Fluvial Architecture and Connectivity of the Williams Fork Formation, Piceance Basin, Colorado: Combining Outcrop Analogs and Reservoir Modeling for Stratigraphic Reservoir Characterization*

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Abstract

This study addresses the field-scale architecture and static connectivity of fluvial sandstones of the lower Williams Fork Formation through analysis and reservoir modeling of analogous outcrop data from Coal Canyon, Piceance Basin, Colorado. The Upper Cretaceous lower Williams Fork Formation is a relatively low net-to-gross ratio (commonly <30%) succession of fluvial channel sandstones, crevasse splays, flood-plain mudstones, and coals that were deposited by meandering river systems within a coastal-plain setting. The lower Williams Fork outcrops serve as proximal reservoir analogs because the strata dip gently eastward into the Piceance Basin where they form natural gas reservoirs.

Three-dimensional architectural-element models (3-D reservoir models) of the lower Williams Fork Formation that are constrained to outcrop-derived data (e.g., sandstone body types, dimensions, stratigraphic position) from Coal Canyon show how static sandstone body connectivity is sensitive to sandstone body width and varies with net-to-gross ratio and well spacing. With a low well density (e.g., 160-acre well spacing), connectivity is low for net-to-gross ratios less than 20%; connectivity increases between net-to-gross ratios of 20 to 30%, and levels off above a net-to-gross ratio of 30%. As well density increases, static connectivity increases more linearly with an increasing net-to-gross ratio. For a 20-acre well spacing, static connectivity can range from approximately 35 to 75% and 45 to 80% for net-to-gross ratios of 10 and 15%, respectively, depending on sandstone body width. Given the lower net-to-gross ratio and continuity of lower Williams Fork deposits, this underscores the importance of representative sandstone body statistics (e.g., sandstone body type, dimensions) to aid in subsurface correlation and mapping and to constrain reservoir models.

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Fluvial architecture and connectivity of the Williams Fork Formation, Piceance Basin Colorado:

combining outcrop analogs and reservoir modeling for stratigraphic reservoir characterization

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The University of Oklahoma

The UNIVERSITY of OKLAHOMA
Mewbourne College of Earth and Energy
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January 15, 2014
OCGS Luncheon

OKLAHOMA CITY GEOLOGICAL SOCIETY

Outline

- **Research objectives**
- **Study area, setting, stratigraphy**
- **Fluvial sandstone-body types**
- **Outcrop-based dimensional data**
- **Controls on fluvial reservoir connectivity**
- ***Final thoughts…***

Reservoir Characterization and Modeling Laboratory

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The University of Oklahoma

Research Objectives

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For the Cretaceous Williams Fork Formation and equivalent strata:

- **Evaluate the stratigraphic variability and reservoir-scale architecture of fluvial sandstone bodies**
- **Establish a database of fluvial sandstone-body dimensions for reservoir modeling (mapping)**
- **Evaluate relationships among sandstone-body parameters and reservoir connectivity**
- **Apply outcrop-based concepts and statistics for integrated reservoir characterization**

Research Sponsors

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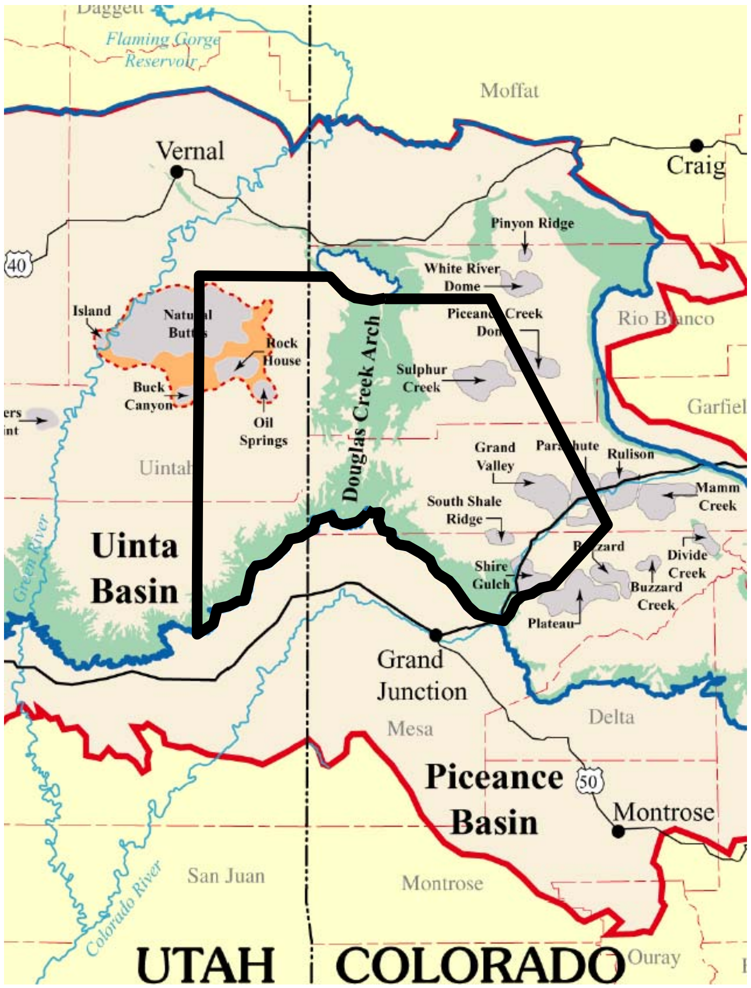
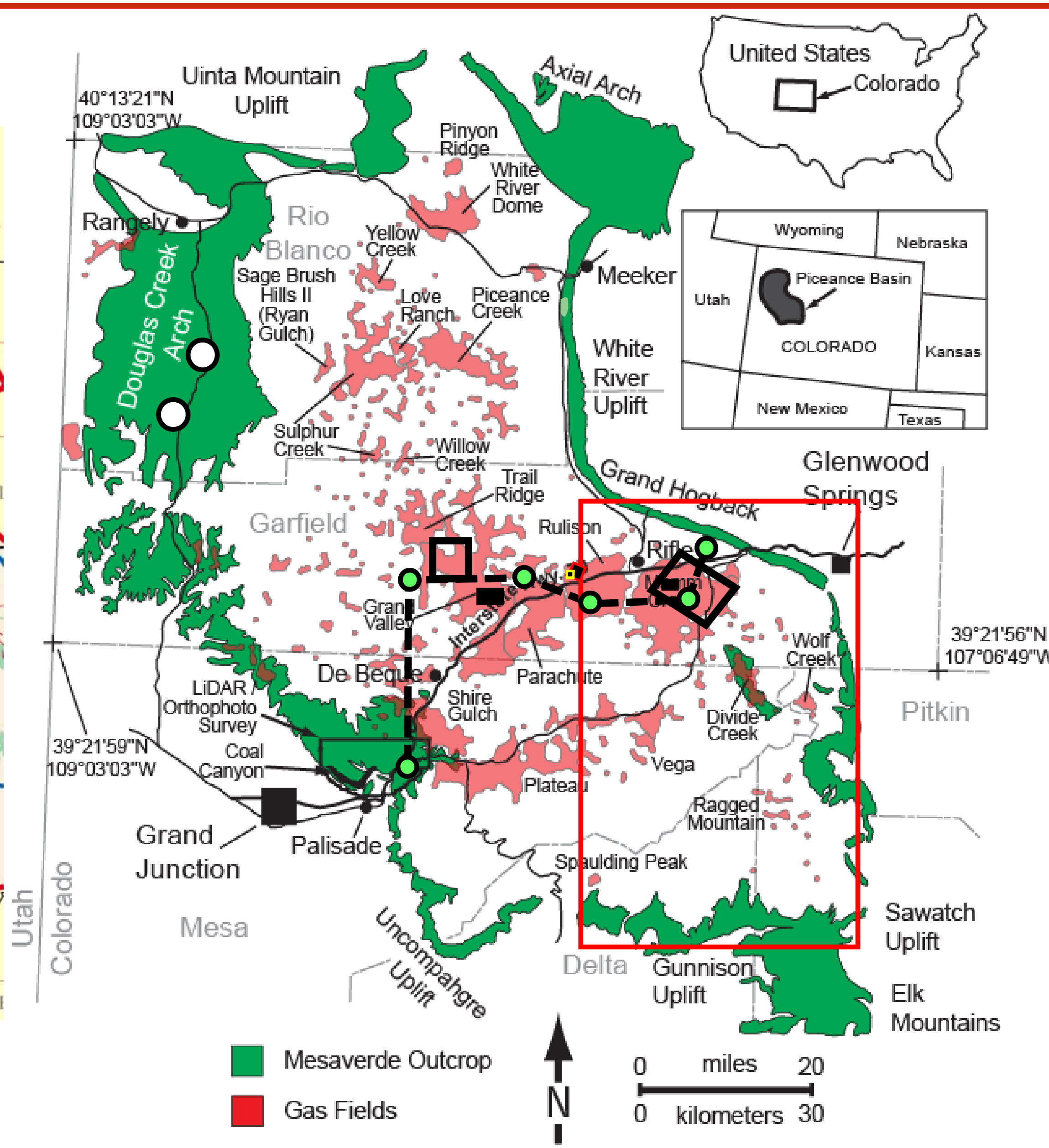
EnCana
MERRICK® BUILDING QUALITY SOLUTIONS
UNOCAL 76
ExxonMobil
NEWFIELD
Williams

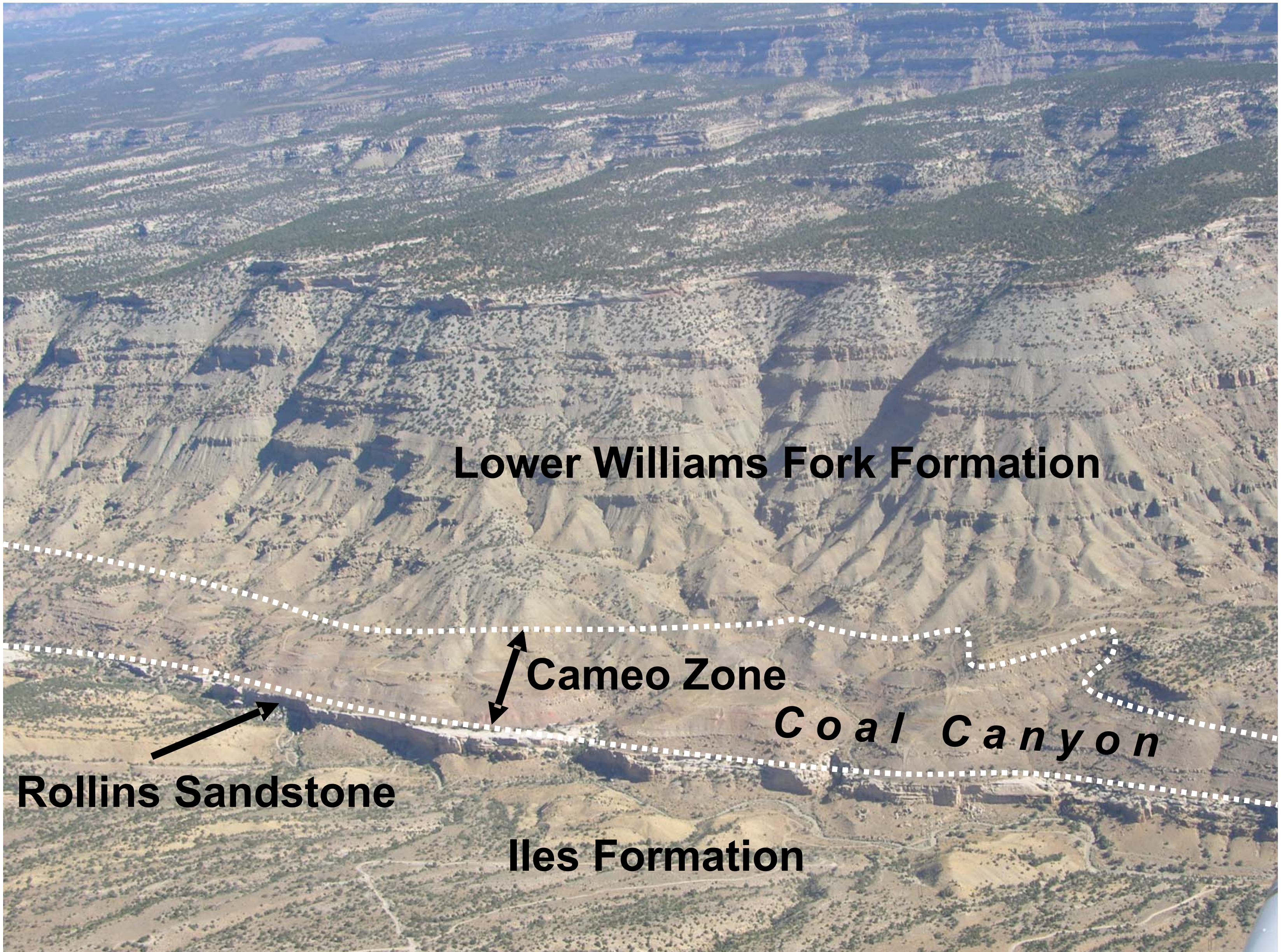
Study Area





Pranter et al. (2009)

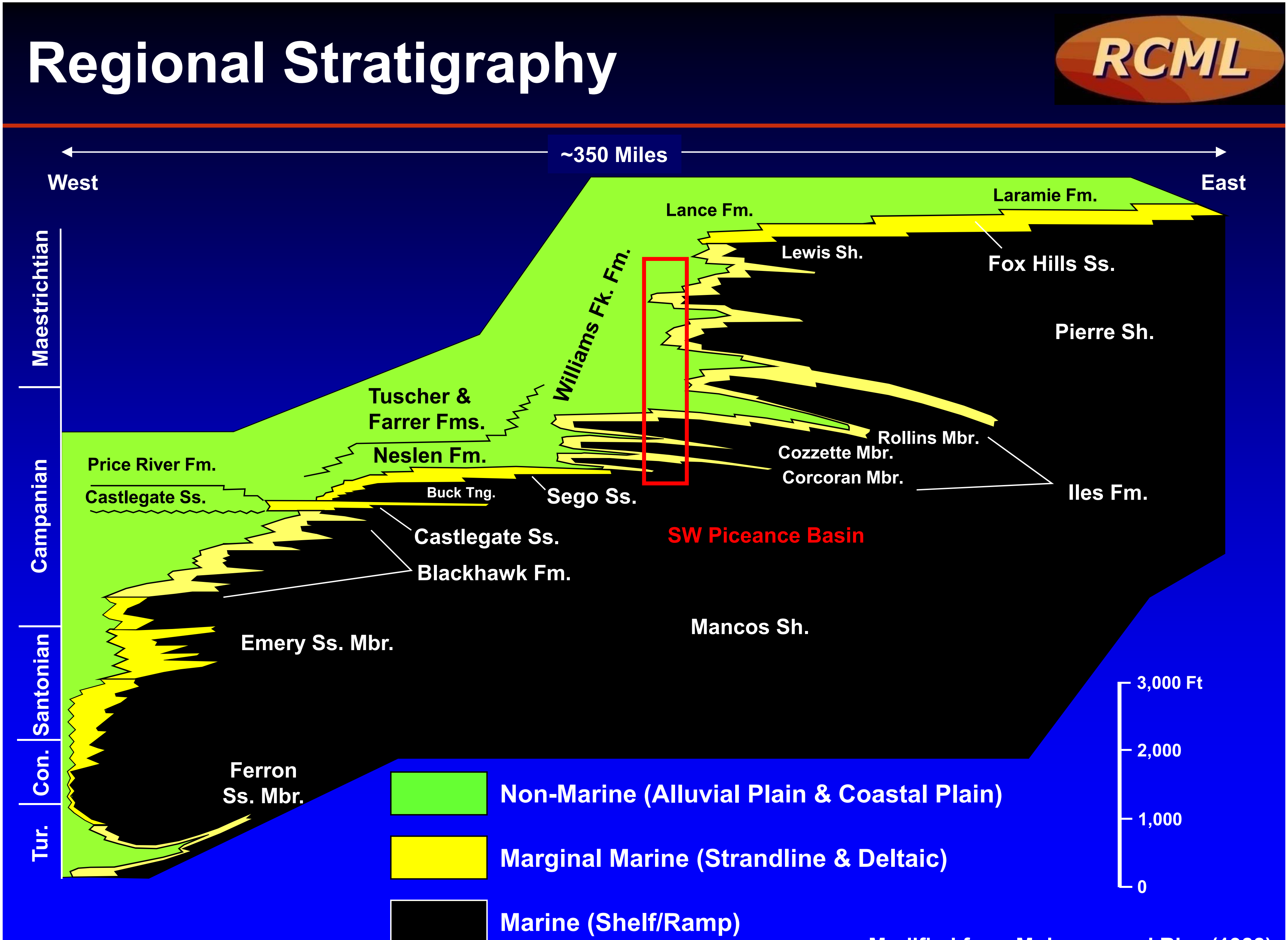
Study Area



Lower Williams Fork Formation
Cameo Zone
Coal Canyon
Rollins Sandstone
Iles Formation

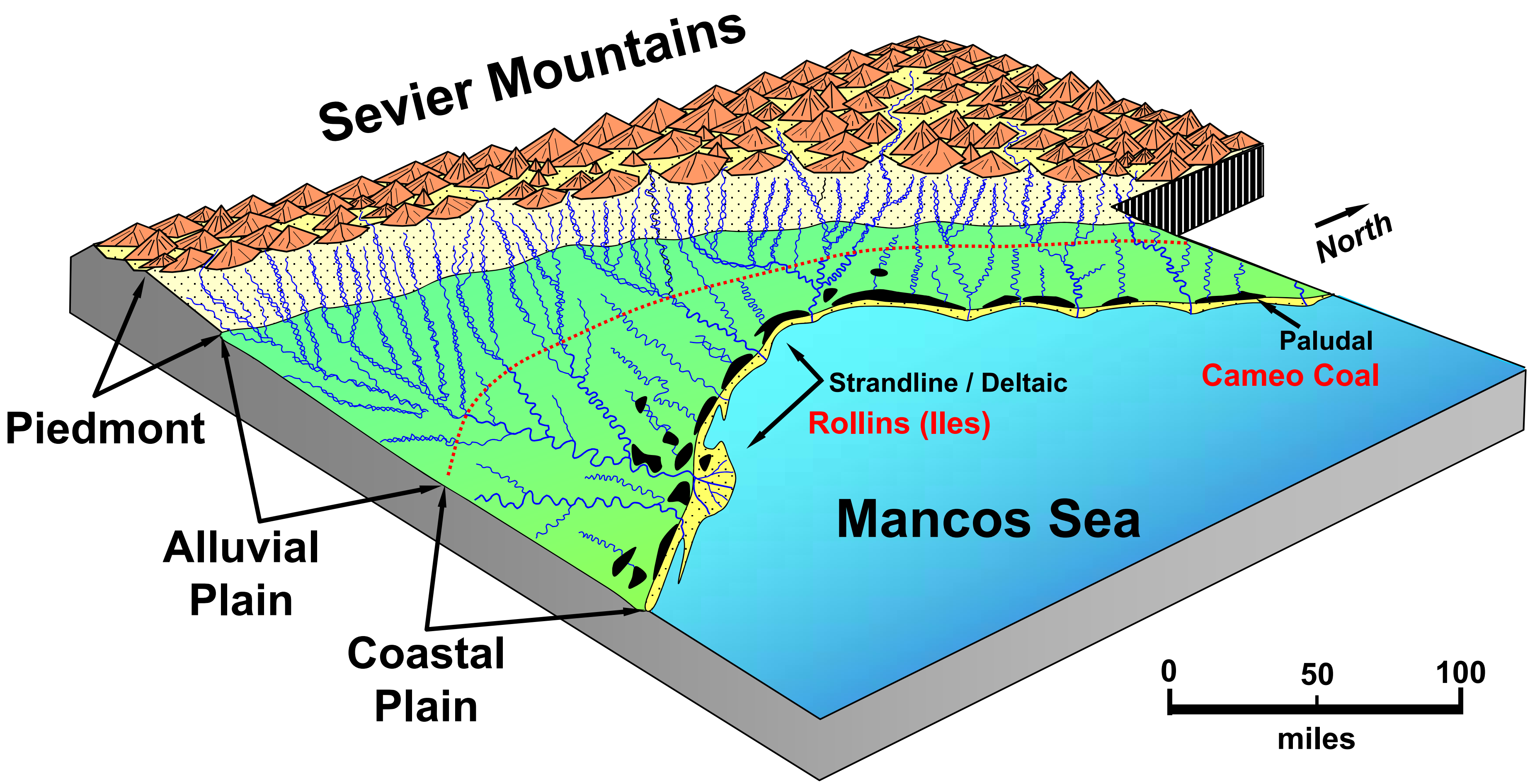
Late Cretaceous (~75 ma)

