

# **An Outcrop Based Integrated Reservoir Model of the Frontier Formation Hybrid Play in the Powder River Basin, Wyoming, USA\***

**M.H. Hofmann<sup>1</sup>, N. La Fontaine<sup>1</sup>, T. Le<sup>2</sup>, and T. Hoffman<sup>2</sup>**

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<sup>1</sup>University of Montana, Missoula, MT, United States ([michael.hofmann@umontana.edu](mailto:michael.hofmann@umontana.edu))

<sup>2</sup>Montana Tech, Butte, MT, United States

## **Abstract**

The quantification of reservoir heterogeneities and their effect on reservoir behavior is becoming an increasingly important aspect to predict reservoir performance in low permeability plays. However, it is notoriously difficult to capture the stratigraphic architecture from the tools available for subsurface evaluation. Outcrops can serve as an excellent tool to improve the understanding of the reservoir behavior, in particular in a setting where outcrops are close to the producing fields, and stratigraphic architecture observed in outcrop is representative of the subsurface reservoir heterogeneity. Here we present the results of an integrated outcrop to geocellular modeling to reservoir simulation study to better understand the reservoir behavior of the tight oil reservoirs of the Frontier Formation in the Powder River Basin, Wyoming, USA. To capture and understand the effect of thin beds and drapes in this heterolithic reservoir, we first created representative geomodels at a centimeter resolution for all facies observed in outcrop. Although the architecture was captured from outcrop, the facies properties were taken from nearby well locations to have the best representation of the subsurface reservoir conditions. Flow simulations on these models resulted in anisotropic flow properties ( $K_x$ ,  $K_y$ ,  $K_z$ ) that then were used to upscale to a full field geocellular model. In this latter model stratigraphic architectures were again captured from 3D outcrop models. Simultaneously we defined the reservoir properties through a single horizontal well flow simulation model to estimate the reservoir properties to use as input parameters for the outcrop geocellular models. Historical production data was matched by modifying the initial fluid saturation and the rock physics parameters such as relative permeability and capillary pressure. Our results suggest that of all the variables tested the presence or absence of mud drapes and low permeability thin beds within heterolithic deposits is the most fundamental and

critical parameter in the effective permeability of the Frontier Formation. Other important parameters but secondary to the former, are bed geometry and continuity, facies variability on the parasequence scale, and structural complexity. This integrated multi-step study aids with development and completions strategies including optimization of well and fracture spacing in tight oil reservoirs.

### **Reference Cited**

Nyman, S.L., R.M. Gani, J.P. Bhattacharya, and K. Lee, 2014, Origin and distribution of calcite concretions in Cretaceous Wall Creek Member, Wyoming: Reservoir-quality implication for shallow-marine deltaic strata: *Cretaceous Research*, v. 48, p. 139-152, <https://doi.org/10.1016/j.cretres.2013.12.009>

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**Authors:** Hofmann, M.H.<sup>1</sup>, La Fontaine, N.<sup>1</sup>, Le, T.<sup>2</sup>, Hoffman, T.<sup>2</sup>

**Affiliations:** <sup>1</sup>University of Montana, <sup>2</sup>Montana Tech

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# Outline

- **Introduction**

Why?    Where?    How?

- **Results**

- Depositional Environment, Facies
- Facies Quantification (Dimensions and Geometries, Transmissibility) and Flow-based Upscaling (Sensitivity Analysis)
- Integrated Outcrop Geomodel Reservoir Simulation

