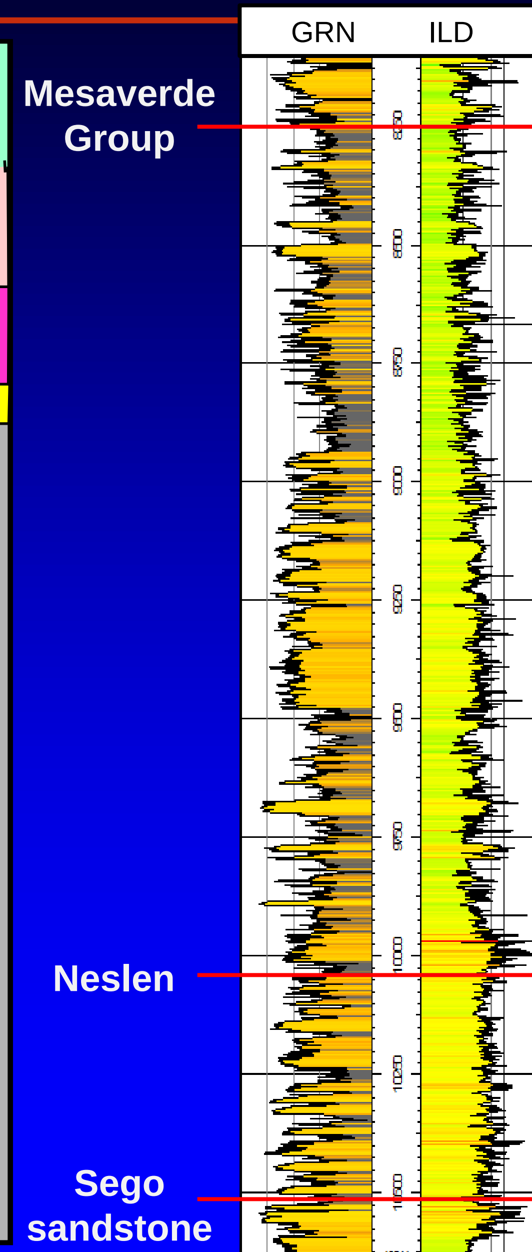
Depositional Setting



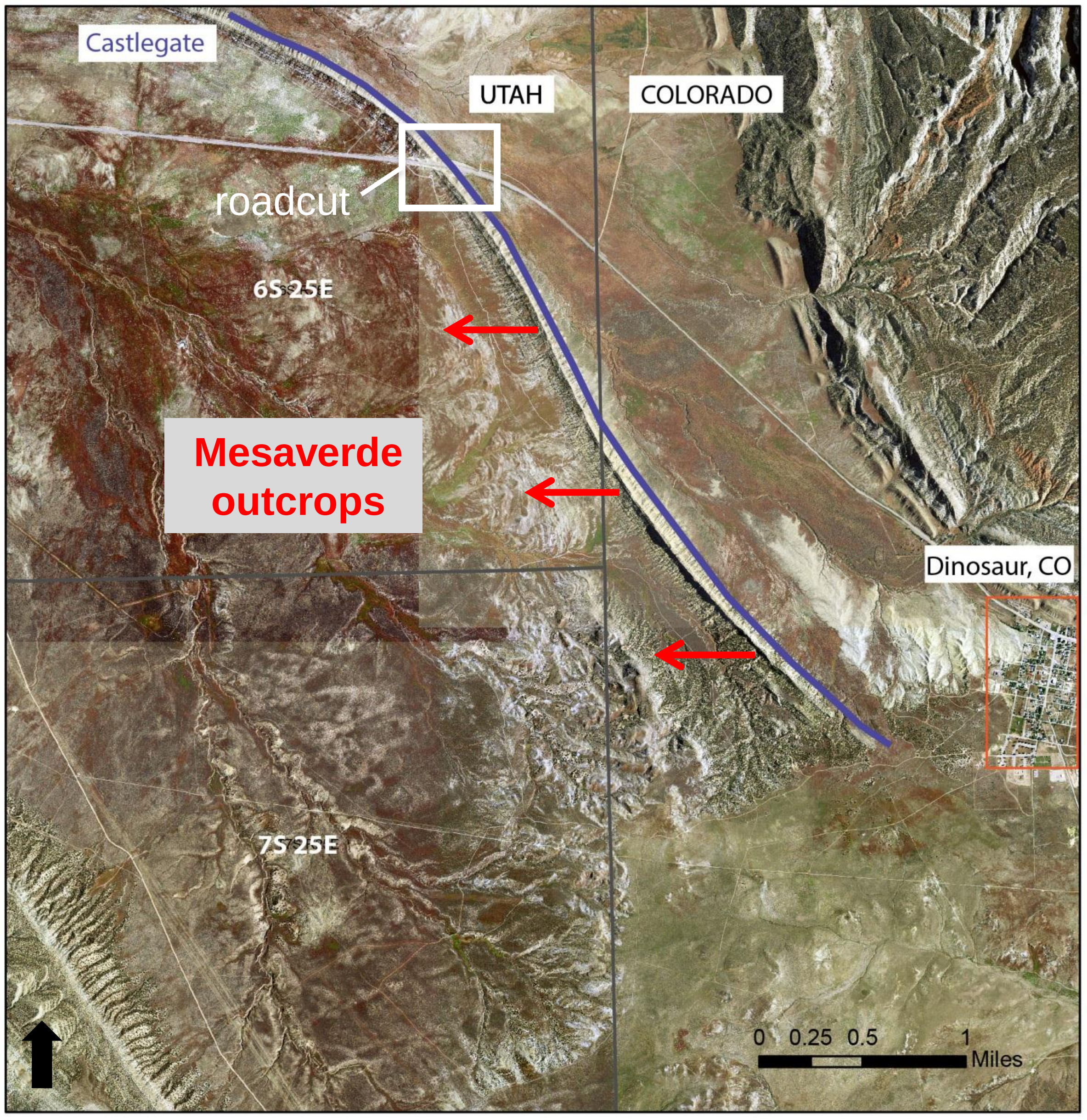
Modified from Ryer and McPhillips (1983); Provided by Rex Cole

Mesaverde Group: Stratigraphy

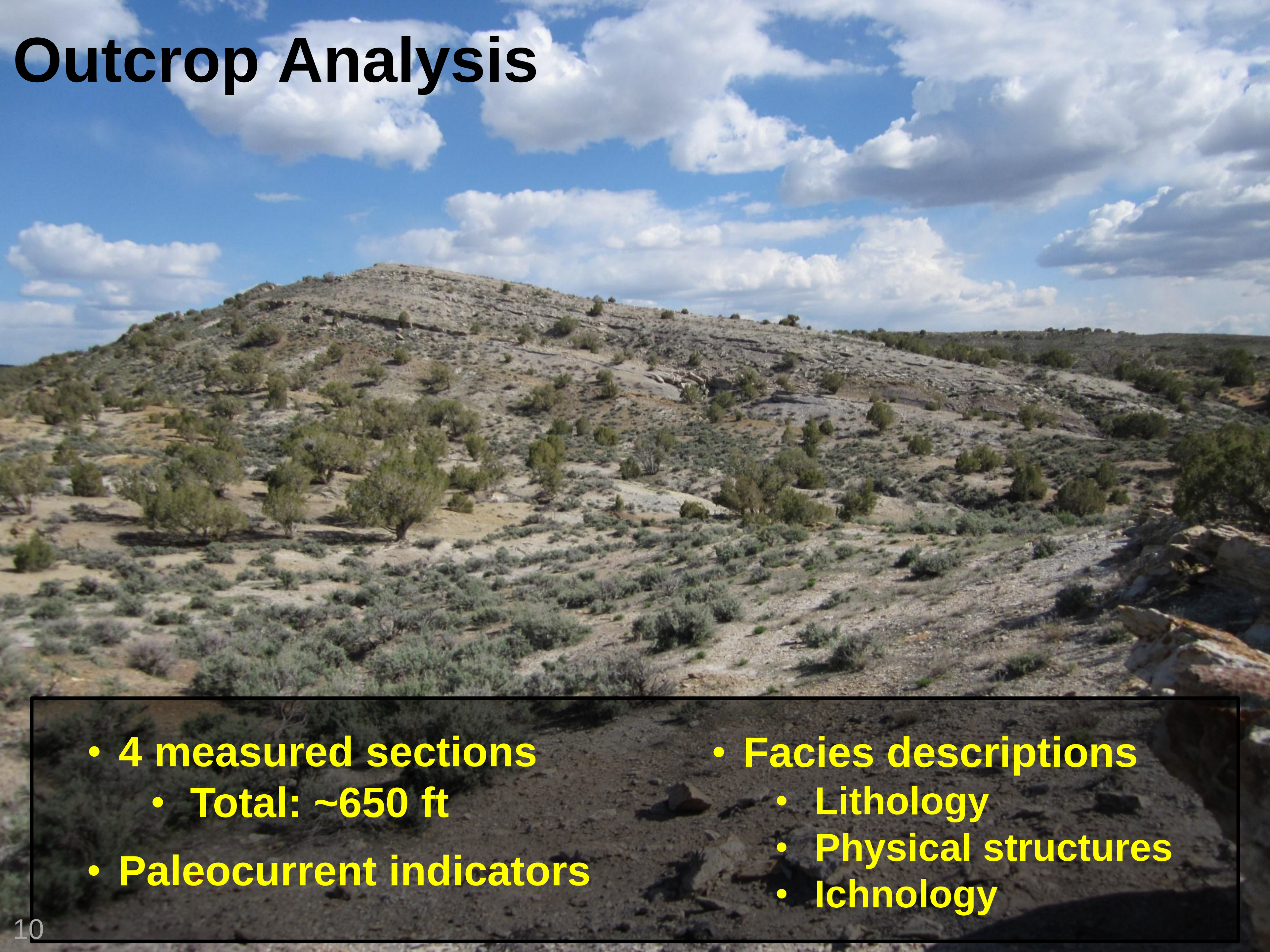




Field Area


Castlegate
UTAH
COLORADO
roadcut
6S 25E
Mesaverde outcrops
Dinosaur, CO
7S 25E
0 0.25 0.5 1
Miles