Regional Stratigraphy



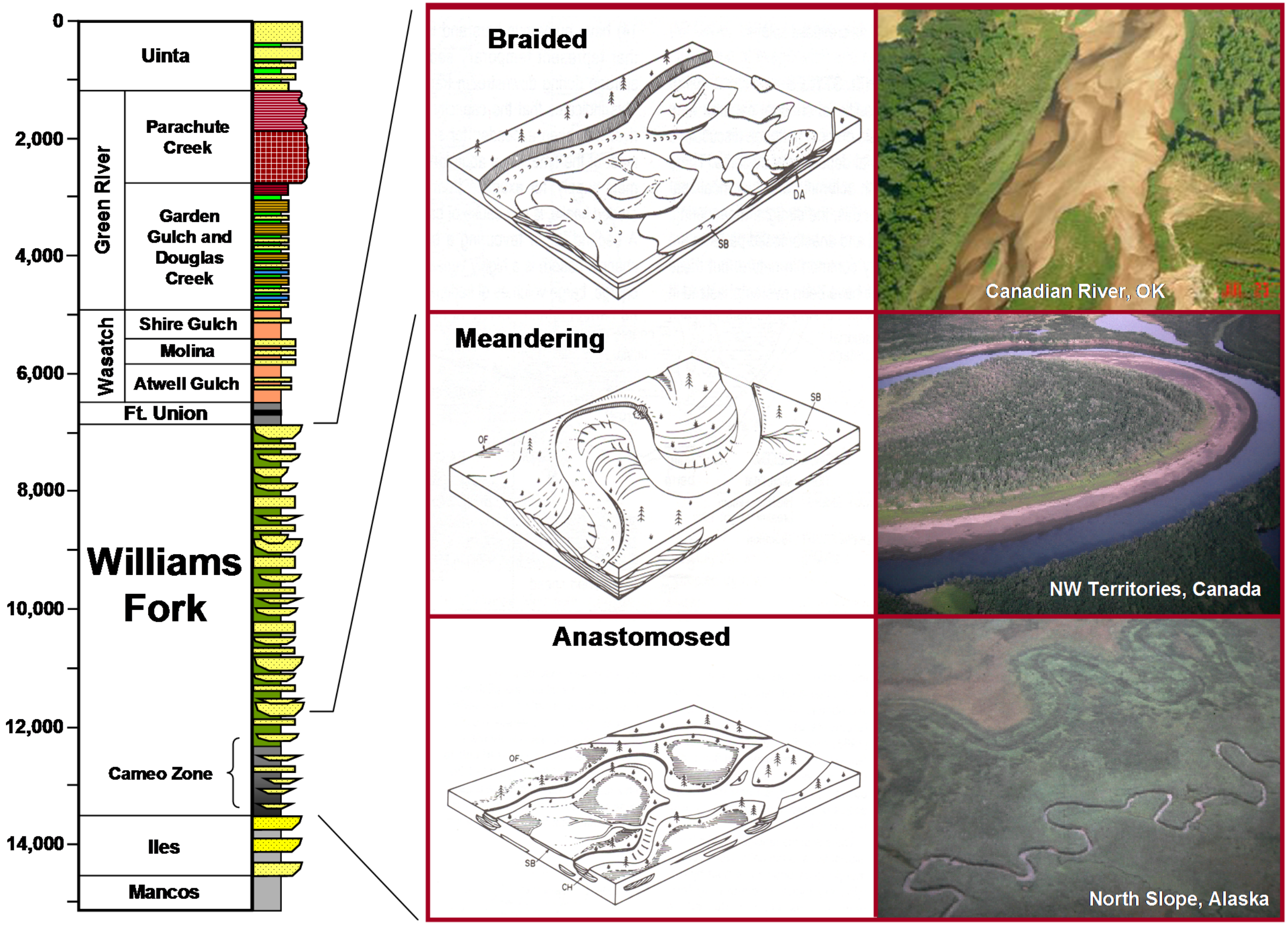
Modified from Molenaar and Rice (1988)

Depositional Setting

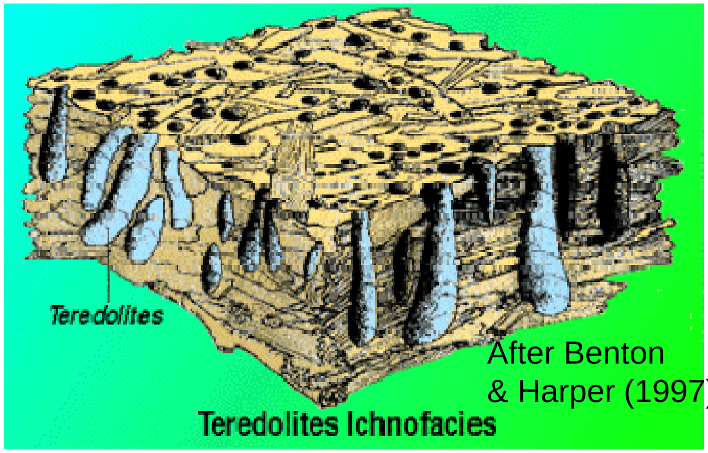


Modified from Ryer and McPhillips (1983); Provided by Rex Cole

Stratigraphy and Fluvial Styles

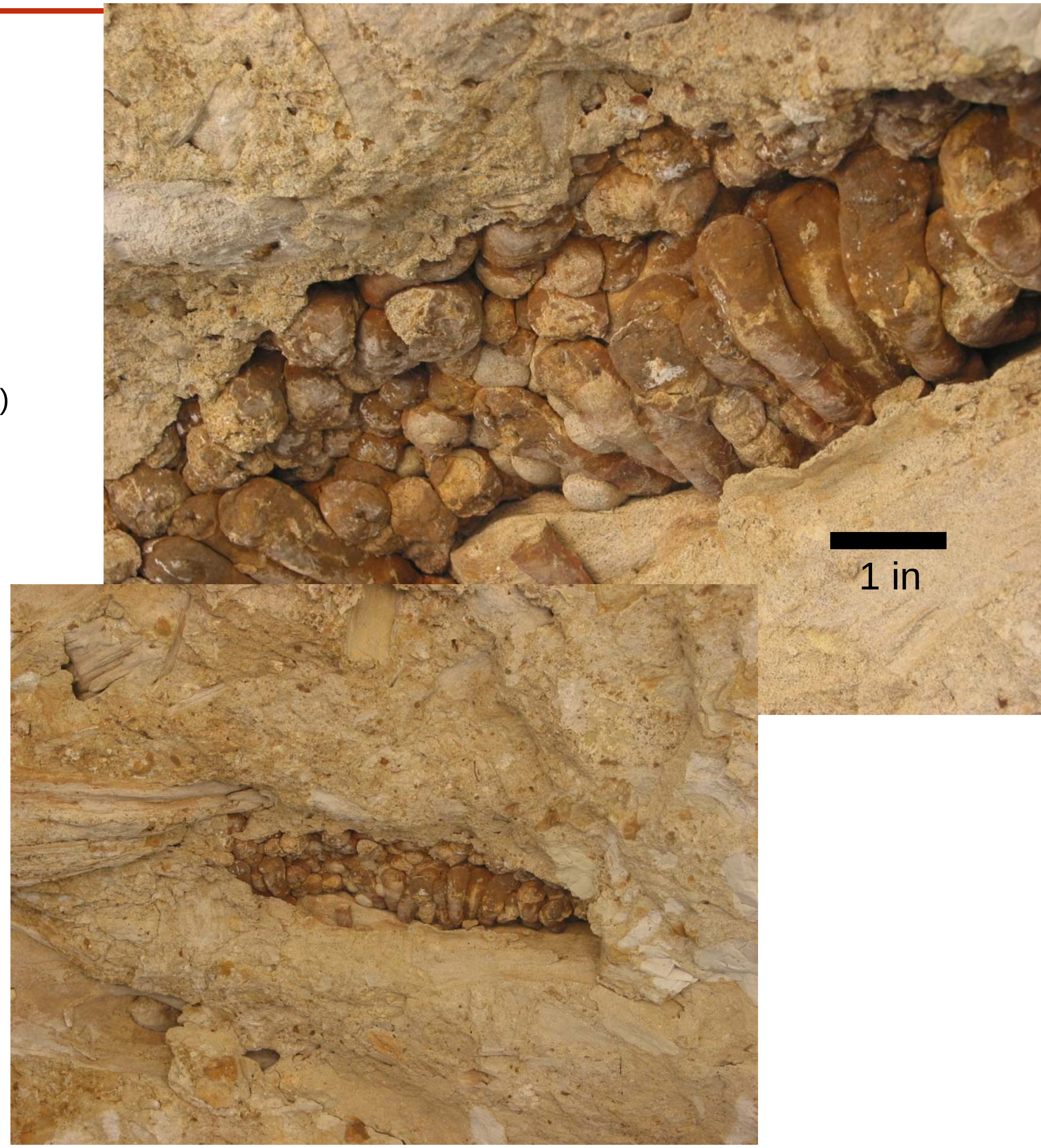


Teredolites Ichnofacies – indicating marine influence

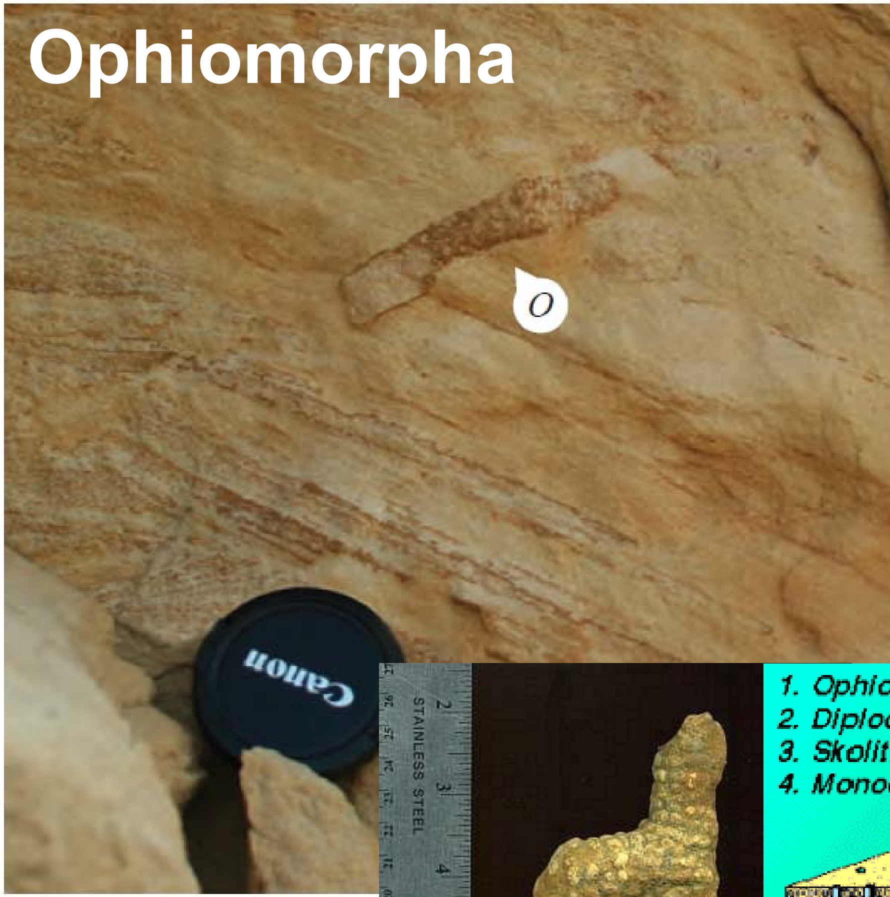


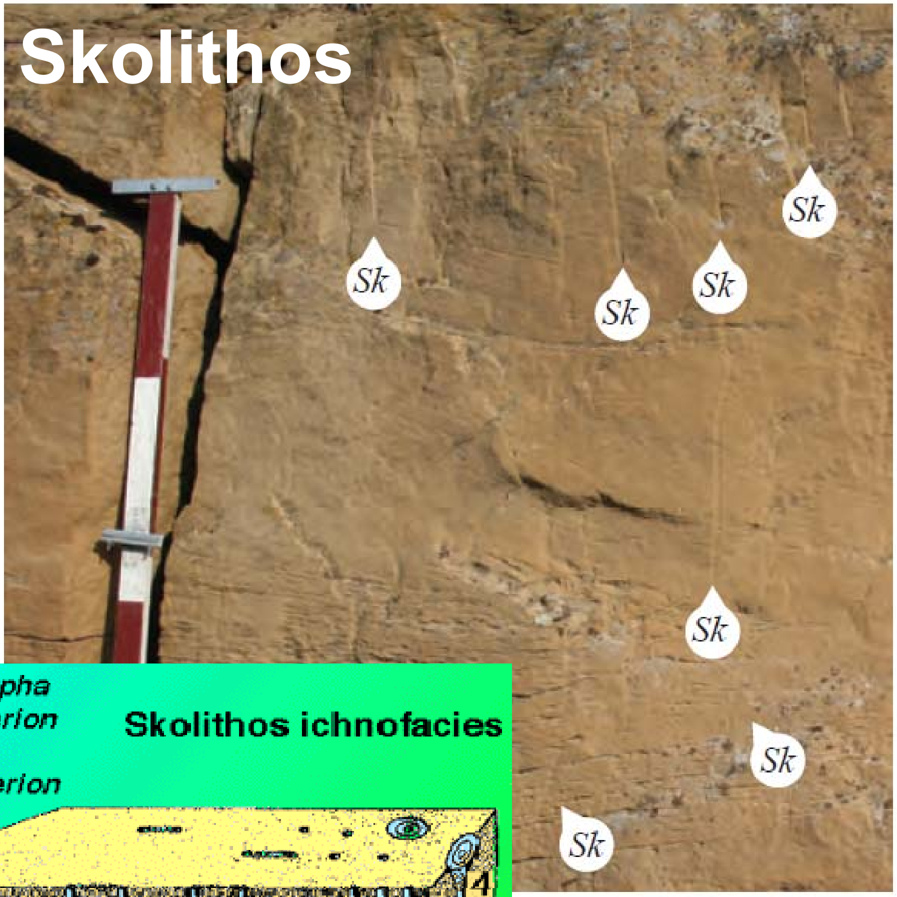
After Benton & Harper (1997)

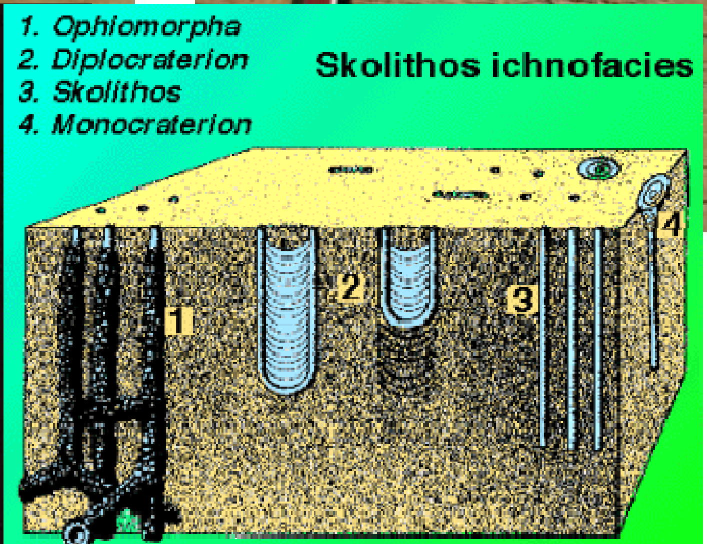
The Teredolites Ichnofacies is identified by the presence of borings in wood (e.g., Teredolites), especially those produced by marine bivalves such as the modern ship worm, Teredo.



Skolithos Ichnofacies – indicating marine influence







After Benton & Harper (1997)

