Bioturbation and Its Effects on Permeability in Wave-Dominated Shoreface Rocks of the Spring Canyon Member, Blackhawk Formation, Utah, USA*

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Abstract

Burrowing organisms displace and mix sedimentary grains by burrowing, feeding and relocating. Their activity within the substrate can add to sedimentary heterogeneity, but more importantly alters horizontal and vertical permeability. Understanding the subtle changes in permeability that result from biogenic structures within sediments is an important concern for operators working IOR and EOR projects, such as steam-assisted gravity drainage and CO_2 sequestration.

A geologic process-oriented stochastic method was used to model the wave-dominated shoreface outcrop and biogenic structures of the Spring Canyon Member (Upper Cretaceous), Blackhawk Formation, Utah. Outcrop sedimentologic studies, modern and ancient analogs and probe permeameter provided input for these process-oriented stochastic models. This stratigraphic interval was chosen because it contains heterolithic shoreface-transition facies exhibiting abundant burrowing trace fossils (Ophiomorpha, Asterosoma, and Chondrites). Biogenic structures were modeled as 3D objects of varying dimensions and orientations, and superimposed on process-oriented stochastic models. Permeability was assigned to primary burrows, burrow rims and host lithologies. Multiple realizations were generated to adequately quantify parameter variability.

This study documents the impact of biogenic structures on estimates of effective directional permeability by varying model parameters like orientation, abundance, diversity, and permeability in burrow and burrow rims. These simulation models underwent flow-based upscaling to calculate the effective directional permeabilites for each uncertainty realization.

1. Introduction

What value does this study provide and who could benefit from it?

By modeling biogenic structures in clastic facies, it is possible to investigate and quantify contrasts in burrow/matrix model permeability that can lead to predictive estimates of bioturbation's impact on horizontal and vertical reservoir facies permeability.

This study investigates burrowing trace fossils located in wave-dominated shoreface deposits. Outcrop exposures of the Cretaceous Blackhawk Formation located at Gilson Gulch, Utah, U.S.A inspired this study. Three-dimensional models that captured the dimensions, orientation, and diversity of bioturbation of the outcrops were constructed using SBED process-oriented modeling. Permeability values were assigned to each biogenic structure model, to rims/linings, and to the host lithologies. The resulting models then underwent flow-based upscaling to calculate resulting tensor permeabilities (kx, ky, kz) for each uncertainty realization. Multiple realizations were generated to adequately quantify parameter variability.

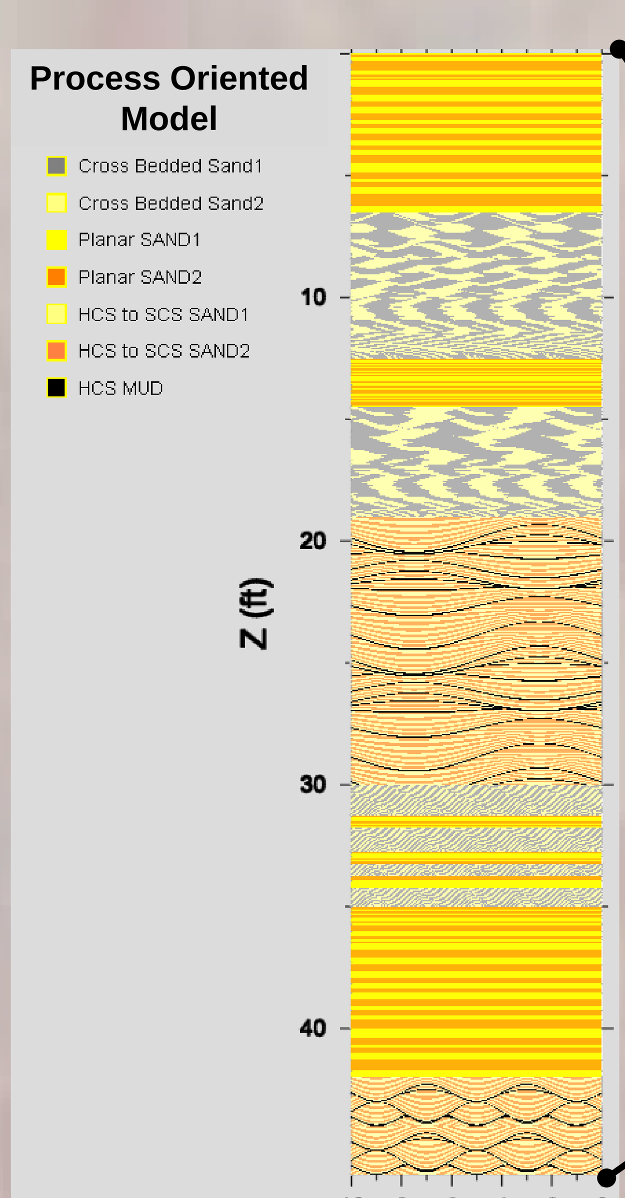
Large-scale studies of sequence, parasequence, and internal architecture of the Blackhawk Formation provide great value in understand the behavior of subsurface reservoirs (Torabi, 2010). However, an equally important understanding of how biogenic structures impact permeability anisotropy can be achieved through small-scale reservoir facies analysis.

Geologically realistic 3D models based on detailed sedimentology and stratigraphy will result in more predictive dynamic simulations, thereby improving our understanding of complex, heterolithic reservoirs.

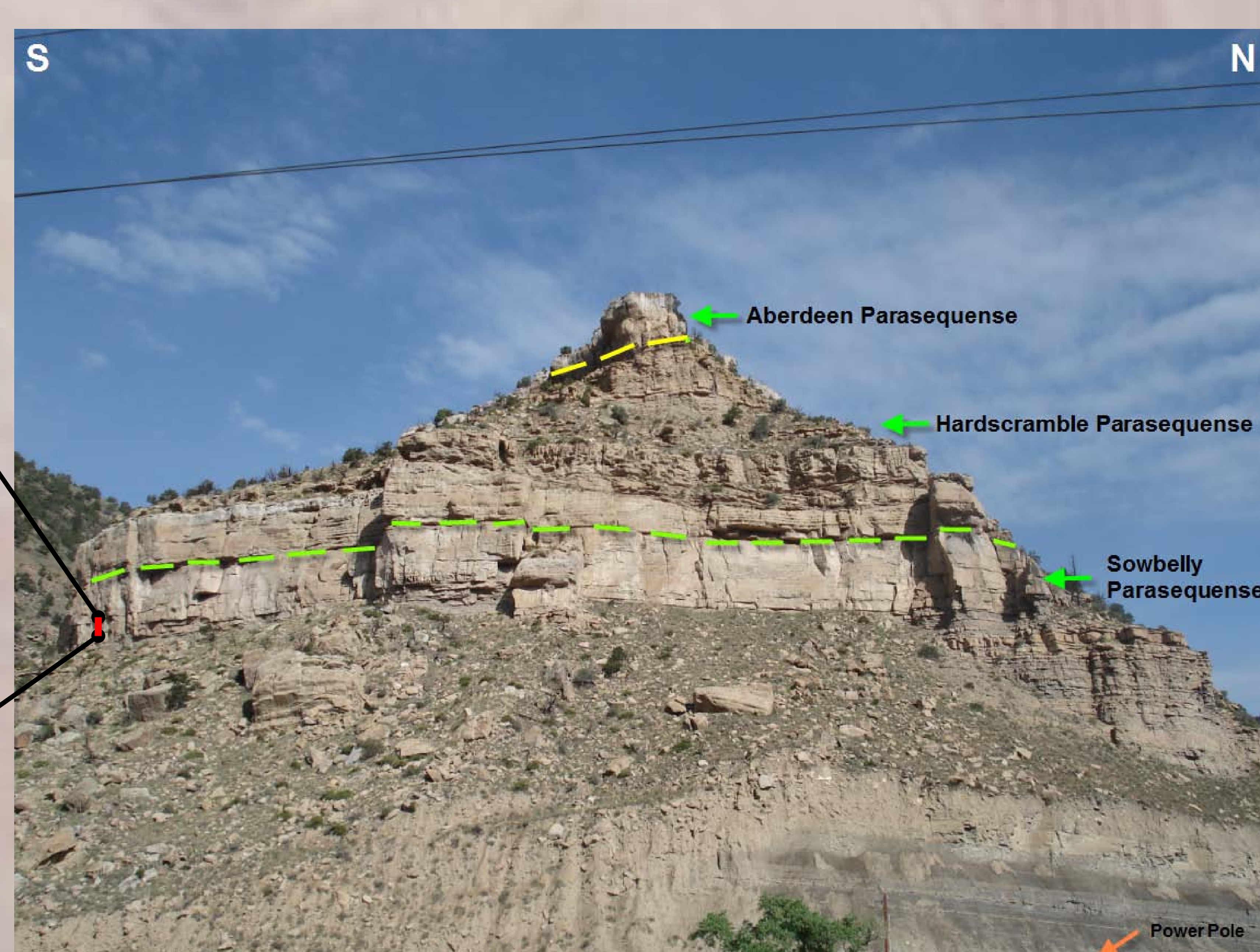
This study demonstrates how small-scale modeling using qualitative and quantitative data from a wave-dominated shoreface outcrop can provide predictive estimates of vertical permeability. This workflow can be applied (even in the field) to any heterolithic clastic outcrop identified as a subsurface reservoir analog.