Outcrop Analysis



- 4 measured sections
  - Total: ~650 ft
- Paleocurrent indicators

- Facies descriptions
  - Lithology
  - Physical structures
  - Ichnology

Facies Associations

Unit 2, MS-03

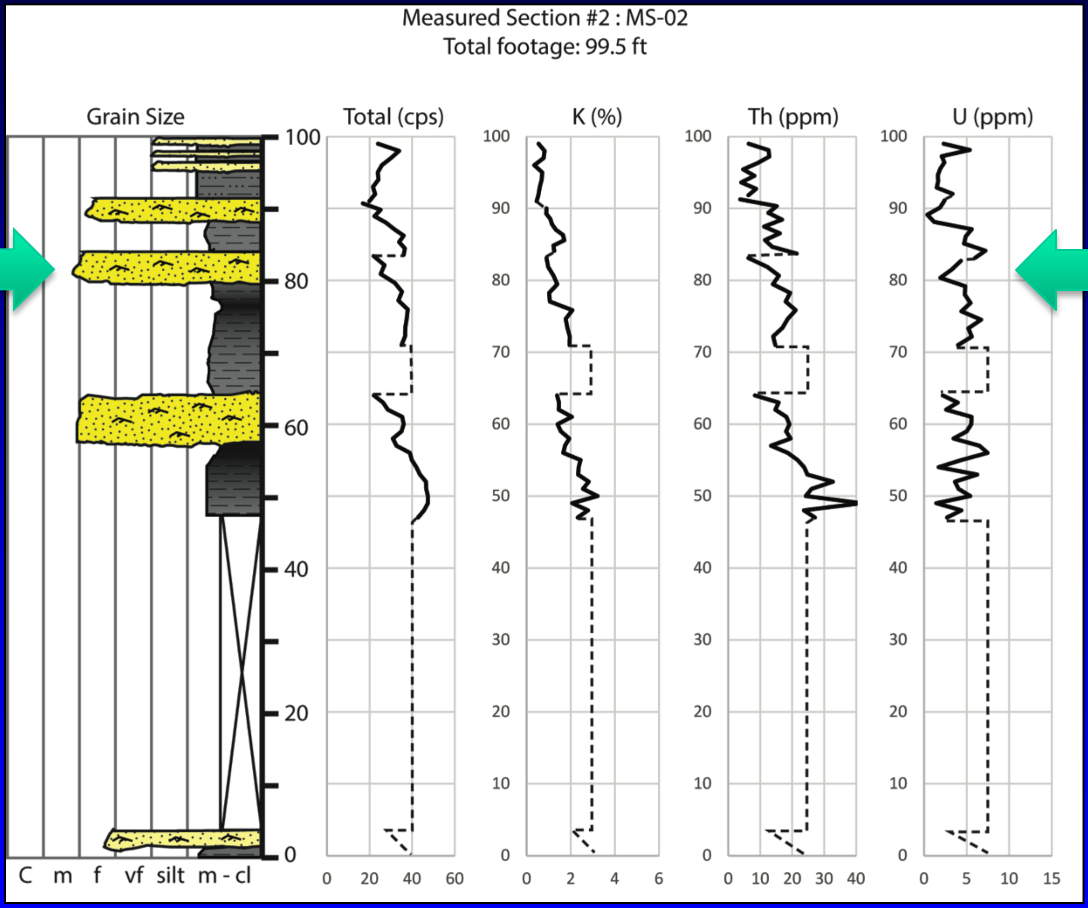
Level of marine influence low

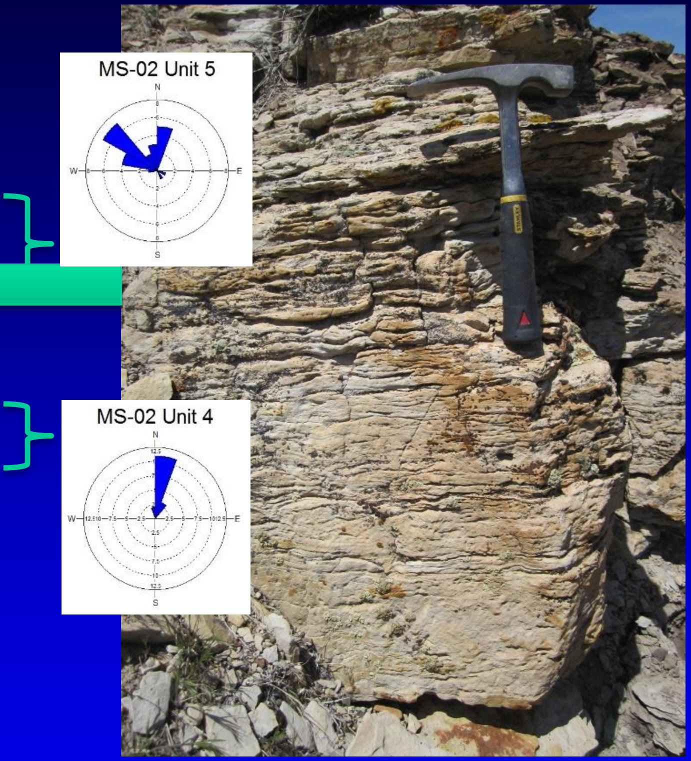
Ripple cross-laminated sandstone

Coal w/ abundant plant fragments

Fissile, organic-rich mudstone

Outcrop Analysis

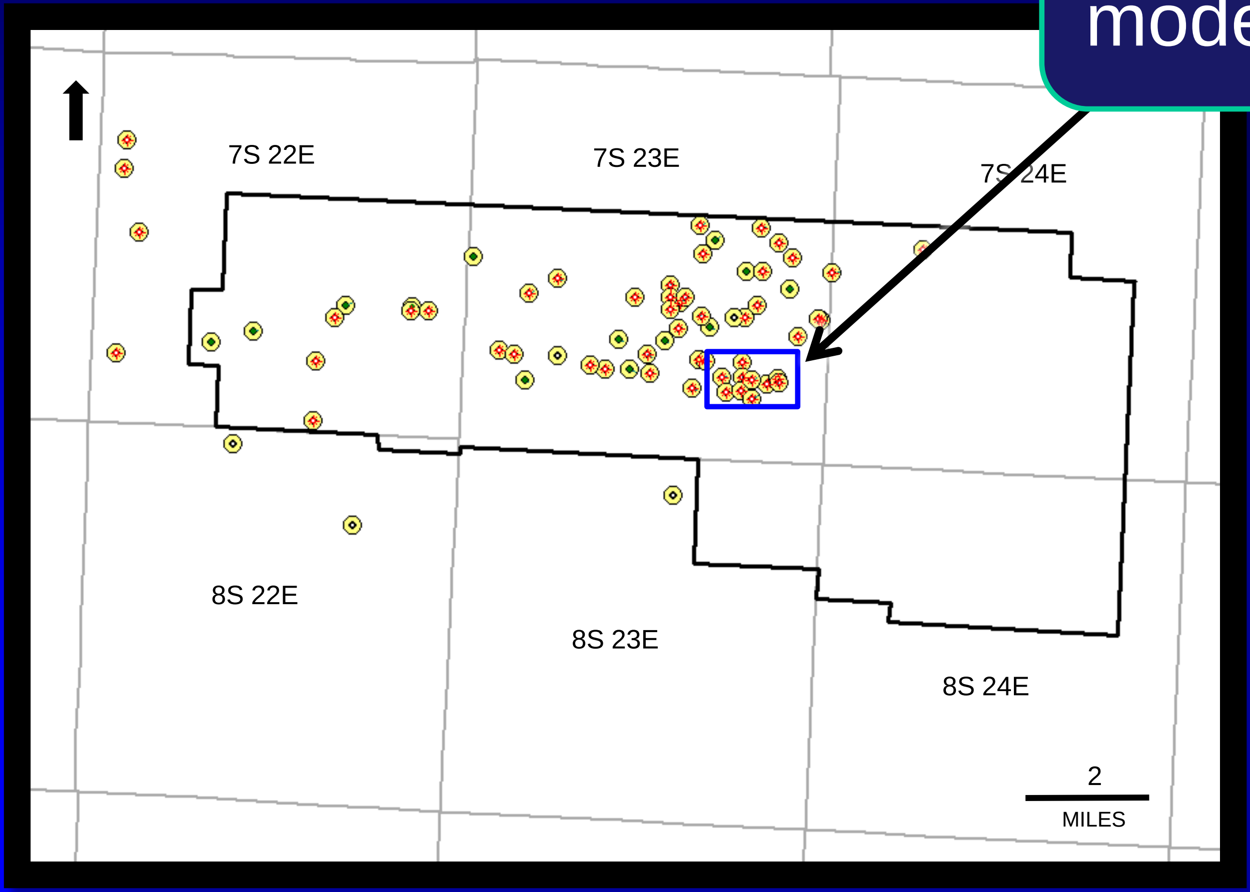




Sand-body thickness, facies associations, and paleocurrent data → 3D fluvial reservoir modeling

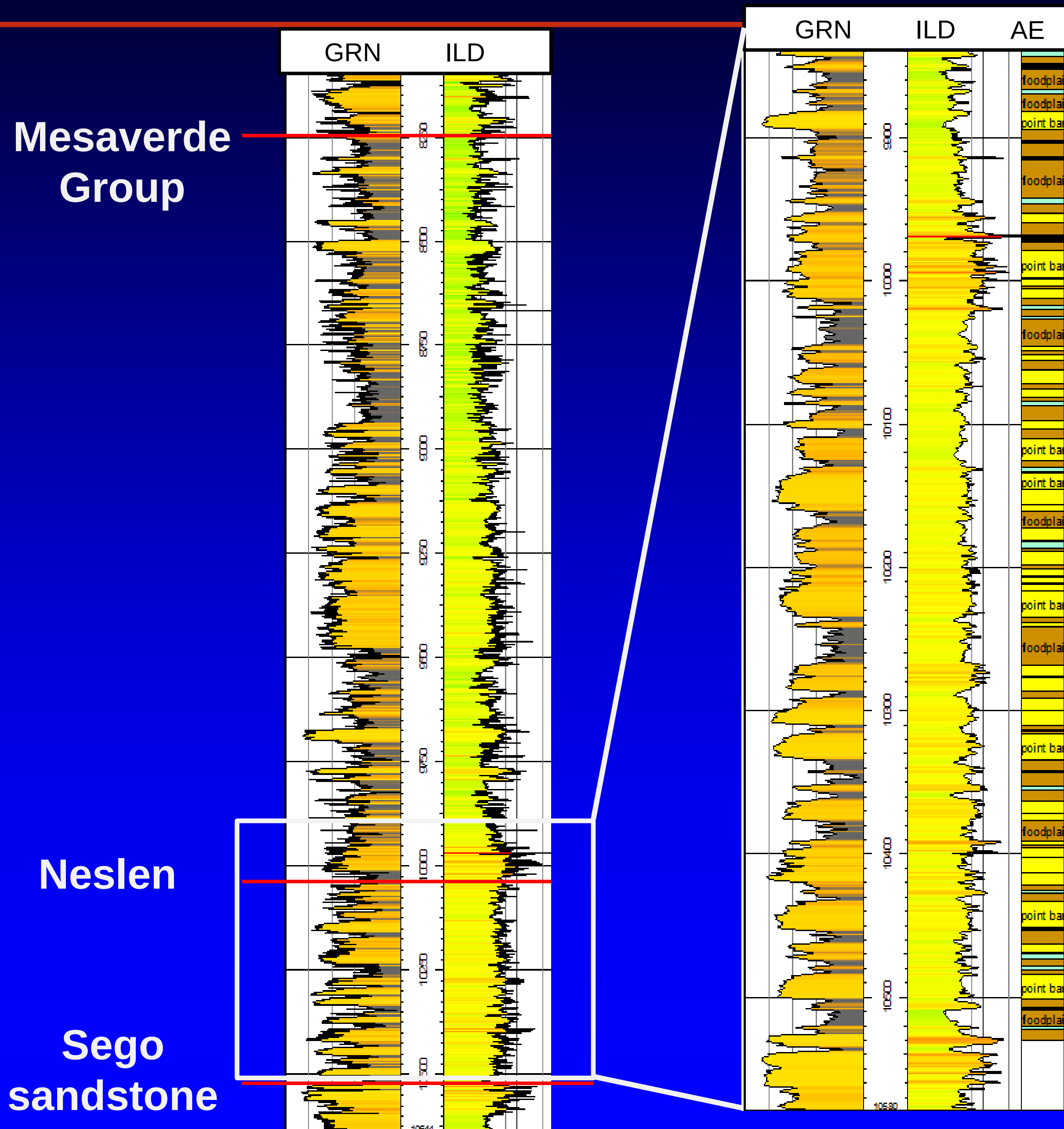
Subsurface Data

Red Wash Field



3D reservoir model area

Architectural-Element Logs



Channel/Fluvial bar criteria

- < 96 API GRN cut-off
- < 0.25 DPHI signature
- Fining-upward log signature
- Sharp base

Crevasse Splay criteria

- < 96 API GRN cut-off
- Coarsening-upward log signature

Floodplain criteria

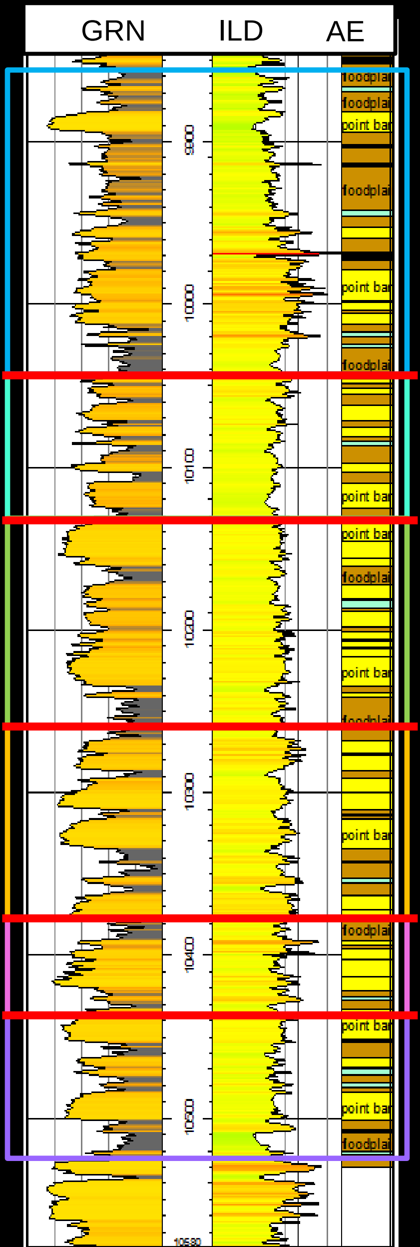
- >96 API GRN cut-off

Coal criteria

- < 96 API GRN cut-off
- > 0.25 DPHI signature

Stratigraphic Framework

RCML



Zone 1

Zone 2

Zone 3

Zone 4

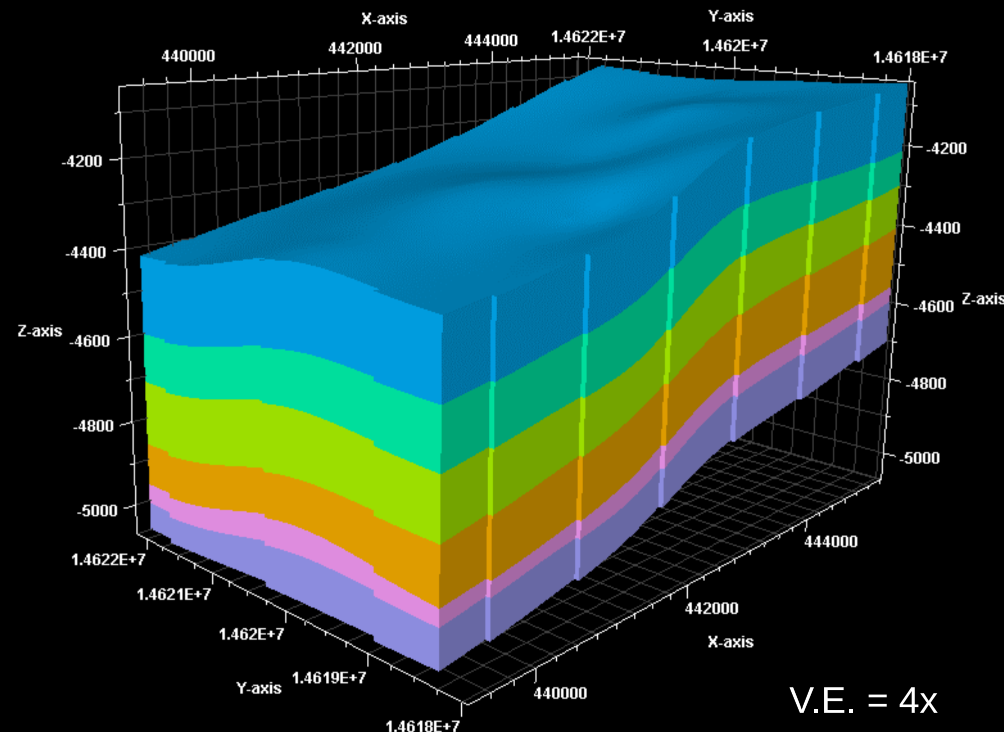
Zone 5

Zone 6

Cell size: 50 x 50 ft X 1.5 ft

Model area: 6260 x 4210 ft

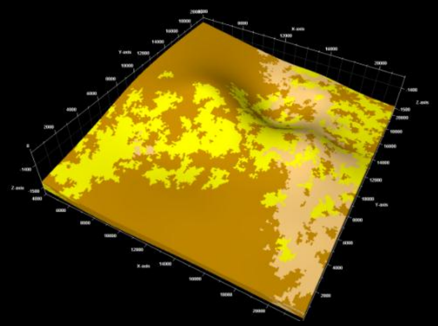
Model thickness: ~500-600 ft



V.E. = 4x

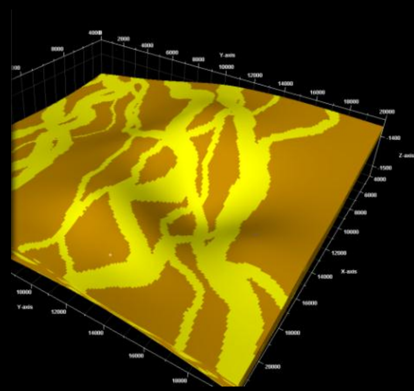
Modeling Techniques

Sequential-Indicator Simulation (SIS)



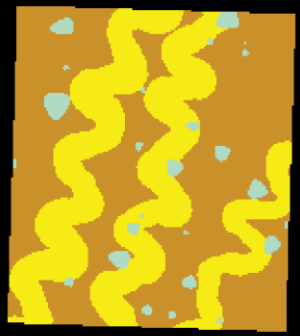
- **Sequential Indicator Simulation** (SIS - cell-based)
  - Assign geologic/petrophysical properties cell-by-cell
  - Variogram based - geologic shapes are difficult to model

Object-Based Modeling (OBM)



- **Object-based (Boolean)**
  - Defined facies objects to populate the model
  - Size, geometry, and orientation of distinct geologic bodies (i.e., from outcrop)

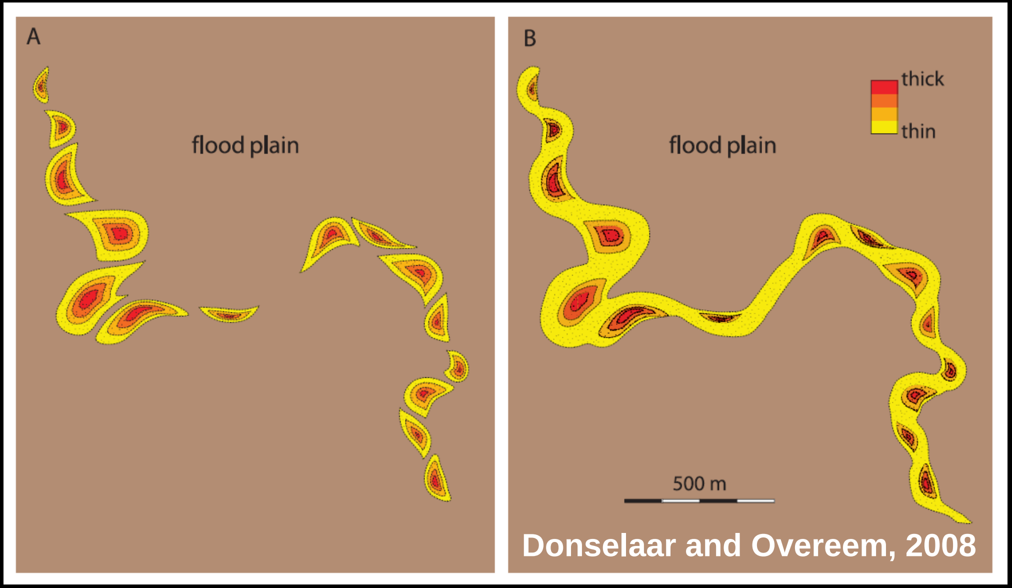
Multi-point Statistical Simulation (MPS)



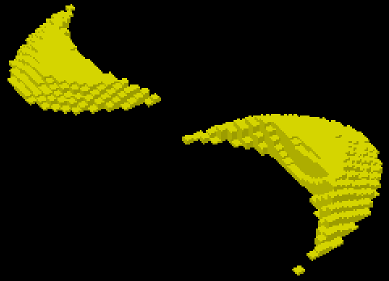
- **Multi-point Statistics (image-based)**
  - Training image → replaces the variogram
  - Model spatial geologic relationships and concepts

Modeling Architectural Elements

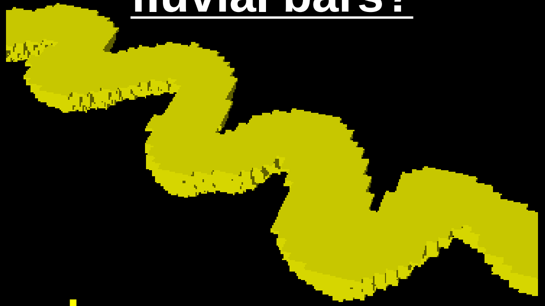
What are the preserved geometries of the deposits?



Crescent-shaped fluvial bars?



Sinuous channel sandstones / fluvial bars?