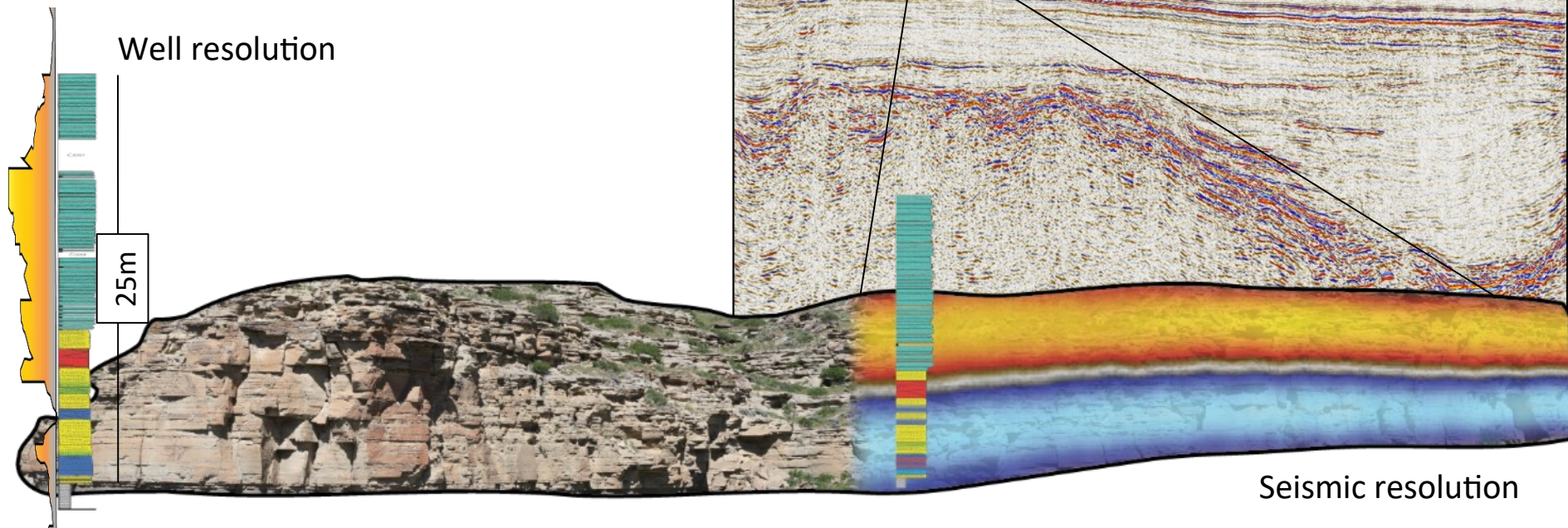
- **Conclusion**

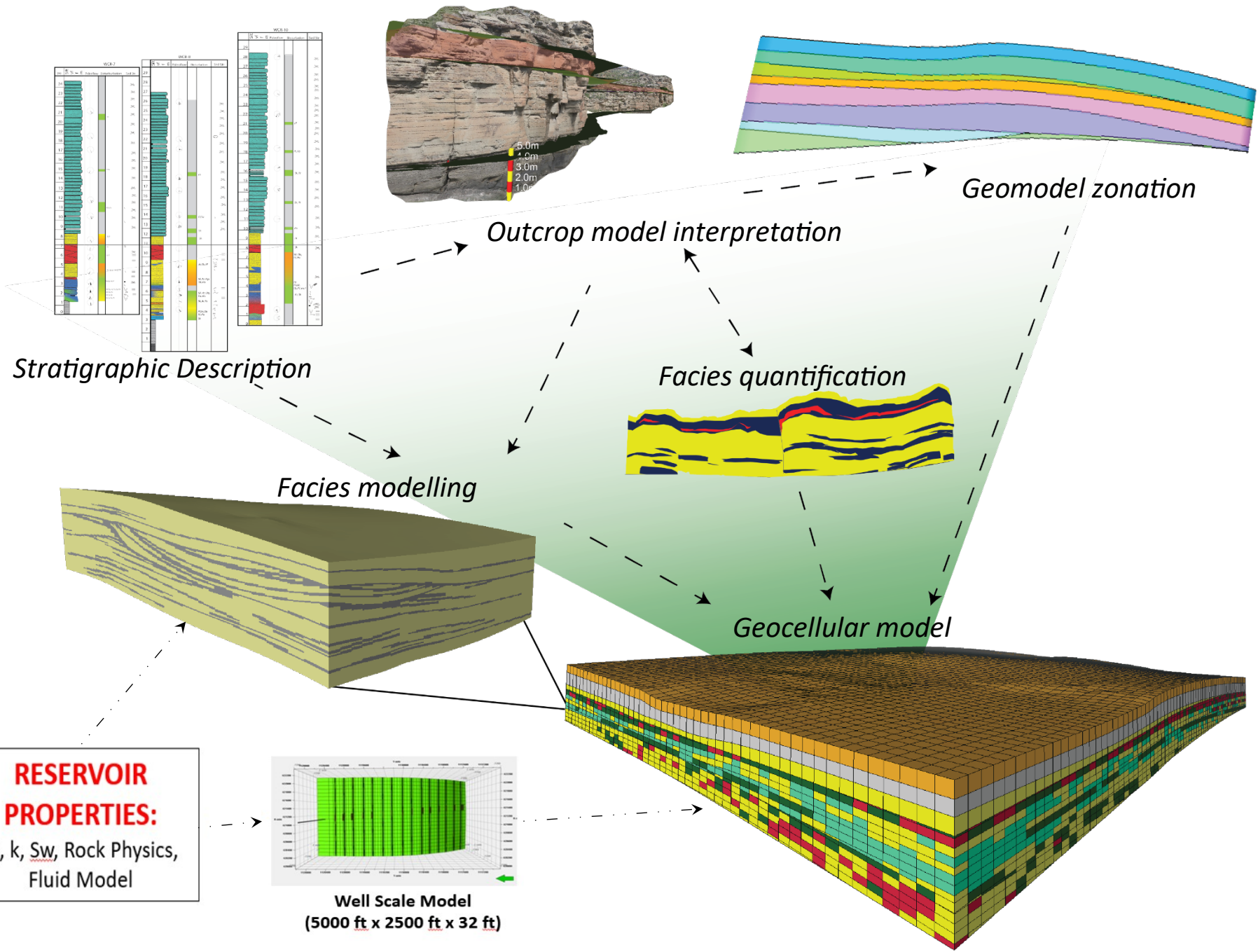


# The Challenge

Fluid paths in a reservoir are controlled by multi-scale stratigraphic heterogeneities, but are difficult to characterize in the subsurface.

**Facies Architecture on the bed scale** include: lateral facies distribution, bed geometries and dimensions, networks of low permeability thin beds (transmissibility barriers)





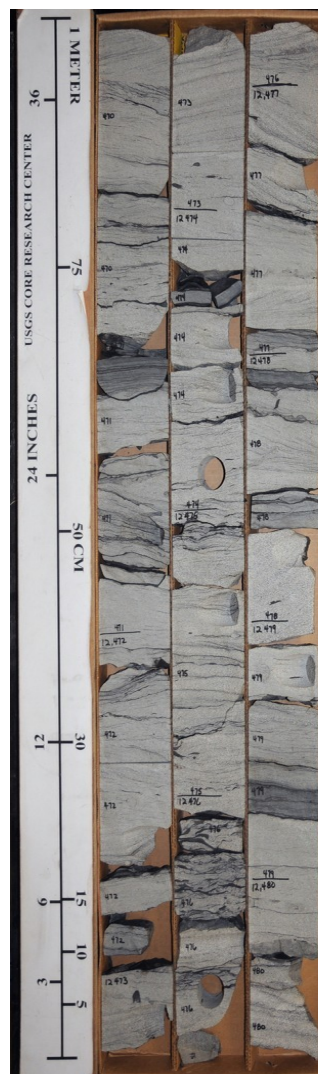


# Geologic Setting

- Cenomanian-Turonian Frontier Formation deposited in Western Interior Seaway (KWIS).

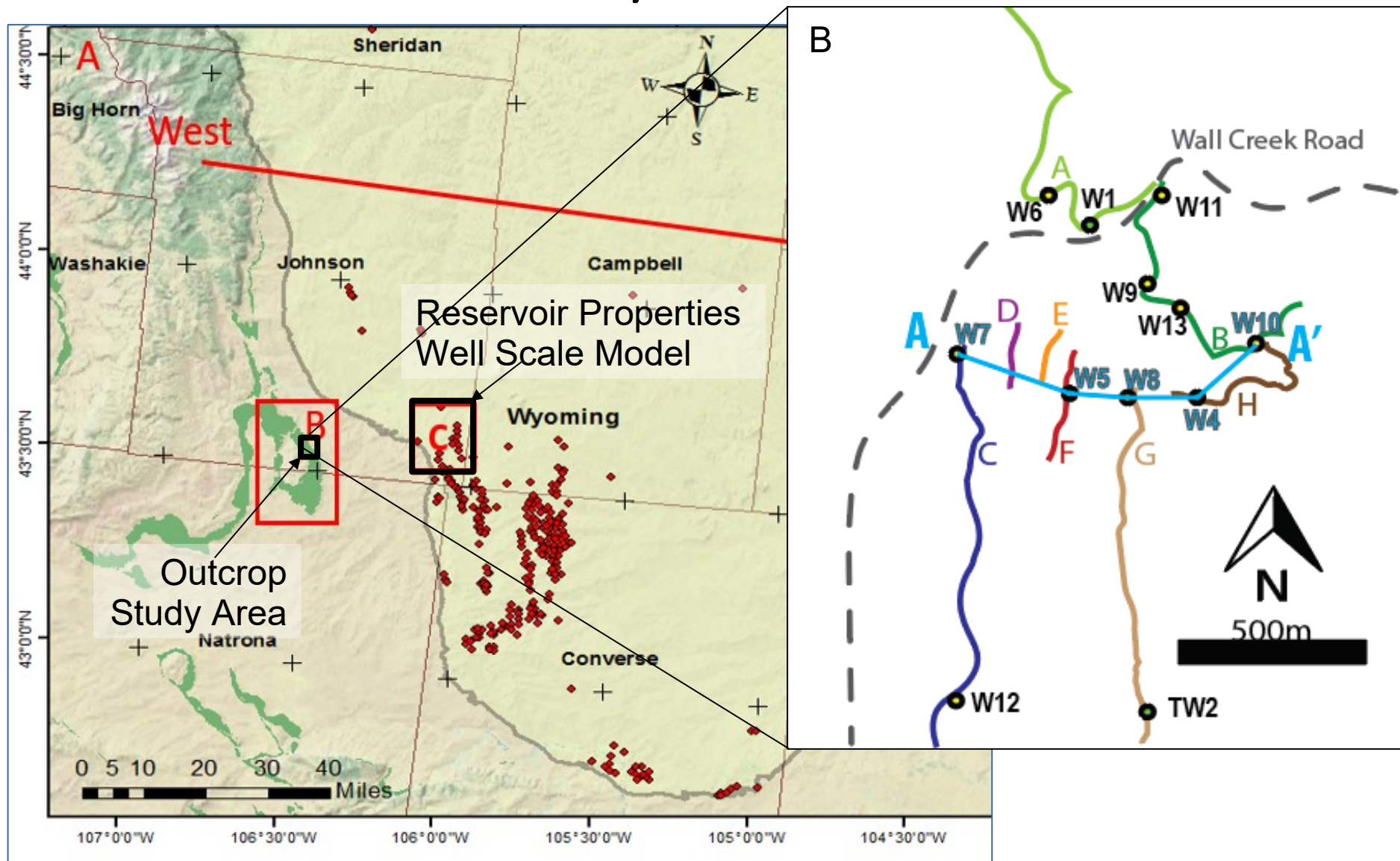
SYSTEM	STAGE	Picks (Ma)	FORMATION
CRETACEOUS	Upper	65.0	Lance Formation
			Fox Hill Sandstone
		78.3	Lewis Shale
			Mesaverde Group
		83.5	Shannon sandstone
	Lower	85.8	Cody Shale
		89.0	<i>Wall Creek Mbr</i>
		93.5	Frontier Formation
		99.0	Mowry Shale
		112	Thermopolis Shale
		124	