Book Cliffs, Utah, U.S.A

Ophiomorpha, Sowbelly parasequence. U.S. quarter for scale.



Process oriented model of shoreface deposit.

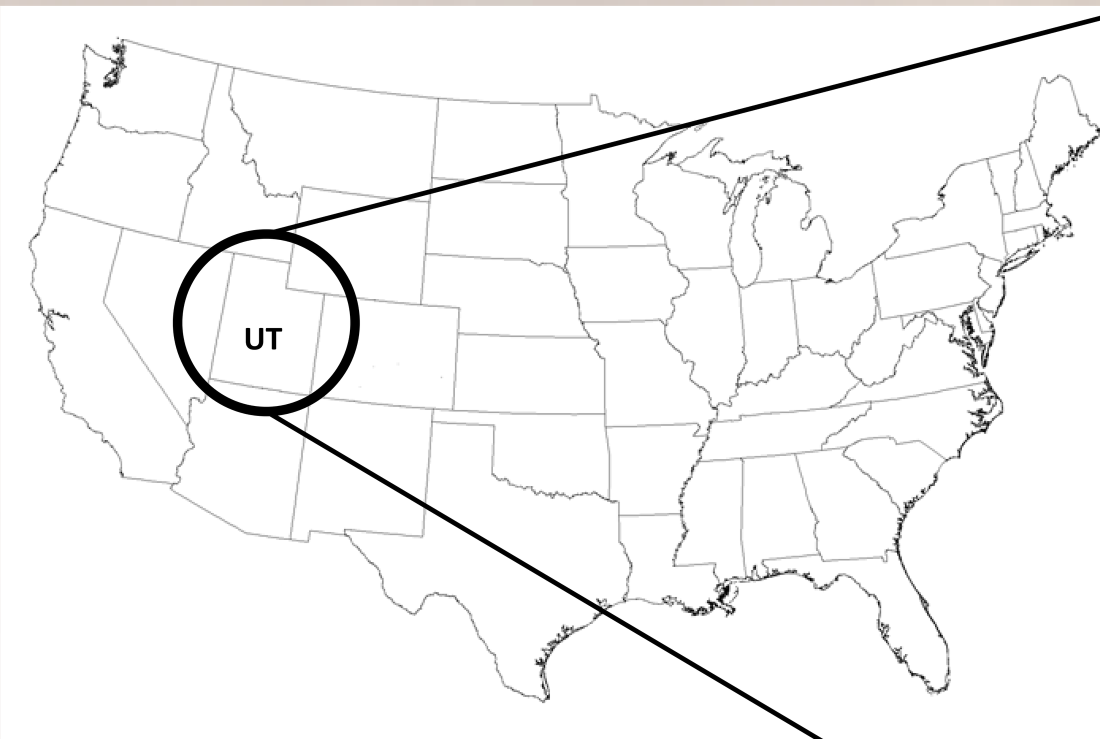


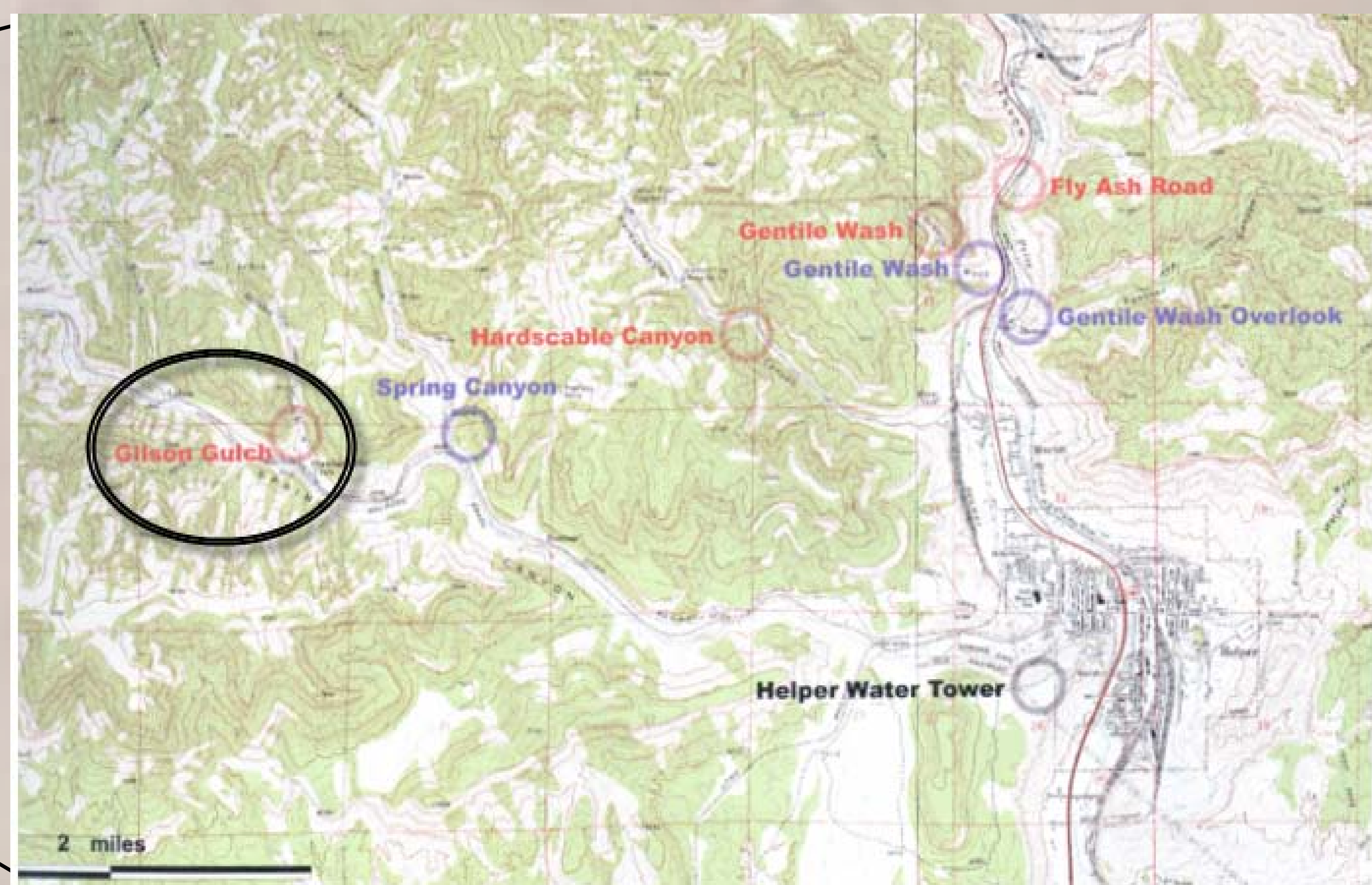
Spring Canyon Member (Sowbelly and Hardscramble parasequences) overlain by Aberdeen parasequence, Gentile Wash, Utah.

2. Geological Setting

Location

Gilson Gulch is a valley in the Book Cliffs located in Section 8, Township 13S, Range 9E; approximately 3.8 miles west and 1 mile north of the town of Helper, Utah, U.S.A.