Probably none of the above…

Integrated Modeling Approach

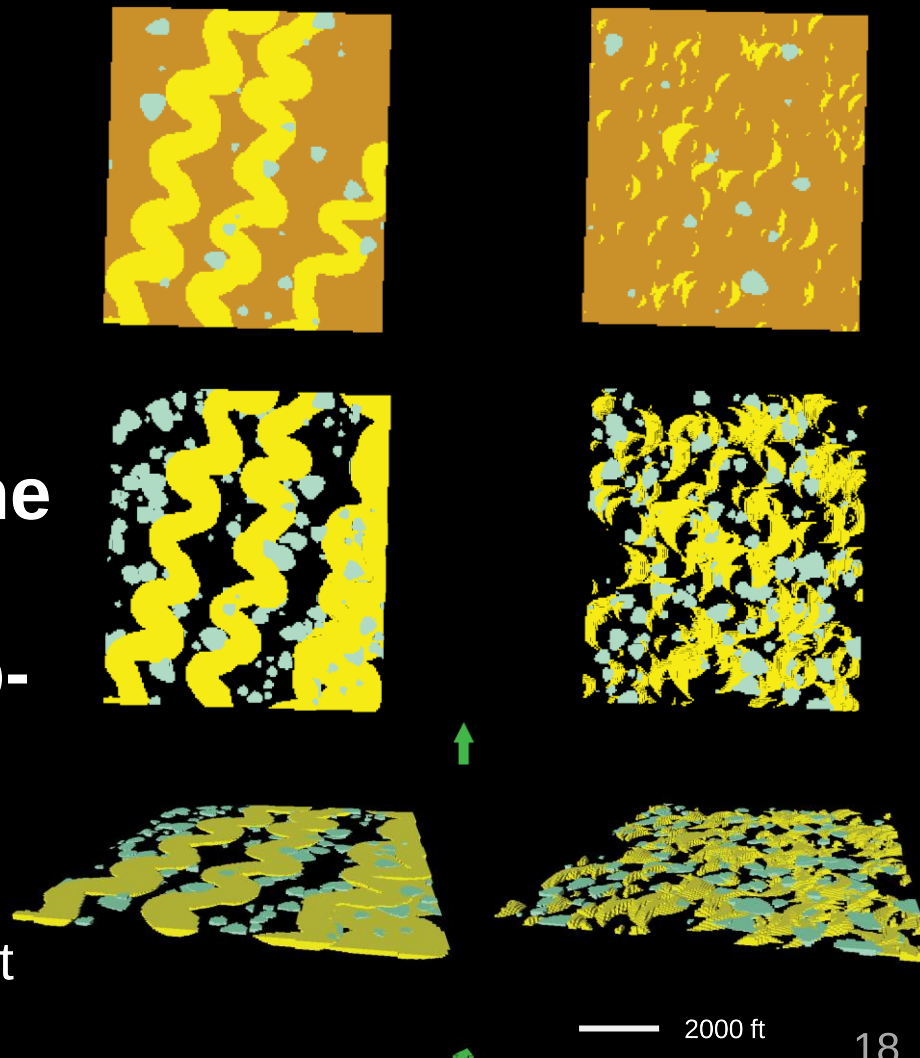
RCML

Multiple-point geostatistics (MPS)

Training images →

- **object-based modeling of two scenarios**
  - **Generated for each zone**
  - **Constrained to outcrop-based statistics**

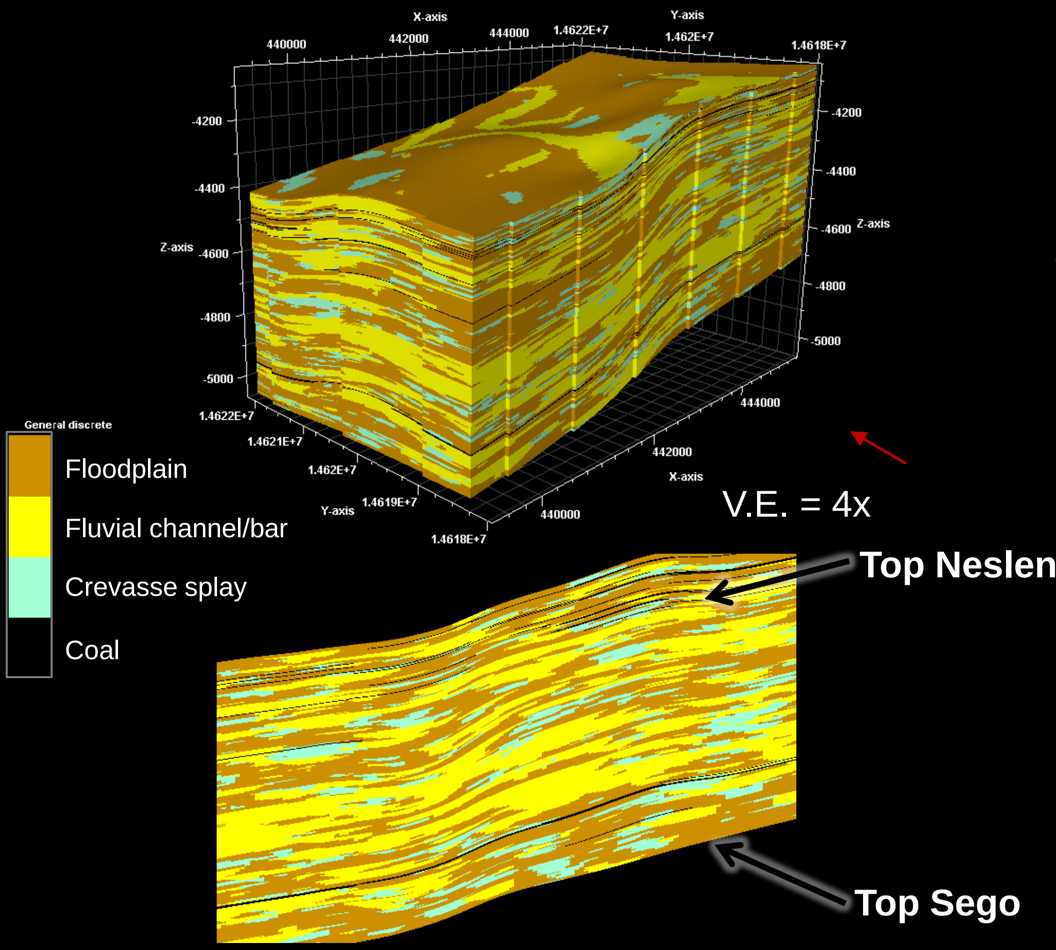
Sinuous channels / fluvial bars | Crescent-shaped fluvial bars



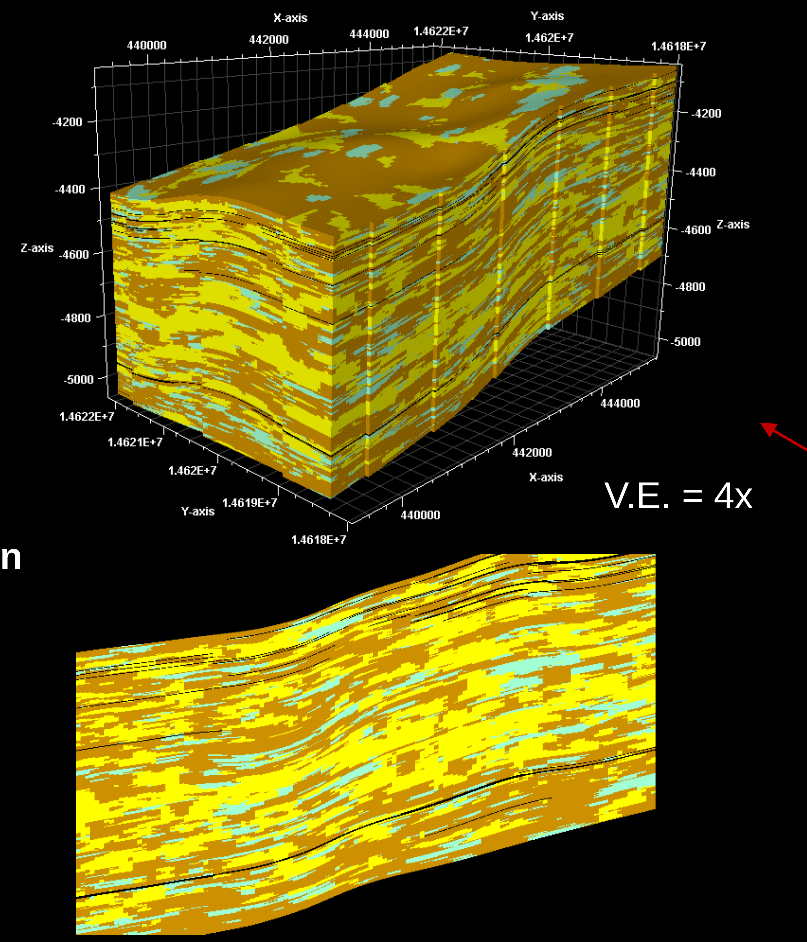
- Training image size: 7810 x 8820 x 30 ft
- Cell size: 50 x 50 x 1 ft

MPS-Based Fluvial Reservoir Models

Sinuous channels / fluvial bars

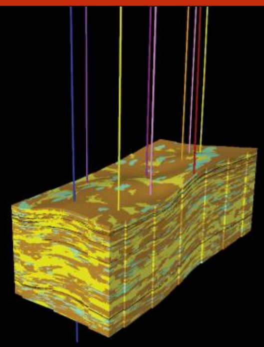


Crescent-shaped fluvial bars



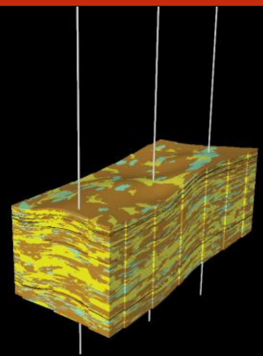
W ——— E W ——— E

Static Connectivity



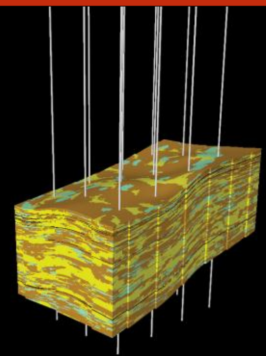
Current

10 wells
(approx. 40-ac)



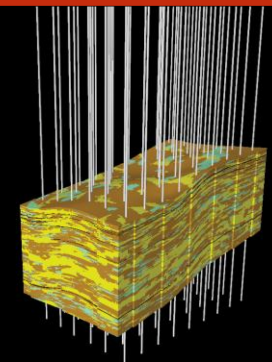
160-ac

3 wells
(2640 ft apart)



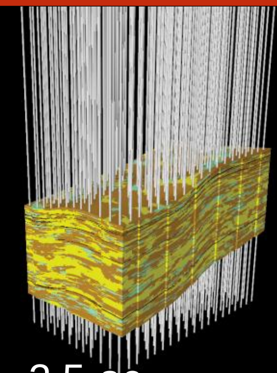
40-ac

12 wells
(1320 ft apart)



10-ac

54 wells
(660 ft apart)

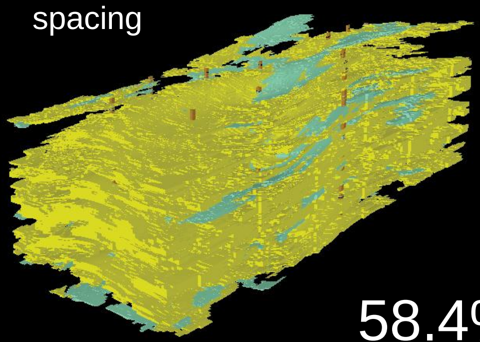


2.5-ac

228 wells
(330 ft apart)

$$\text{Static connectivity} = \frac{\text{Connected Sandstone Volume}}{\text{Total Sandstone Volume}}$$

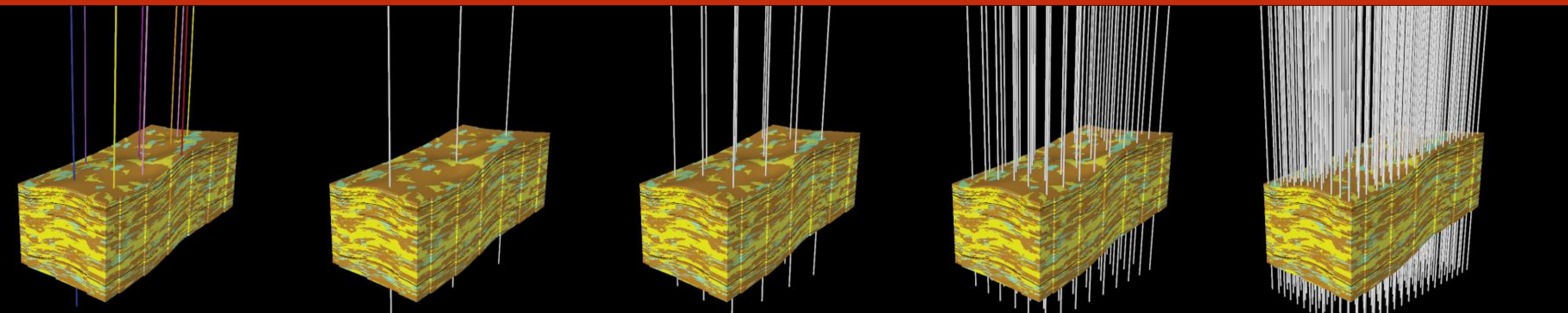
Example: 40-ac spacing



58.4%
4.9%/well

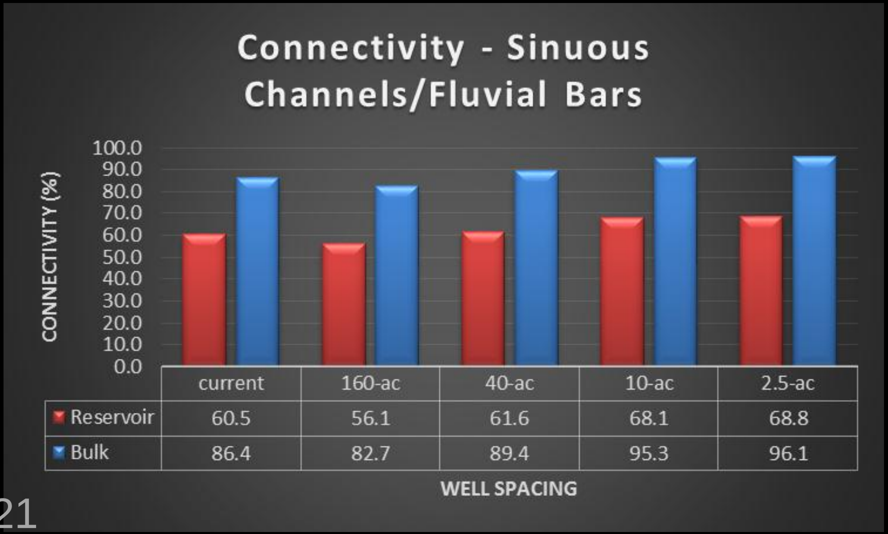
Static Connectivity

RCML

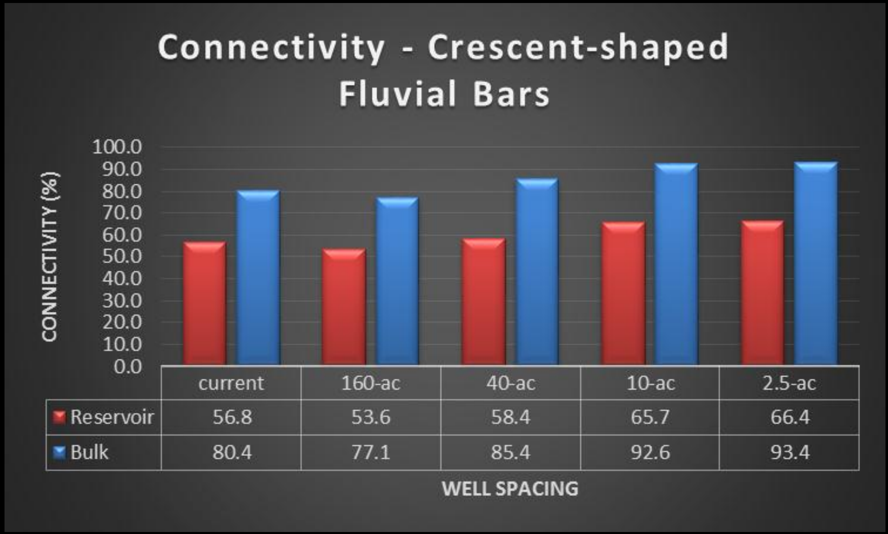


Current	160-ac	40-ac	10-ac	2.5-ac
10 wells (approx. 40-ac)	3 wells (2640 ft apart)	12 wells (1320 ft apart)	54 wells (660 ft apart)	228 wells (330 ft apart)