Modified from Nyman et al. 2014



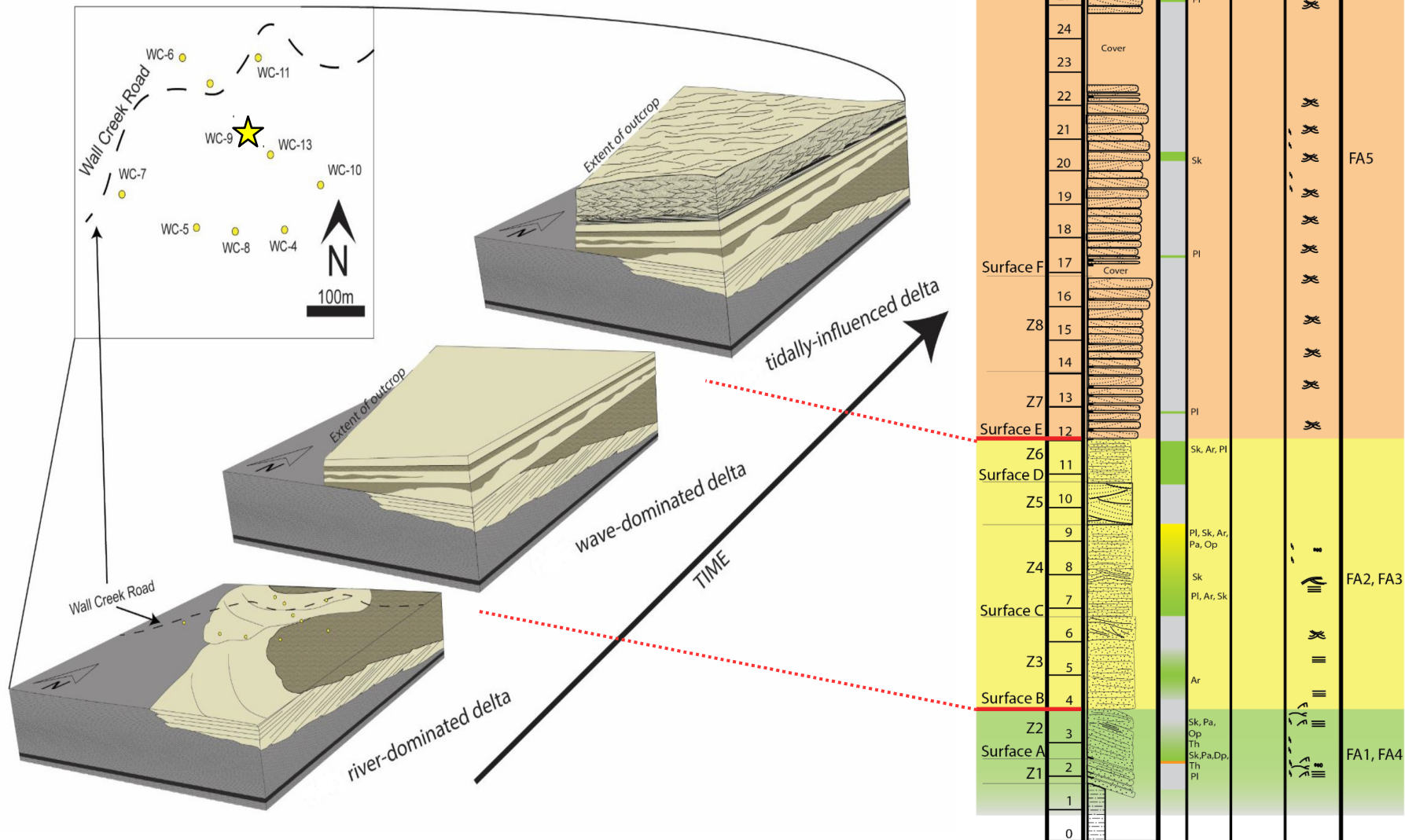


# Study Location



# Depositional Environment

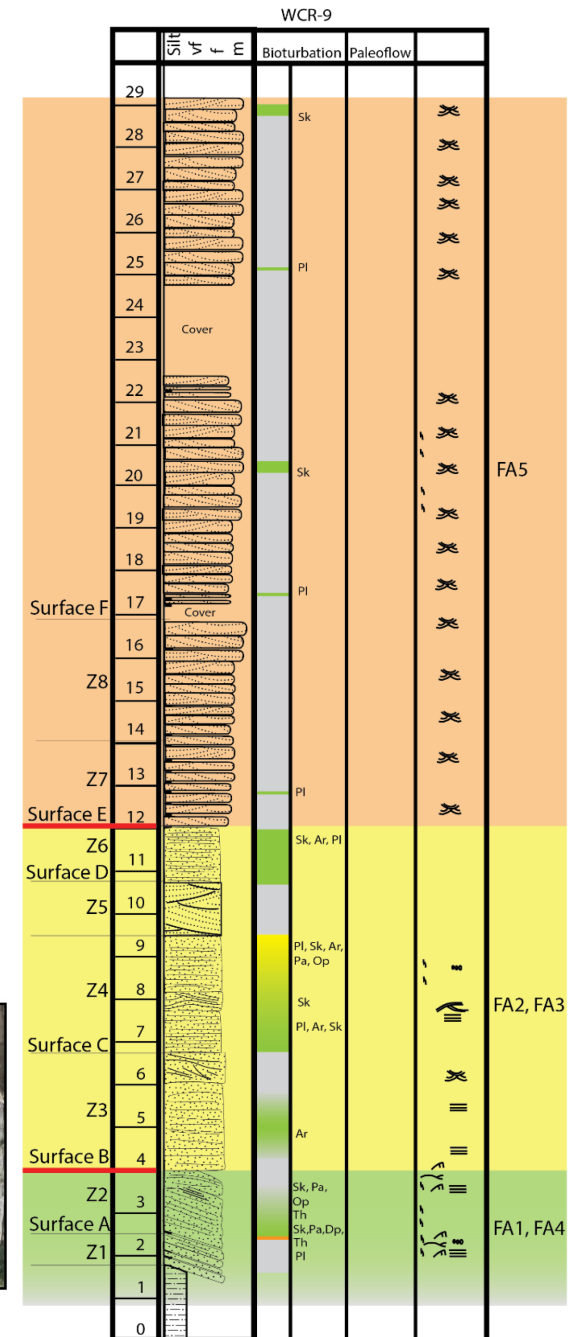
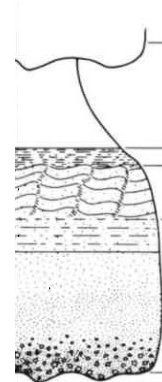
## Wall Creek Type Log and Depositional Setting