Location of Gilson Gulch study area. From Shanley *et al.,* 2003

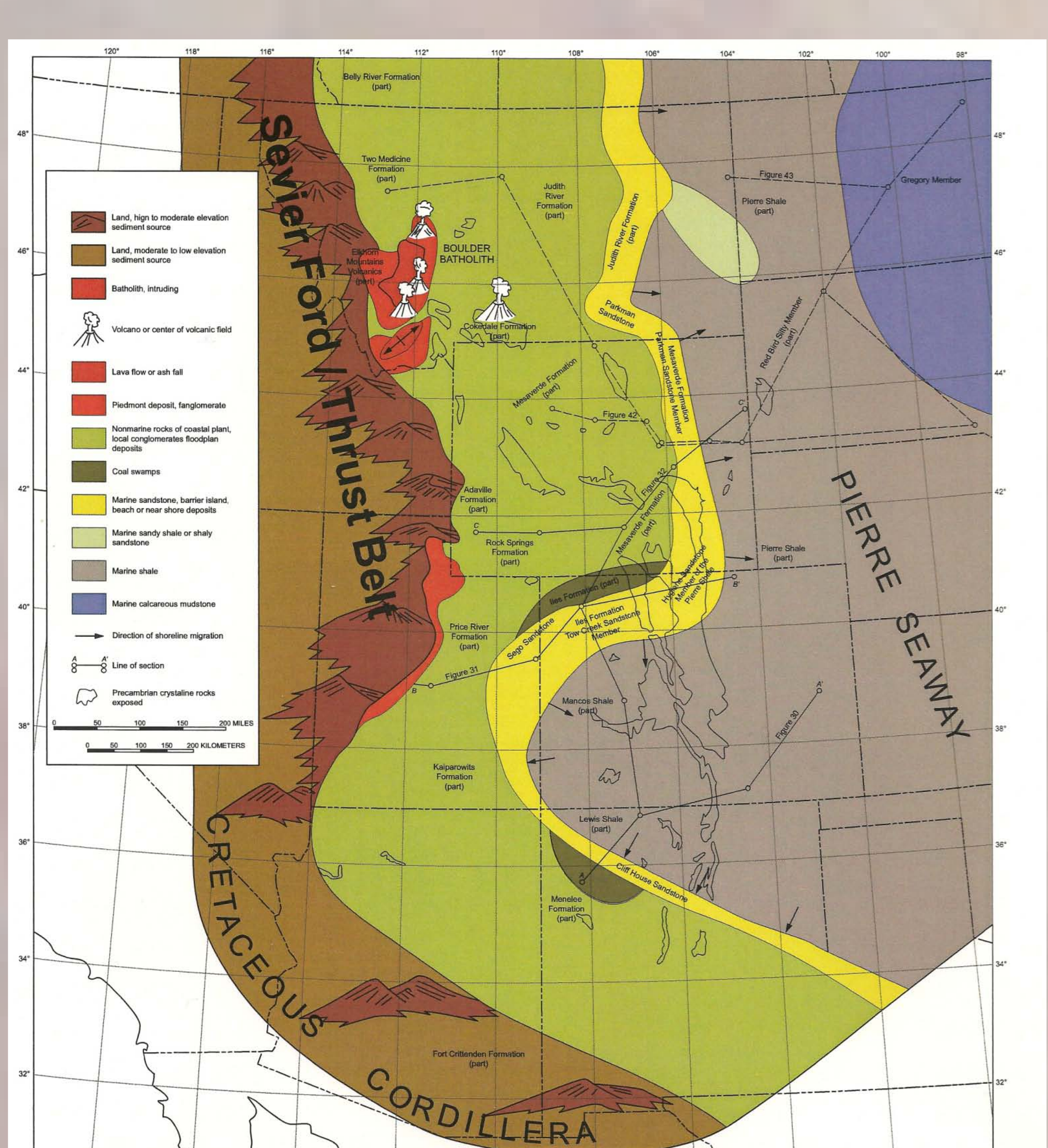
Regional Setting

The study takes place within Upper Cretaceous rocks of the Western Interior Basin. Outcrop exposures at Gilson Gulch are interpreted as Early Campanian (~82.5 Ma) and belong to the Spring Canyon Member of the Blackhawk Formation, Mesaverde Group (Shanley *et al*., 2003). The Mesaverde Group forms a wedge of clastic sedimentary rocks that prograde eastward into the Western Interior Basin from the Sevier Orogen of central Utah. The Blackhawk Formation comprises fluvial-deltaic and shoreface strata that prograded far into the basin in response to pulses of tectonism (Miall, 1993). Sequence stratigraphic analysis in the Blackhawk Formation has identified sequence boundaries interpreted as representing episodes of relative fall of sea level (Van Wagoner *et al*., 1990, Kamola and Van Wagoner, 1995).

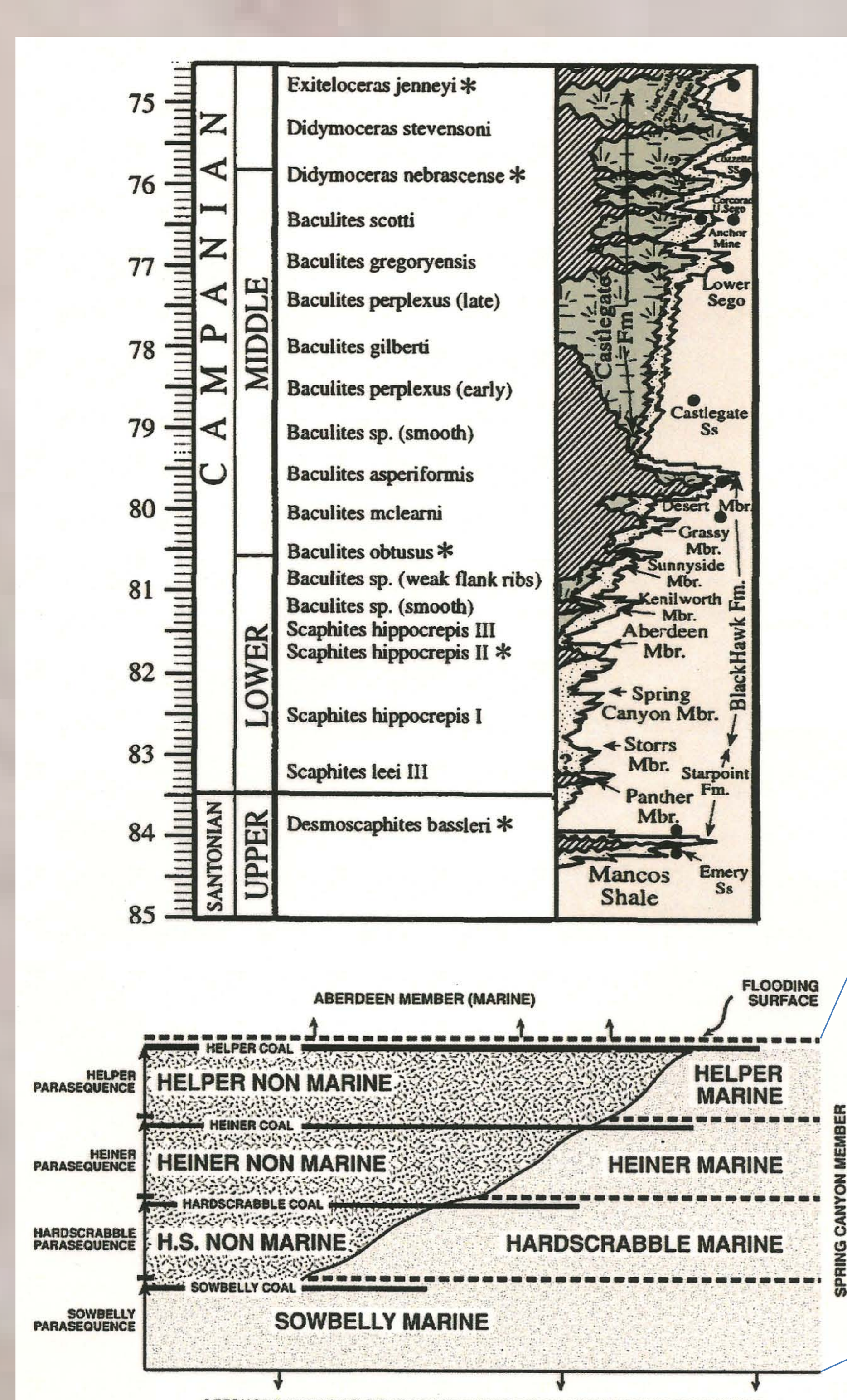
Spring Canyon Member (Blackhawk Formation)

The Spring Canyon Member is the oldest member of the Blackhawk Formation. It is composed of six prograding nonmarine to marine parasequences interpreted as wave-dominated sandstone and siltstone deltaic deposits that interfinger with the Mancos Shale to the east (Kamola and Huntoon, 1995). A study by Kamola and Huntoon (1995) confirmed a basinward progradational stacking pattern of each younger Spring Canyon Member parasequence by plotting the up-dip terminations of each marine facies.