Sandstone connectivity & "Reservoir-quality" sandstone connectivity (6%-15% porosity)



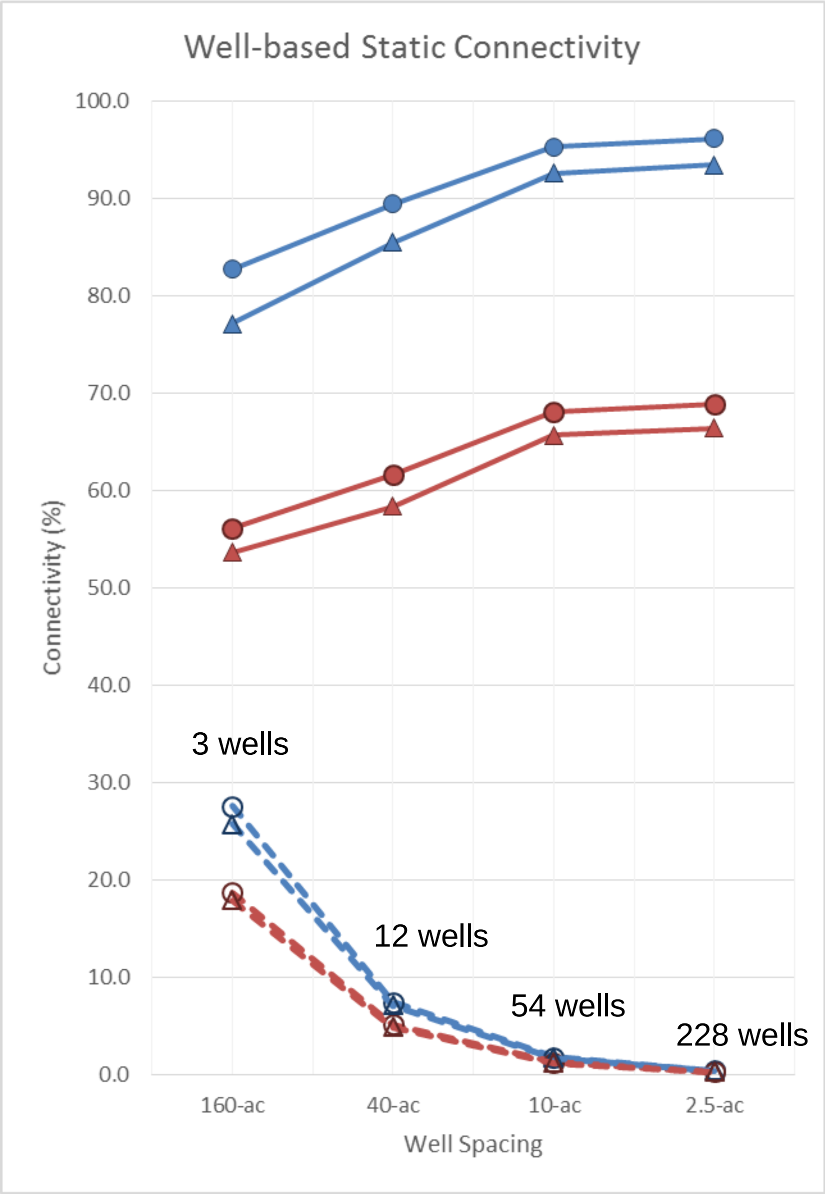
	current	160-ac	40-ac	10-ac	2.5-ac
Reservoir	60.5	56.1	61.6	68.1	68.8
Bulk	86.4	82.7	89.4	95.3	96.1



	current	160-ac	40-ac	10-ac	2.5-ac
Reservoir	56.8	53.6	58.4	65.7	66.4
Bulk	80.4	77.1	85.4	92.6	93.4

Static Connectivity

○ Sinuous Channels
△ Crescent Fluvial Bars
■ All Sandstone
■ "Reservoir" Sandstone
——— Total Connectivity
- - - - - Connectivity per well

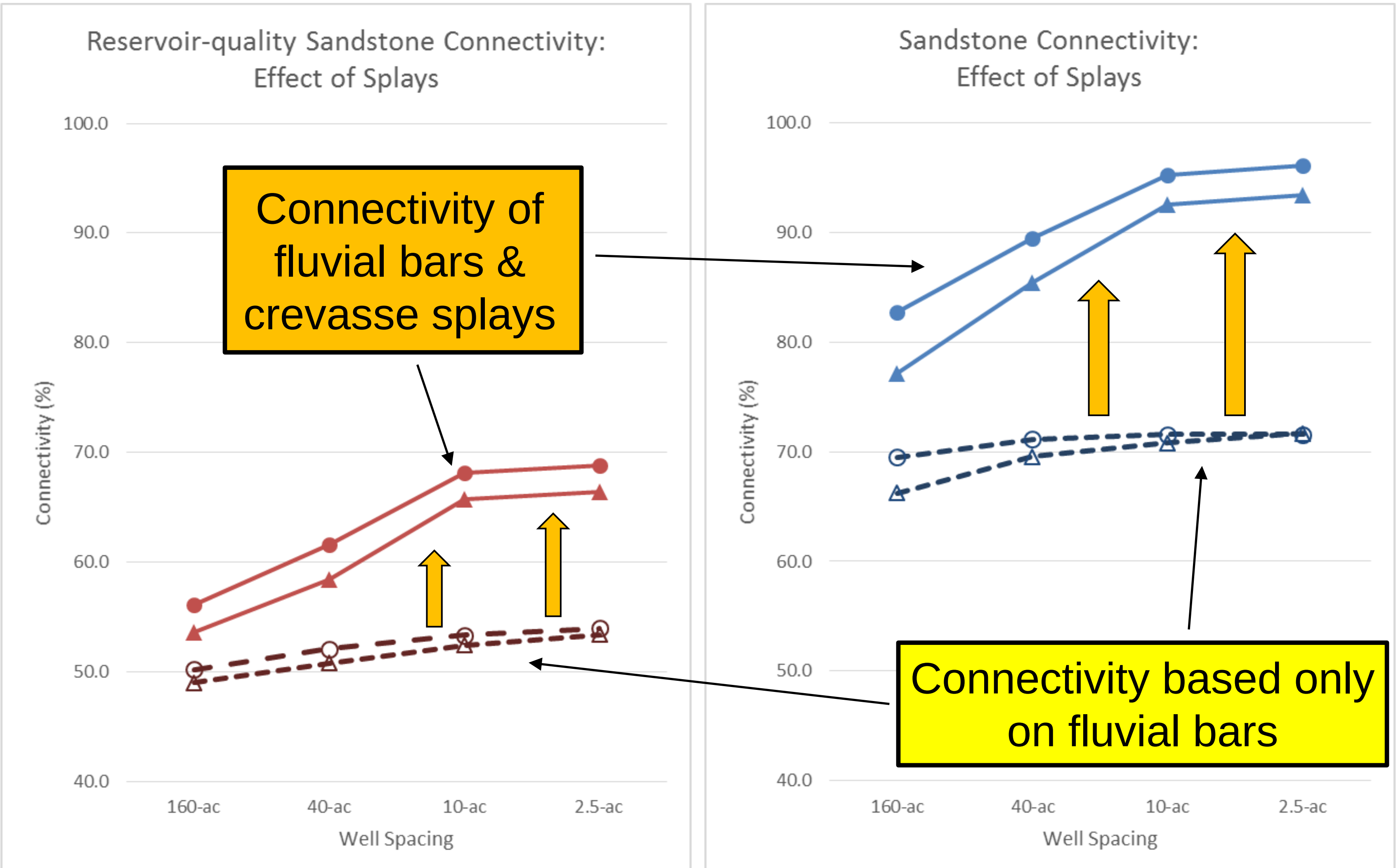


Total connectivity

Connectivity per well

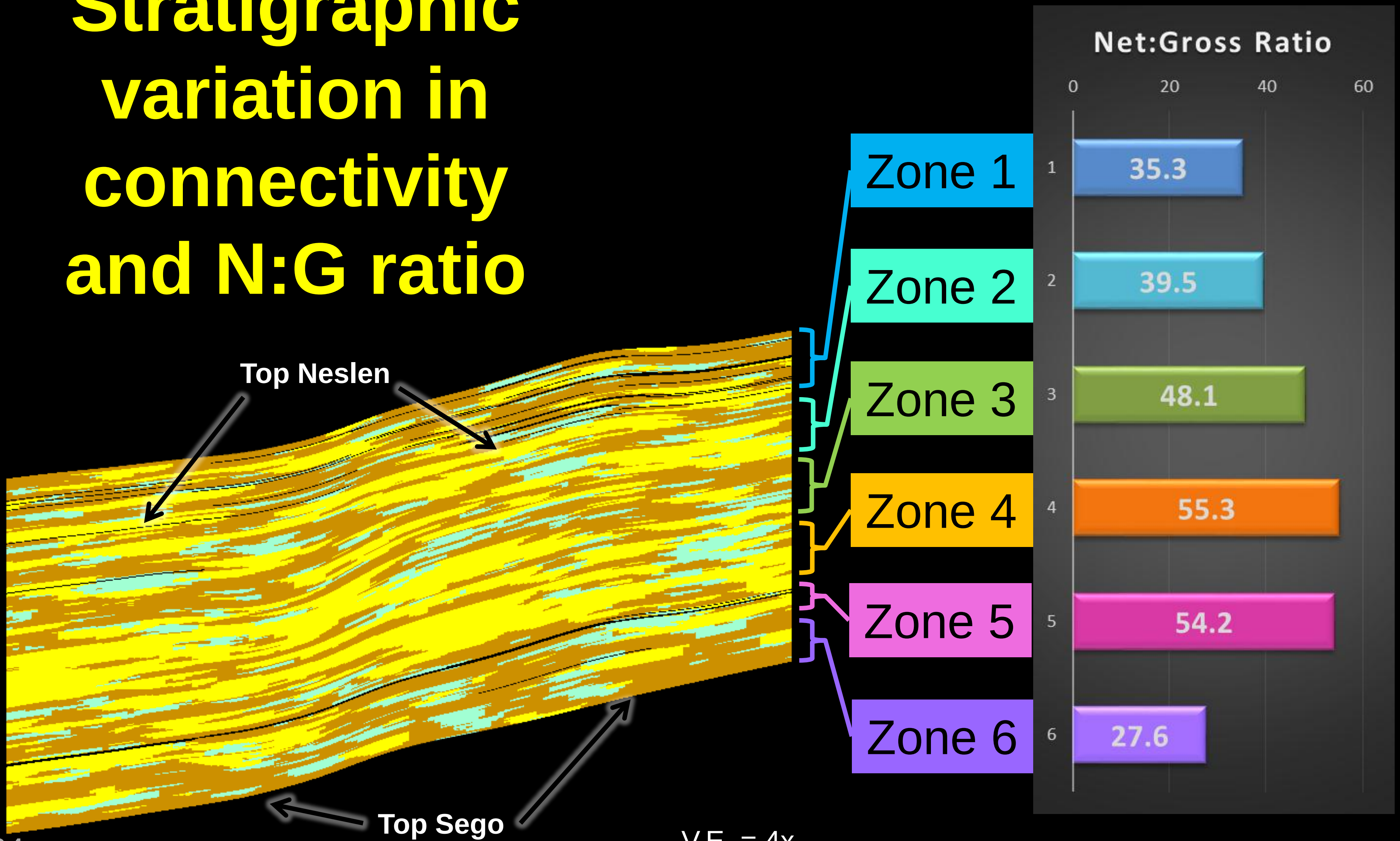
Impact of Crevasse Splays

Static reservoir sandstone connectivity impacted by the presence of crevasse splays



Static Connectivity by Zone

Stratigraphic variation in connectivity and N:G ratio



Static Connectivity by Zone

Zone 1

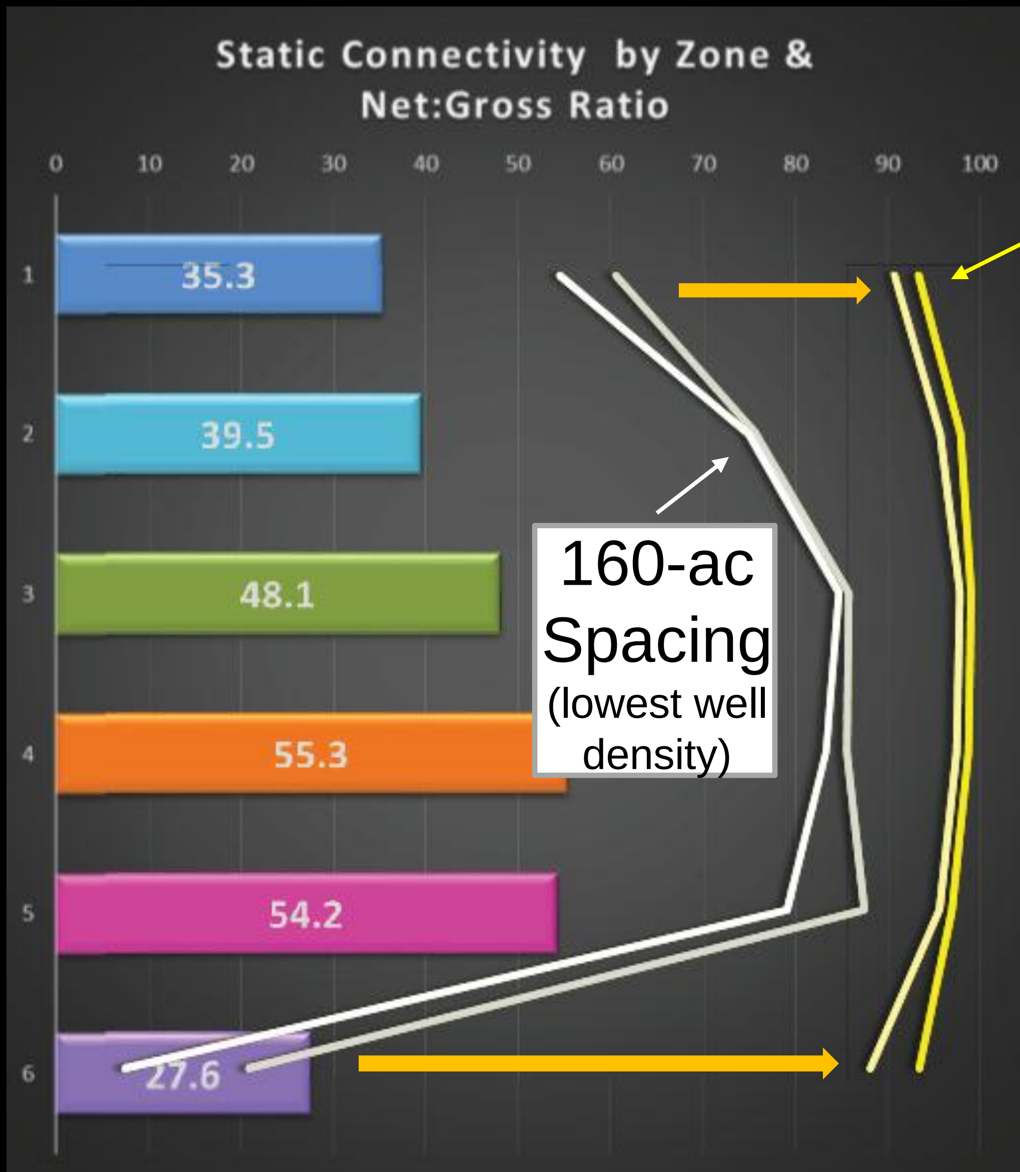
Zone 2

Zone 3

Zone 4

Zone 5

Zone 6



2.5-ac Spacing (highest well density)

High well density → little variation in connectivity

Low well density → variable connectivity based on N:G ratio

Conclusions

RCML

For the lower Mesaverde Group:

- Consists of continental fluvial deposits, where the occurrence of fluvial bars and N:G increases up section
- No significant difference in static connectivity between the two MPS modeling scenarios (average 6% difference)
- Static connectivity varies stratigraphically with well density and N:G ratio, which also varies as a function of stratigraphy
- Crevasse splays enhance static connectivity at all well spacings; therefore, understanding their reservoir quality and spatial distribution is important

Presenter's notes: Outcrop dimensions are consistent with other studies conducted along the DCA. Uncertainty regarding the preserved geometry of fluvial deposits was addressed using two MPS modeling scenarios: sinuous channel fill/bars & crescent-shaped channel bars. Static connectivity of fluvial sandstones increases with higher well density, but decreases on a per-well basis. High well density (2.5-ac) produces little variation in static connectivity regardless of N:G ratio. Low well density (160-ac) produces variable static connectivity as N:G ratio varies stratigraphically.