Stratigraphy and Type Well

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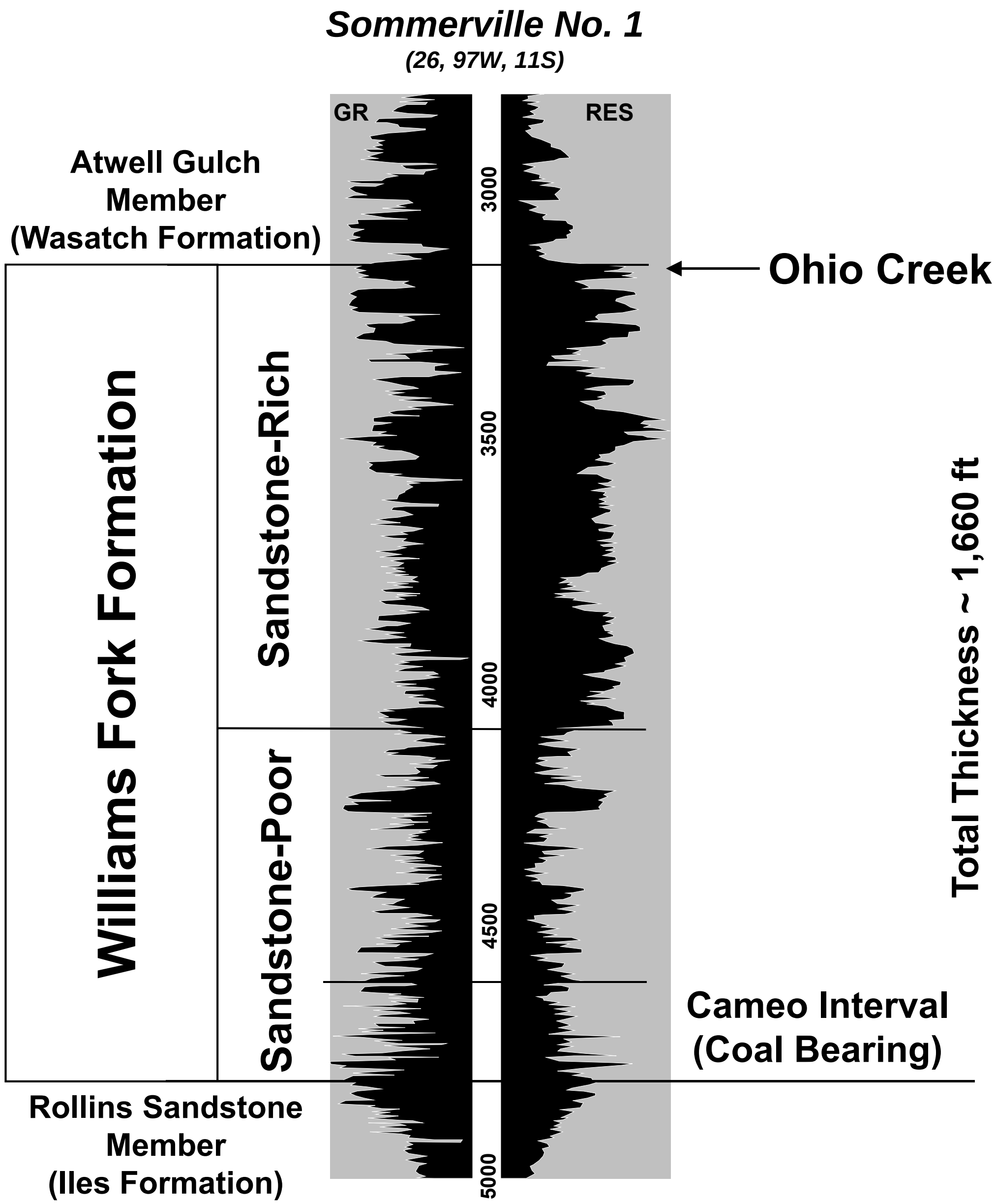
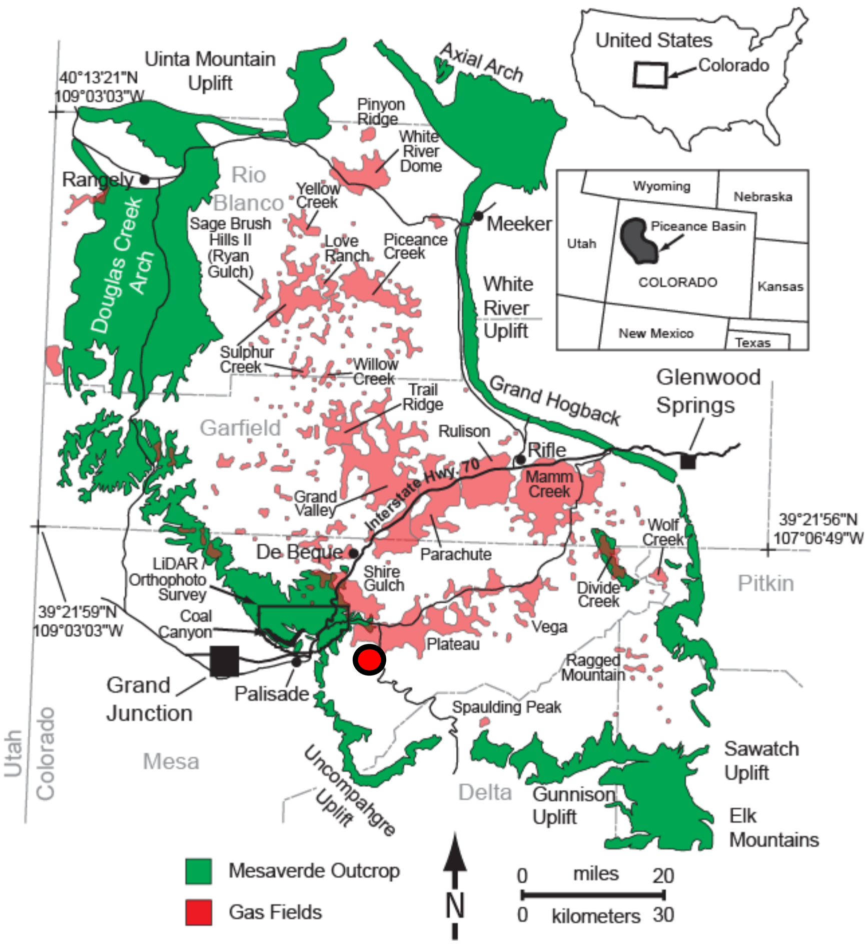
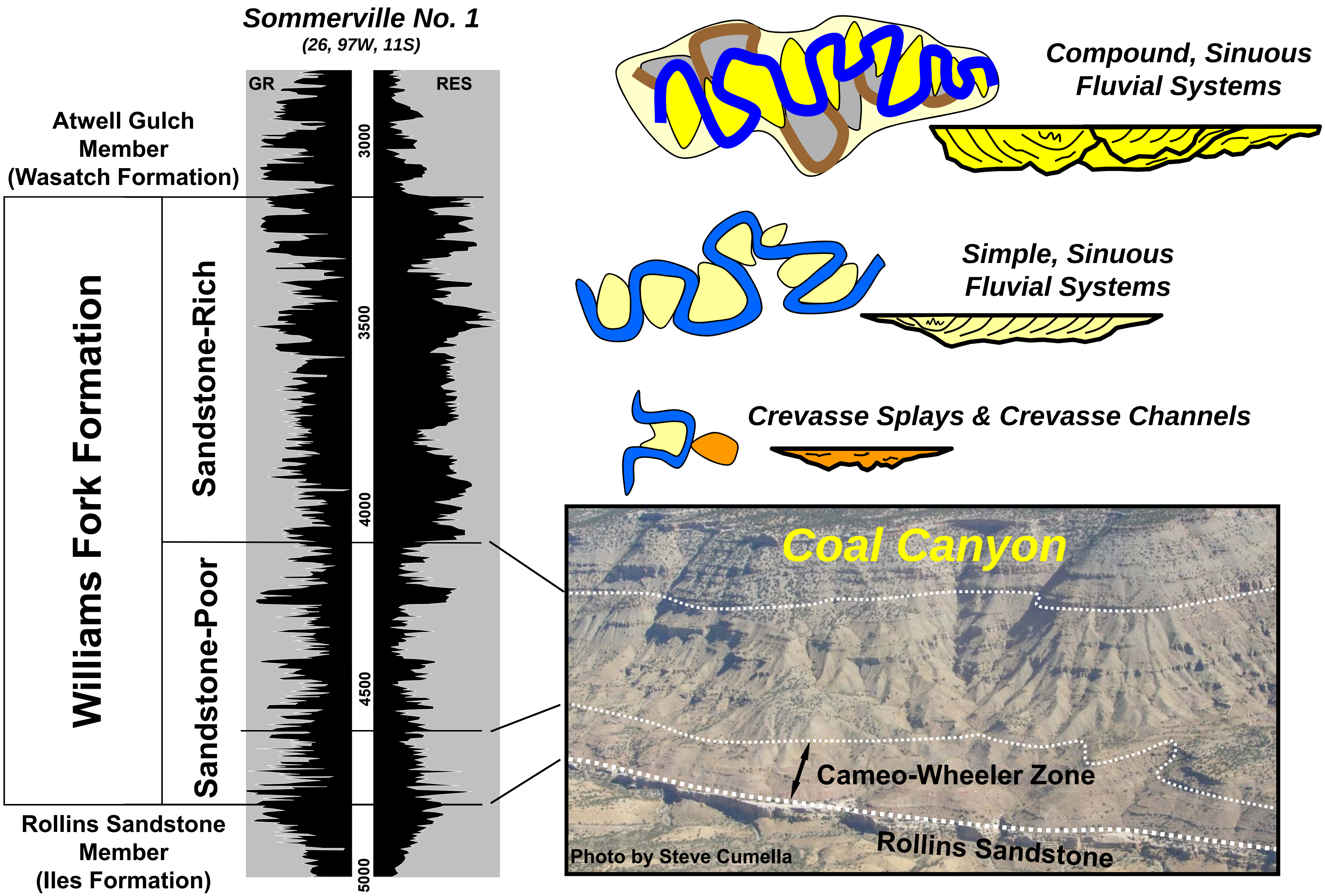
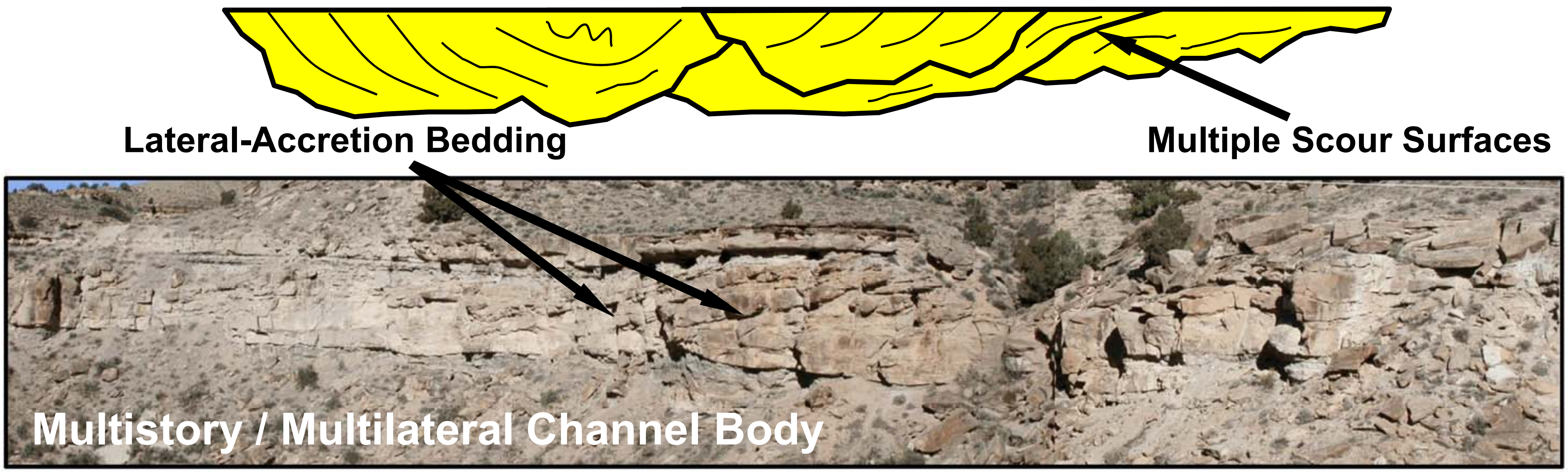




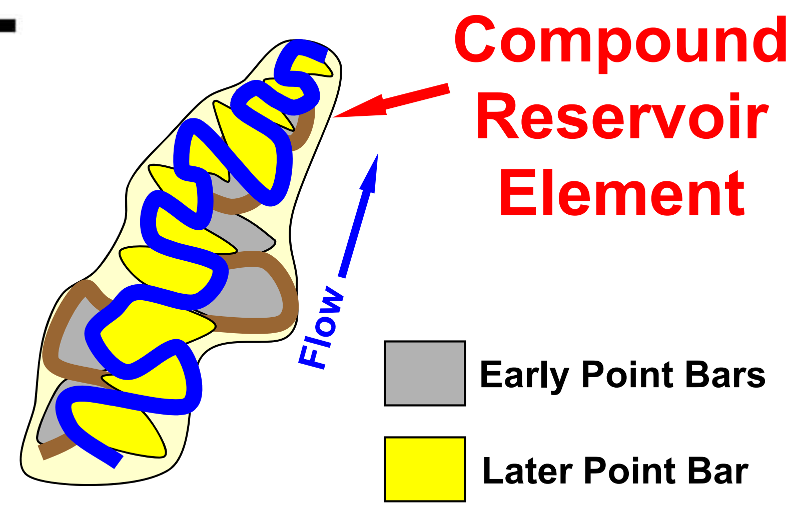
Sandstone-Poor
lower Williams Fork Formation



Compound, Sinuous Architectural Element
Multistory / Multilateral Channel Body

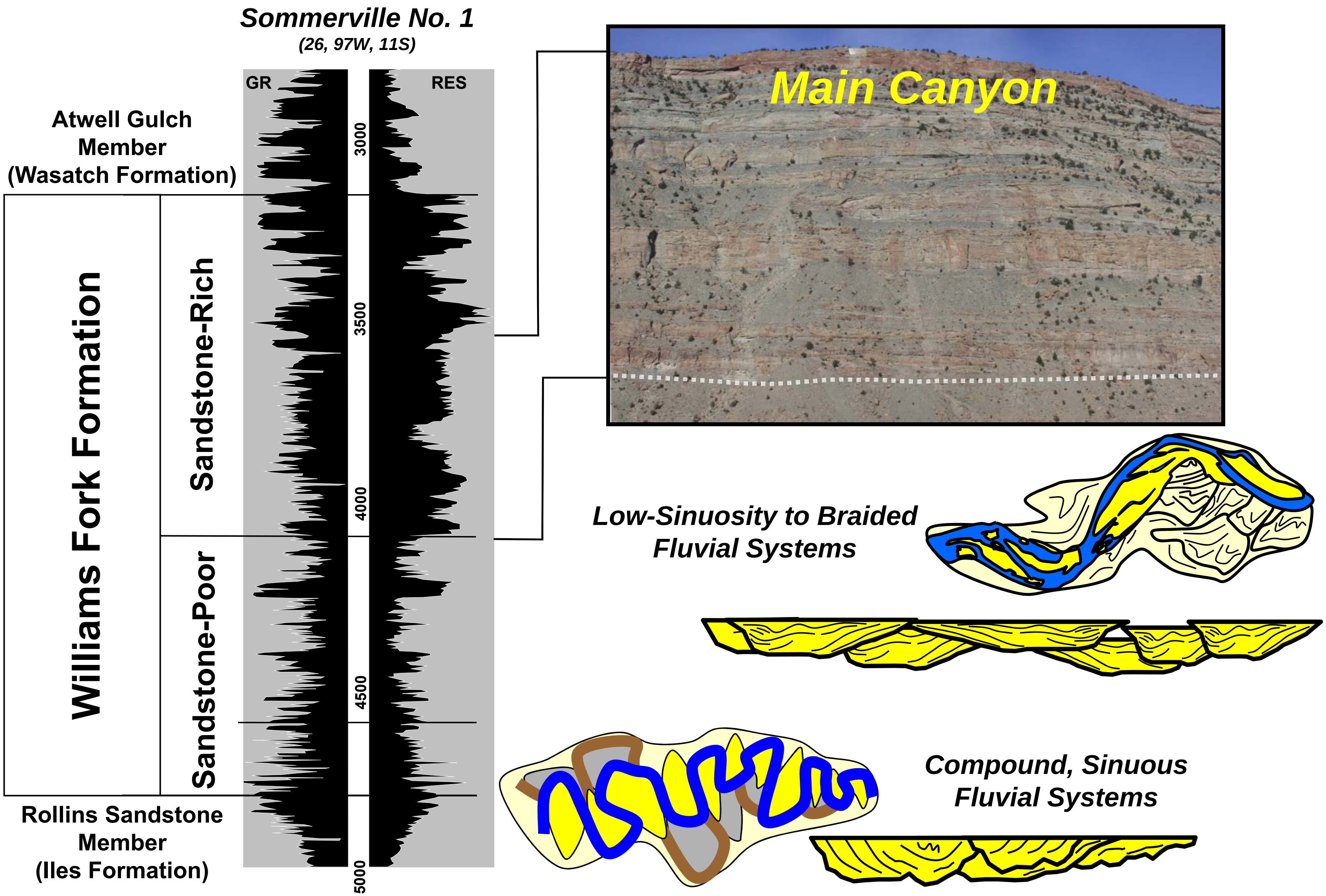


~ 30 Ft



Modified from Cole and Cumella (2005) & Pranter et al. (2009)

Sandstone-Rich
lower to middle Williams Fork Formation



Sandstone-Rich
lower to middle Williams Fork Formation

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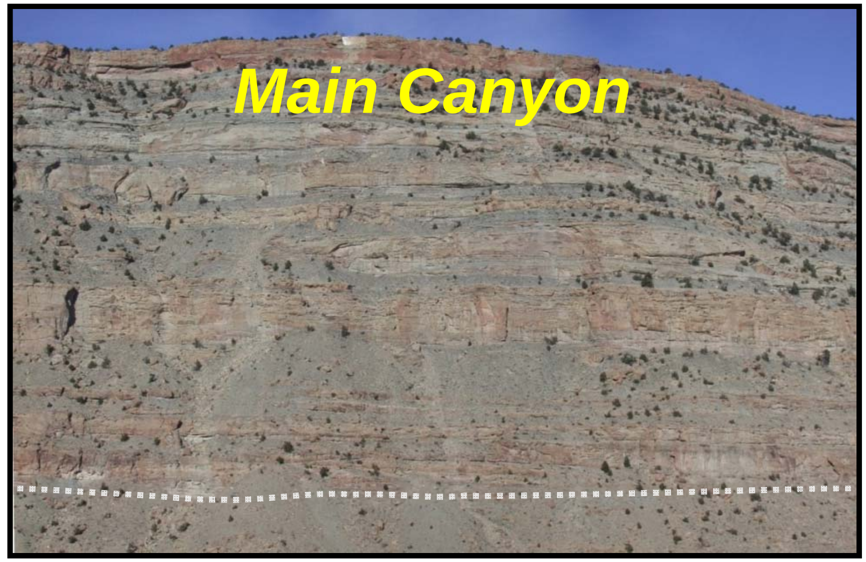
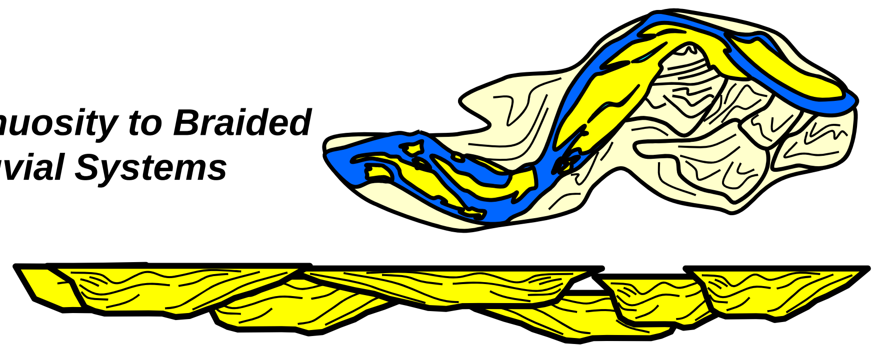
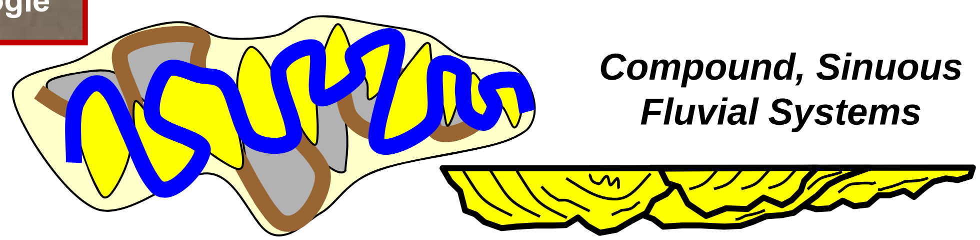


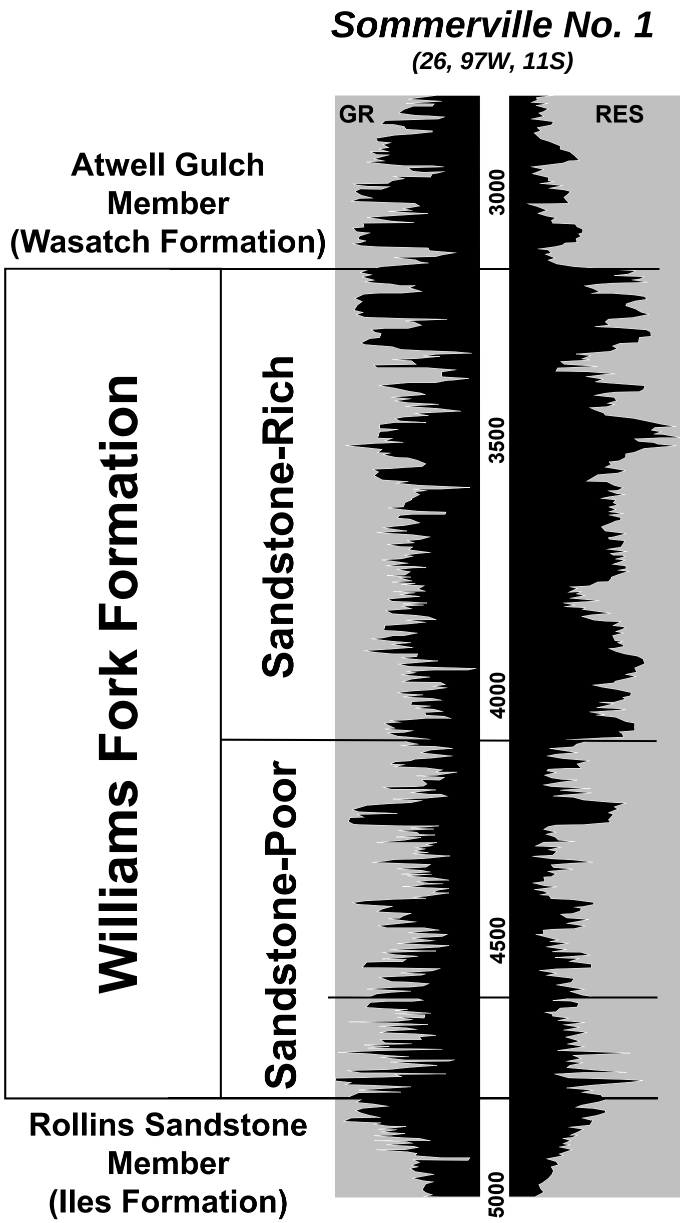


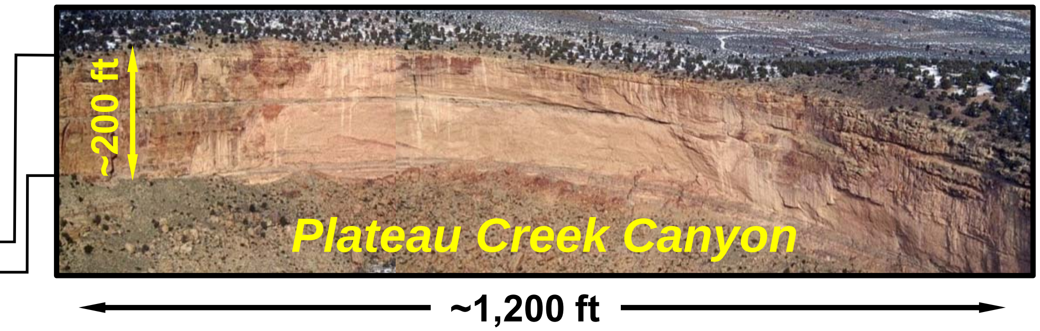
Low-Sinuosity to Braided Fluvial Systems