# Green Interval (Sequence 1)

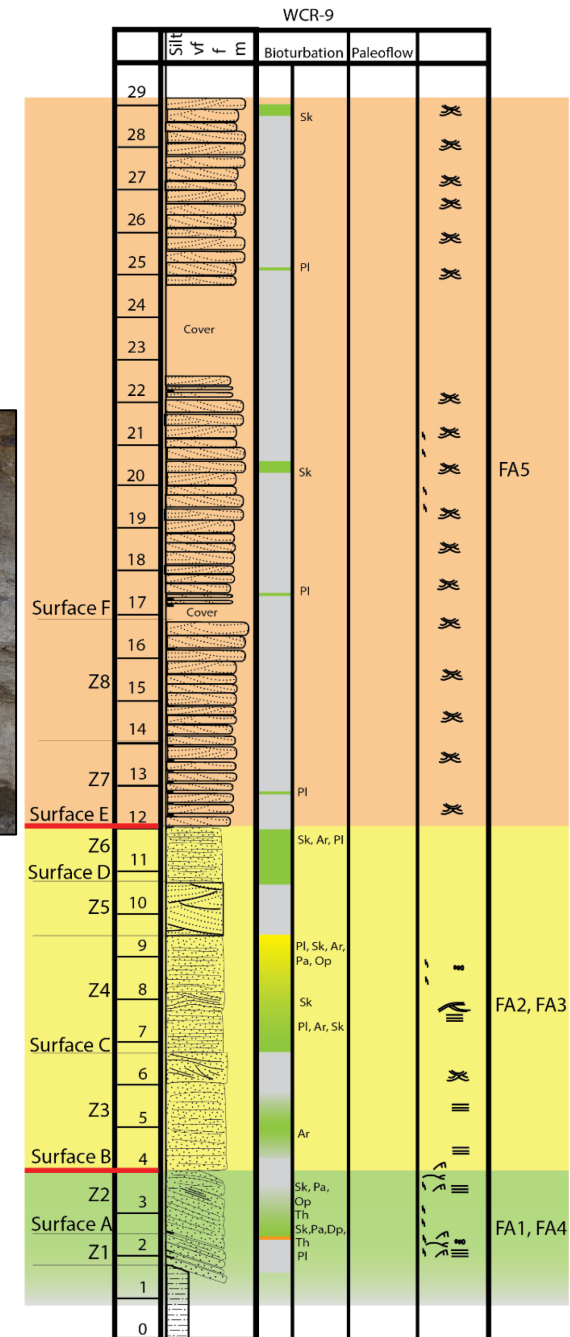
- Low angle clinoforms
- Low bioturbation index and variability
- High organic content (terrestrial organics)
- Minor storm and wave influence (HCS, SCS)
- Abundant gravity flow deposits





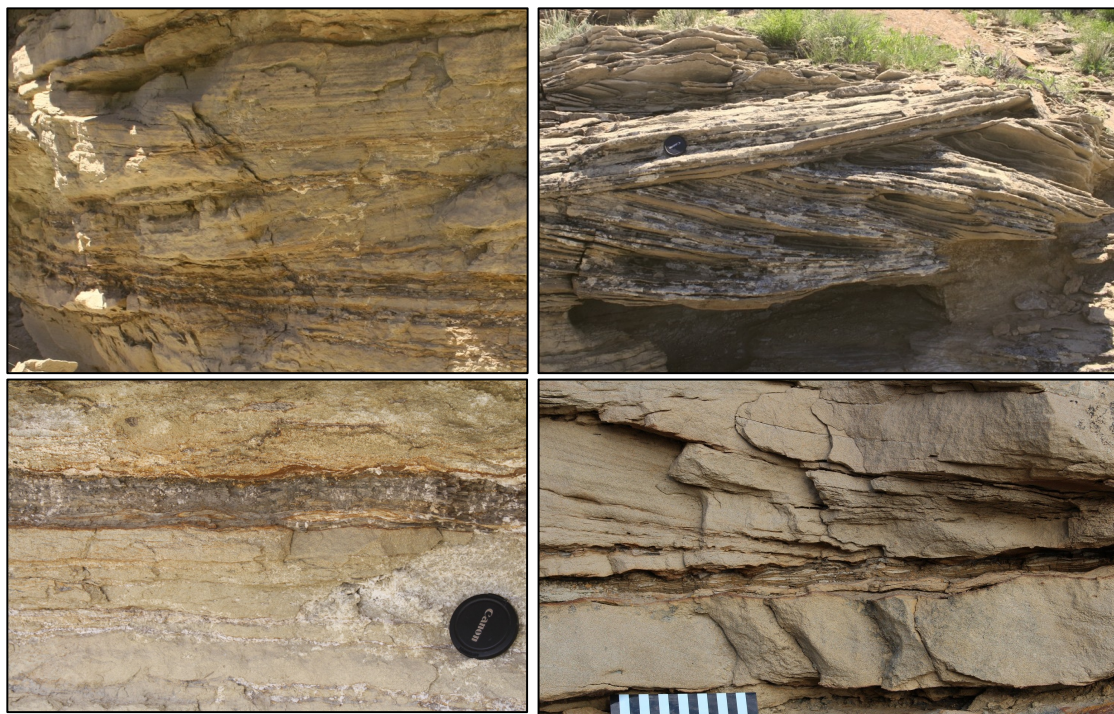
# Yellow Interval (Sequence 2)

- High bioturbation index and variability (*Skolithos* and *Cruziana* ichnofauna)
- Common storm and wave influence (HCS, SCS)

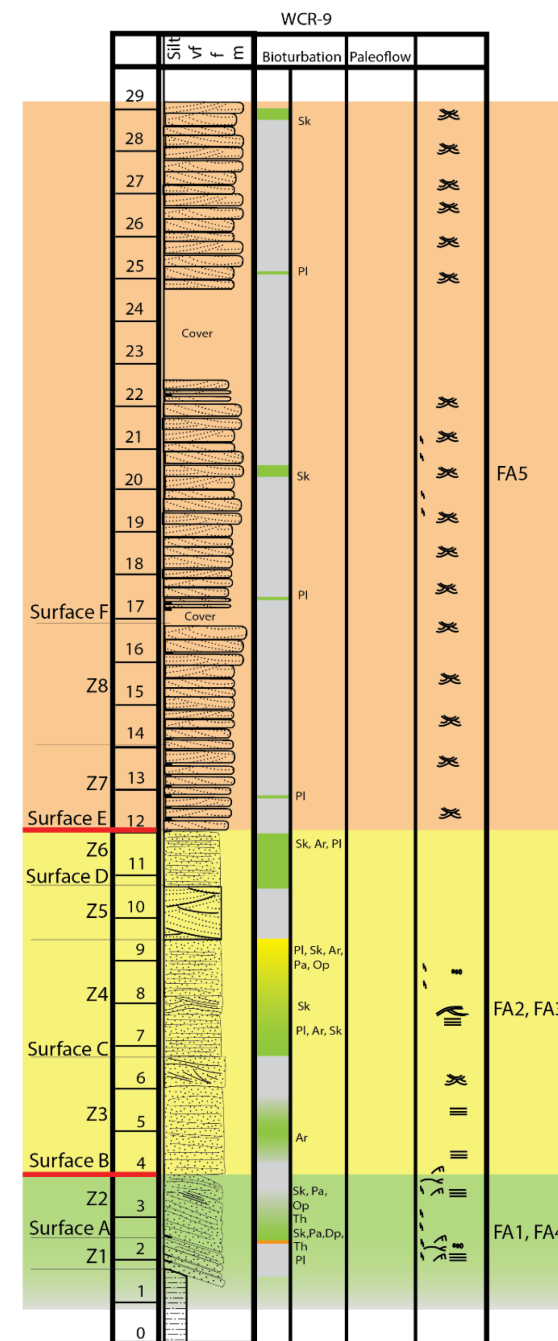




# Orange Interval (Sequence 3)



- Heterolithic Strata (abundant thin mud interbeds)
- Wavy and lenticular bedding
- Abundant heterolithic cross bedded sandstones
- Low bioturbation index and very low variability



# High Resolution Facies Modeling

## Wave-dominated facies



## Tidal-dominated facies



### Fine grained thin bed dimensions

	Wave dominated	
	Depositional Dip	Depositional Strike
Average length (m)	<b>7.5</b>	<b>10.4</b>
StDev	5.8	7.4