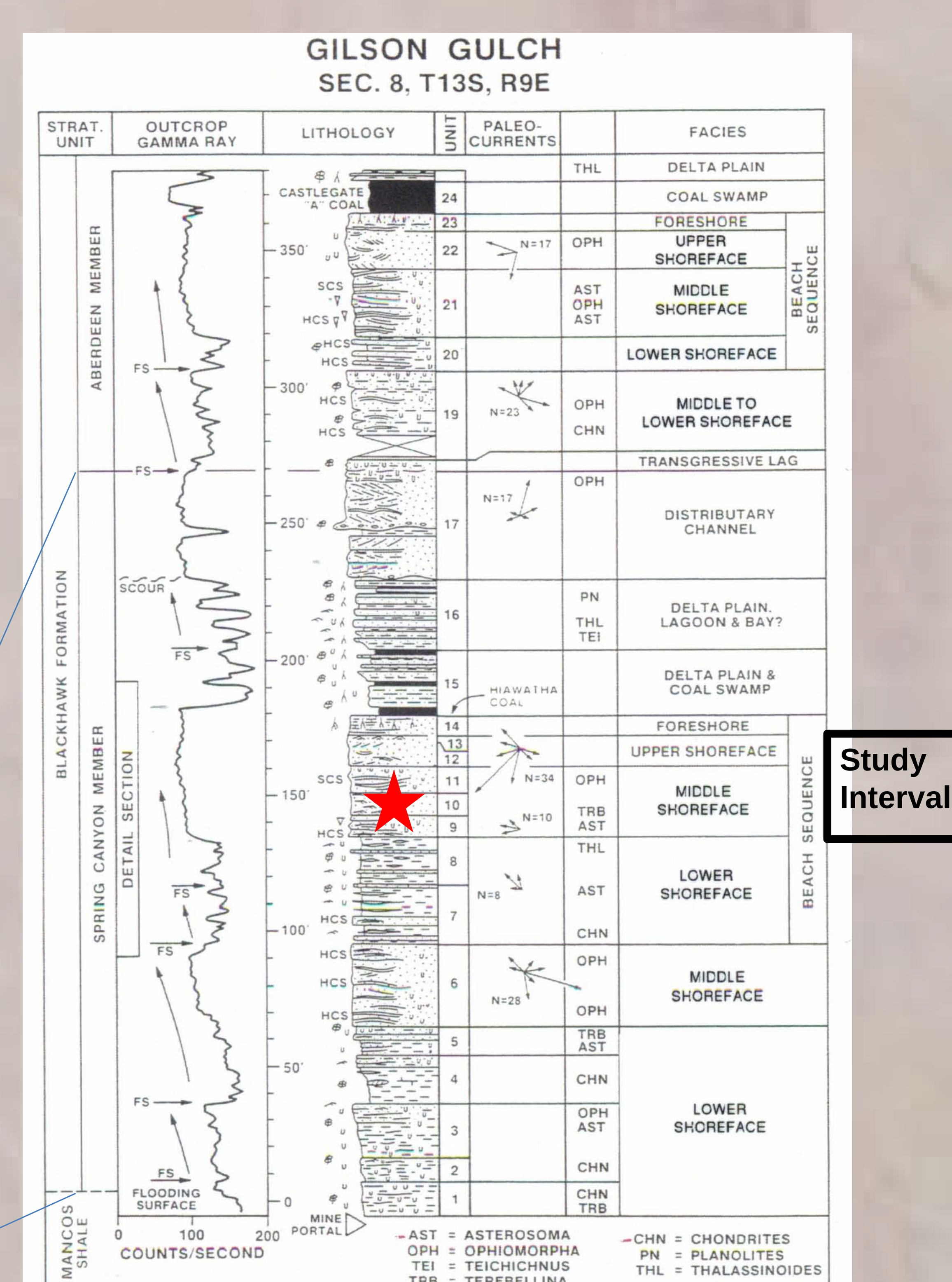
The Sowbelly marine parasequence was selected for this study. This interval is the oldest stratigraphic unit in the Spring Canyon Member. The Sowbelly parasequence facies consists of shoreface-transition facies exhibiting abundant burrowing trace fossils (e.g., *Ophiomorpha, Asterosoma*, *Thalassinoides* and *Chondrites*) hosted by heterogeneous sedimentary rocks (Shanley and Boyles, 2009).



Position of shoreline deposits relative to Sevier Orogeny and Western Interior Sea. From Shanley *et al.*, 2003



Spring Canyon Member parasequence subdivision.
After Shanley and Boyles, 2009



Facies interpretation at Gilson Gulch, Utah, U.S.A. Units 9-11 represent the study interval. Modified after Shanley and Boyles, 2009

Field Setting

This study builds upon on work completed by R.D. Cole, A.S. Trevena and M.P. Morton (1993), who mapped and sampled the eastern exposure of Gilson Gulch Section No. 2. The team collected probe permeameter data, gamma-ray measurements and rock descriptions over 50-foot (15.2-meter) vertical and 128-foot (39-meter) horizontal transects. Based on their descriptions the outcrop exposure was interpreted to represent wave-dominated lower to upper shoreface deposits (Shanley *et al*., 2003). This study models rock units 9, 10, and 11 as identified by Shanley *et al*. (2003).