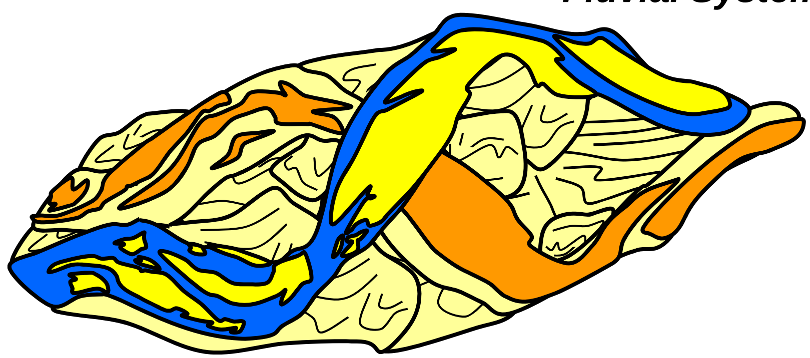
Compound, Sinuous Fluvial Systems

Sandstone-Rich
middle and upper Williams Fork Formation





Amalgamated Low-Sinuosity to Braided Fluvial Systems

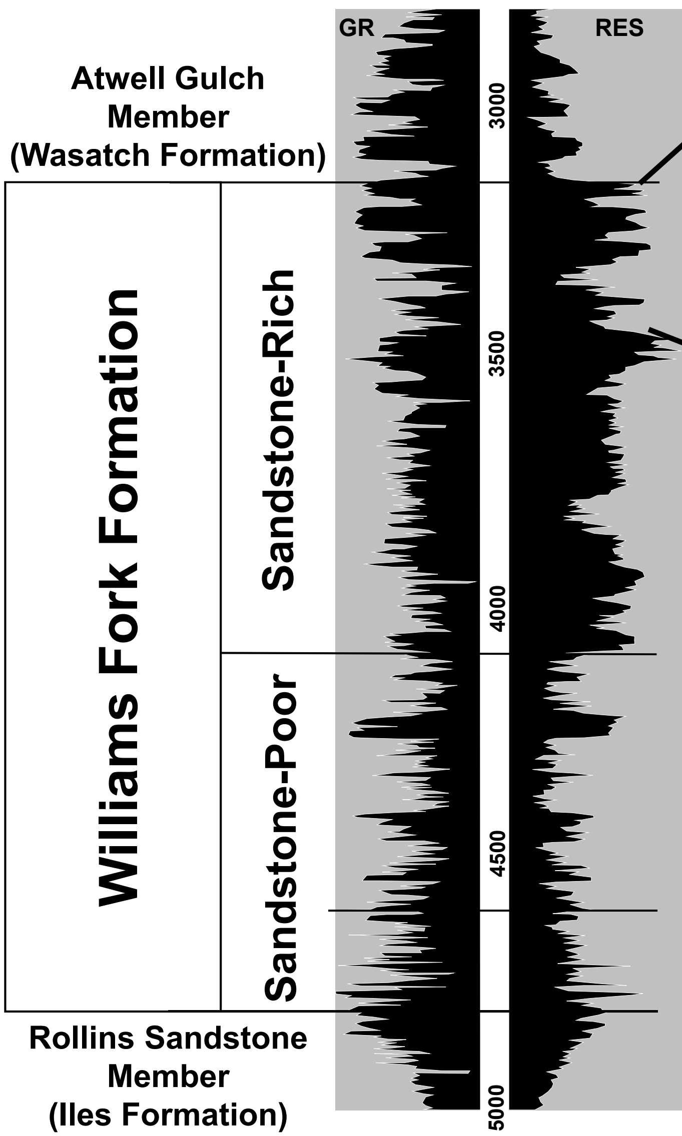


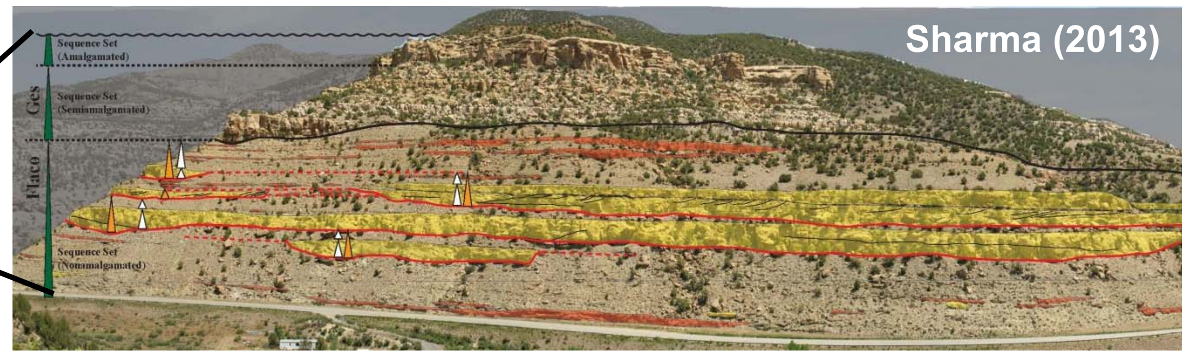
Apparent width of 100s to 10,000s of feet

Sandstone-Rich
middle and upper Williams Fork Formation

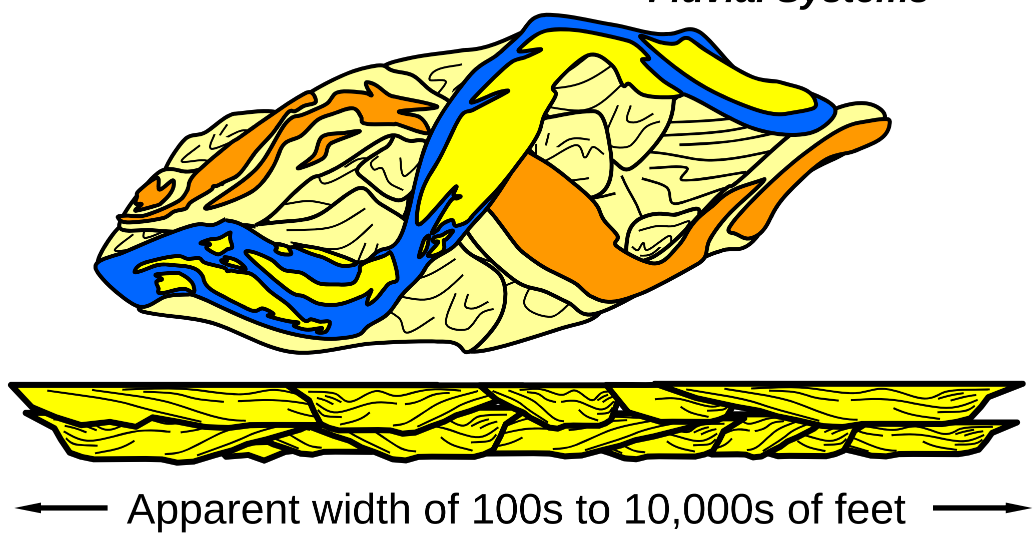
Sommerville No. 1

(26, 97W, 11S)

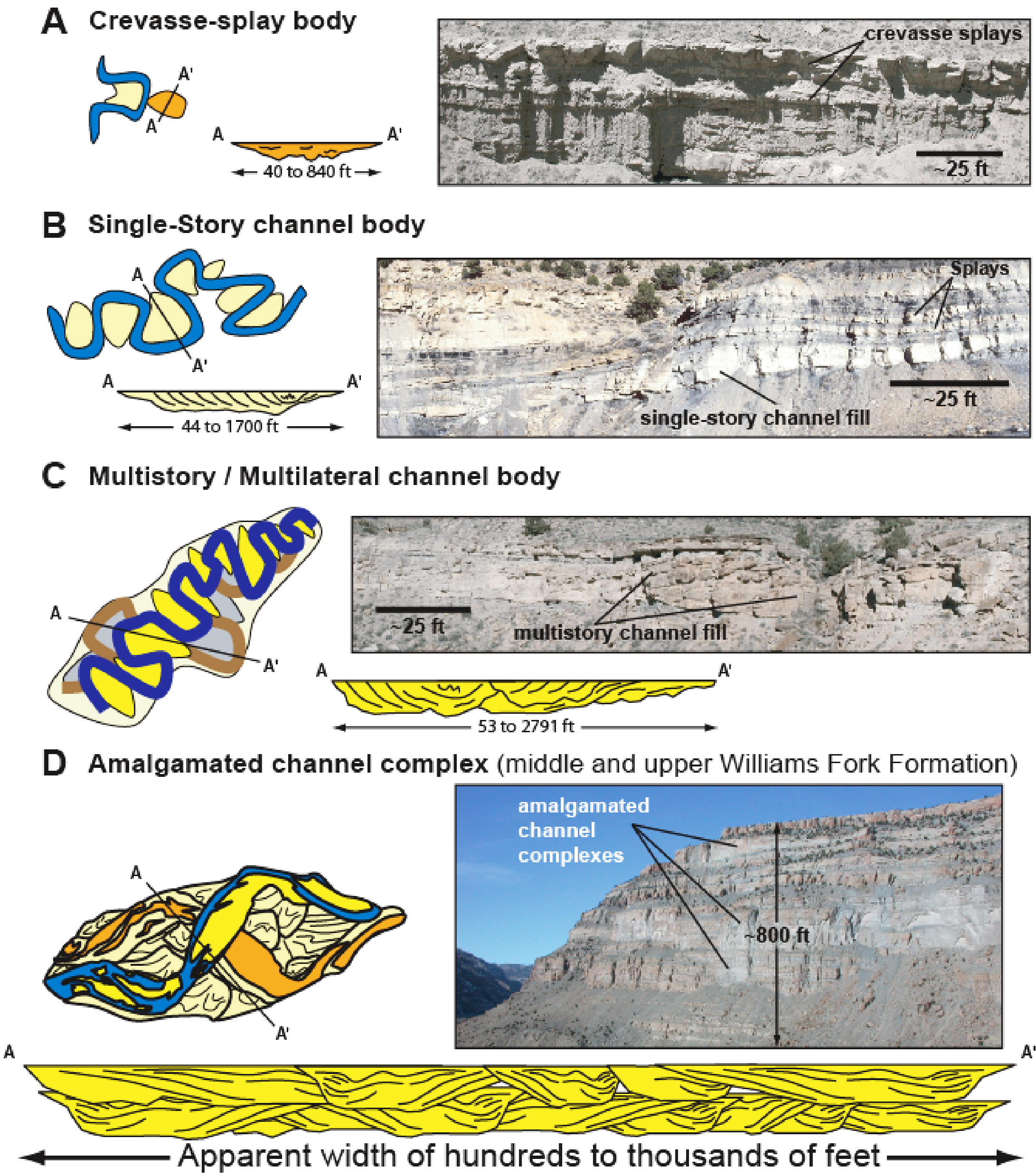




Amalgamated Low-Sinuosity to Braided Fluvial Systems



Summary of Fluvial Architectural Elements



Pranter et al. (2009); Pranter and Sommer (2011)

Methodology: *Outcrop Measurements*

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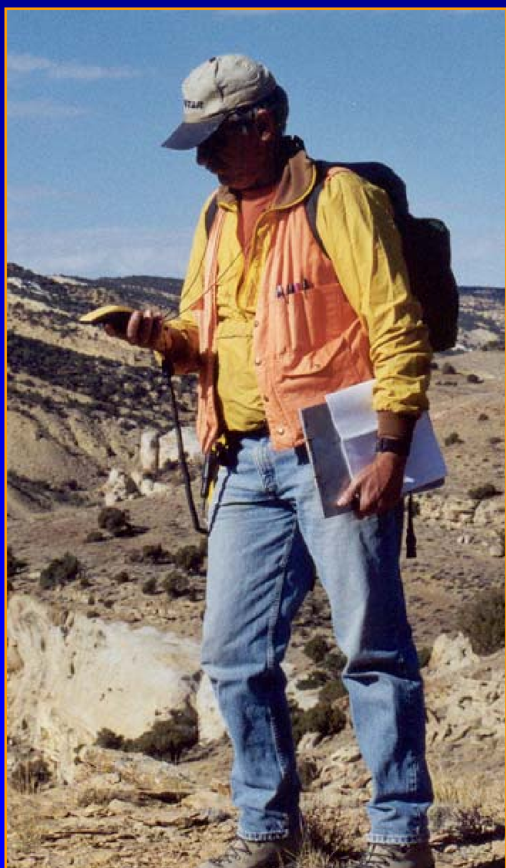
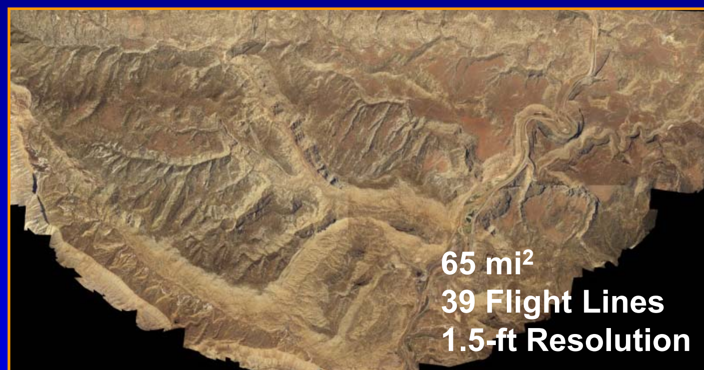
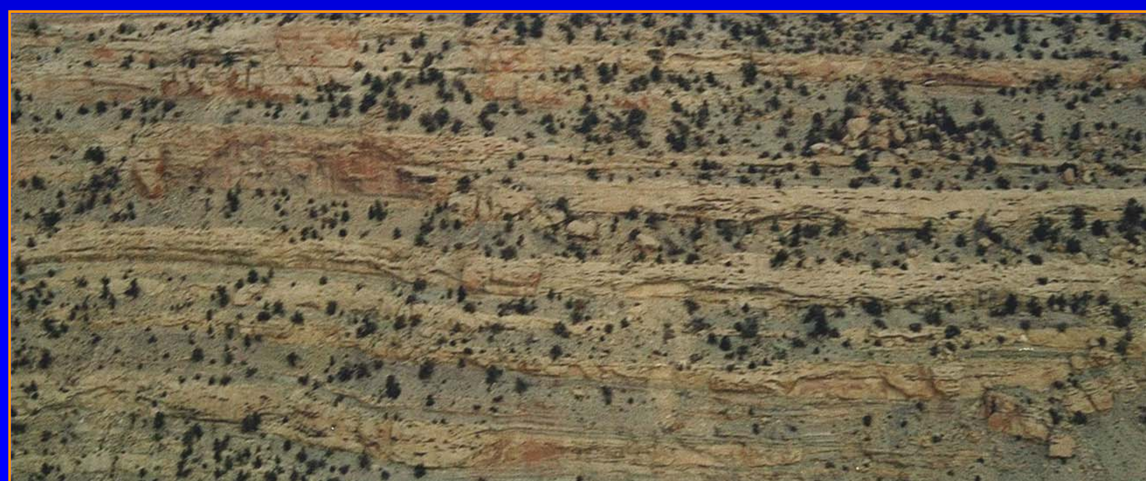
Fluvial Sandstone-Body Dimensions were Measured 3 Ways

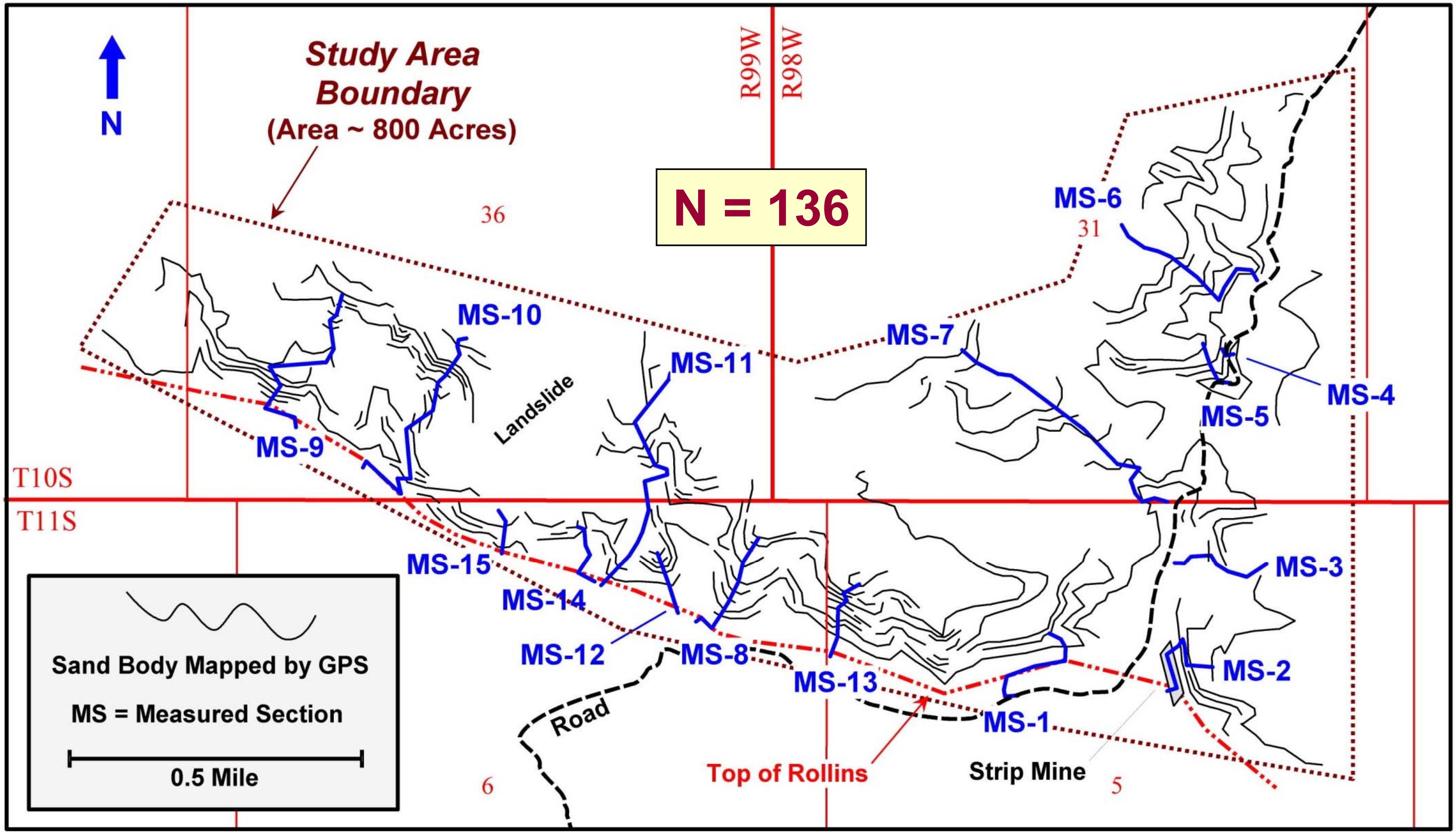
1. Field Mapping (GPS & Measured Sections); *Ground Pounding*
2. Aerial LiDAR coupled with Aerial Orthophotographs (Petrel)
3. Calibrated Photo Panoramas of Cliff Faces