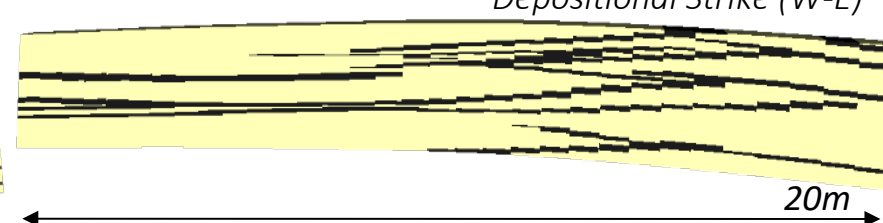
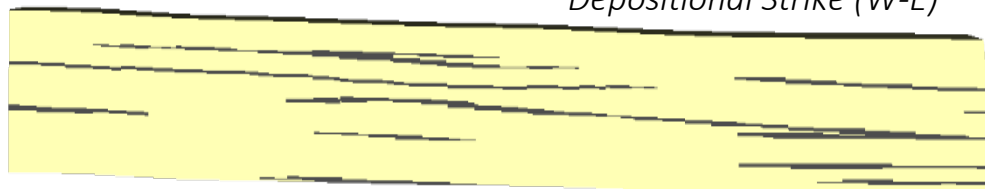
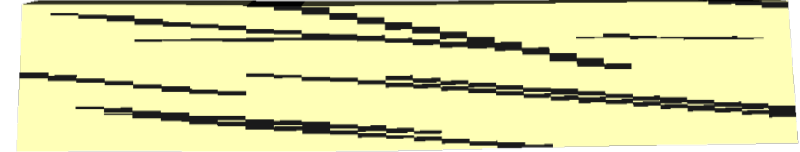
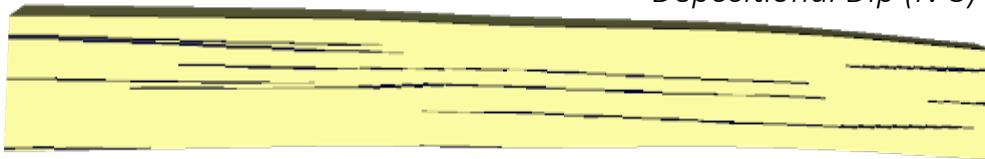
Tidal Dominated	
Depositional Dip	Depositional Strike
<b>9.8</b>	<b>12.5</b>
4.6	4.7

*Depositional Dip (N-S)*

*Depositional Dip (N-S)*

*Depositional Strike (W-E)*

*Depositional Strike (W-E)*

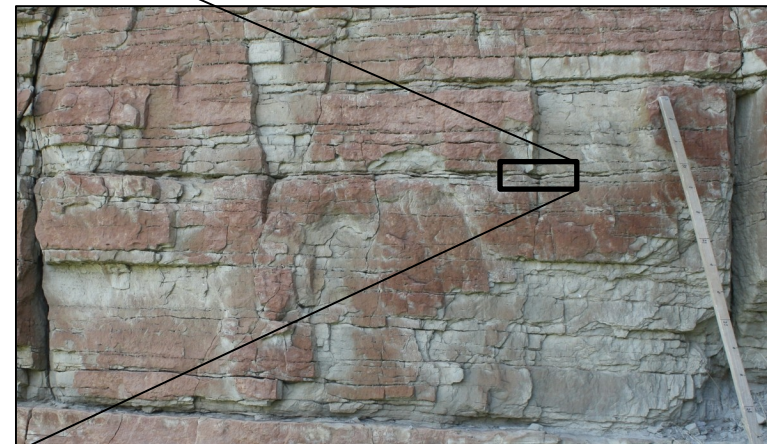
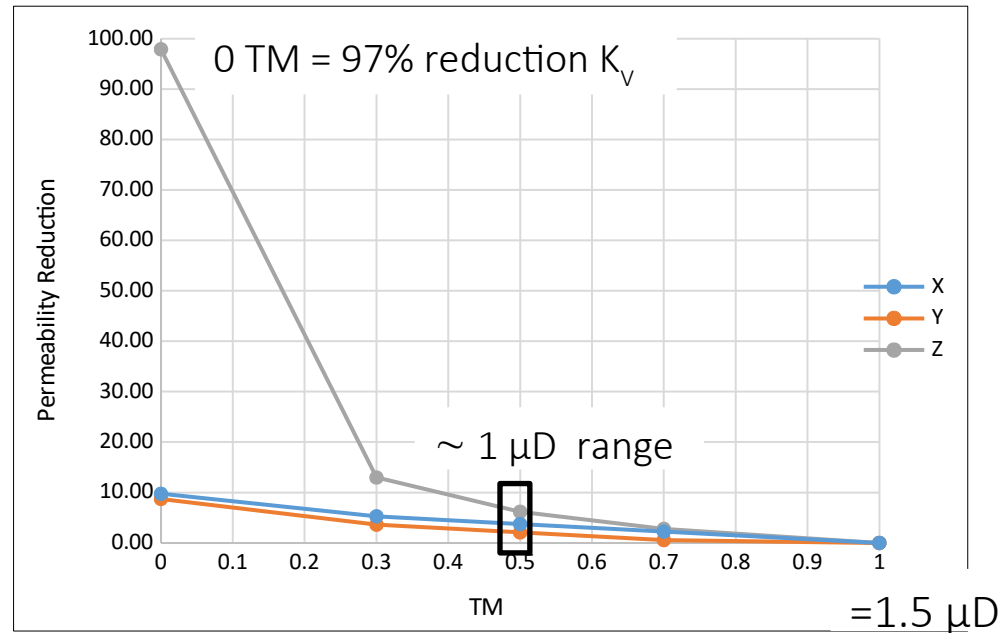




# Wave Dominated Facies – Flow Characteristics

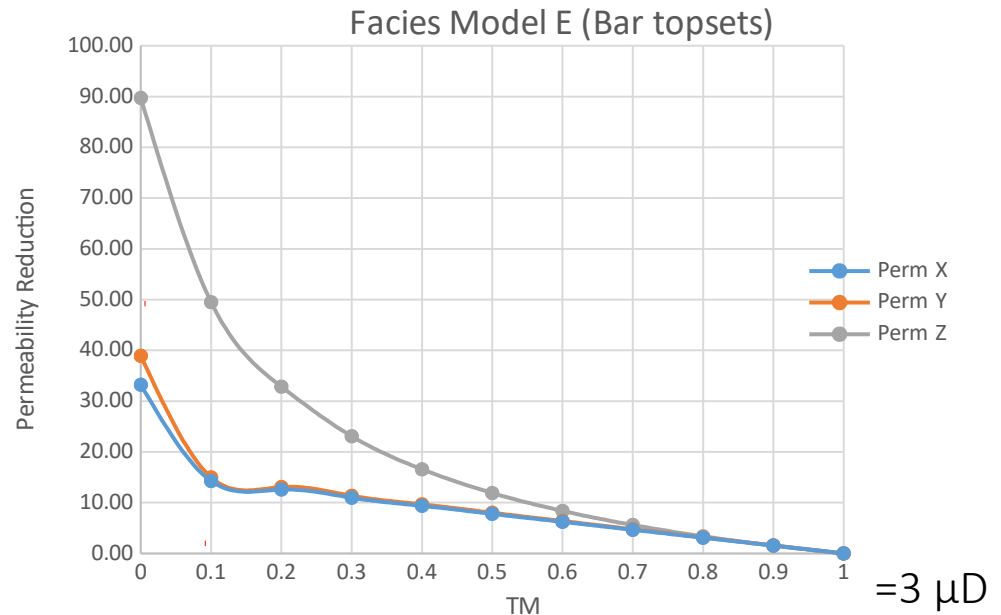
Significant  $K_v/K_h$  anisotropy

- No appreciable  $K_h$  anisotropy
  - Thin-bed dimensions insignificant
- Lower delta front mud drapes likely have high transmissibility
- TM of  $\sim 0.3-0.5$  likely best characterization of facies



# Tidal Dominated Facies – Flow Characteristics

- Significant  $K_v/K_H$  anisotropy
- $K_v$  higher than in wave dominated facies model
- $K_H$  lower than in wave dominated facies
- Isotropic  $K_H$  except at  $TM = 0$
- Low  $TM$  (0, 0.1) likely best characterization of facies