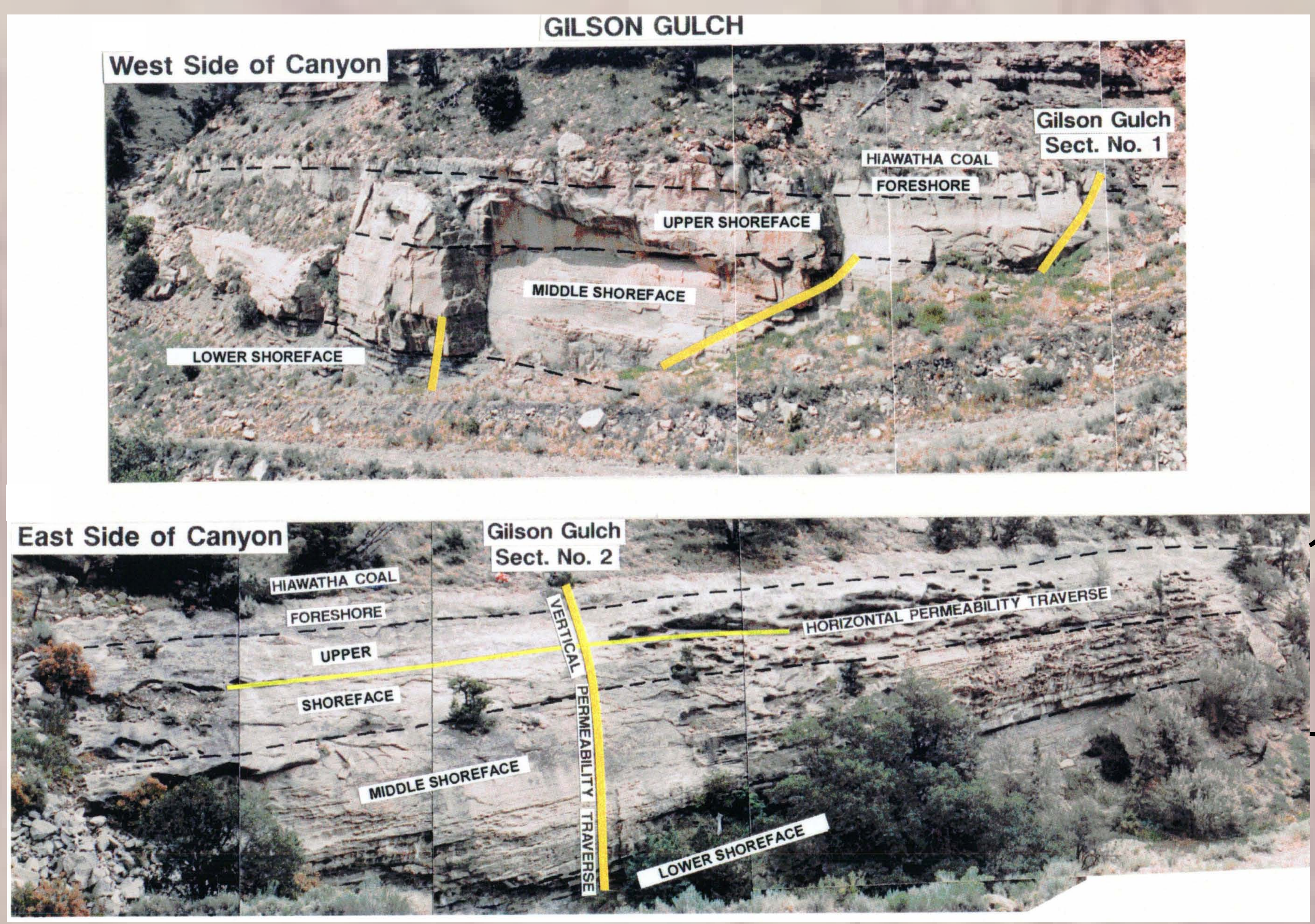
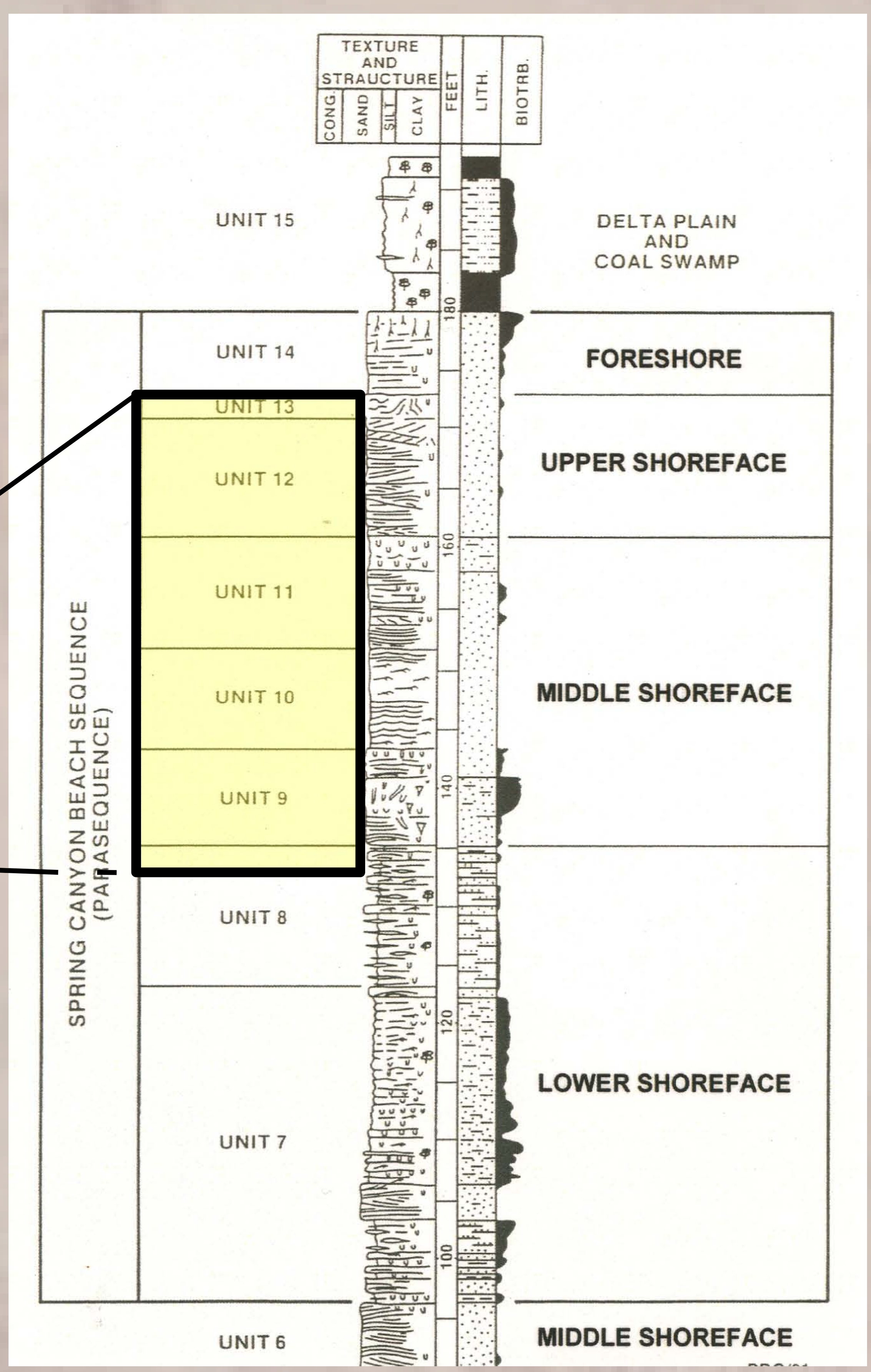
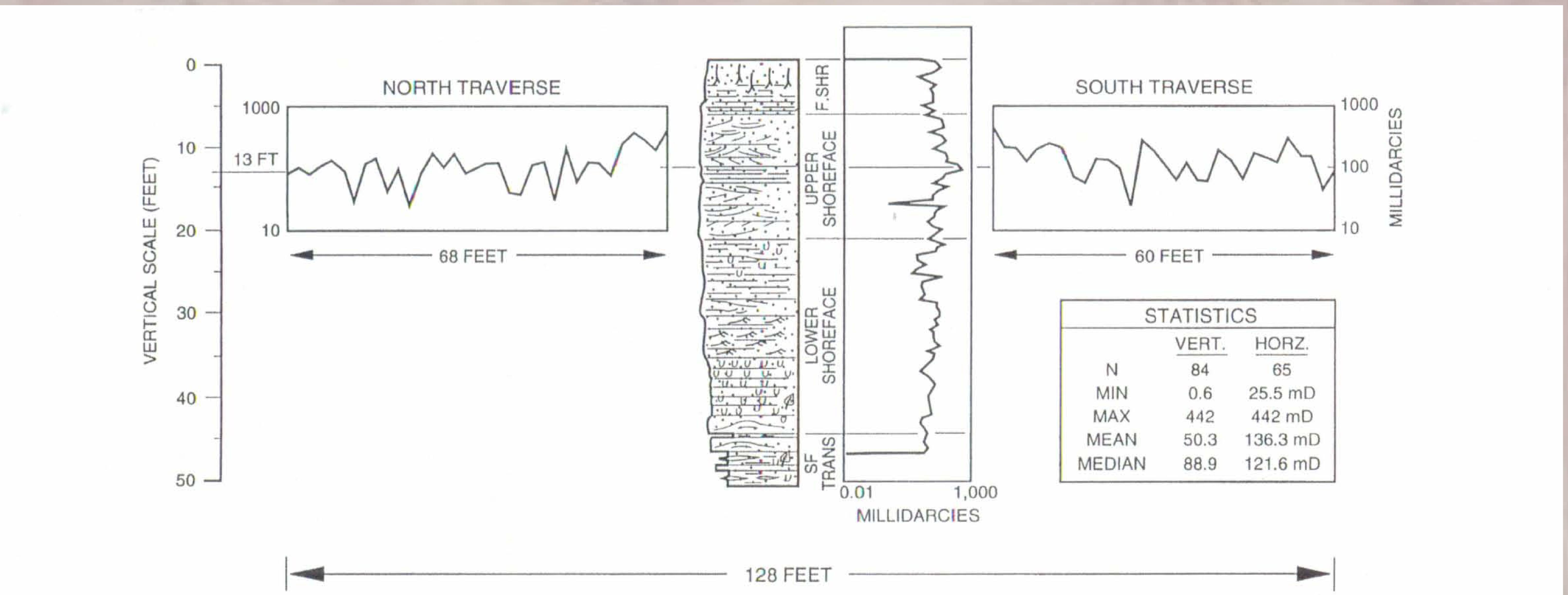


Photo mosaic of western and eastern canyon of Gilson Gulch. Vertical and horizontal transect of Gilson Gulch No.2 highlighted in yellow (data collection by R.D. Cole, A.S. Trevena and M.P. Morton, 1993) and lithofacies interpretation superimposed on photo mosaic . From Shanley *et al.,* 2003



Rock unit classification of outcrop occurrence, Gilson Gulch. From Shanley *et al.,* 2003.

During AAPG field trip #13 (2009, additional rock descriptions and photographs were collected of statigraphically equivalent lithofacies at Gentile Wash, Utah. The Gentile Wash outcrop exposures provided similar lithofacies and stacking patterns to those identified in the Gilson Gulch No.2 exposure. This field data was cross-referenced with published data by Shanley *et al*.(2003) and Shanley and Boyles (2009) to ensure accurate modelling of small-scale features like burrowing trace fossils, lithofacies, bedform geometry, and sand /mud lamina proportions.