Sandstone-Body Distribution



2001 & 2002

Cole and Cumella (2005)

Ground-Based LiDAR – "pilot" study

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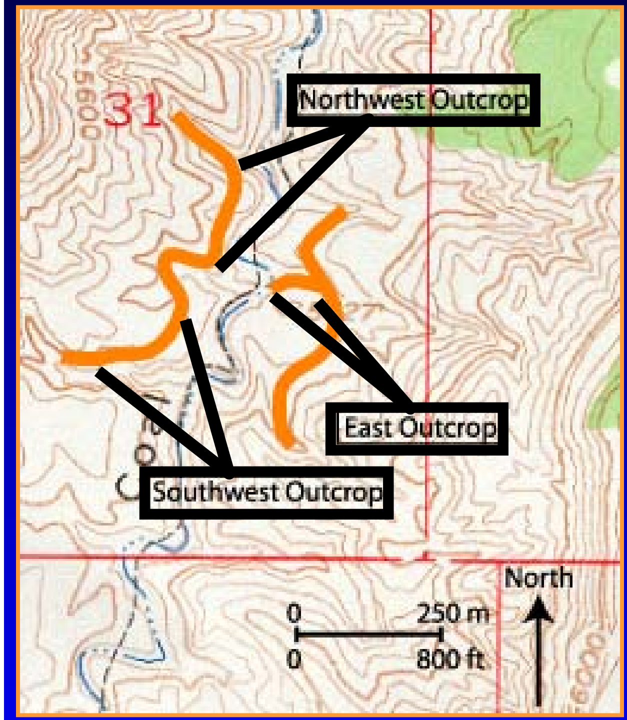
May 2003

Horses for scale

Architectural-Element Heterogeneity



Modified from Ellison (2004) and Pranter et al. (2007)

Architectural-Element Heterogeneity

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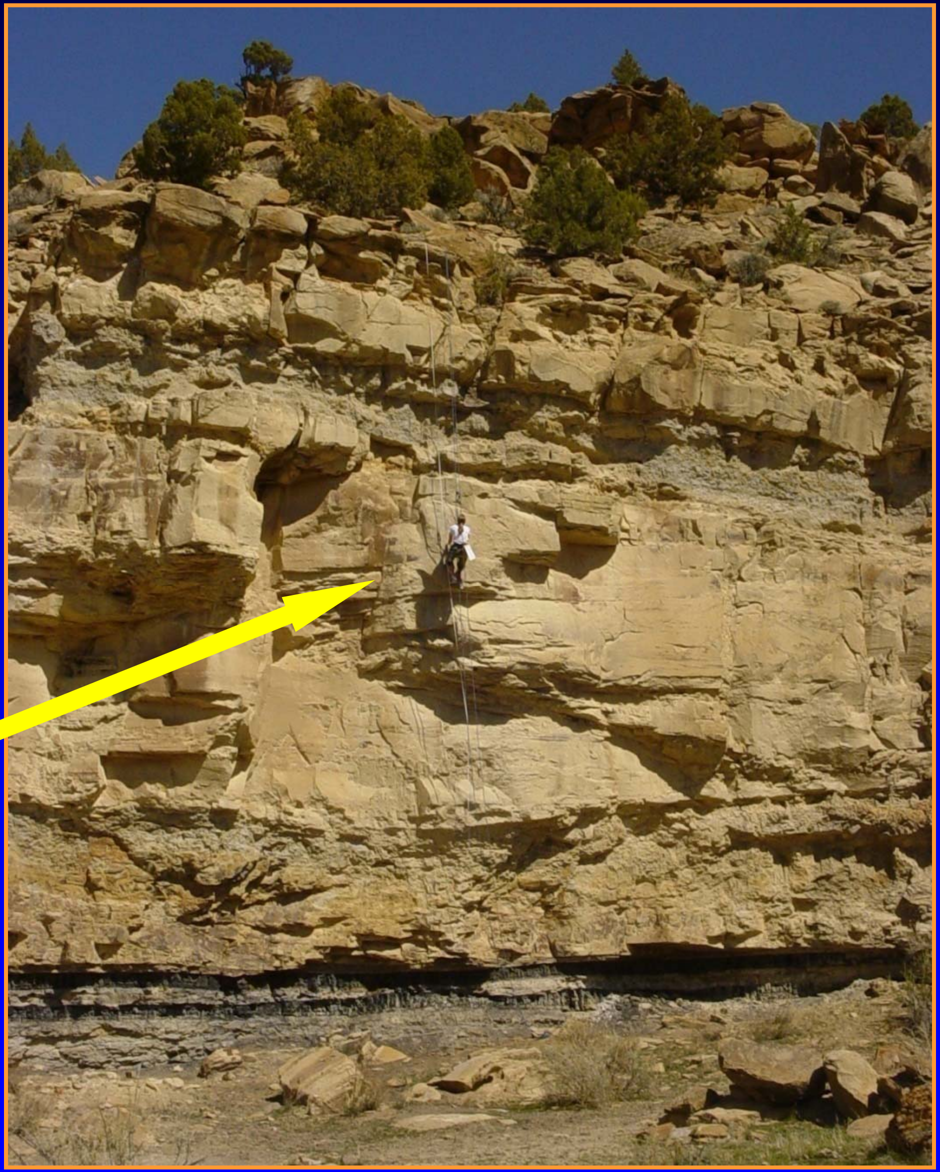
Hanging out on the Rocks!

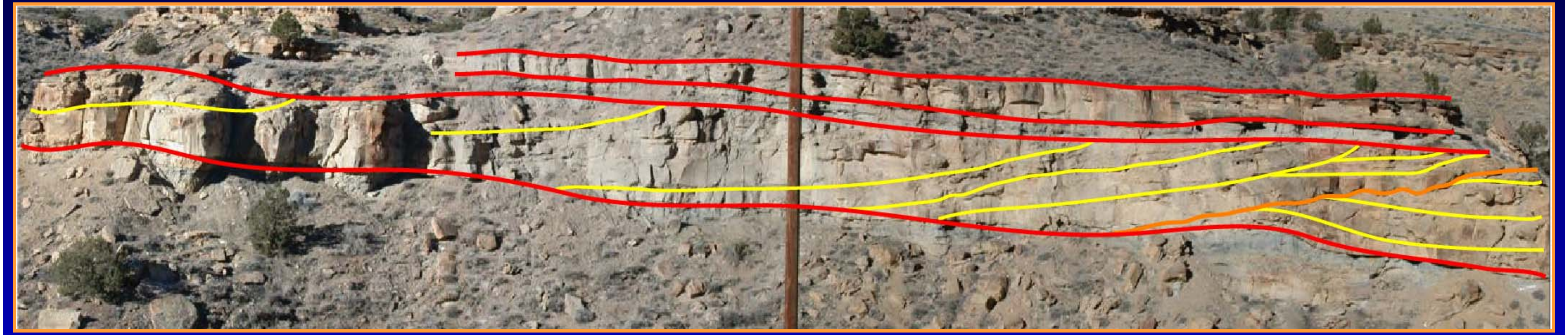


Graduate student for scale

Architectural-Element Heterogeneity

South

North



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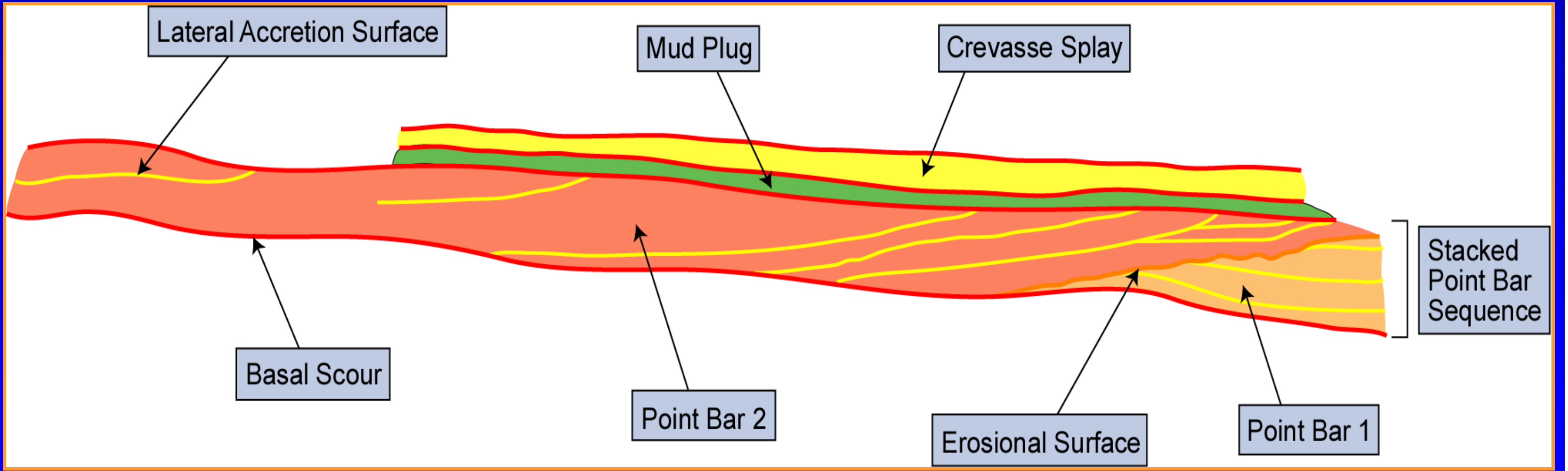
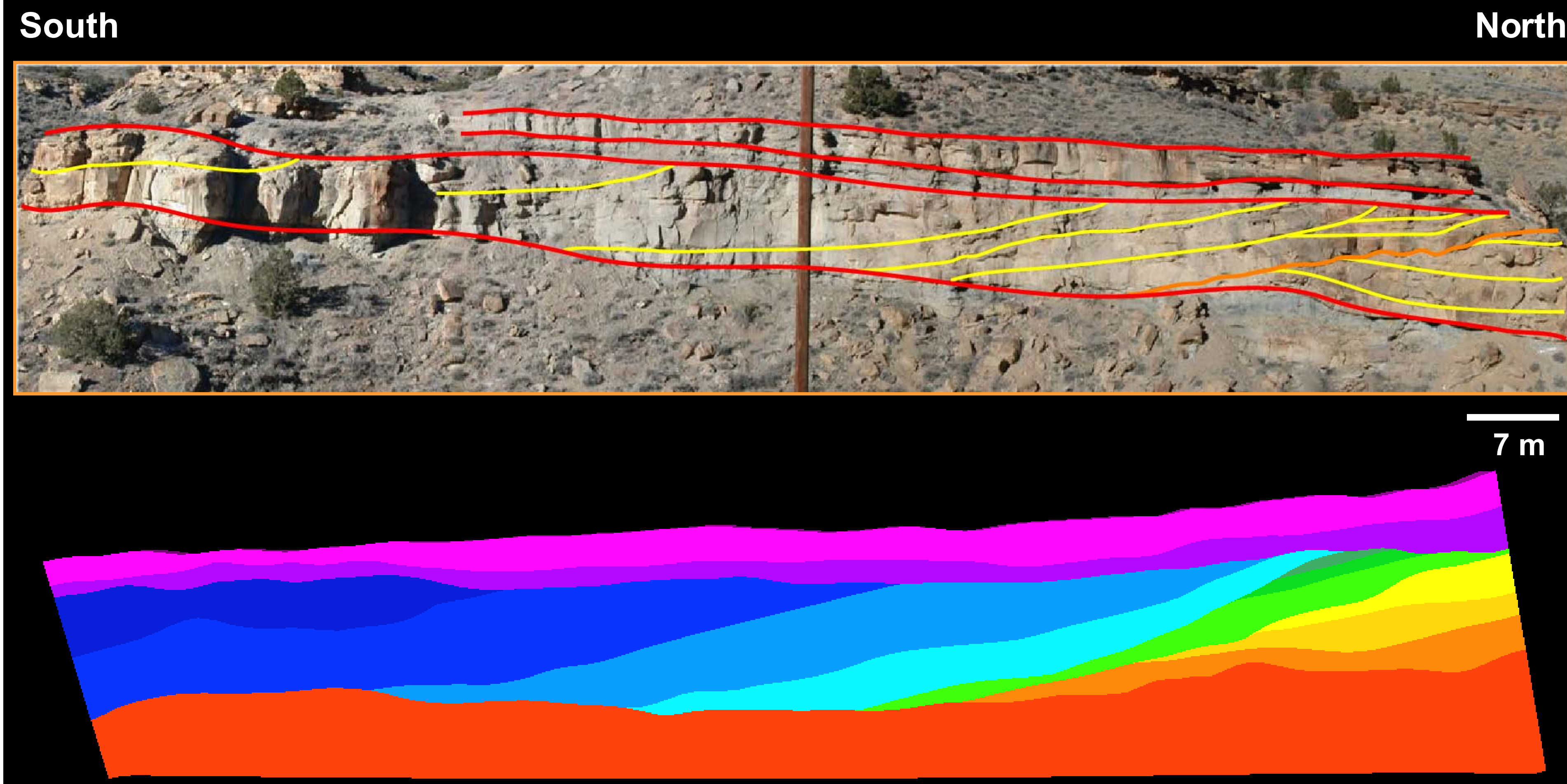


Modified from Ellison (2004) and Pranter et al. (2007)

2-D and 3-D Point-Bar Reservoir Models



Modified from Ellison (2004) and Pranter et al. (2007)

2-D and 3-D Point-Bar Reservoir Models

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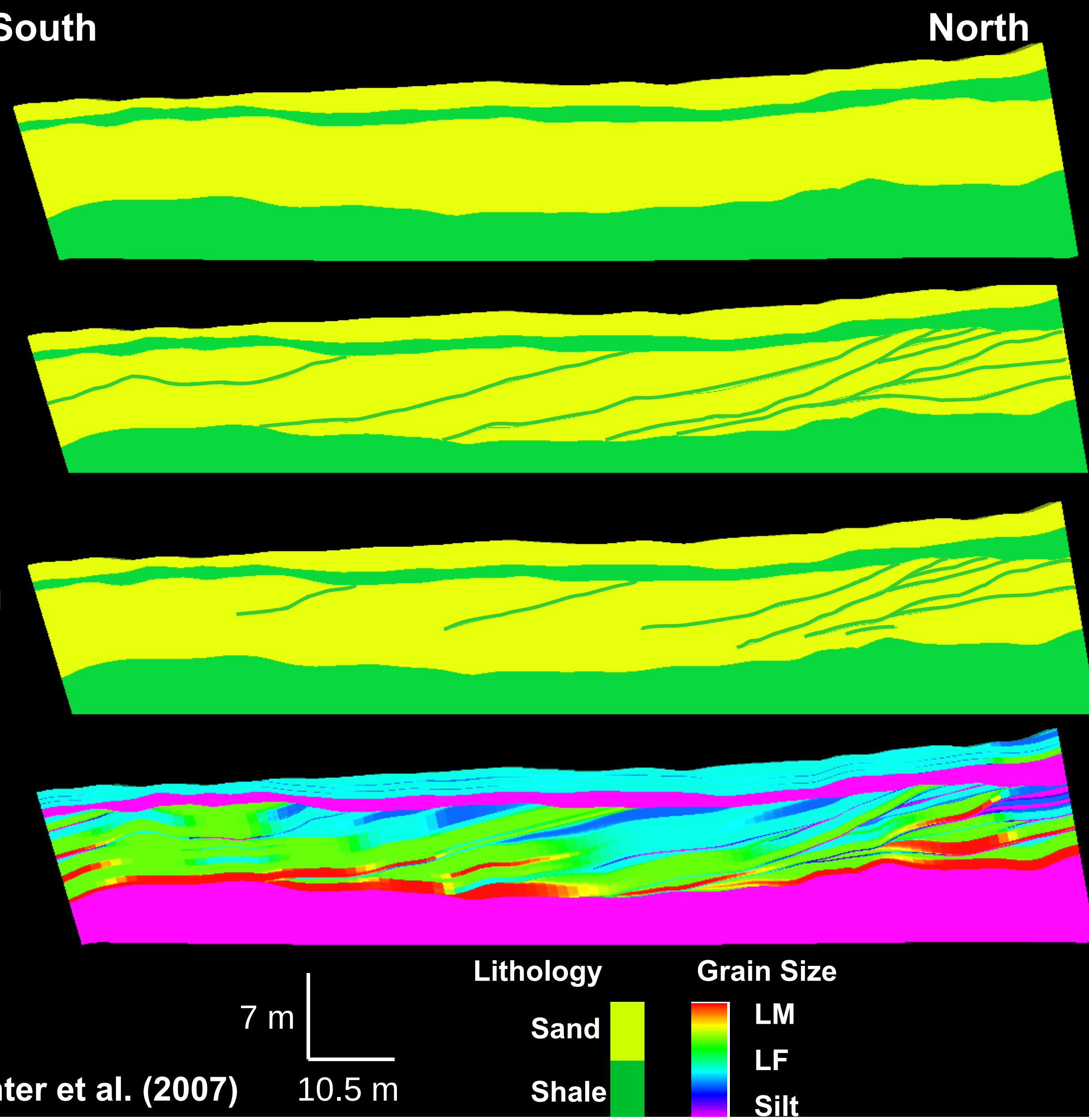
Lithology Model 1:
Homogeneous point bar deposit