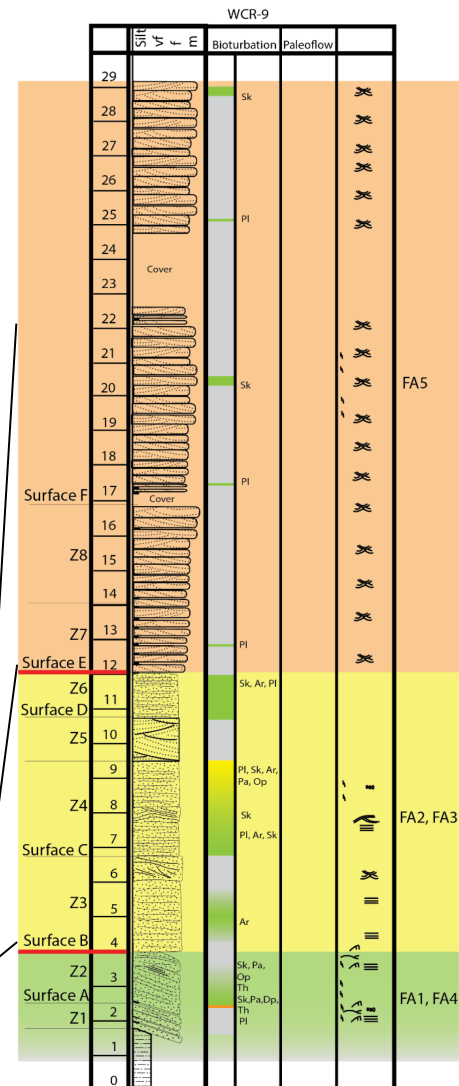
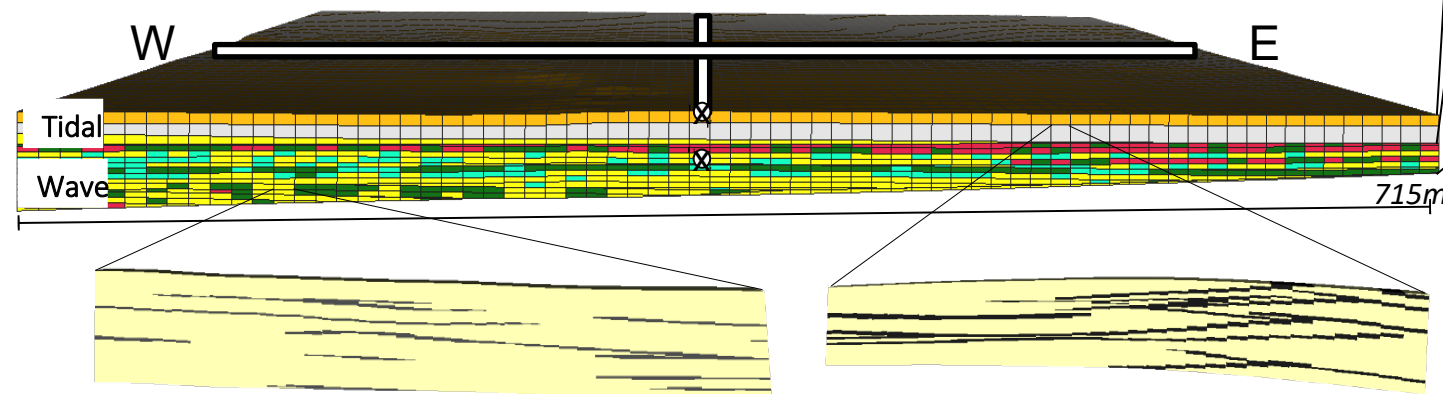




# Geomodel Reservoir Simulation

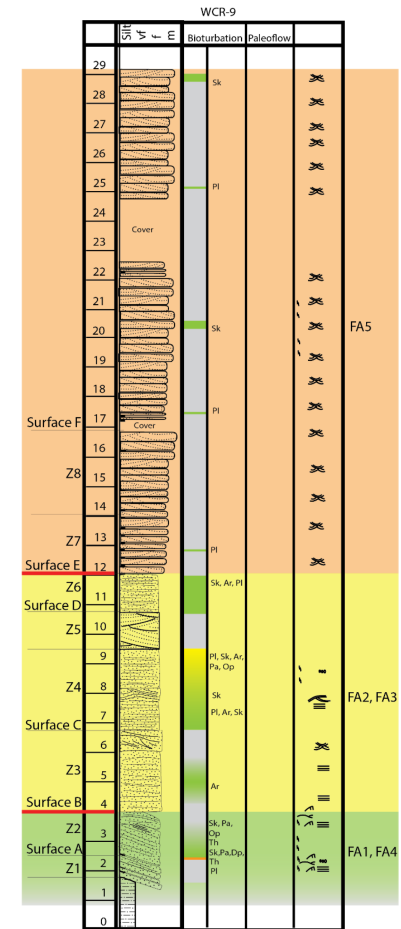
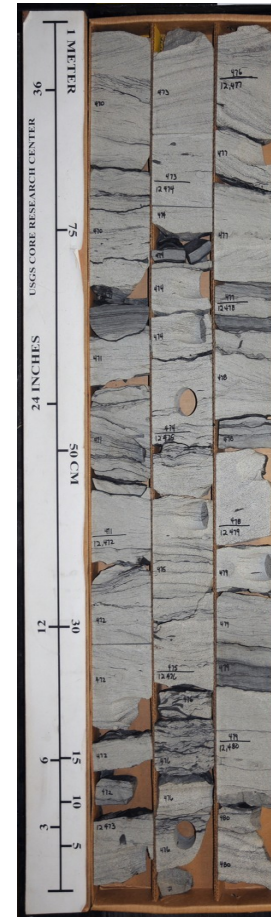
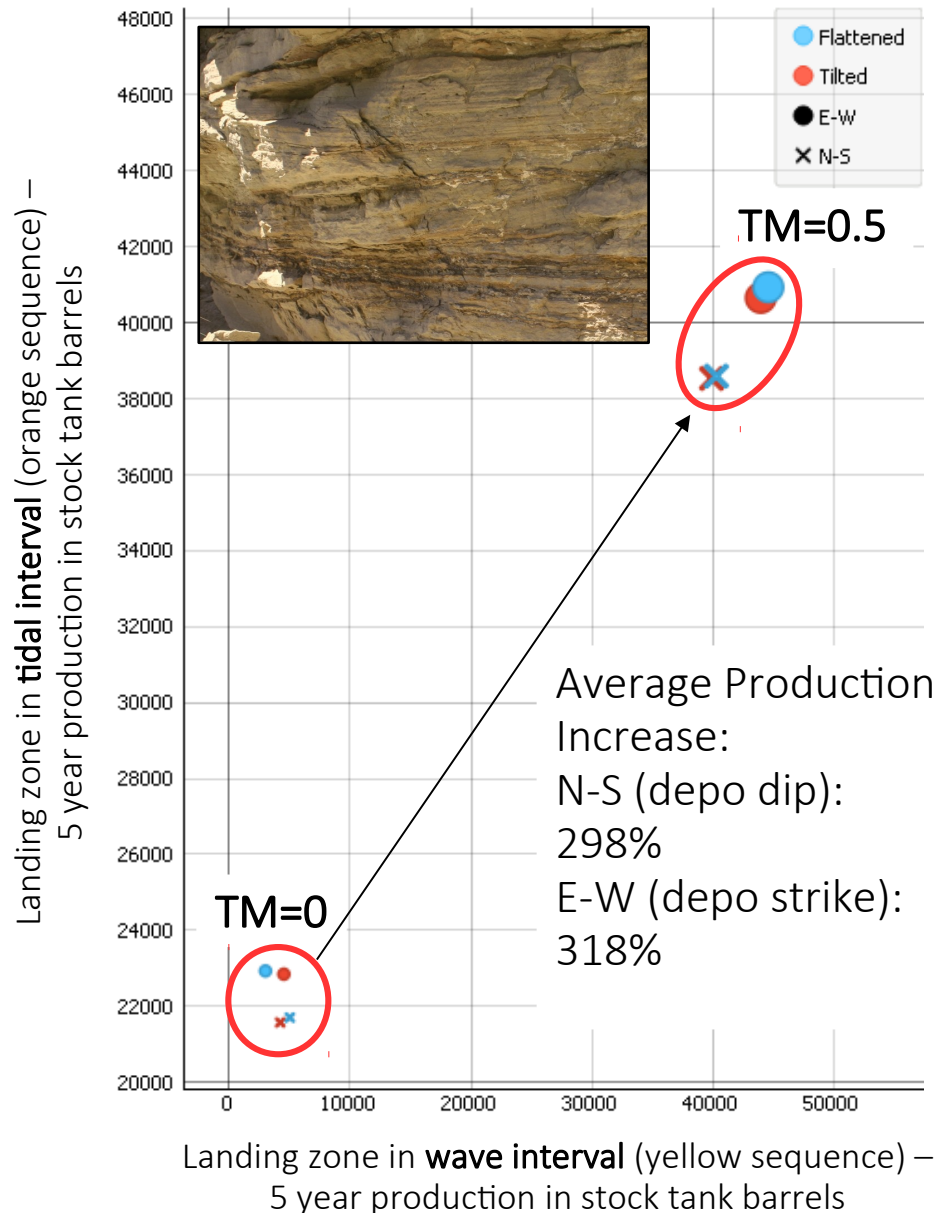
## Well configurations and model scenarios:

- **TM=0 and TM=0.5:** What is the impact of stratigraphic heterogeneity and thin-bed permeability on production?
- **Well placement** (N-S vs E-W, and Wave vs Tidal): Can we optimize well placement stratigraphically and spatially?
- **Unfractured and artificially fractured:** What is the uplift that induced fractures provide on production?
- **Dipping vs flattened:** Do structures (5 degree dip to the east) influence production in this tight oil reservoir?



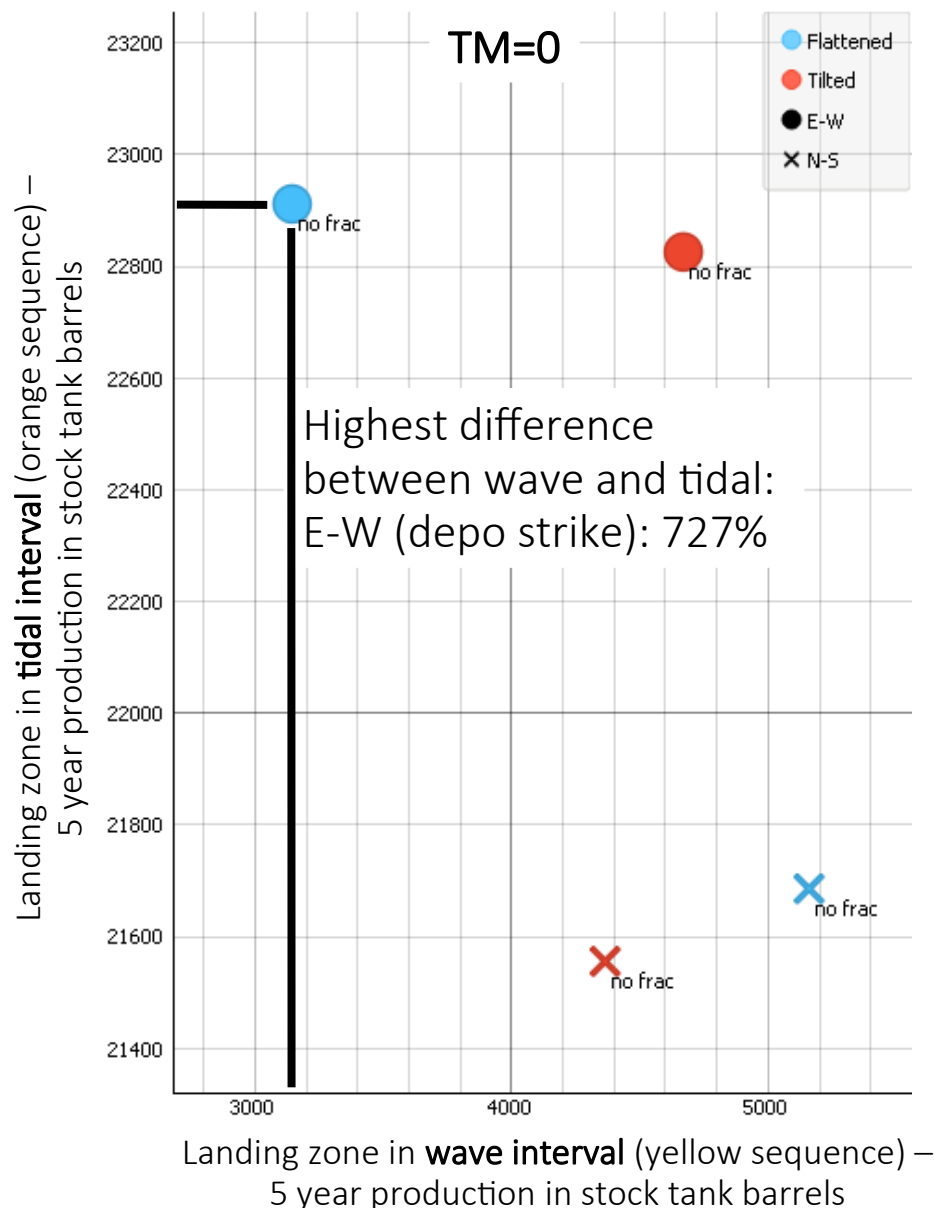


# Stratigraphic Architecture/Facies – Thin Beds



- The **permeability (TM)** of thin beds has significant impact on production
- Production is ~300% higher in the case of TM=0.5 (higher perm)