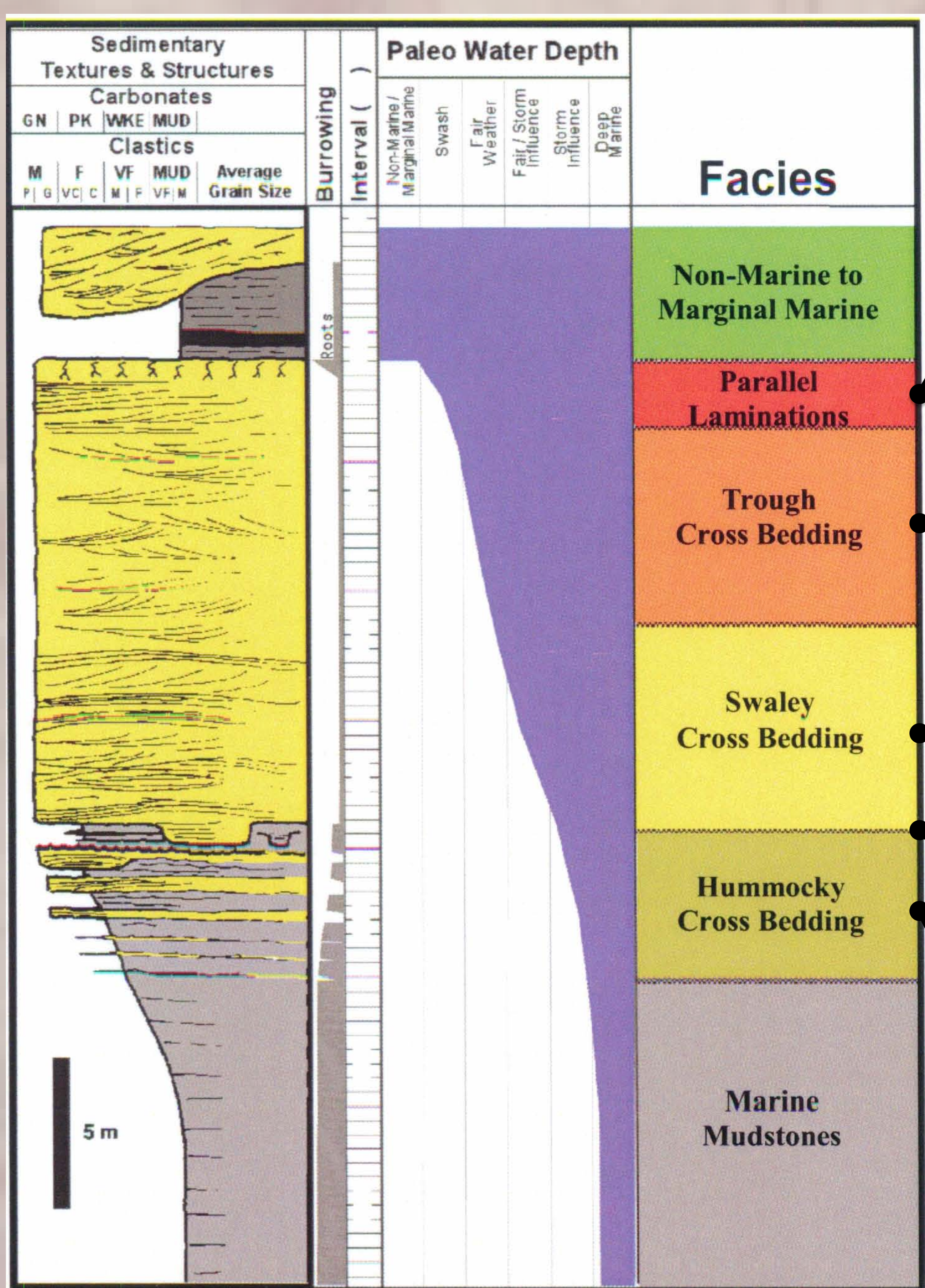
Probe permeameter data collected by R.D. Cole, A.S. Trevena and M.P. Morton, 1993) from Gilson Gulch No.2 vertical and horizontal transects. From Shanley *et al.,* 2003

This study used only probe permeability data collected from the vertical transect, which included several representative samples from each lithofacies.

3. Target: Lower and Middle Shoreface Deposits

General Characteristics

1. Wave-dominated heterolithic lower and middle shoreface-transition facies.
2. Heterolithic intervals with abundant mud drapes and burrowing trace fossils.
3. Ichnofacies include *Ophiomorpha*, *Thalassinoides* and *Asterosoma.*
4. Permeability contrasts between mud and sand components.



Ideal shoreface succession for the Book Cliffs. From Shanley *et al.,* 2003

Photographs of Sowbelly parasequence lithofacies, Gentile Wash, Utah. From top to bottom: planar beds, trough cross beds, swaley cross beds, alternating planar beds with current to wave ripple laminated beds, and hummocky cross beds. US quarter or 3.28 ft (1.0 m) ruler used for scale in photographs.

4. Sampling and Analytical Data

Permeability data for this study was obtained from a plot of probe permeameter measurements in Shanley *et al*. (2003). The measurements were collected by R.D. Cole, A.S. Trevena and M.P. Morton (1993).

Permeability measurements from each lithofacies were plotted against sample depth to allow identification of any permeability trends and permeability subgroups within lithofacies. Permeability measurements of burrows were not available for use.

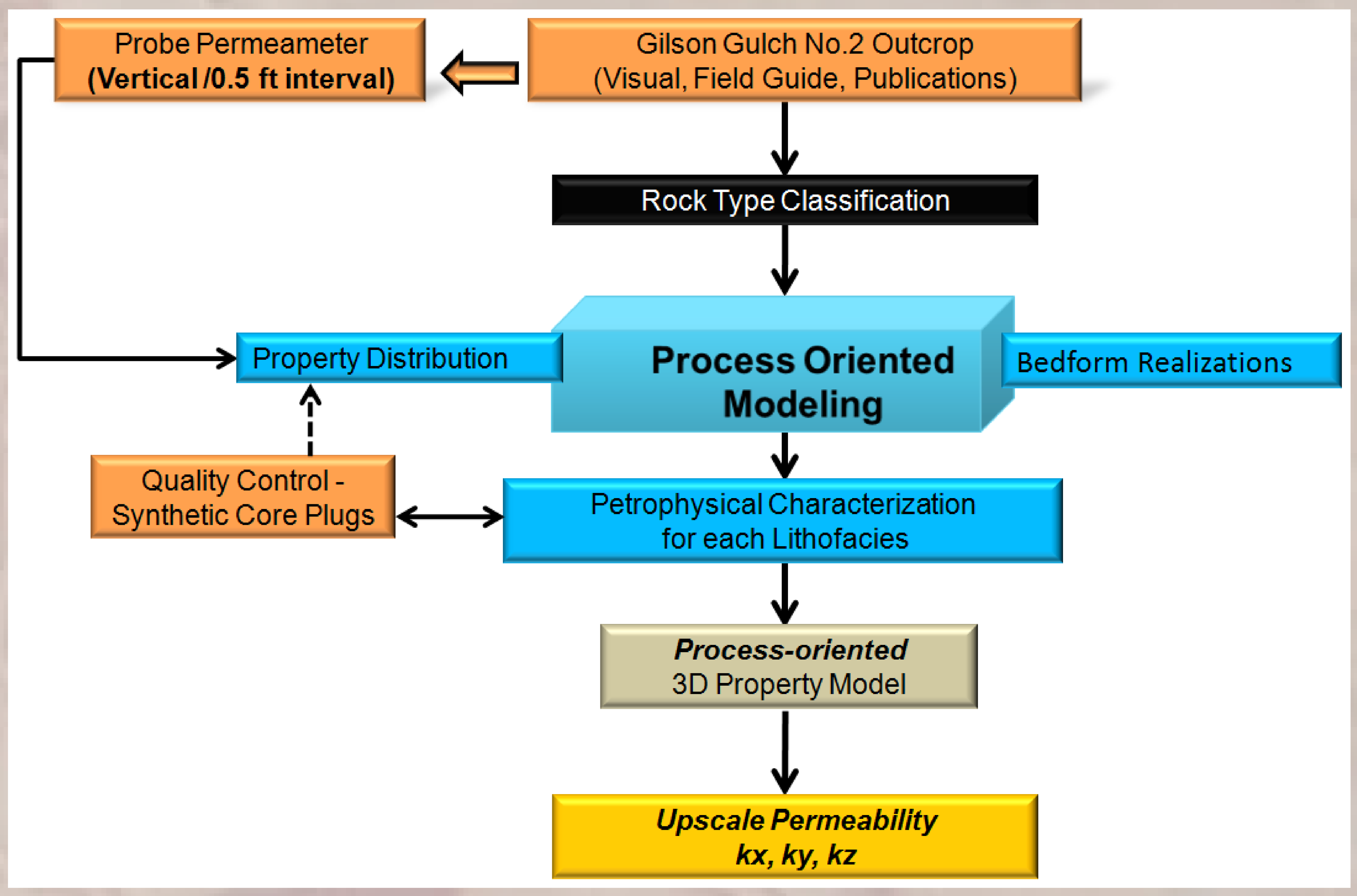
Process-oriented matrix models of hummocky cross stratification, planar bedding and swaley cross stratification from Gilson Gulch No. 2 section represent the controlled variable. The biogenic structures were also reconstructed by process-oriented modeling and represent the independent variable.

For the biogenic structures, permeability varies for both the lining/rim and the fill to quantify their effects on the horizontal and vertical permeability of a non-bioturbated model.

5. Process Oriented Modeling

Workflow

1. Document detailed description of fine-scale bedforms and sedimentary structures.
2. Classification of rock types from descriptions.
3. Petrophysical data analysis.
4. Build lamina-scale bedding models of each lithofacies. Stochastic variance of simulation parameters is used to impose random variability on individual model realizations.
5. Model permeability based on the permeability distributions of the specific lithologies making up each facies.
6. Upscale each property model. Multiple realizations are generated to quantify petrophysical variability.