Lithology Model 2:
Fluid baffles along lateral accretion surfaces

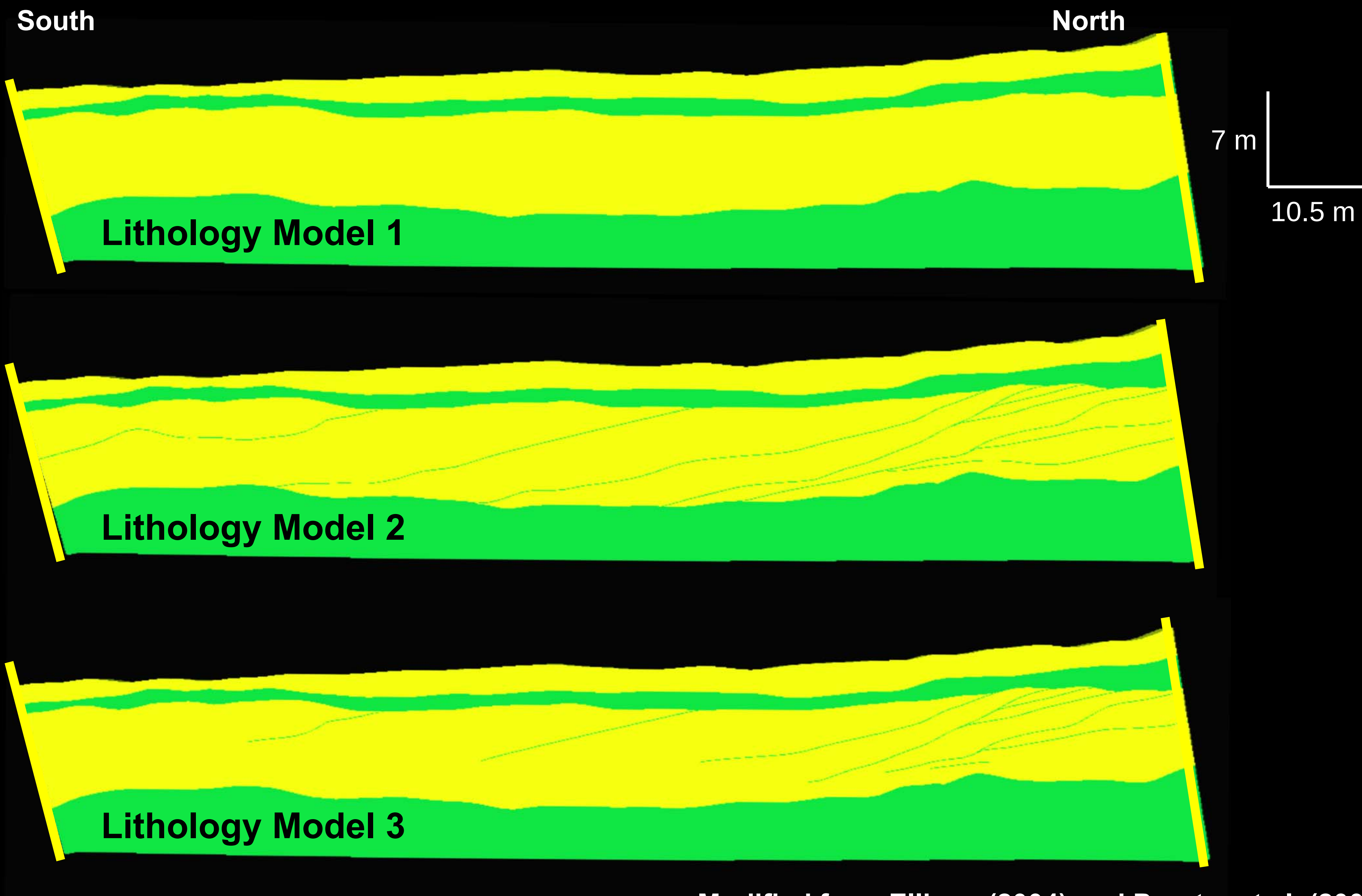
Lithology Model 3:
Fluid baffles associated with shale breaks on lateral accretion surfaces

Grain-Size Model:
Based on measured section data from outcrop



Modified from Ellison (2004) and Pranter et al. (2007)

Significance of Architectural-Element Heterogeneity



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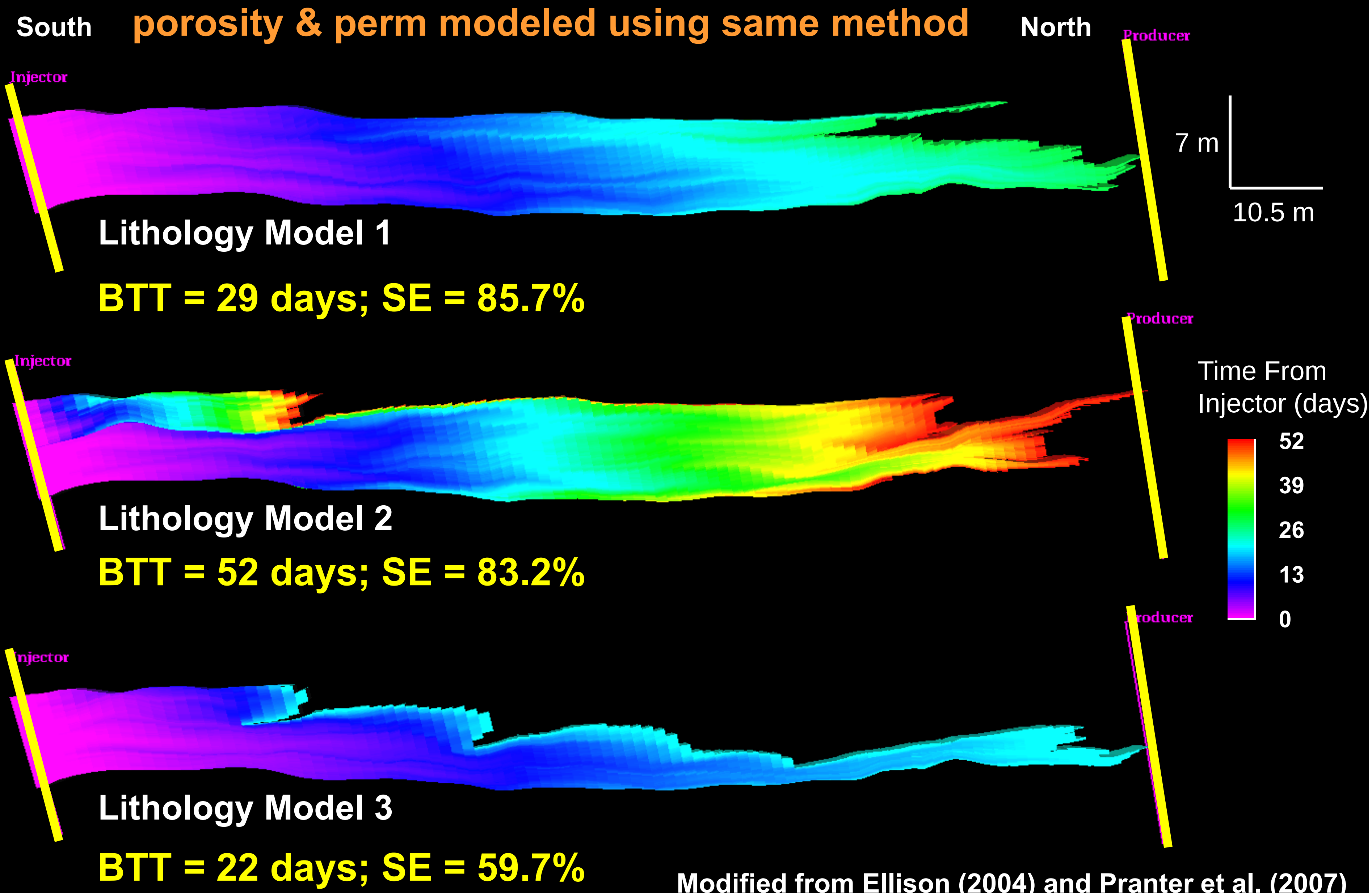
Significance of Architectural-Element Heterogeneity



Modified from Ellison (2004) and Pranter et al. (2007)

Aerial LiDAR - Light Detection And Ranging

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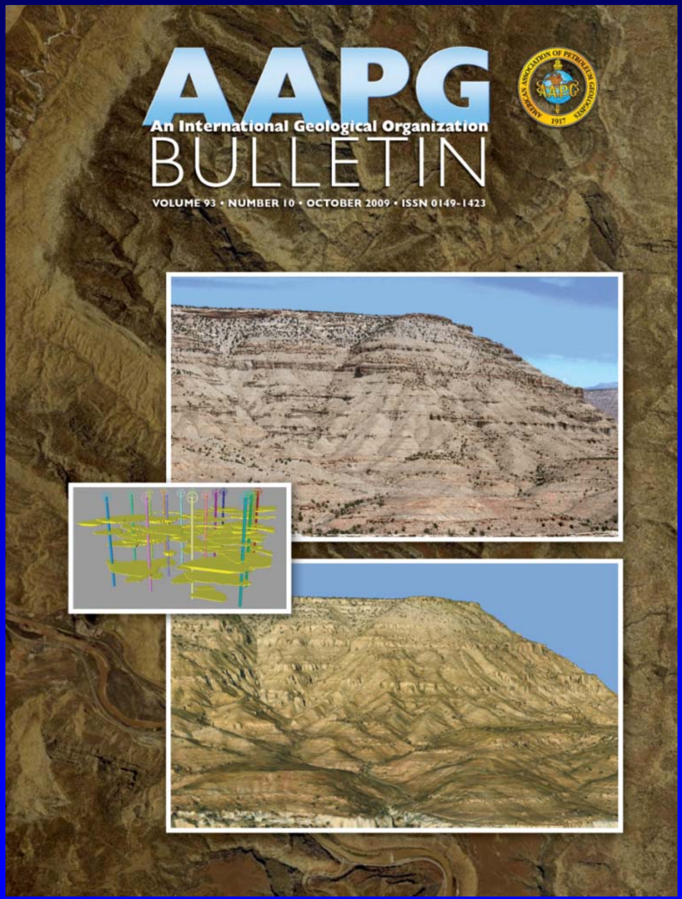
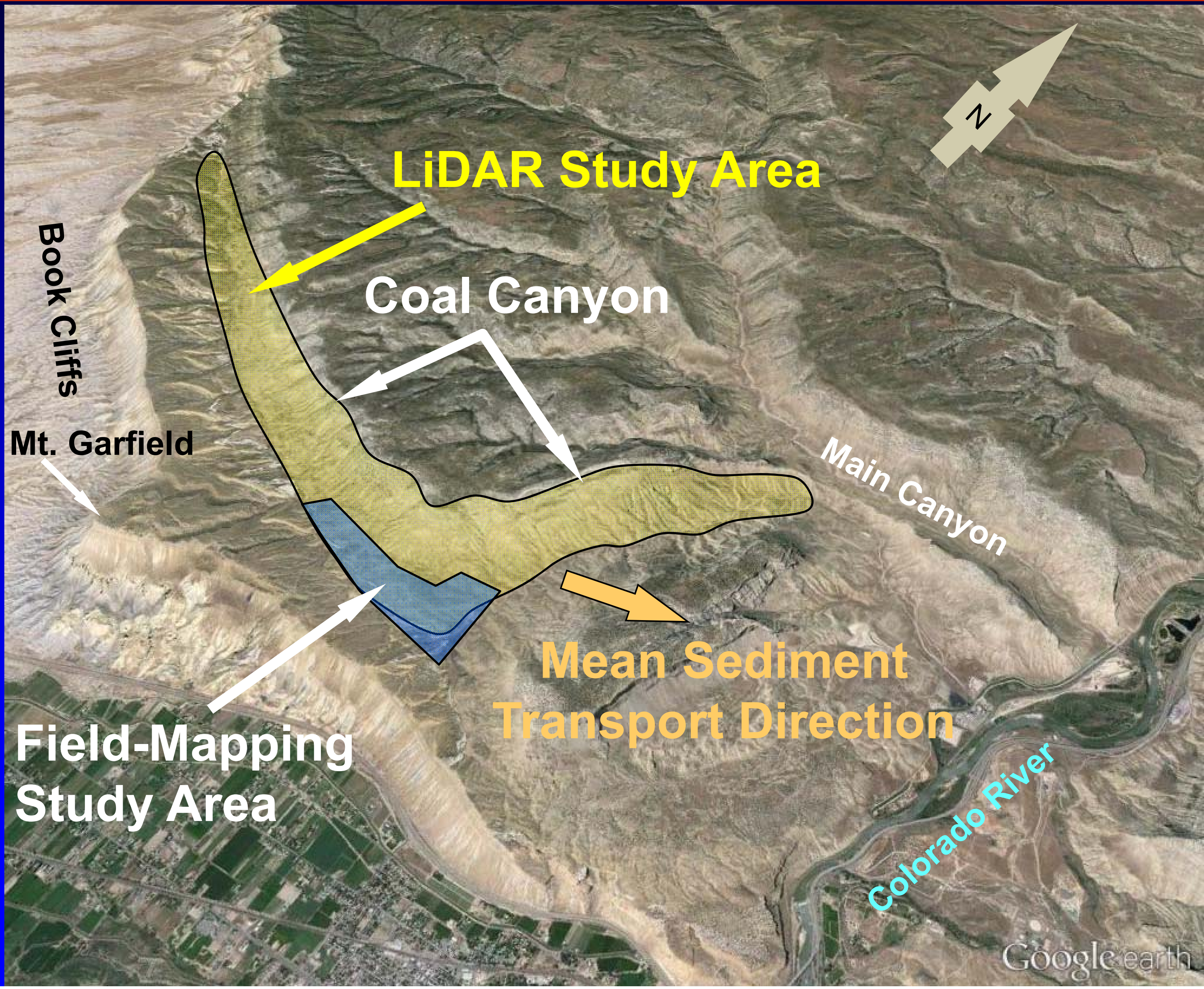
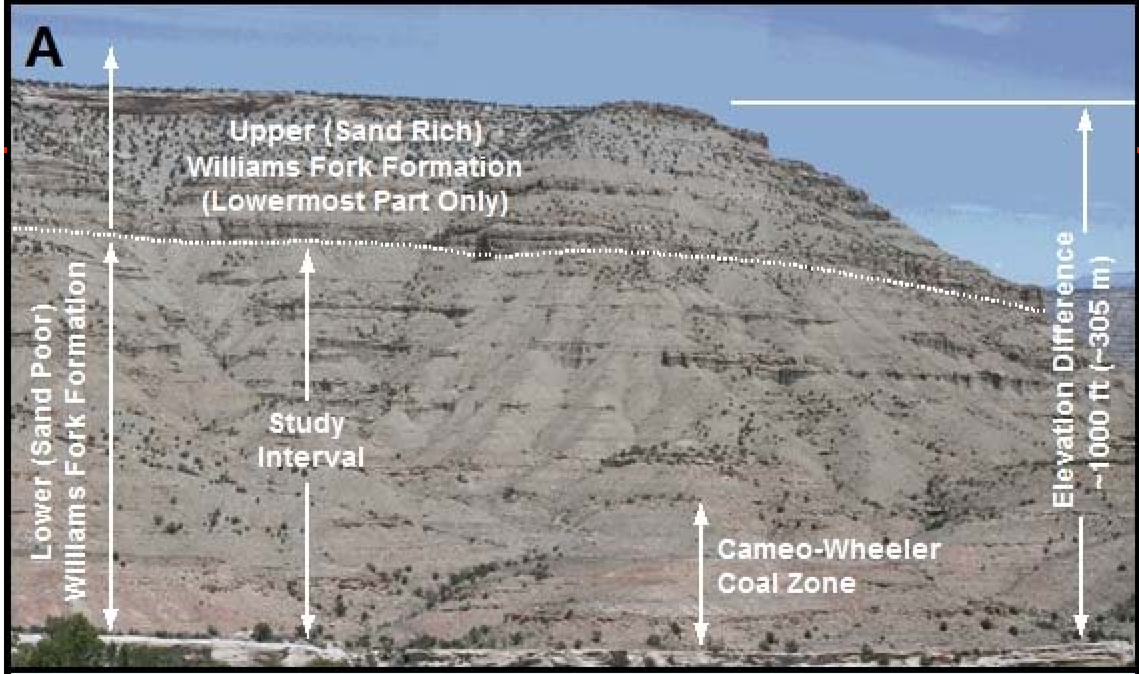
April - June, 2005



Pranter, Cole, Panjaitan, Sommer (2009)

Coal Canyon Study Areas



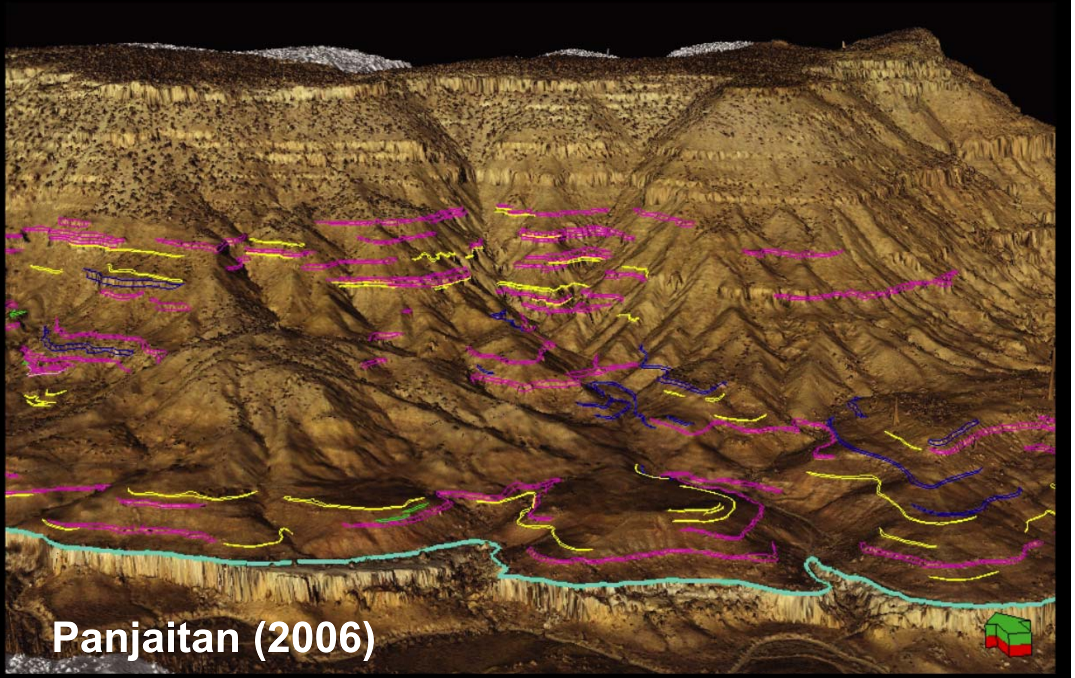


LiDAR - Coal Canyon

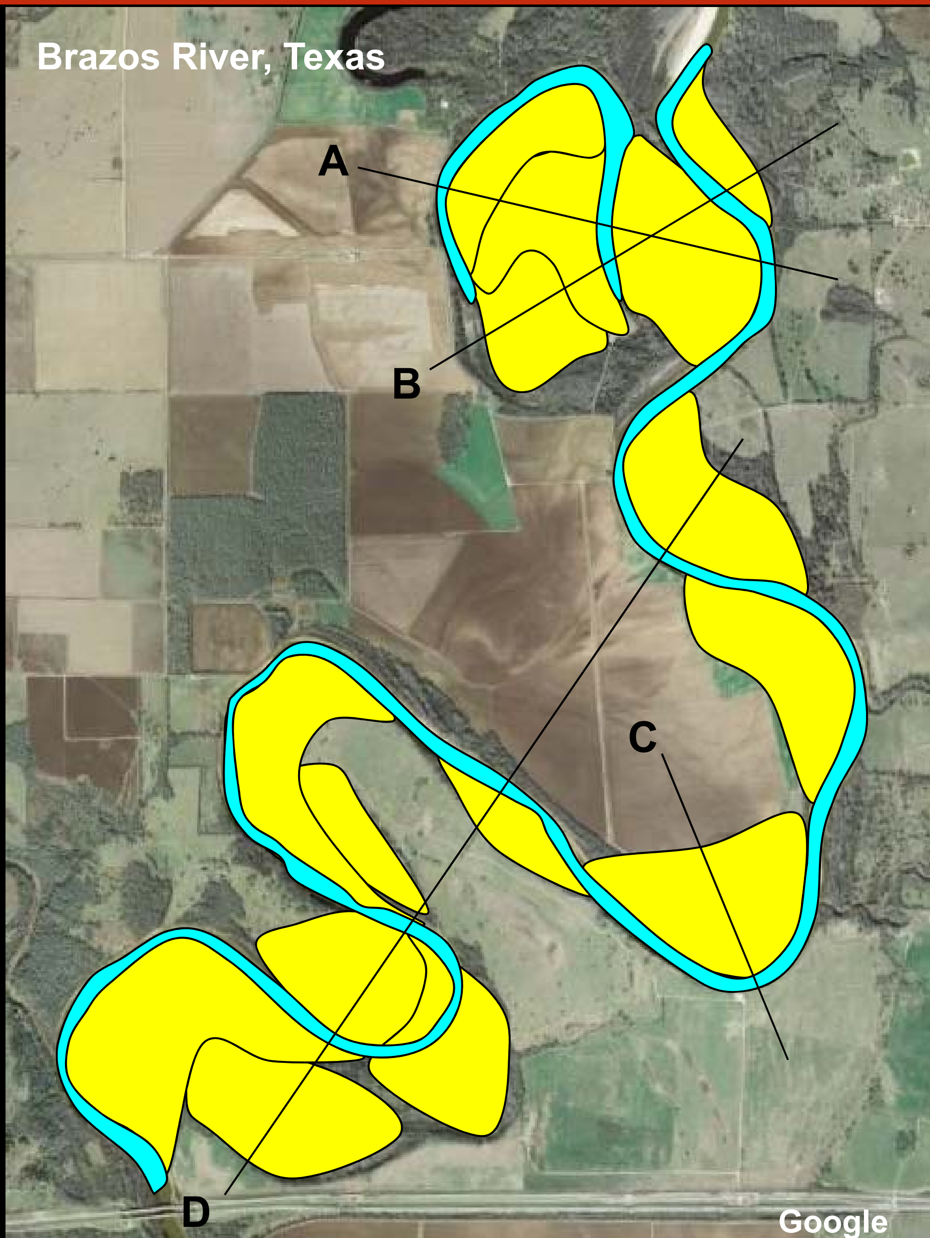
2006 & 2007

Sandstone-Body Dimensions:

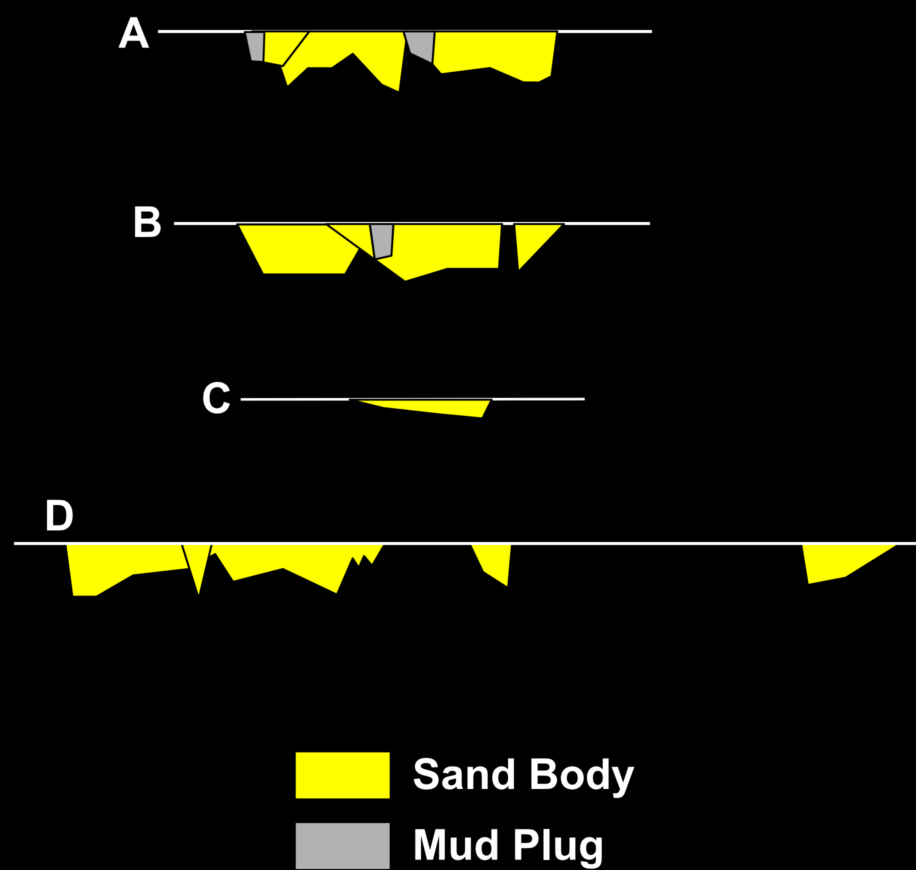
Thickness and *Apparent* Width



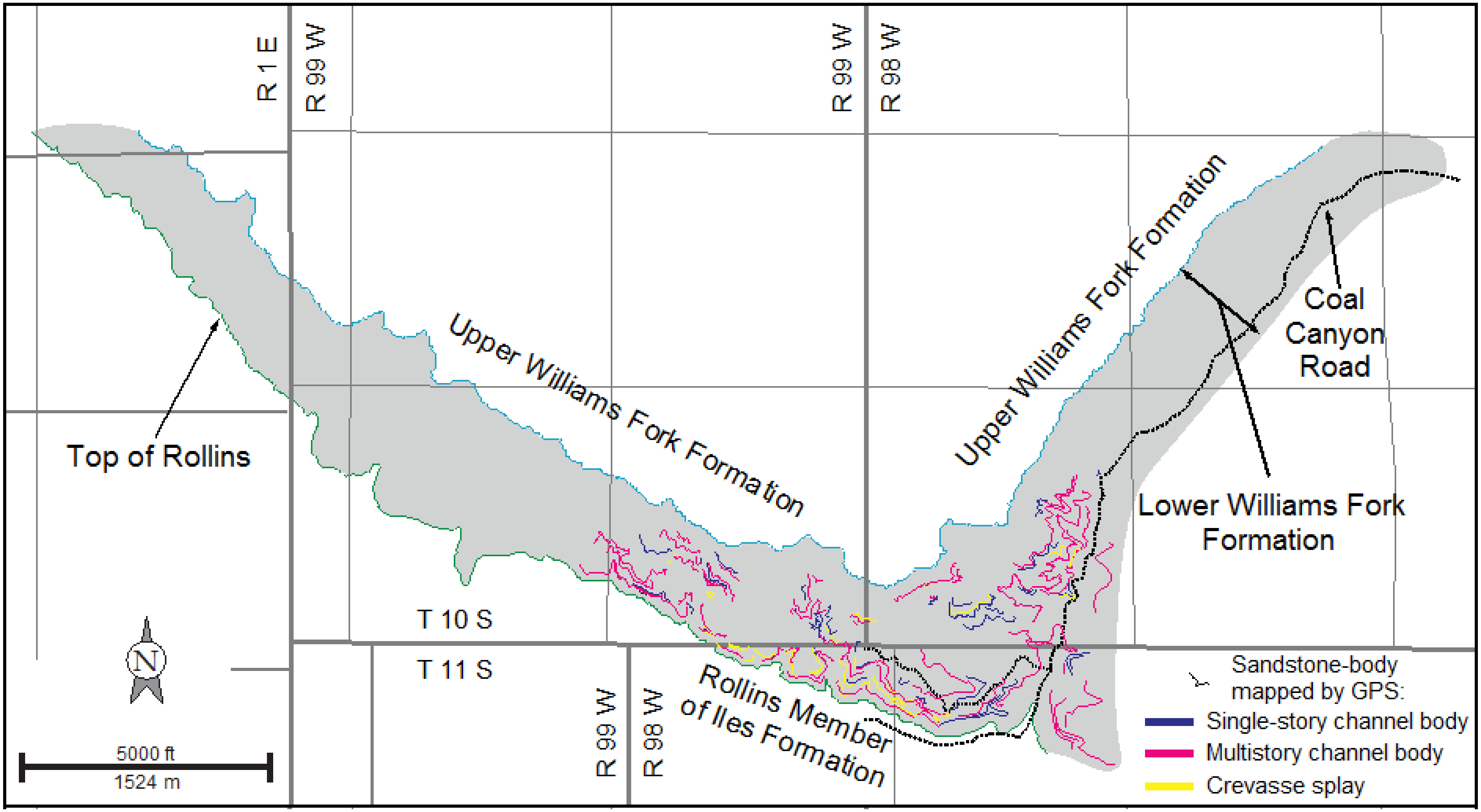
“Slice” Geometries in Modern Point Bar Complex



Apparent Width

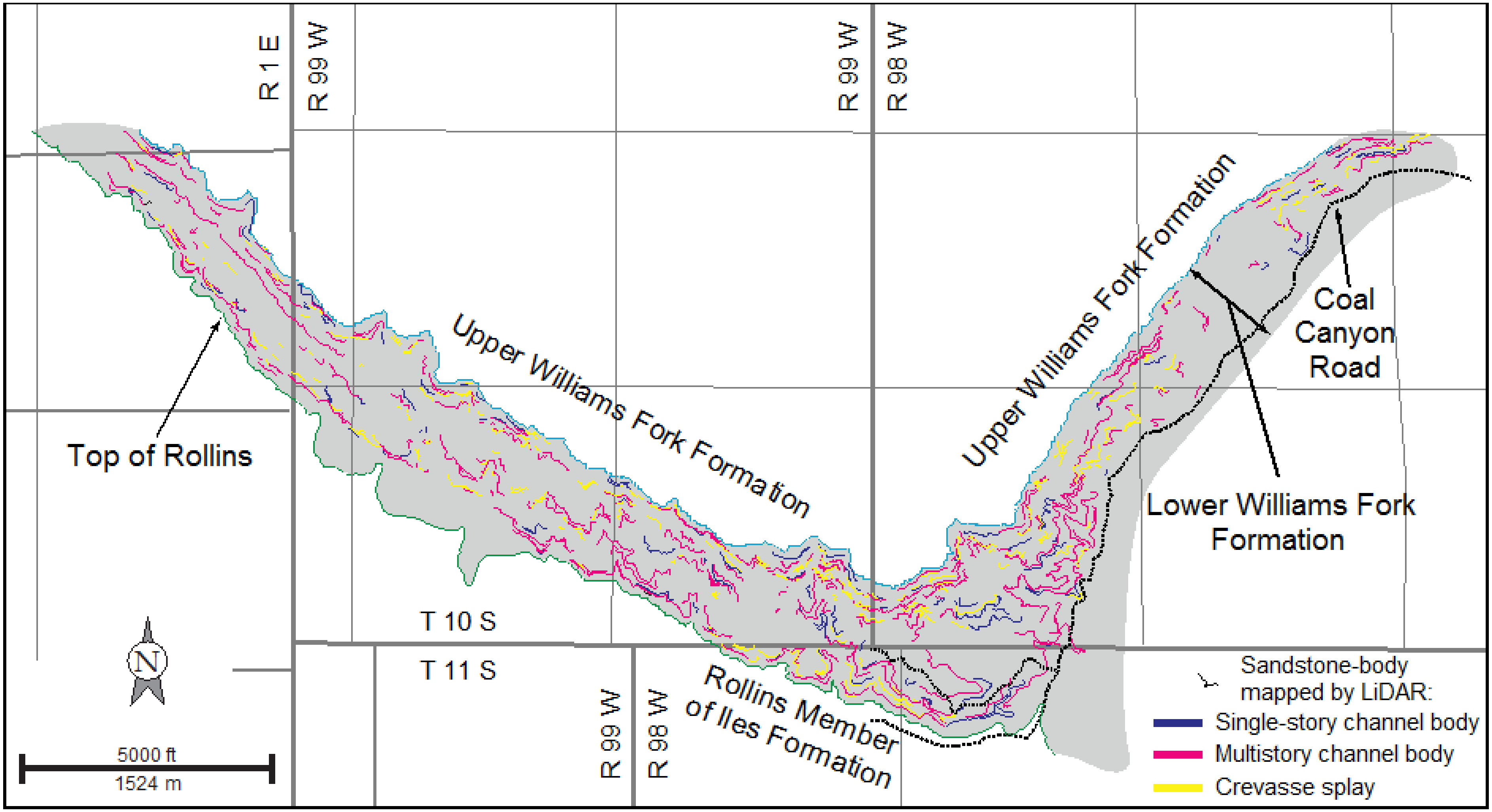


Mapped Fluvial Deposits - GPS



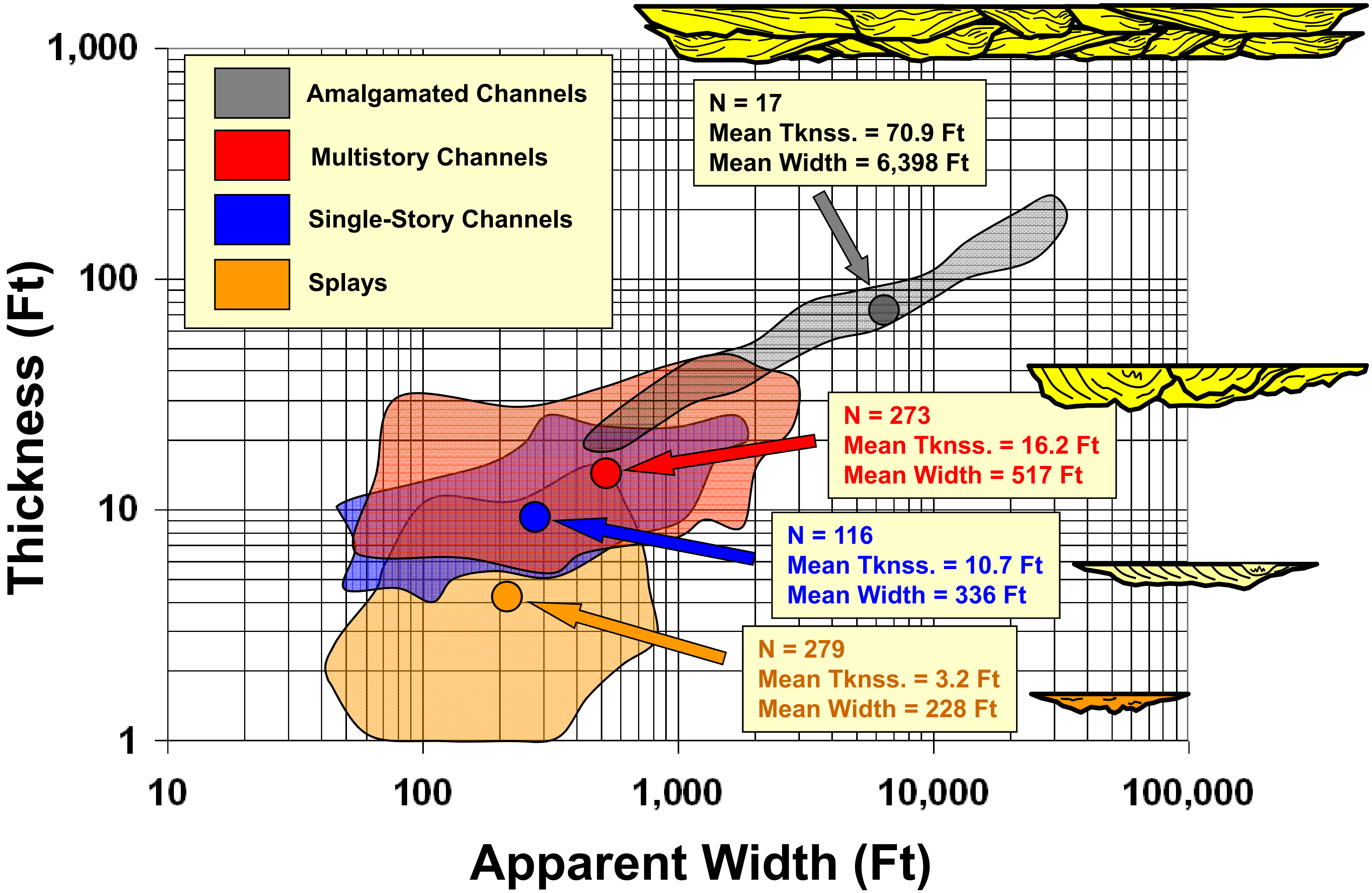
Data from Cole and Cumella (2005), Panjaitan (2006), and Pranter et al. (2009)

Mapped Fluvial Deposits - LiDAR



Data from Cole and Cumella (2005), Panjaitan (2006), and Pranter et al. (2009)

Fluvial Sandstone-Body Dimensions by Type: Coal, Main, and Plateau Creek Canyons

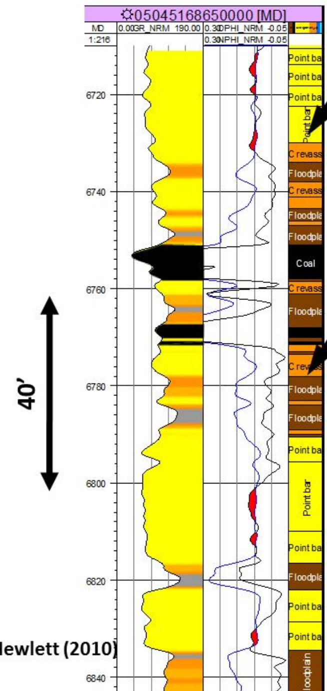


Data from Cole and Cumella (2005), Panjaitan (2006), and Pranter et al. (2009)

Geologically Constrained Architectural-Element Estimation

RCML

Manual Interpretation



Hewlett (2010)

Channel Bar/Point Bar Criteria

- ≤ 96 API GR_NRM cut-off
- fining upward GR_NRM log signature
- 0.05 – 0.25 DPHI_NRM log signature
- sharp base
- thickness: 2' – 30'

Crevasse Splay Criteria

- ≤ 96 API GR_NRM cut-off
- coarsening upward GR_NRM log signature
- <0.05 DPHI_NRM log signature
- thickness: ~1' – 15'

Floodplain Criteria

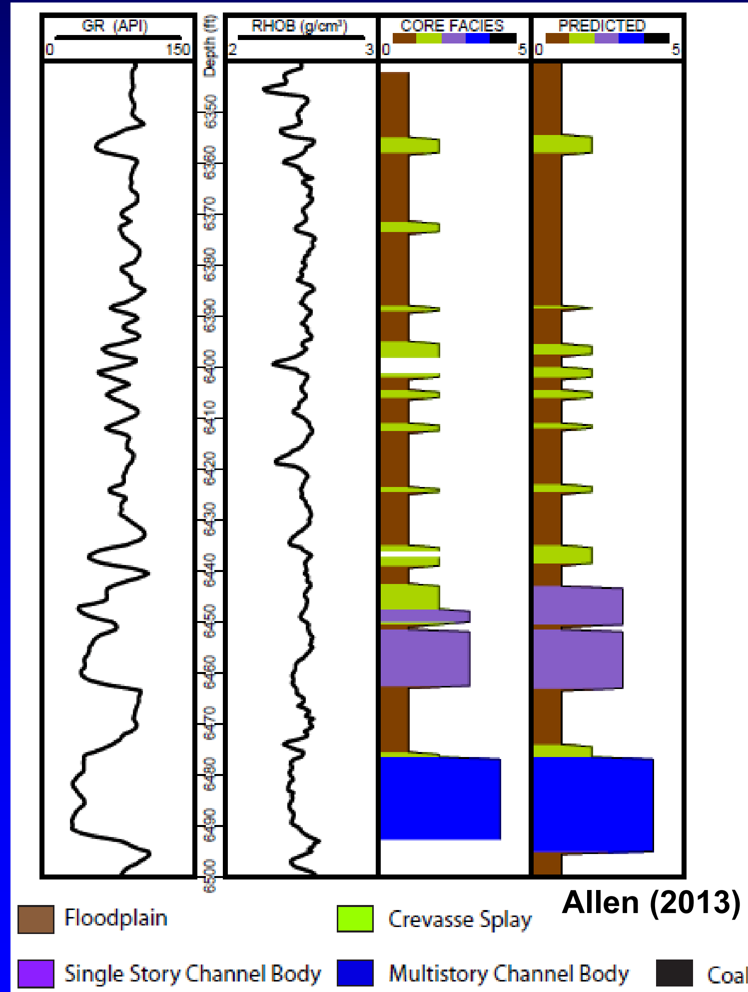
- > 96 API GR_NRM cut-off

Coal Criteria

- ≤ 96 API GR_NRM cut-off
- > 0.25 DPHI_NRM log signature

2010 - 2013

Constrained Quantitative Interpretation

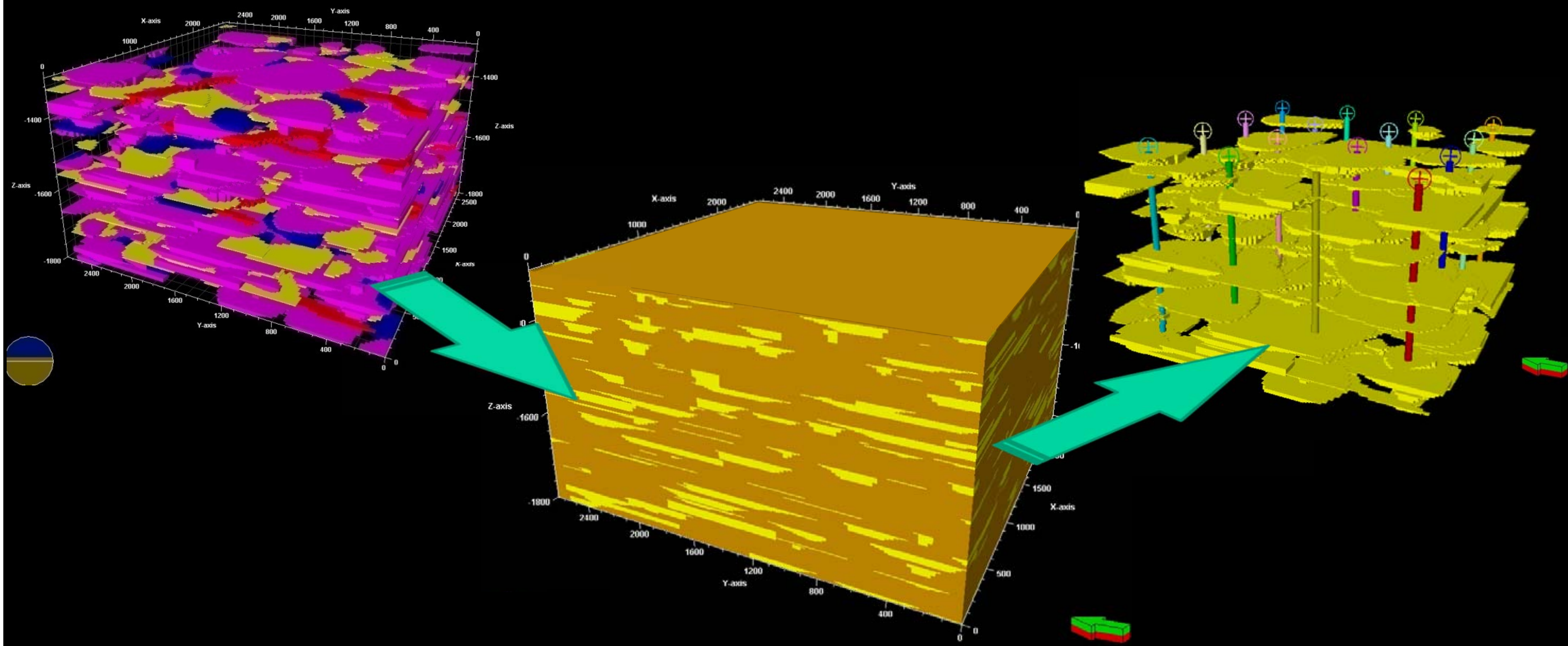


Allen (2013)