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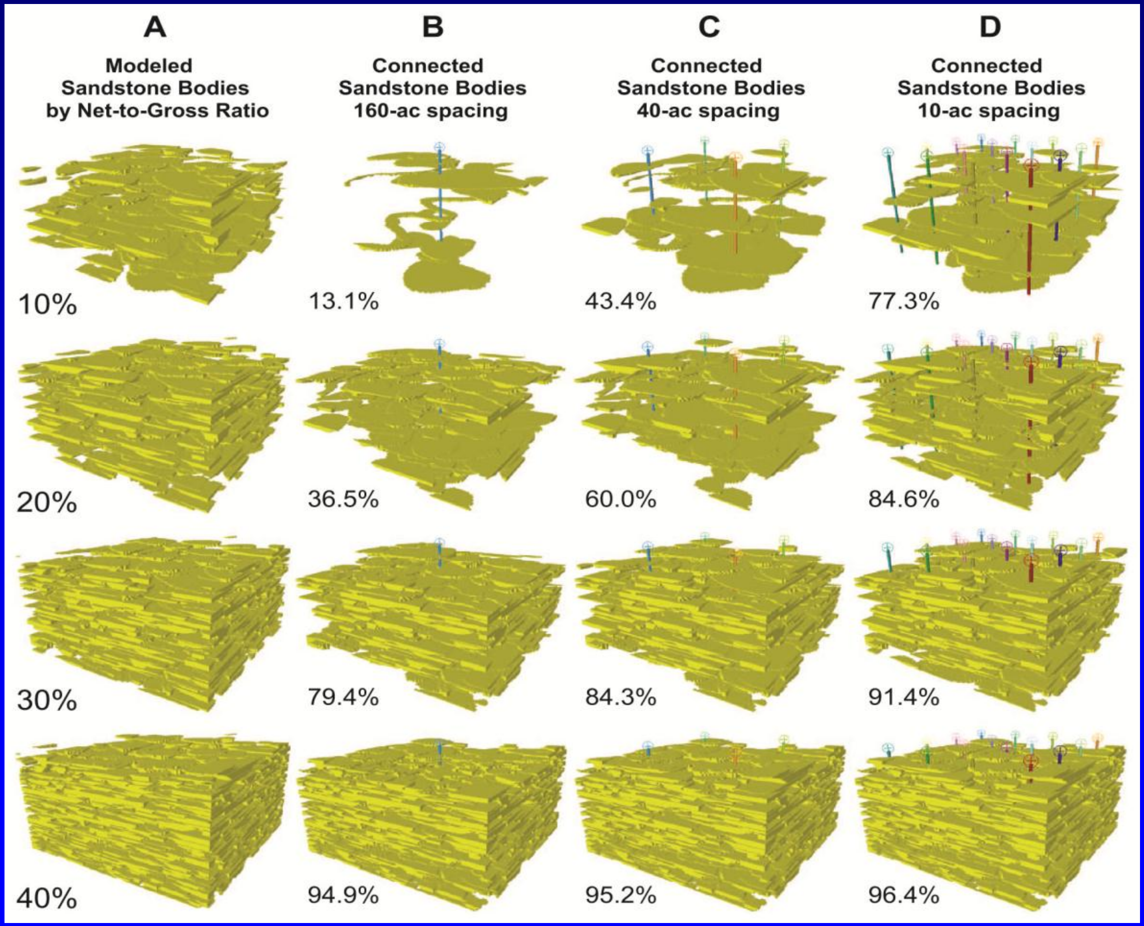
BACKUP SLIDES

Previous Work: Static Connectivity

- Static connectivity: the percentage value that is calculated by the volume of sandstone connected to a particular pattern of wells divided by the total sandstone volume



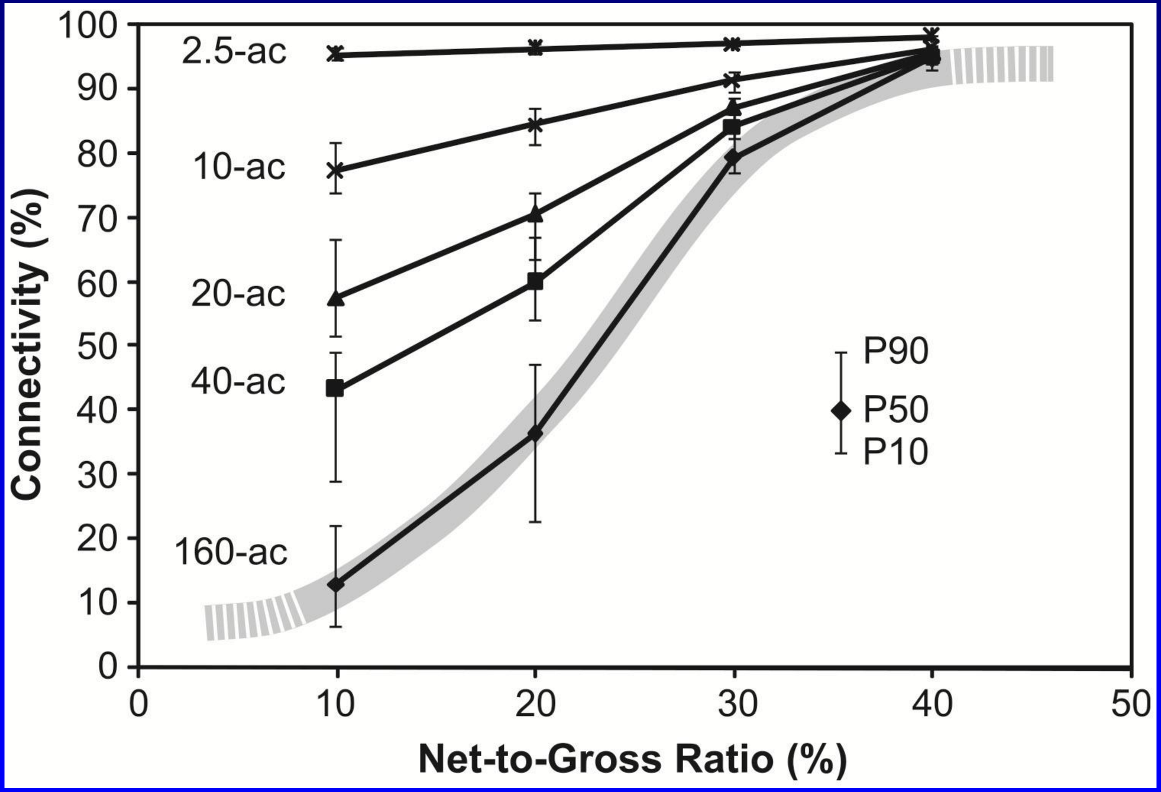
From Pranter and Sommer (2011)

Pranter and Sommer (2011)

- Synthetic outcrop-based model with various net-to-gross and well-spacing scenarios

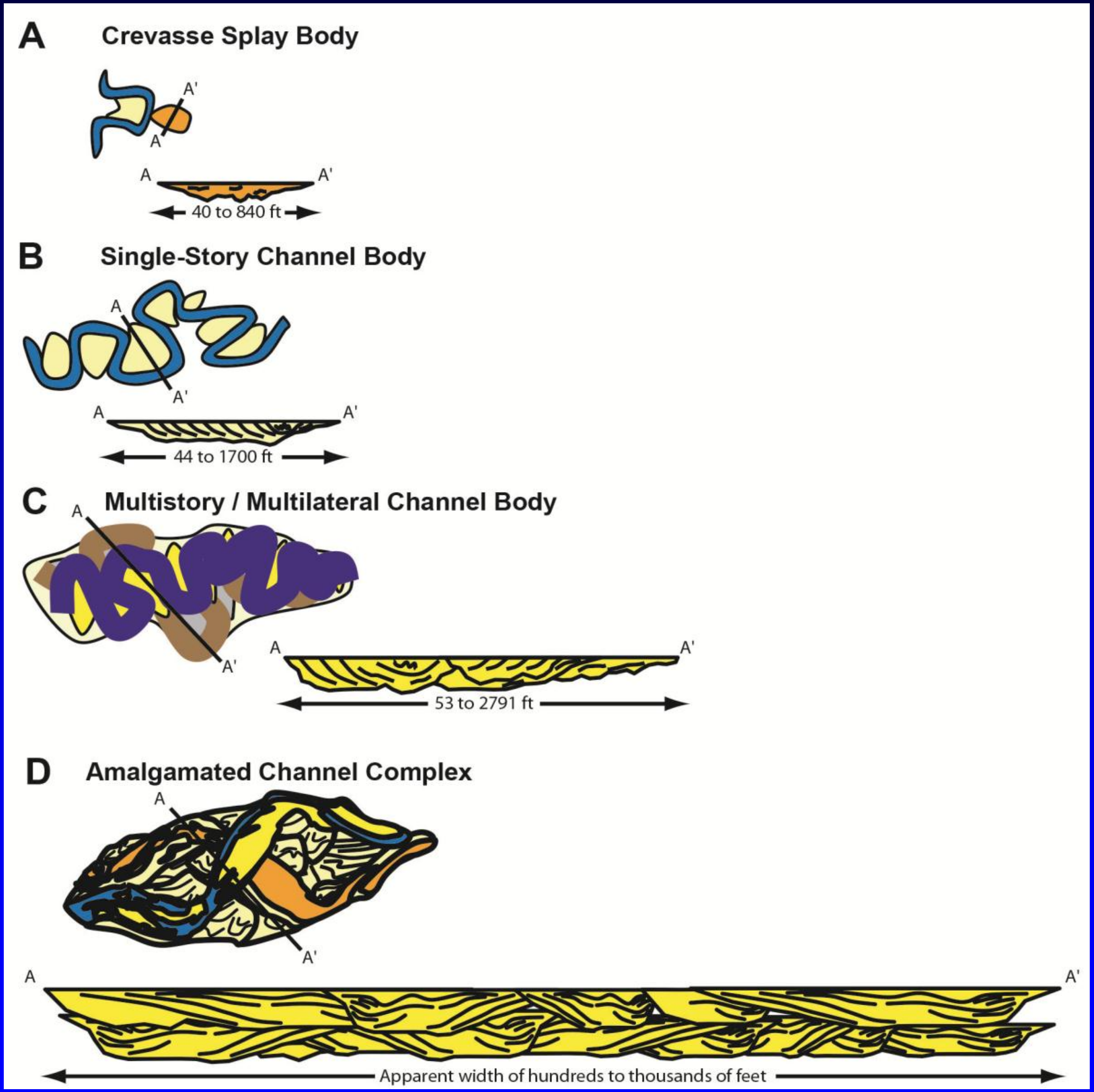
Previous Work: Static Connectivity

Relationship between net-to-gross ratio and connectivity for multiple well-spacing scenarios



From Pranter and Sommer (2011)

Background: Architectural Elements



From Pranter et al. (2009)

- Architectural elements
  - distinct geometry
  - spatial distribution
  - facies/facies associations

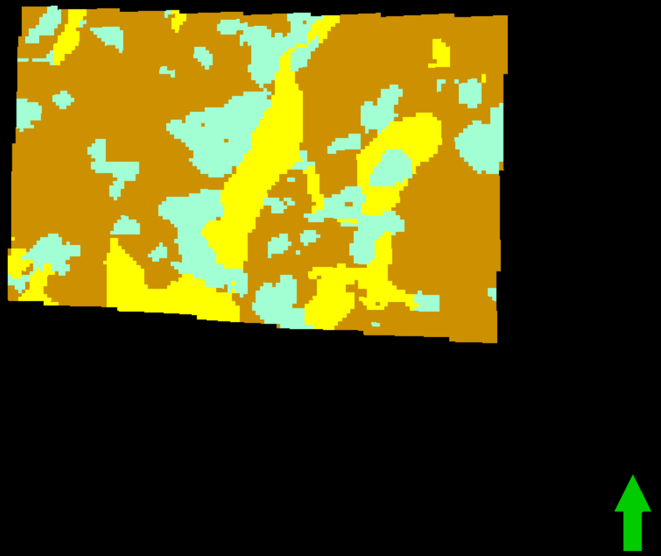
- Analog: Williams Fork Formation, Piceance Basin
  - (Anderson, 2005; Cole and Cumella, 2005; Pranter et al., 2009; Harper, 2011; Hlava, 2011; Pranter and Sommer, 2011)

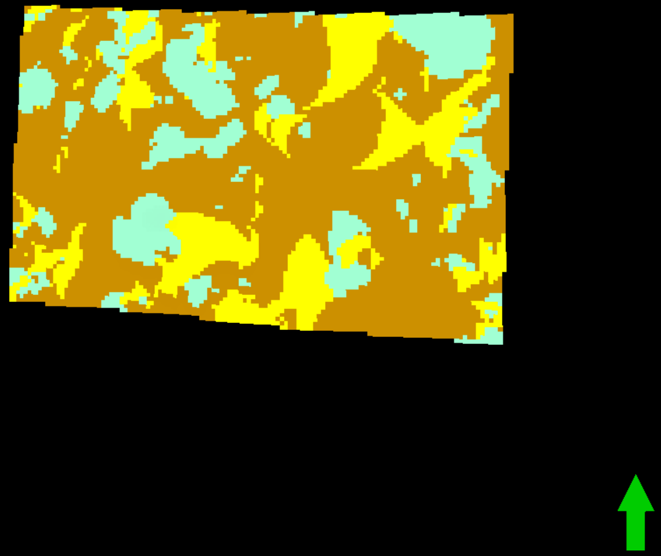
Training Image Testing

Sinuous channel fill/fluvial bars

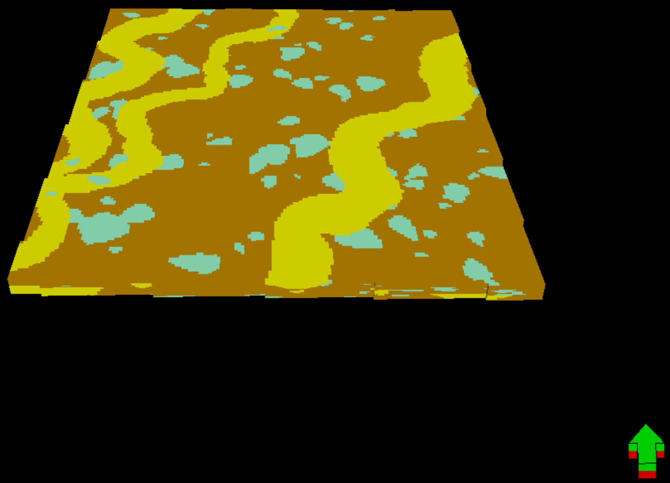
Fluvial crescent-shaped bars

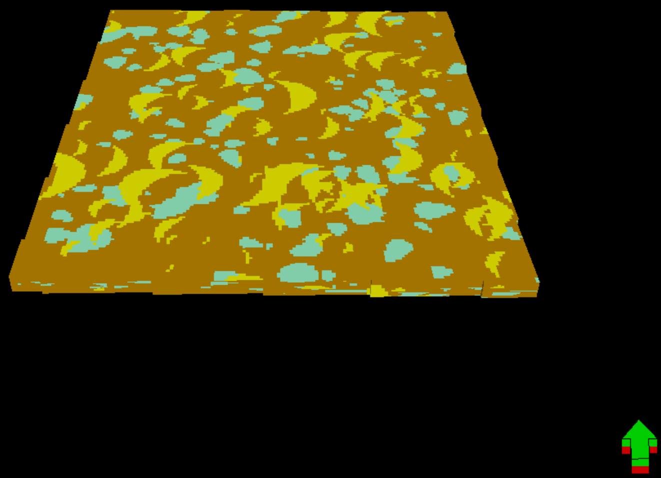
MPS Model Result for Zone 6



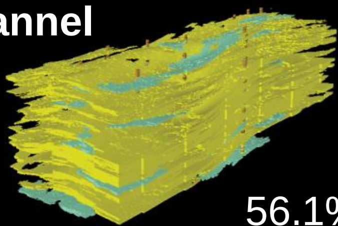
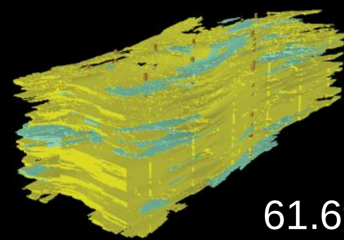
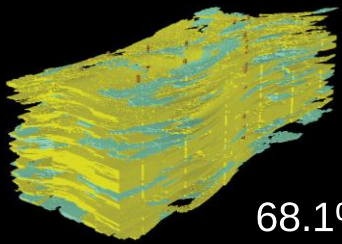
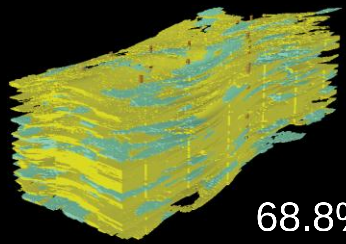
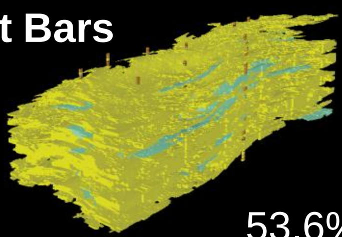
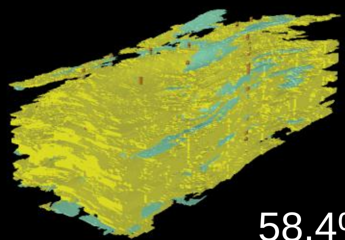
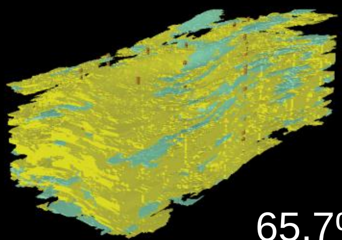
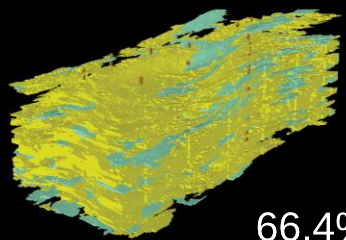