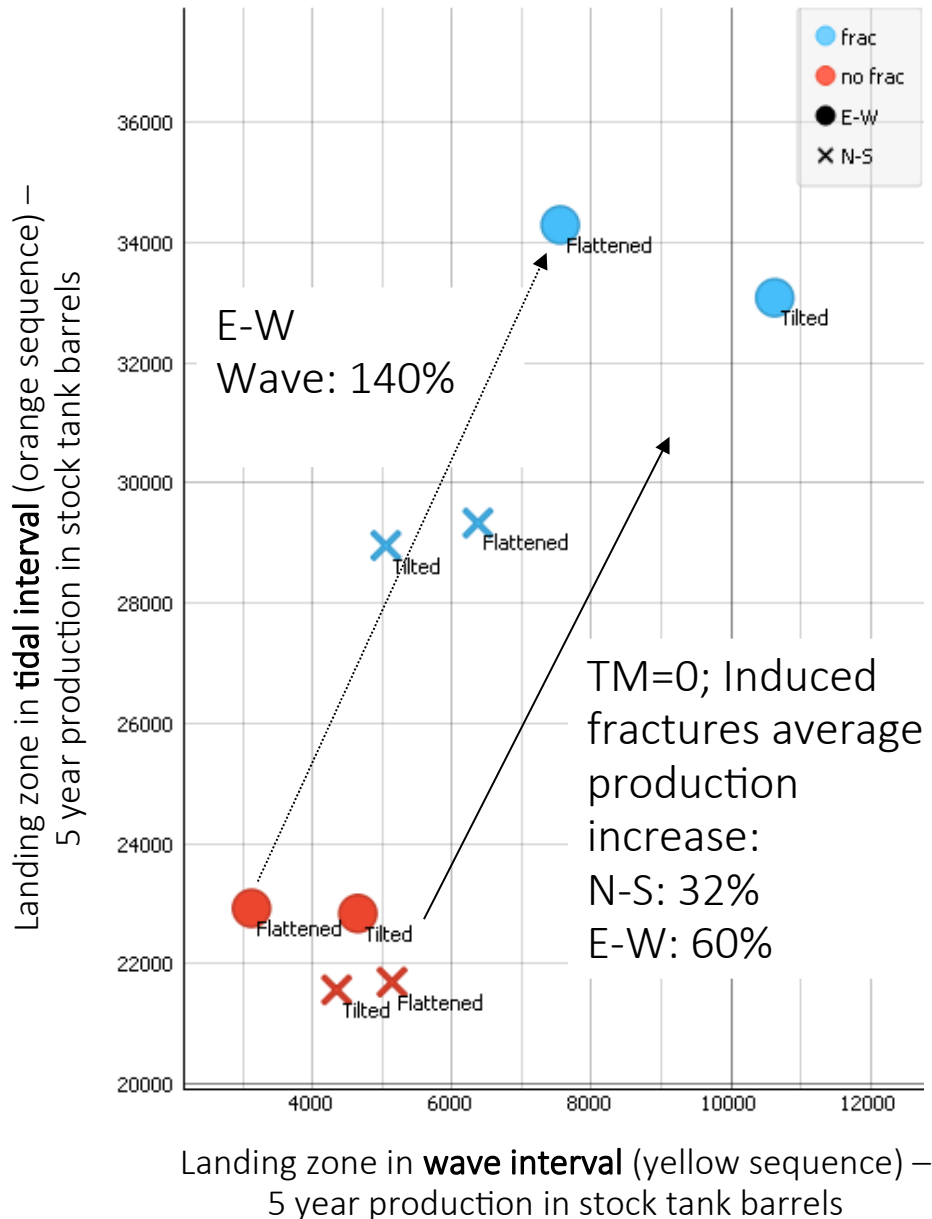
# Stratigraphic Architecture/Facies – Landing Zone



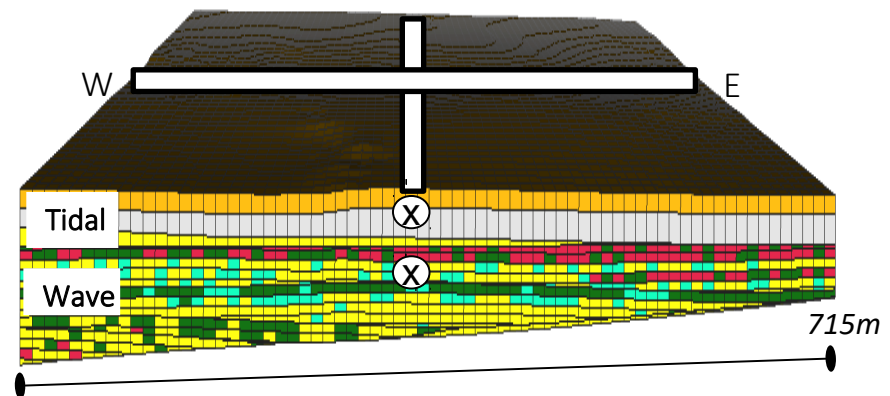
- The **stratigraphic well placement** has the largest impact on production when mudstone barriers are present and have no permeability (TM=0).
- Well placement in the tidal interval results in 420% to 727% higher production** over 5 years compared to the well placed in the wave dominated facies zone.
- This **well placement effect is present even when fracs are applied** (tidal has 310%-570% greater production when fracs are applied).
- Virtually no change when thin mudstone bed permeability is higher (TM=0.5).



# Induced Fractures



- Over 5 years, **induced fractures** result in a limited increase in production (average 32%-60% in the TM=0 cases... BUT
- ...Orientation to stratigraphic heterogeneity and stratigraphic well location matters (not considering any regional or local stress field). Highest increase in production in wells placed in E-W direction in the wave dominated delta facies (140% increase; arrow).

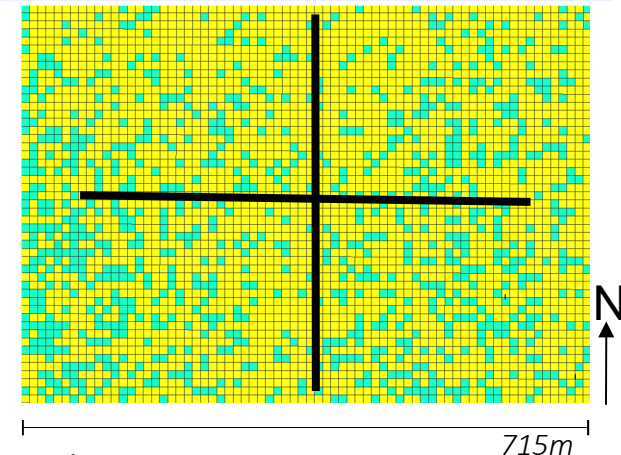
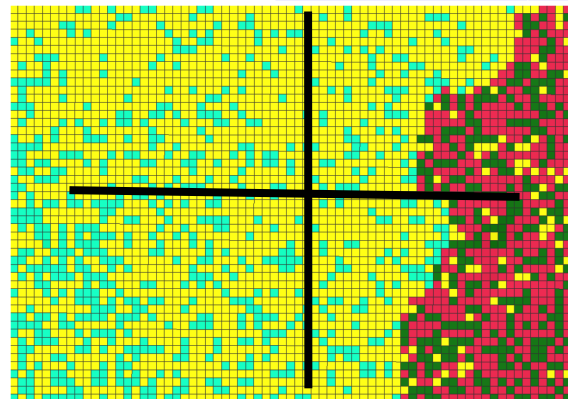
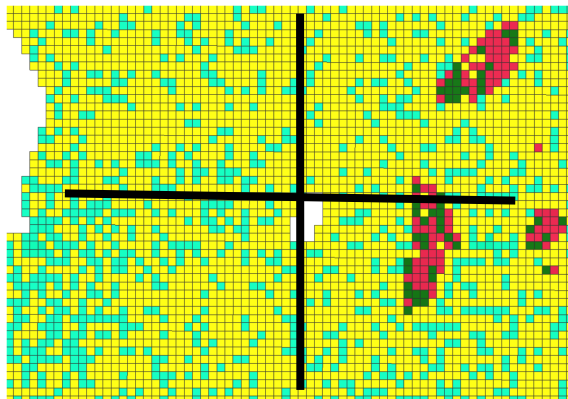


# Induced Fractures



*Flattened Model; TM=0*

Well orientation	Well placement	
	Tidal (Orange Sequence)	Wave (Yellow Sequence)
North-South	29,320 stb (+35%)	6,368 stb (+23%)
West-East	34,280 stb (+50%)	7,579 stb (+140%)



W-E well encounters increased heterogeneity

715m





# Conclusions



- The Wall Creek Member changes from **fluvial, to wave, to tidal dominated delta facies**, each with a unique facies heterogeneity and architecture that have strong influence on fluid flow and production, and can only be characterized from outcrop.
- The permeability (and abundance) of the **fine-grained thin beds is the most critical parameter** controlling reservoir behavior. At low permeability (low TM)  $K_v$  barriers (thin beds) effectively compartmentalize the reservoir. This effect is amplified when wells are placed parallel to depositional strike in the wave dominated delta facies. This effect can only partially be overcome by inducing fractures!
- **Well placement** – stratigraphically (tidal vs wave) and spatially (N-S vs E-W) and not considering regional/local stress field – has **significant impact** on production; wells placed along depositional strike in tidal facies commonly produce best, in wave facies worst.
- **Structural dip** has overall **low impact** on production, but can be important in low  $K_v$  settings if well is placed parallel structural strike.
- **Induced fractures** have highly variable effect (geology matters).



Thank You!