Model Generic Templates

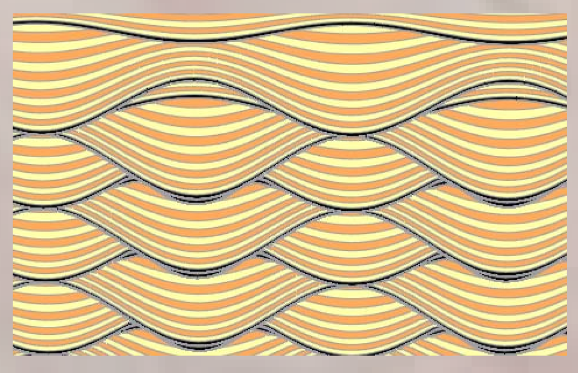
A new 3D modelling approach was used to create realistic models that capture small-scale sedimentary features found in the study interval (*e.g.,* mud drapes and biogenic structures). Single Phase flow-based upscaling was imposed on these models to calculate tensor permeabilities (*kx, ky, kz*) for each facies.

A total of six process-oriented model templates were used, one for each lithofacies identified. To adequately capture the representative sedimentary variability, the following model dimensions for each template were assigned:

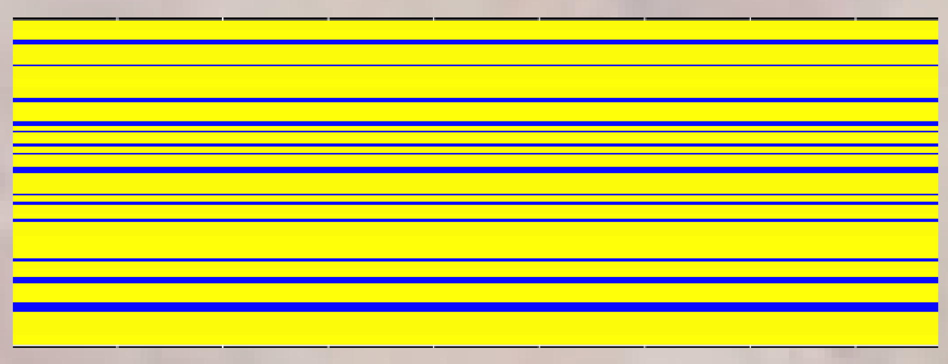
• Model grid - 10 x10 x n (ft) (3.048m x 3.048m x n)

• Grid cell size - 0.1 x 0.1 ft (0.3048m x 0.3048m)

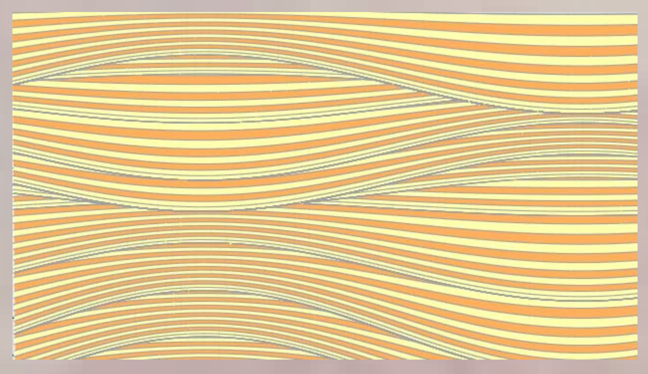
• Model interval – 46-foot (14 meters) vertical section



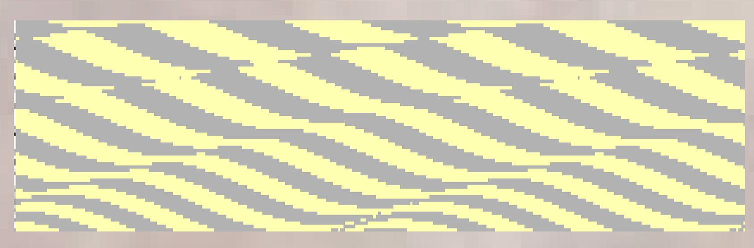
Hummocky Cross Stratification



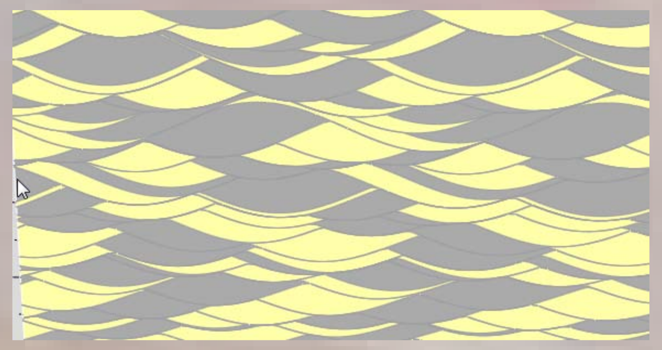
Planar Bedding



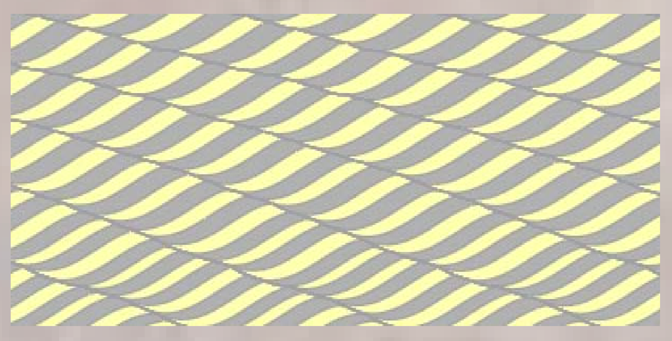
Swaley Cross Statification



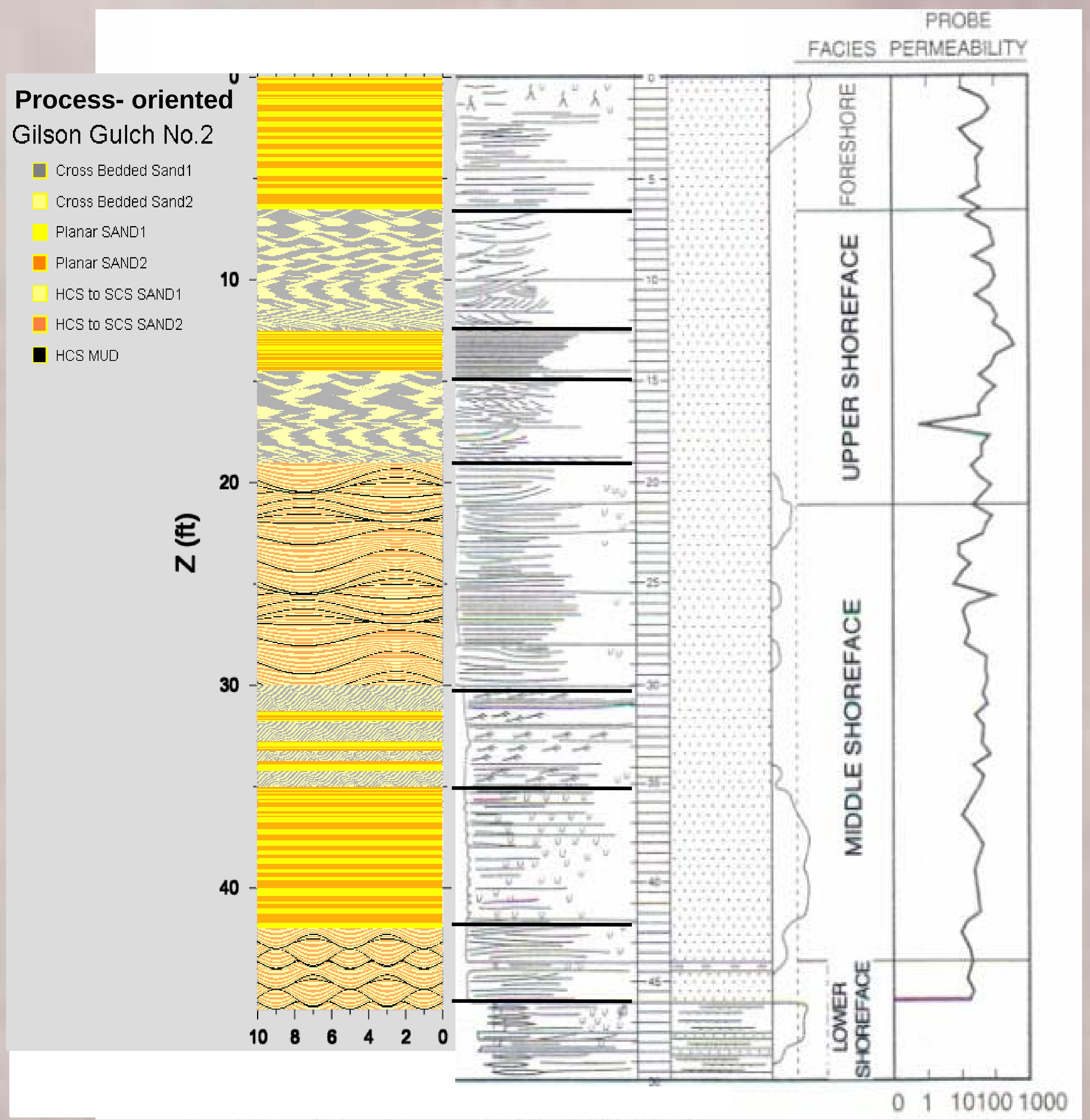
Tabular -Tangential



Trough Cross Bedding



Ripple Lamination



Process oriented interval model by Dabek *et al.,* 2010) alongside Gilson Gulch detailed description and probe permeameter data as documented by R.D. Cole, A.S. Trevena and M.P. Morton 1993). From Shanley *et al.,* 2003