Training Images for Zone 6





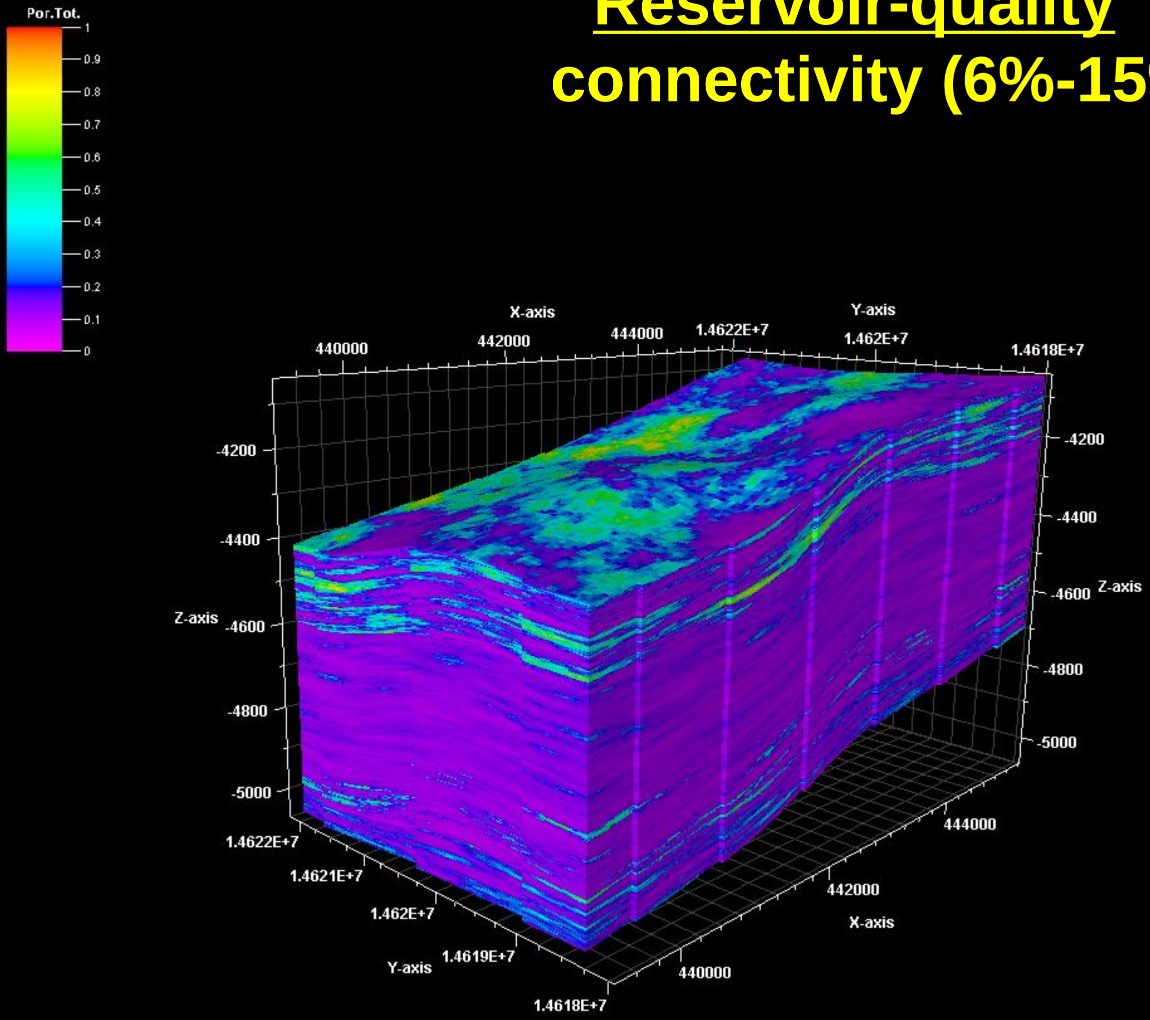
Connectivity per Well

	160-ac spacing	40-ac spacing	10-ac spacing	2.5-ac spacing
Connected Channel	 56.1% 18.7%/well	 61.6% 5.1%/well	 68.1% 1.3%/well	 68.8% 0.3%/well
Isolated Point Bars	 53.6% 17.9%/well	 58.4% 4.9%/well	 65.7% 1.2%/well	 66.4% 0.3%/well

Porosity Model

RCML

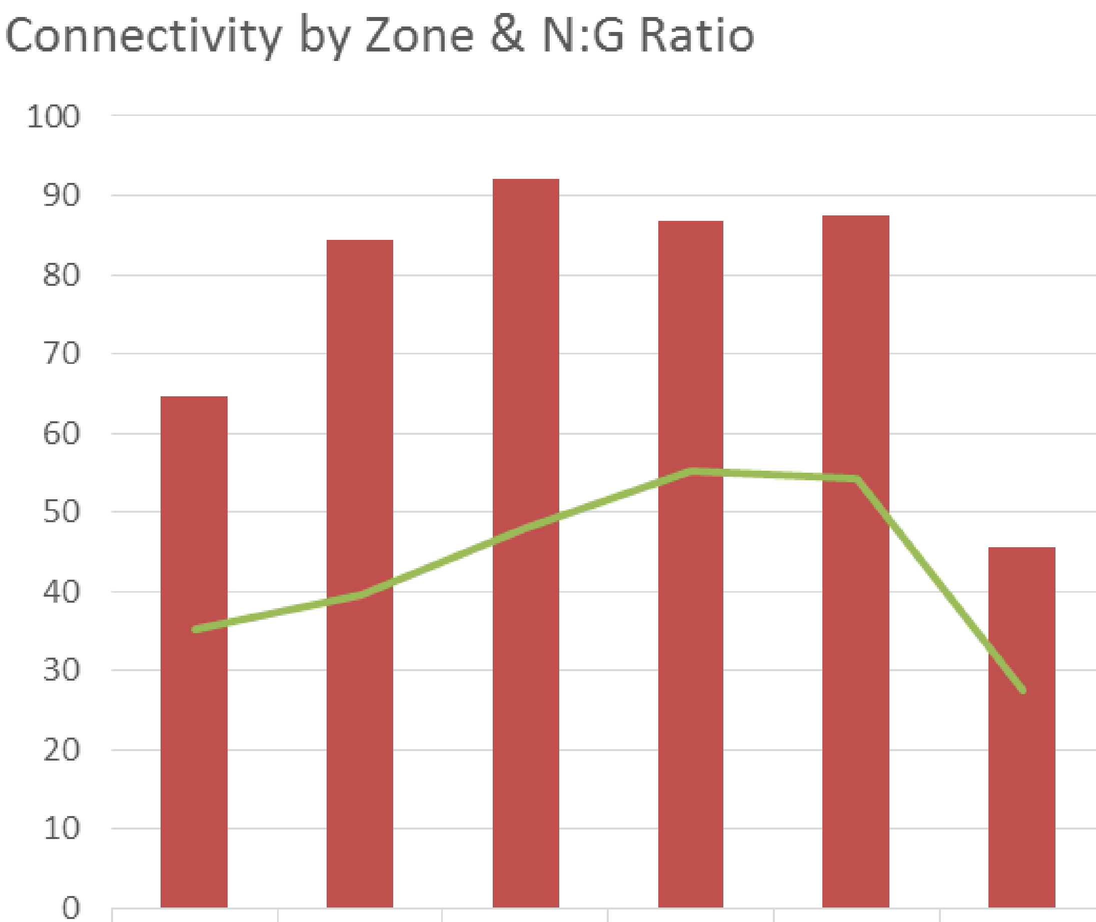
“<u>Reservoir-quality</u>” sandstone connectivity (6%-15% porosity)



Sequential Gaussian Simulation

Connectivity by Zone

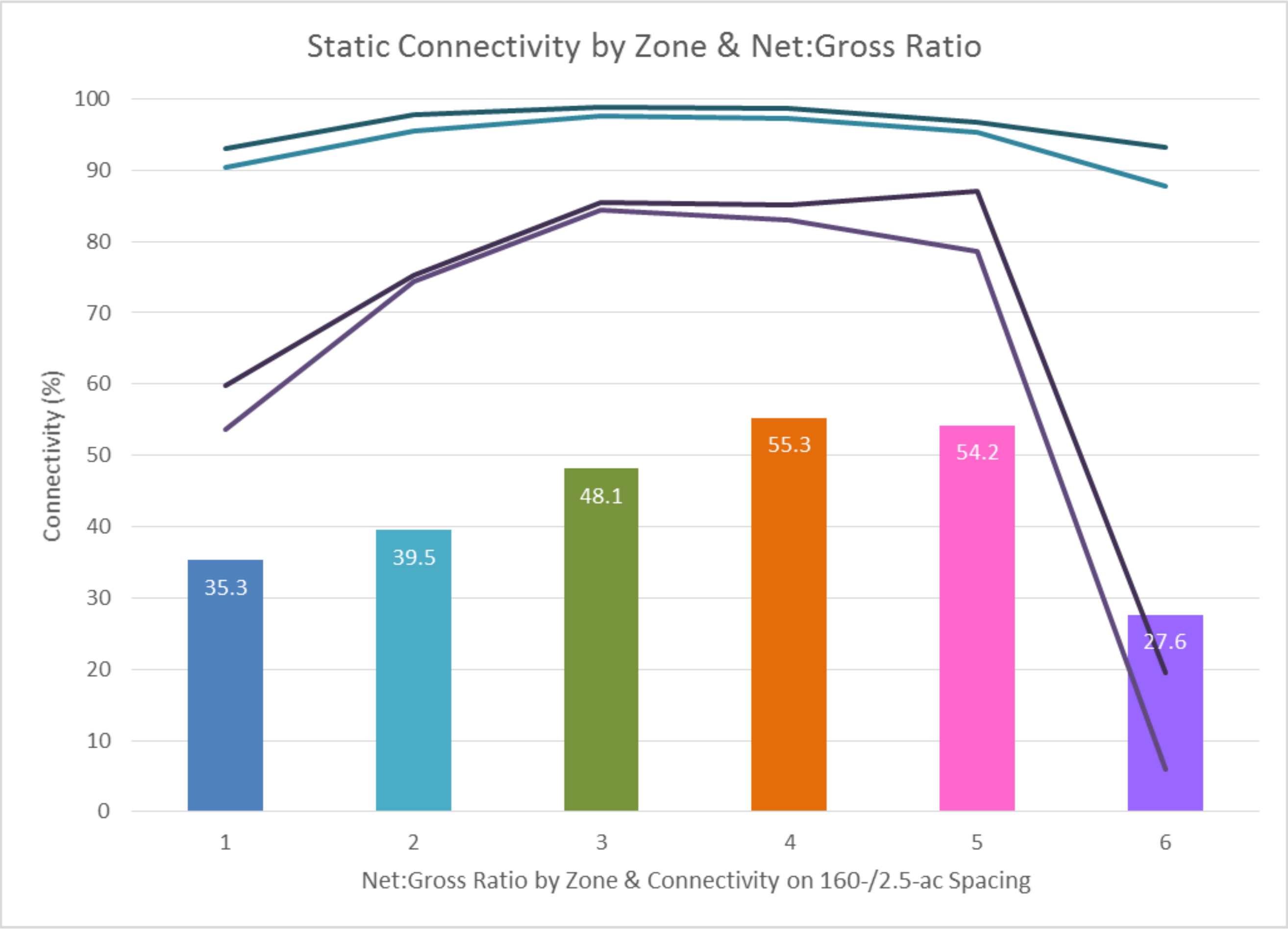
Stratigraphic variation in connectivity and N:G ratio



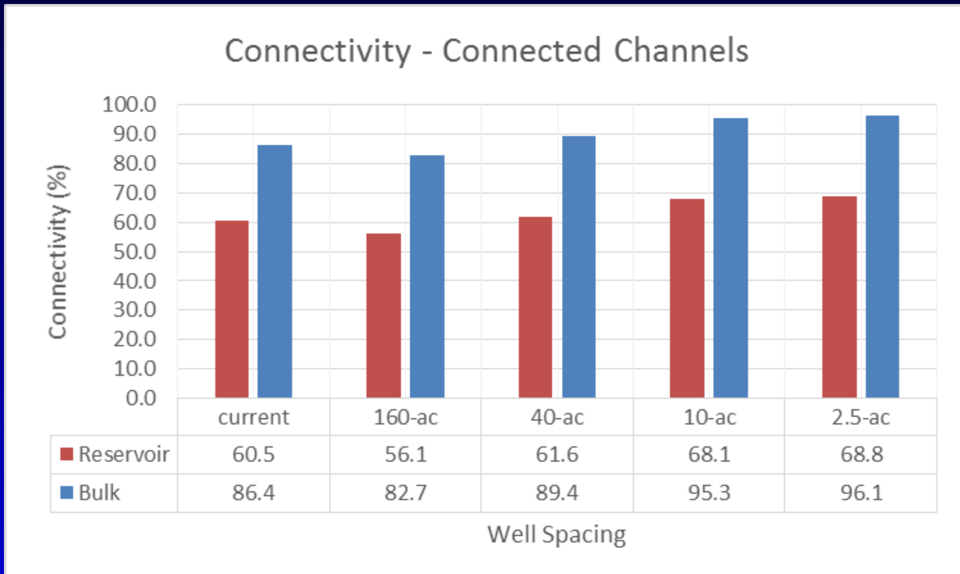
	1	2	3	4	5	6
Reservoir Connectivity	64.6	84.2	92.0	86.8	87.5	45.5
Net:Gross	35.3	39.5	48.1	55.3	54.2	27.6