Overall Accuracy = 84%

Reservoir Connectivity

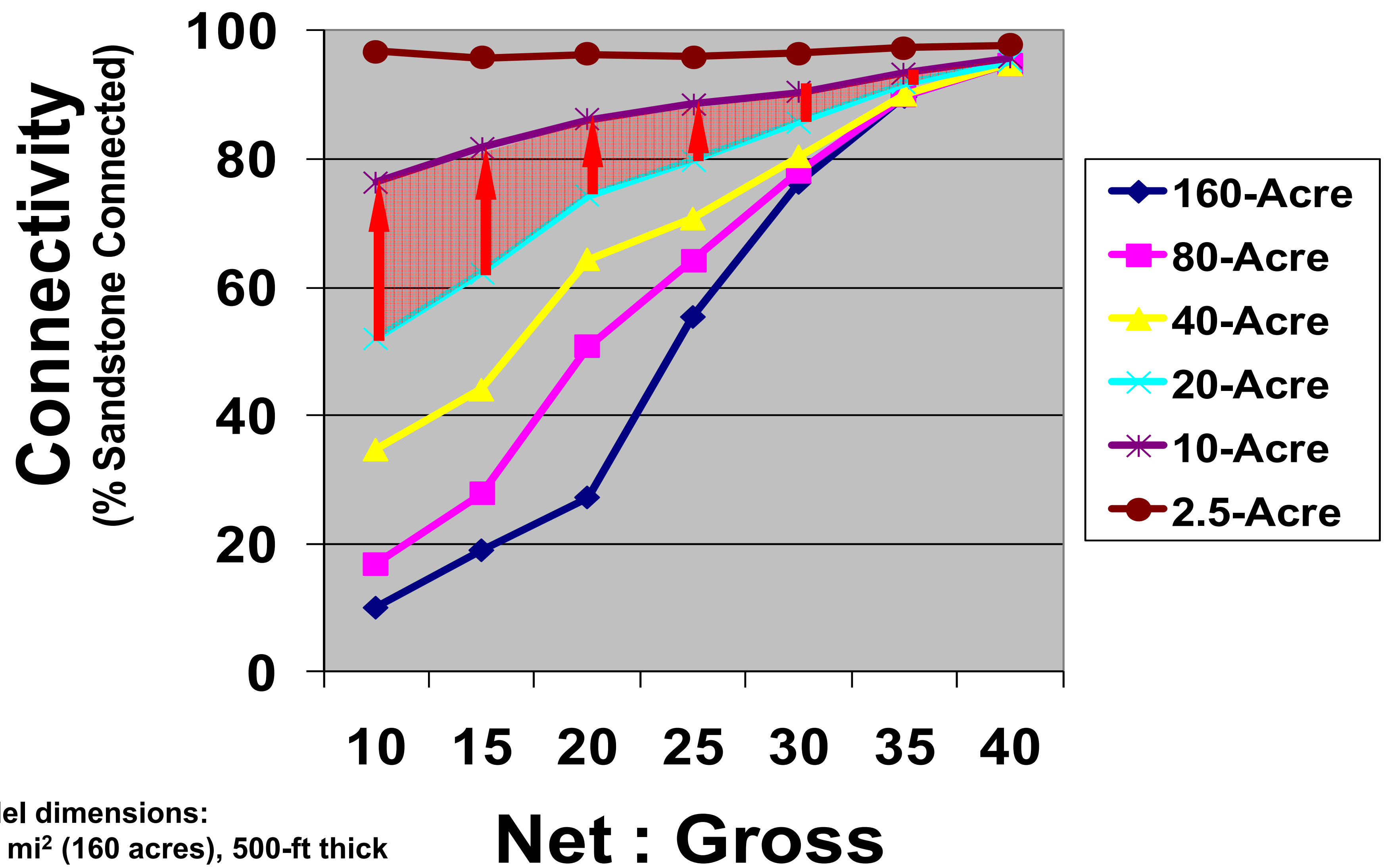
Fluvial 3-D models to assess connectivity of reservoir sandstone bodies



Various modeling methods are used:
SIS, Object-Based, MPS, merged

Sommer (2007); Hewlett (2010); Pranter and Sommer (2011); Sloan (2012); Pranter et al. (2013)

Connectivity Results / Significance

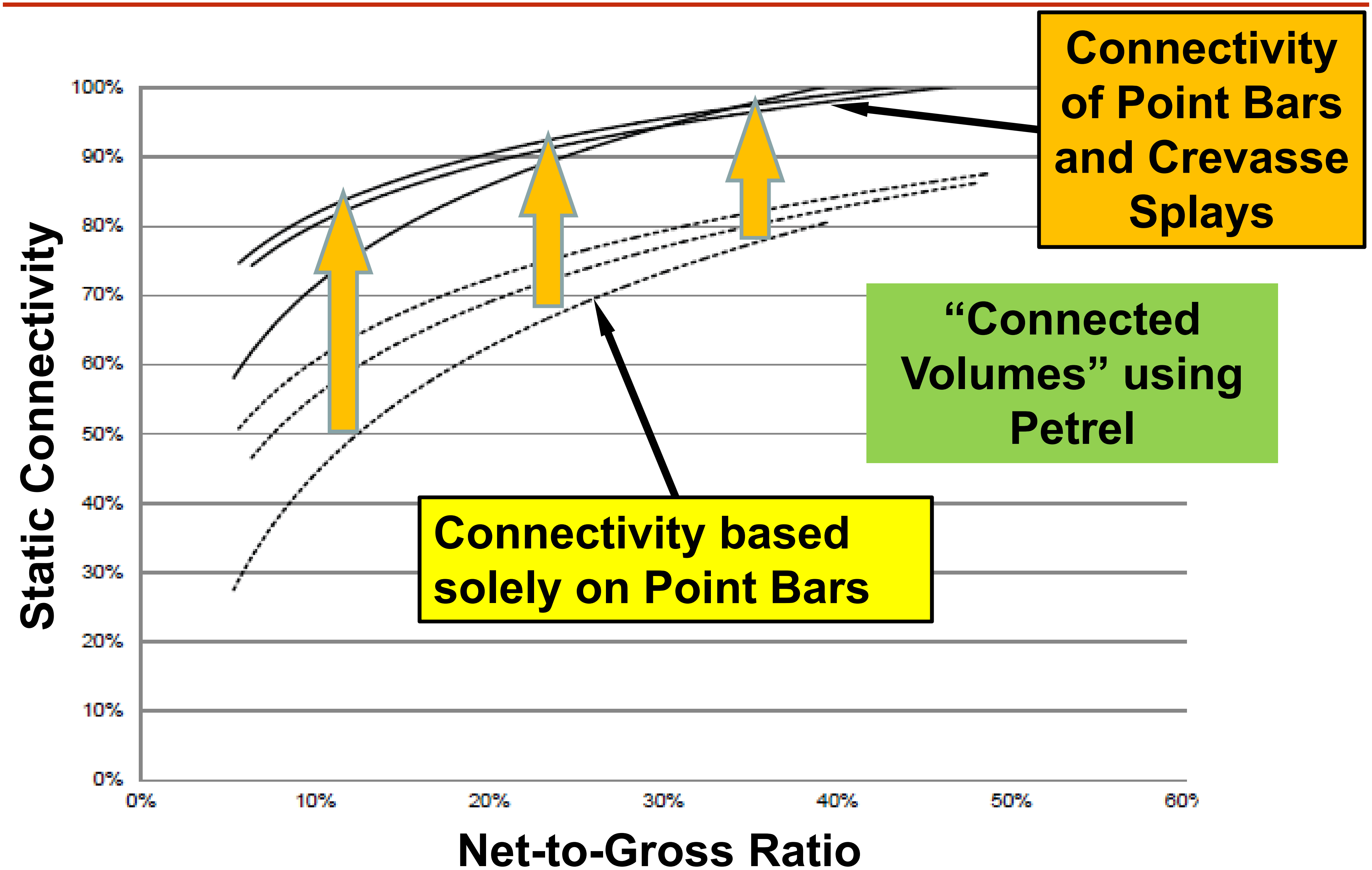


Model dimensions:
0.25 mi^2 (160 acres), 500-ft thick
106 x 106 x 250 cells (I,J,K)
cell dimensions 25 ft x 25 ft x 2 ft

Pranter and Sommer (2011)

Impact of Crevasse Splays

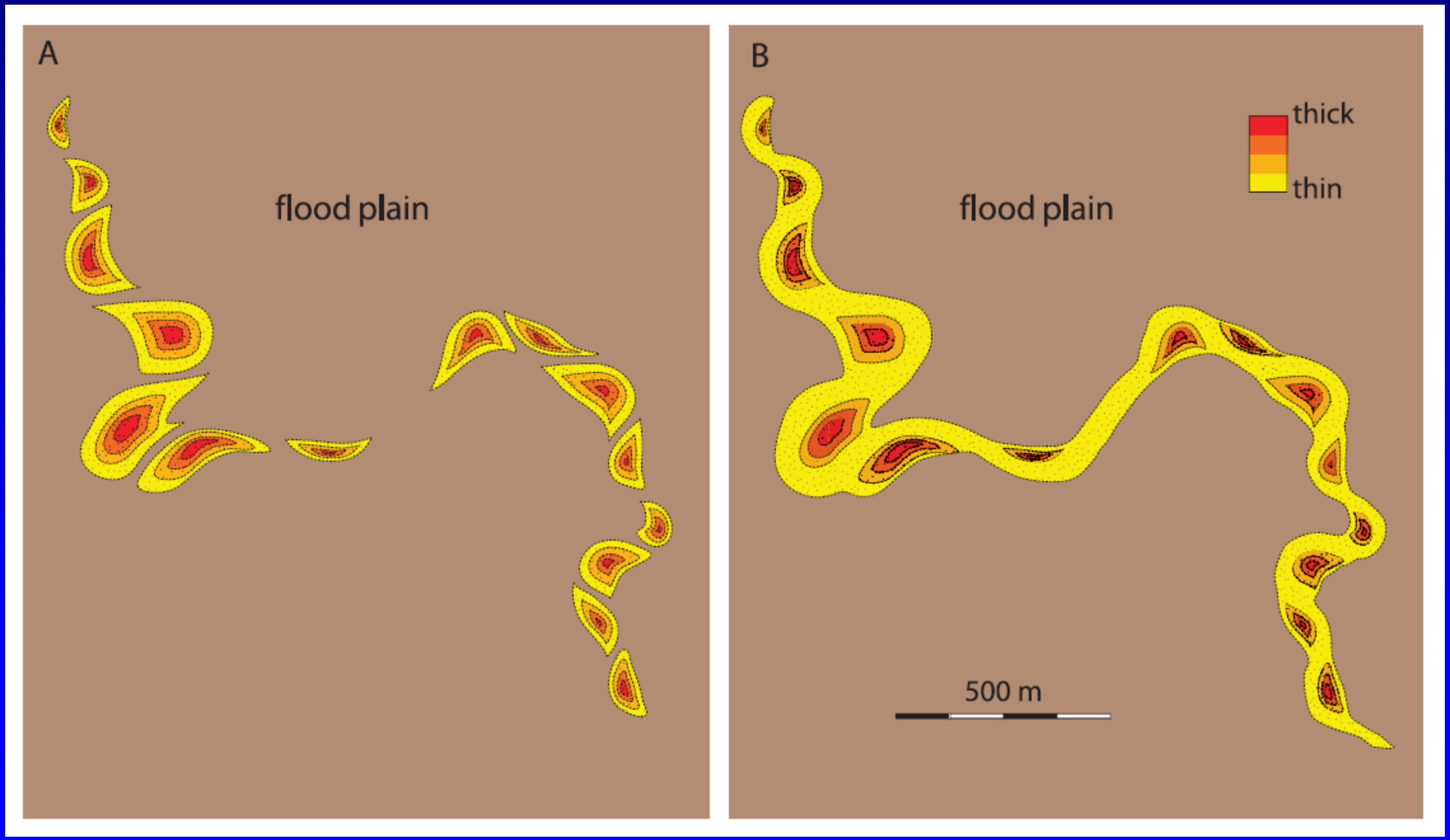
Static Sandstone-Body Connectivity



Reservoir Modeling Approach

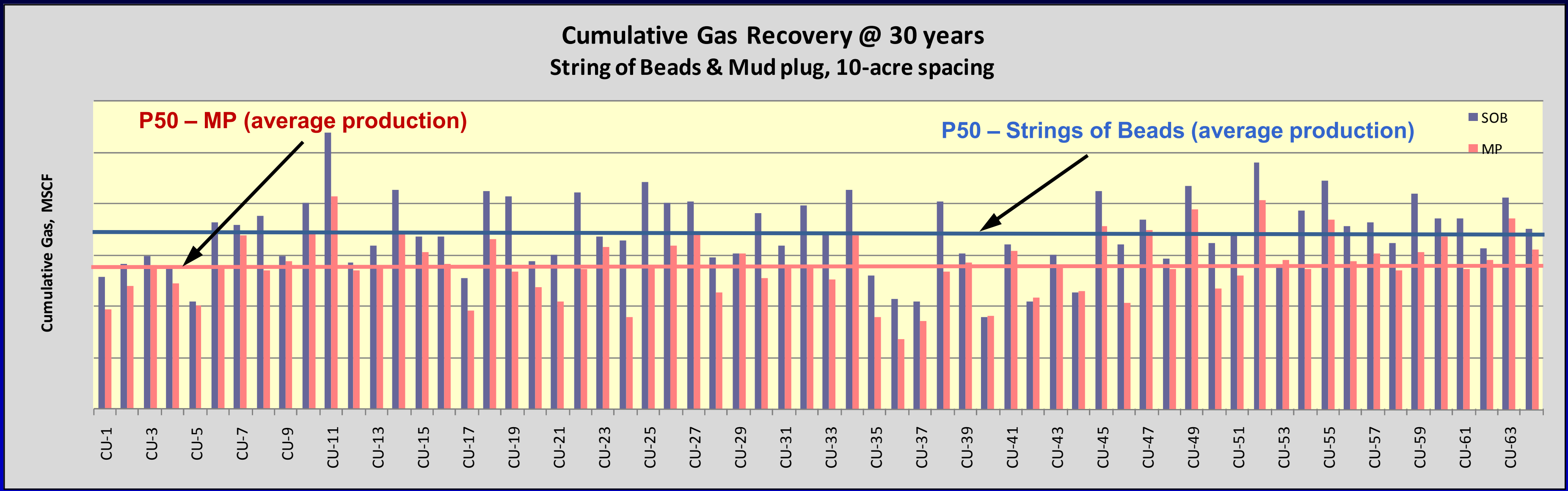
What are the *preserved* shapes and distributions of the fluvial deposits that form the reservoirs?

Two Scenarios (out of many)



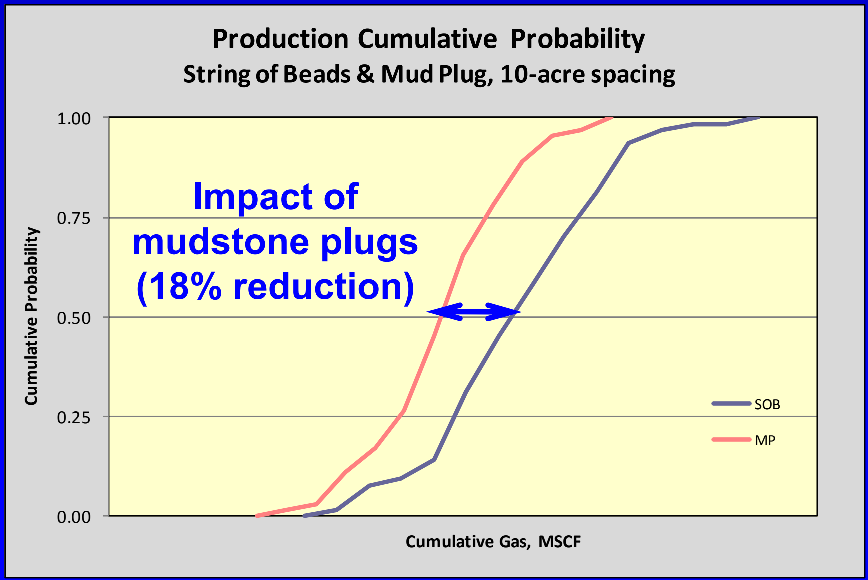
Donselaar and Overeem, 2008

Impact of Mudstone Plugs (abandonment channel fill) on Well Performance



Cumulative gas recovery after 30 years comparing the string-of-beads MPS model with the mudstone-plug MPS model for 64 wells at 10-ac (4-hectare, 330-ft) spacing. Shows the variation in recovery. The string-of-beads MPS model shows the highest recovery over 30 years.

Dynamic Connectivity



Cumulative production probability comparing the string-of-beads MPS model to the mudstone-plug MPS models at 10-ac (4-hectare, 330-ft) spacing. A difference of 18% production between the two models occurs at 0.50 probability. The 18% difference in production is related to the presence of mudstone plugs.

Deep, deep thoughts…
well, perhaps just common sense…

RCML

- **Evaluation of reservoir heterogeneity, connectivity, and performance relies on sound geological characterization at different scales…**
- **Reservoir connectivity is directly related to the stratigraphy, sedimentology, and other geological characteristics…it is a 3-D issue and is actually a dynamic issue…**
- **Static connectivity analysis based on 3-D reservoir models provides, at best, a qualitative assessment of reservoir connectivity…highly constrained 3-D static reservoir models and dynamic simulation are essential…**
- **There are many questions regarding the characteristics of fluvial deposits and reservoirs, and importantly, *how to properly address* the various scales of heterogeneity that exist…**

Thank you!