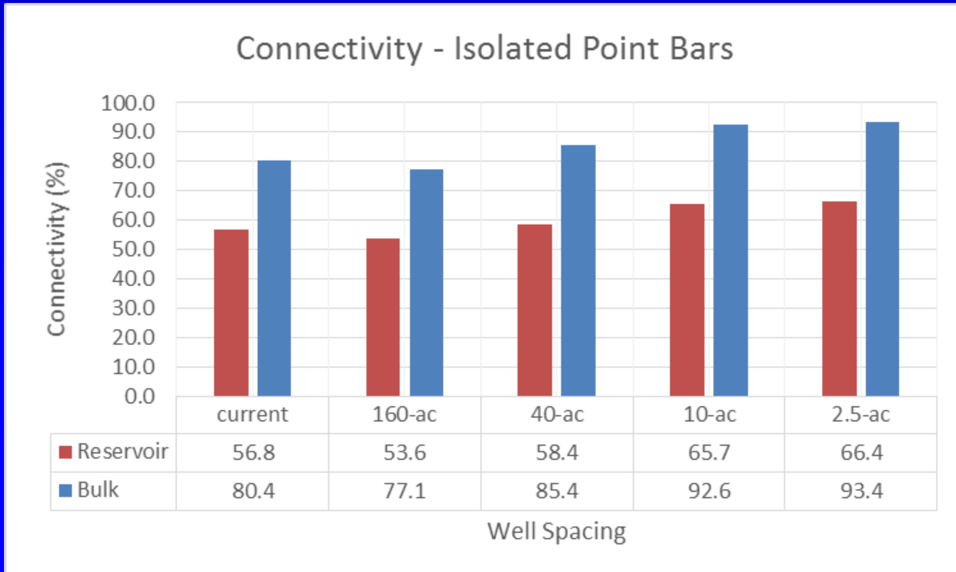
Zone

Connectivity by Zone & N:G Ratio



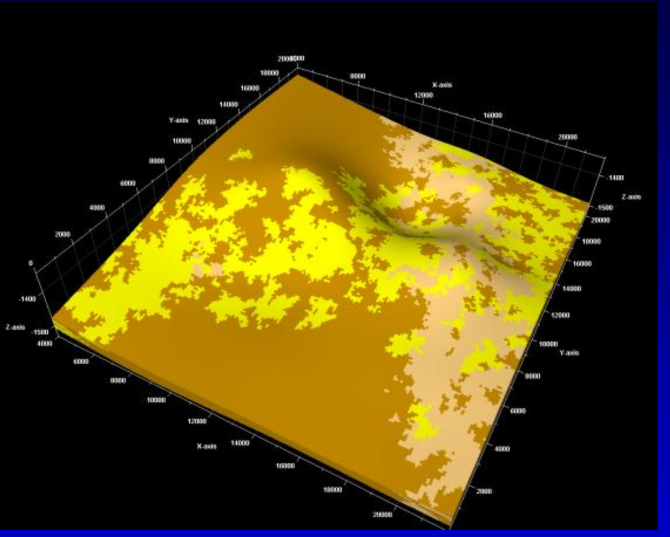
Well-based Connectivity

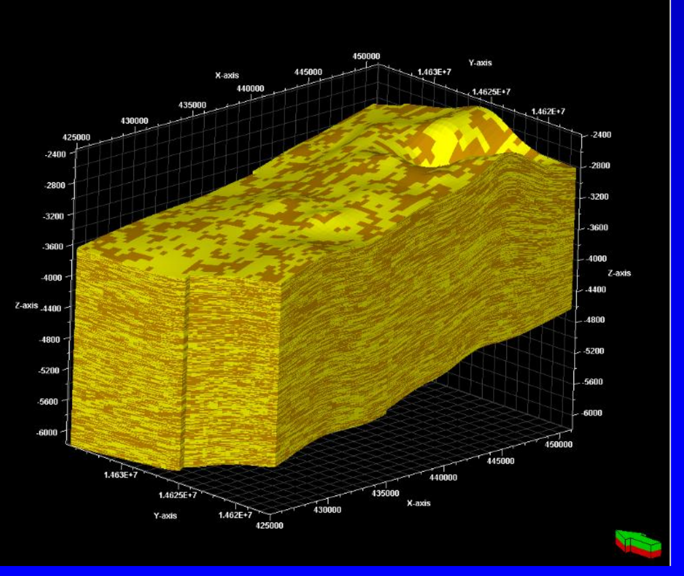




Sequential Indicator Simulation

- Sequential Indicator Simulation (SIS - cell-based)
  - Assign geologic/petrophysical properties cell-by-cell
  - Most common industry standard; highly tested
  - Can honor large amounts of data
  - Geologic shapes are difficult to model

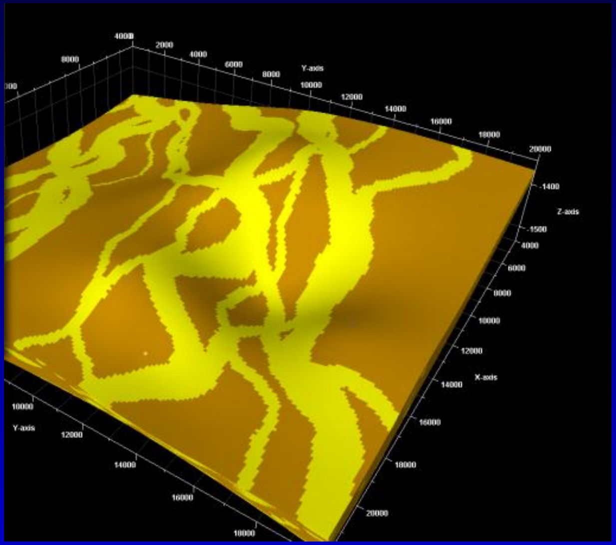


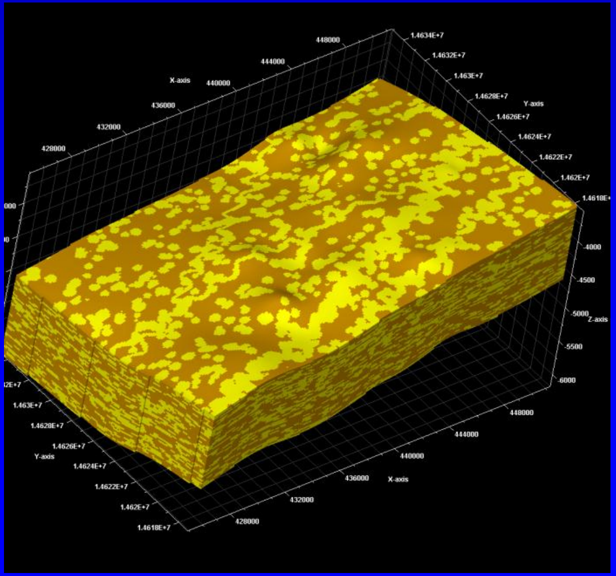


Object-Based Modeling

RCML

- Object-based (Boolean)
  - Defined facies objects to populate the model
  - Rock properties modeled within objects
  - Honor geologic rules
  - More difficult to honor large amounts of data
  - Size, geometry, and orientation of distinct geologic bodies (i.e., from outcrop)

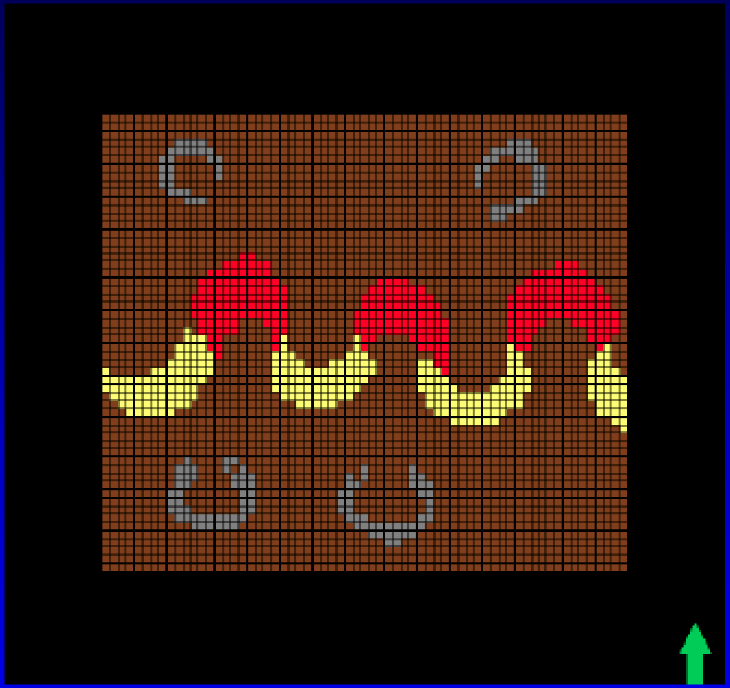




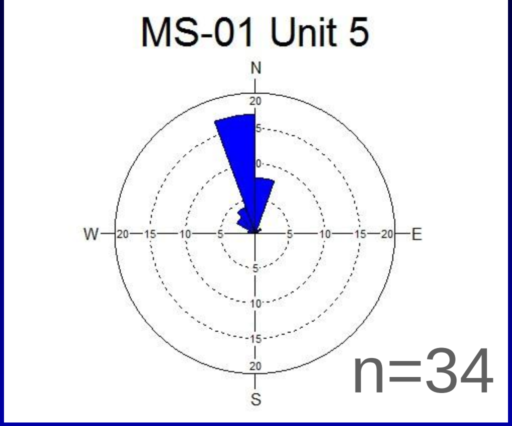
Multi-Point Statistics (MPS)

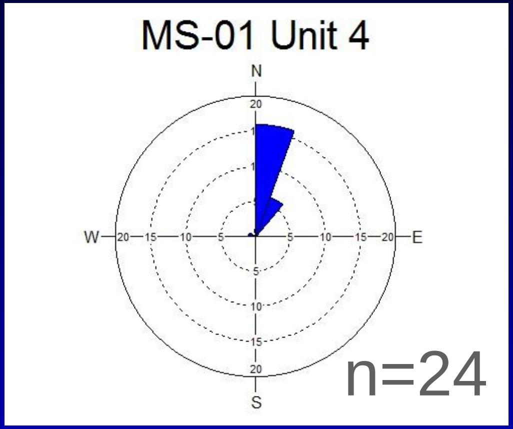
- Multi-Point Statistics (MPS)
  - Training image → replaces the variogram
  - SNESIM algorithm
  - Model spatial geologic relationships and concepts

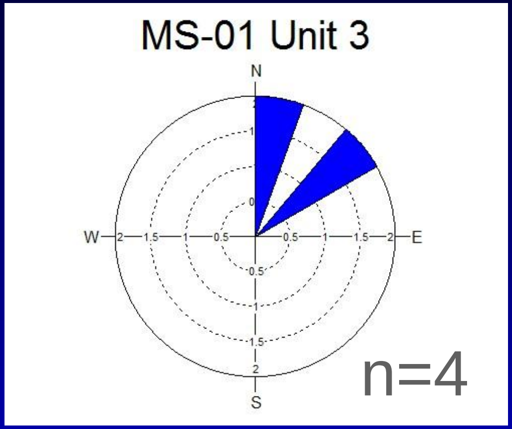
Training Image Example

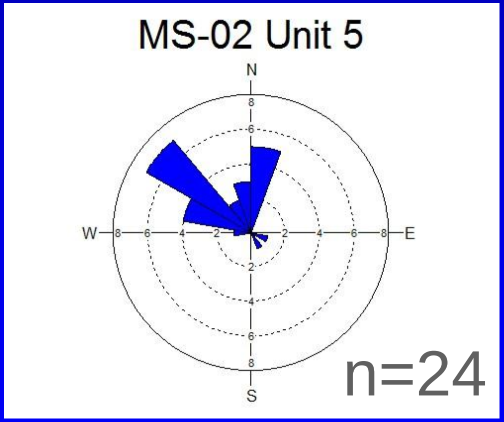


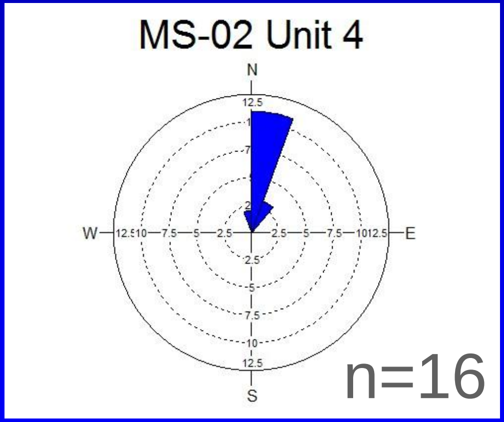
Paleocurrent Data



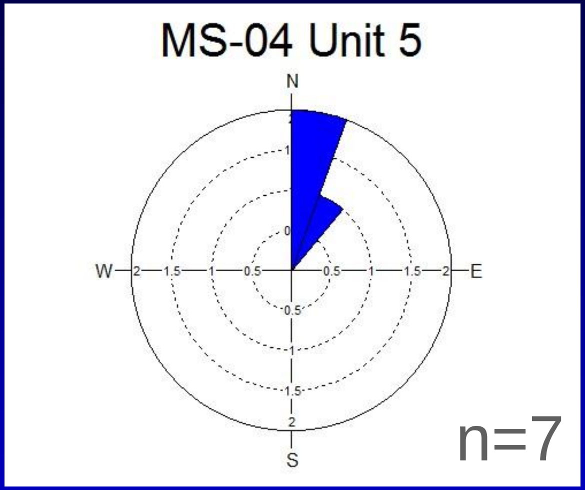


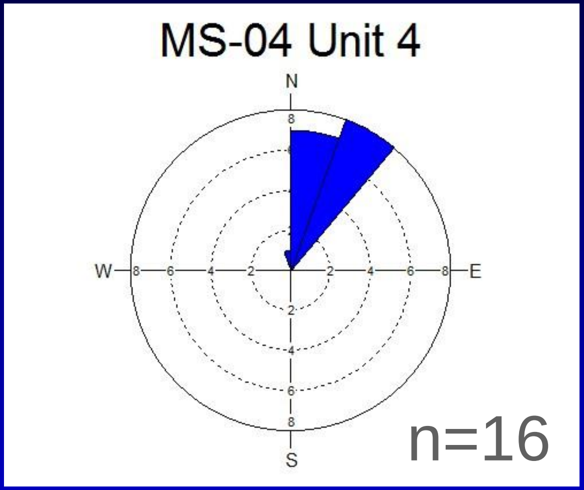


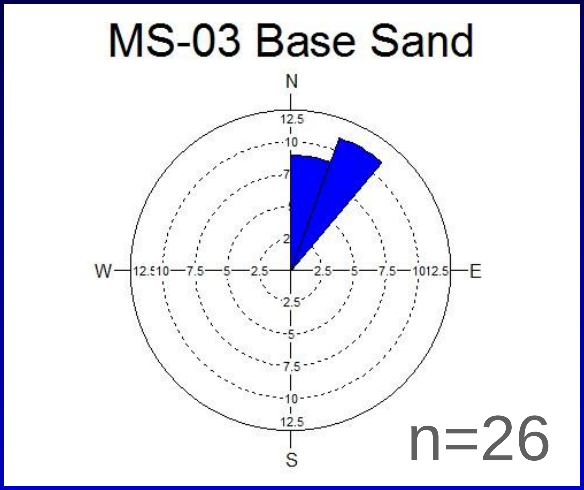




Paleocurrent Data







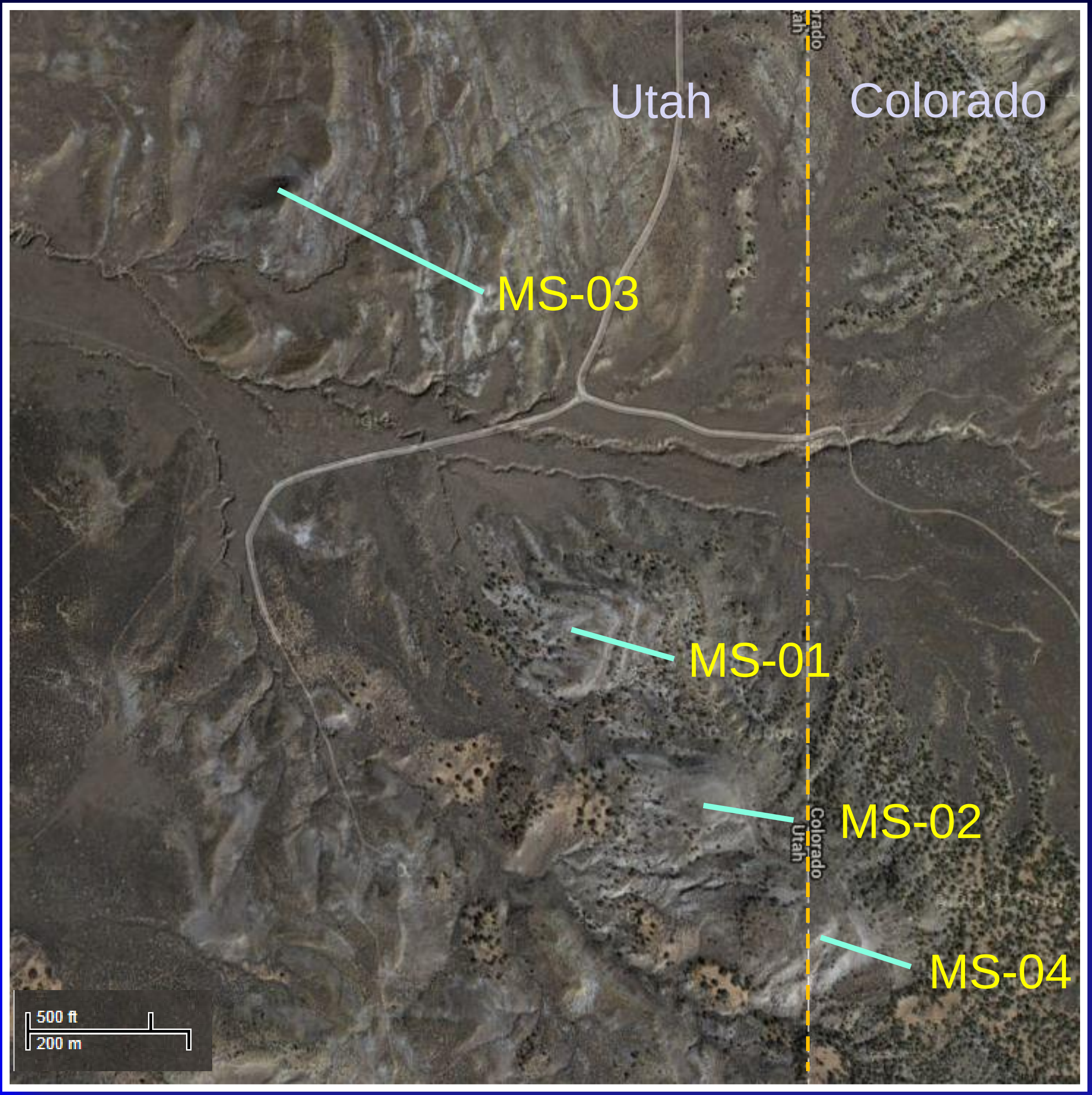
Methods: Fieldwork

- Field observations
  - Lateral and vertical changes in lithology
  - Grain size and sorting
  - Bioturbation
  - Sedimentary structures
  - Paleocurrent indicators
  - Significant surfaces
- Sandstone body measurements
  - Dimensions
  - Abundance
  - Stacking patterns
- Measured sections

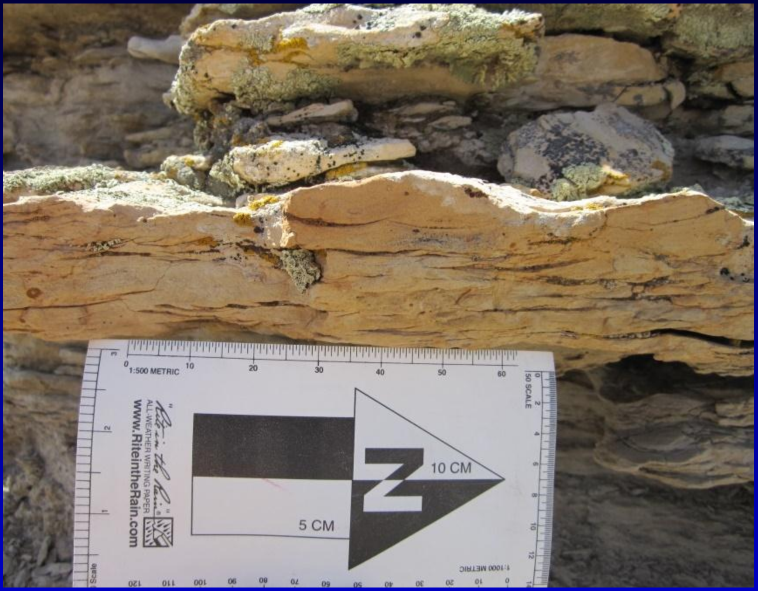
Mesaverde Roadcut

Mesaverde roadcut along US Hwy 40 just west of Dinosaur, CO

Locations of Measured Section



Common Facies Present



<u>Ripple cross-laminated sandstone</u>

- White to beige fine- to medium-grained sandstone
- Climbing asymmetrical ripples

<u>Fissile mudstone</u>

- Dark grey to black, organic-rich, fissile mudstone
- Abundant plant debris
- Associated with thin (<1 ft) coal beds

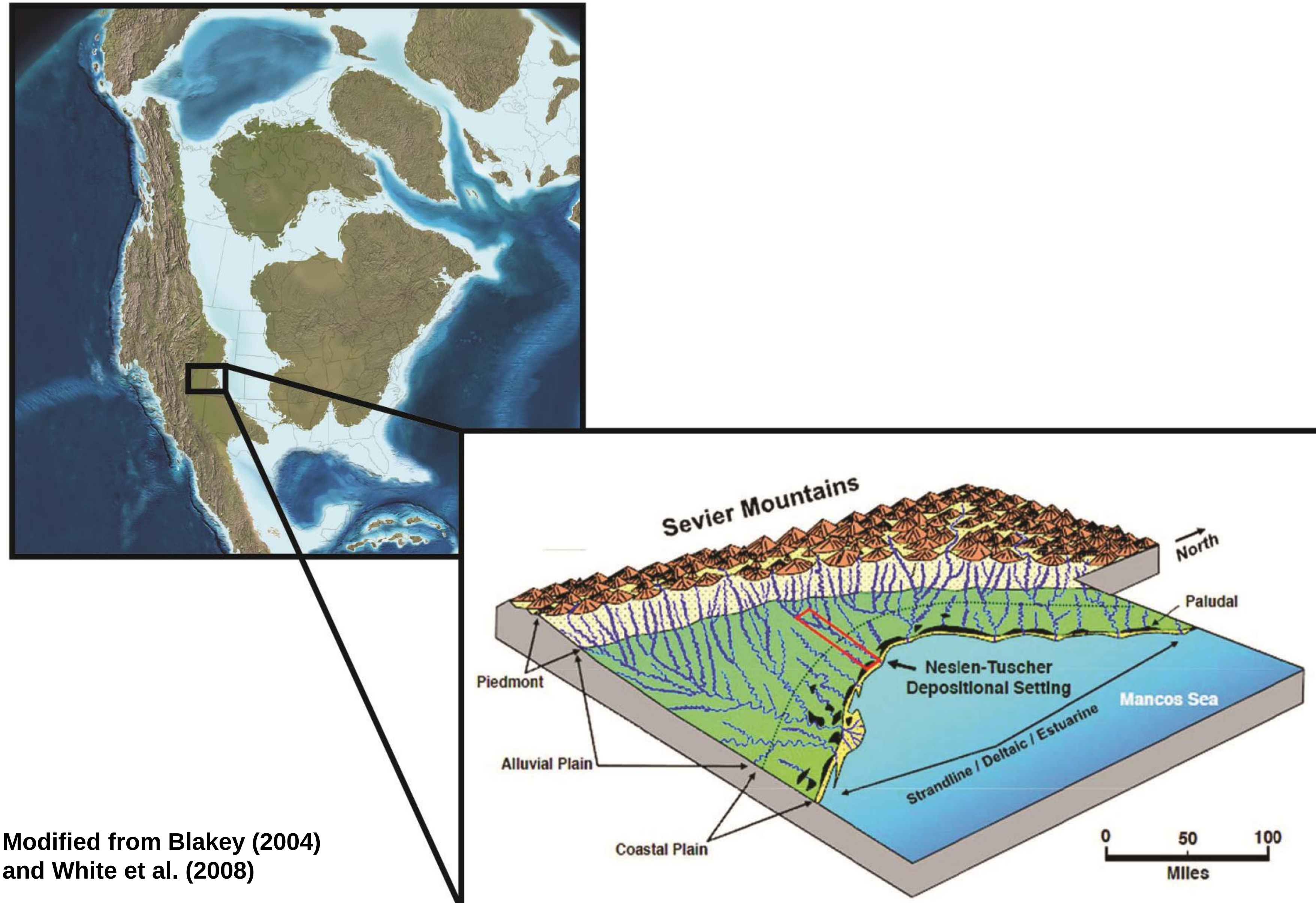
Common Facies Present

Convolute sandstone
•Beige fine- to medium-grained sandstone
•Soft sediment deformation

Sandstone with wood fragments
•White fine- to medium-grained sandstone
•Poorly indurated
•Wood fragments and plant debris

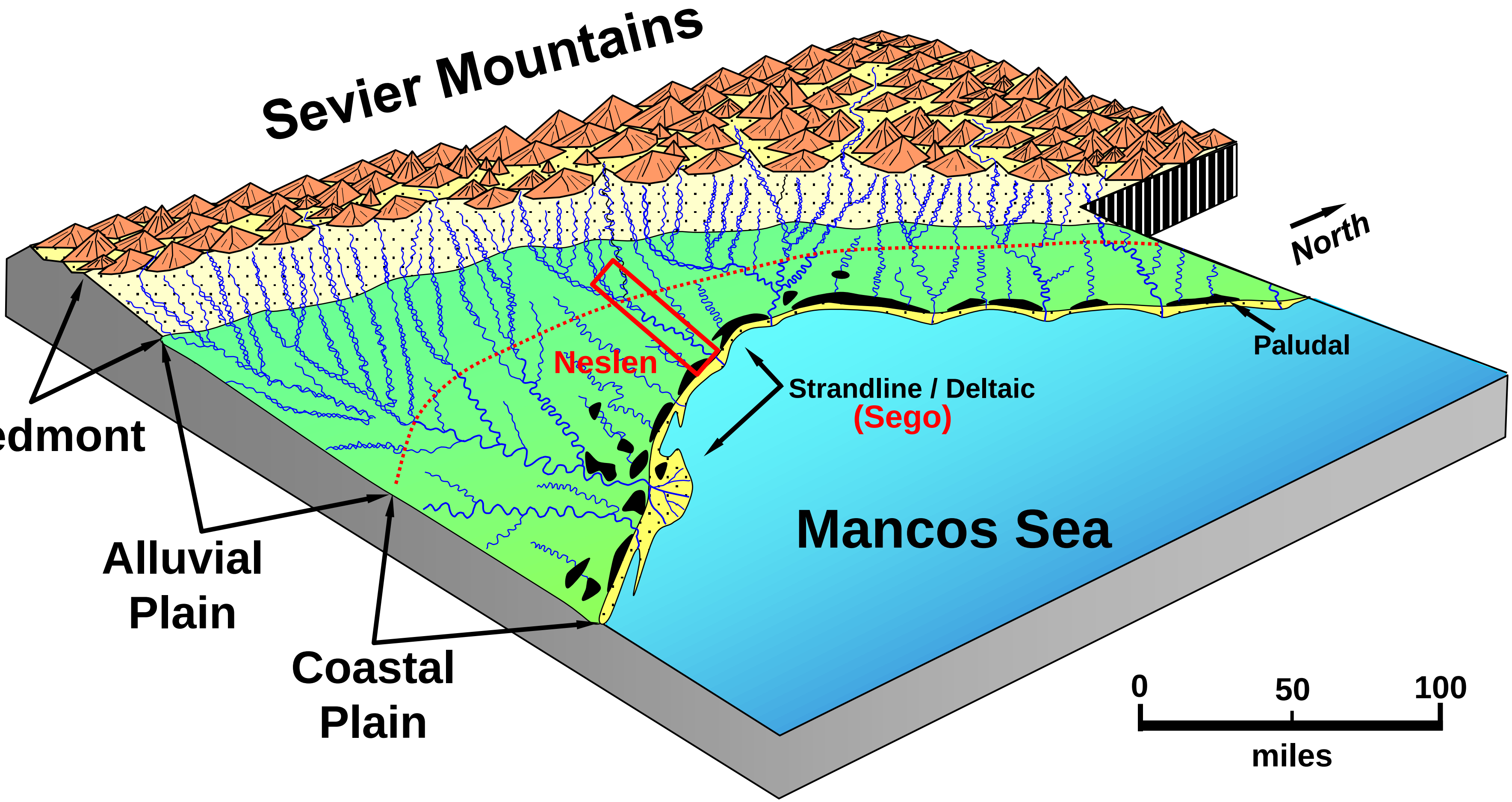
Cross-bedded sandstone
•Low- to high-angle cross-bedded sandstone

Geologic History



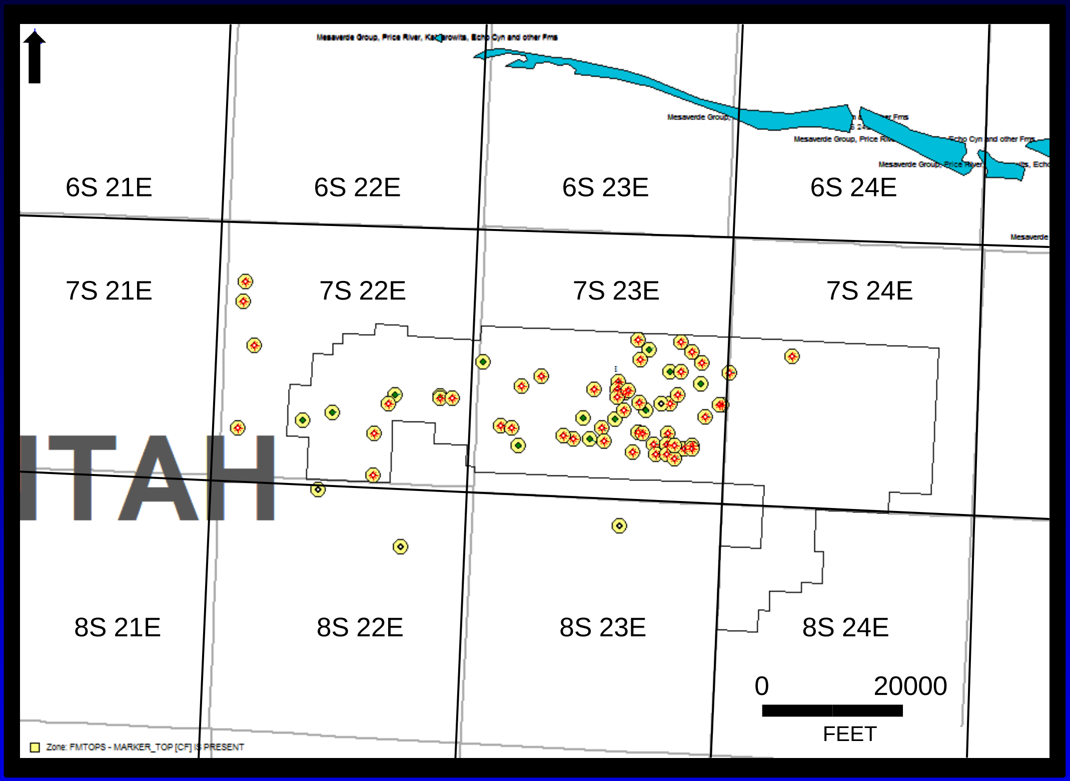
Modified from Blakey (2004) and White et al. (2008)

Depositional Setting



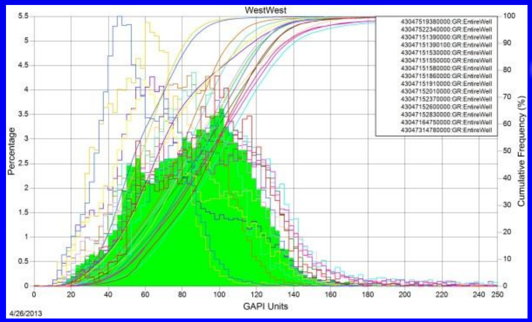
Modified from Ryer and McPhillips (1983); Provided by Rex Cole

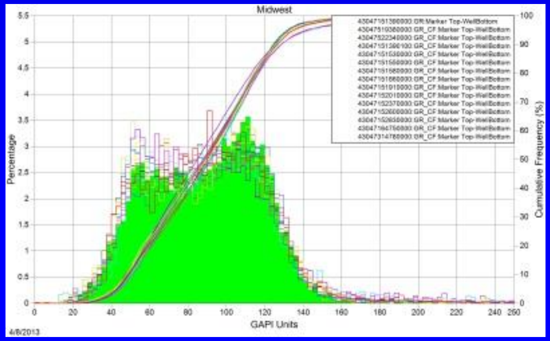
Methods: Subsurface Data Set



- Well logs for ~70 wells in Red Wash Field
- Manual interpretation of architectural elements

Normalized gamma ray curves in PowerLog





Multi-well histograms for grouped gamma ray log normalization using PowerLog