Model Biogenic Structures

The new 3D process oriented modelling approach was used to model realistic biogenic structures. Two of the five available biogenic structure templates were used to create three burrowing ichnofacies: *Ophiomorpha*, *Thalassinoides* and *Asterosoma*. Biogenic structure models are inserted into the matrix grid with variable dimension, orientation, percentage and trend. Each burrow fill and lining/rim can be assigned variable permeability and porosity. *Ophiomorpha* and *Thalassinoide* process oriented models were assigned the following static simulation parameters.

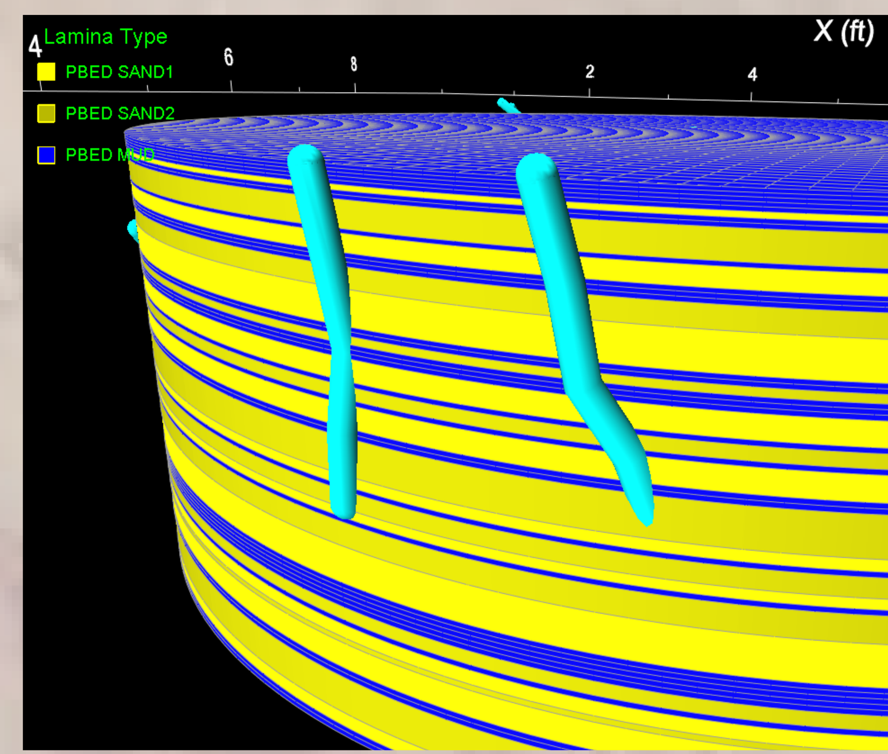
Ophiomorpha

Model Template	Curved rod
Rod length	1.5 ft (0.46 m)
Rod diameter	0.10 ft (0.03 m)
Dip (degrees)	Mean = 75
Azimuth (degrees)	Mean = 30
Lining/rim diameter	0.10 ft (0.03 m)
Trend	Downward decreasing

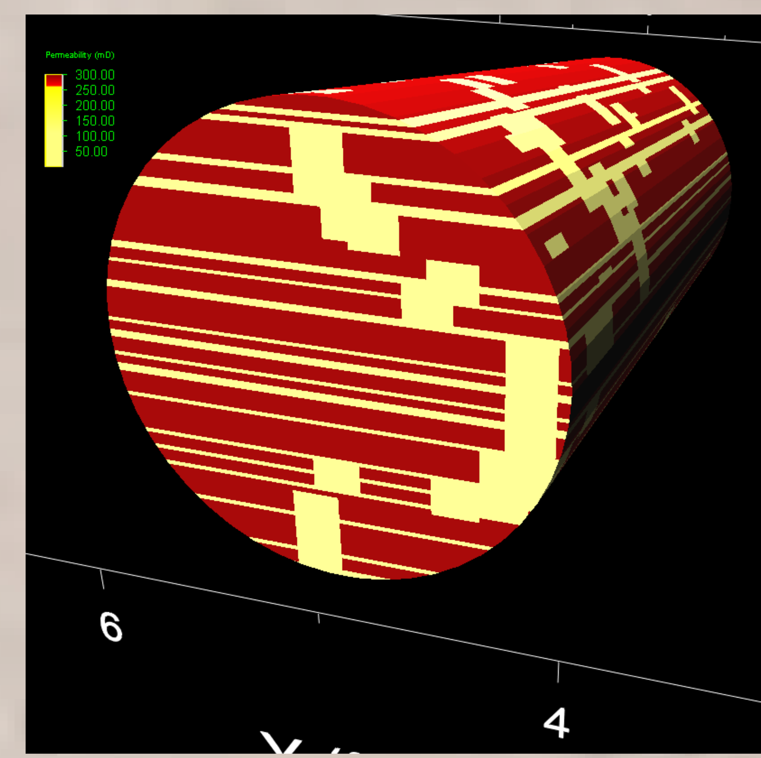
Thalassinoides

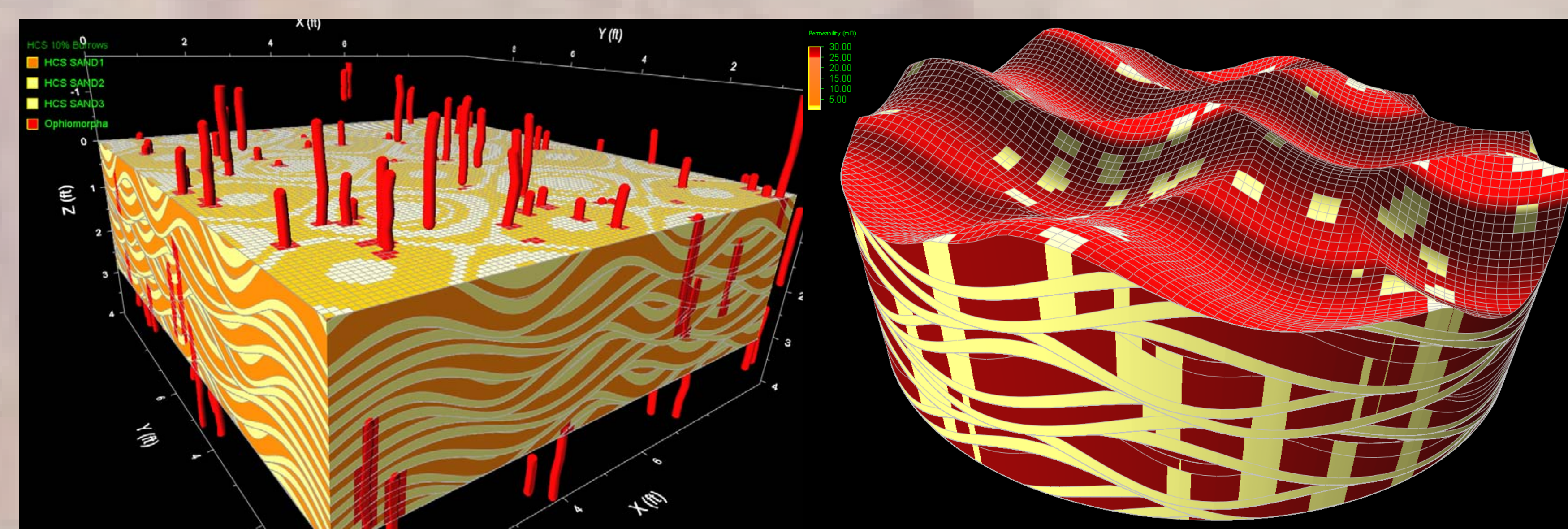
Model Template	Network rod
Rod length	1.5 ft (0.46 m)
Rod diameter	0.10 ft (0.03 m)
Dip (degrees)	Mean = 75
Azimuth (degrees)	Mean = 30
Lining/rim diameter	0.10 ft (0.03 m)
Trend	Downward decreasing

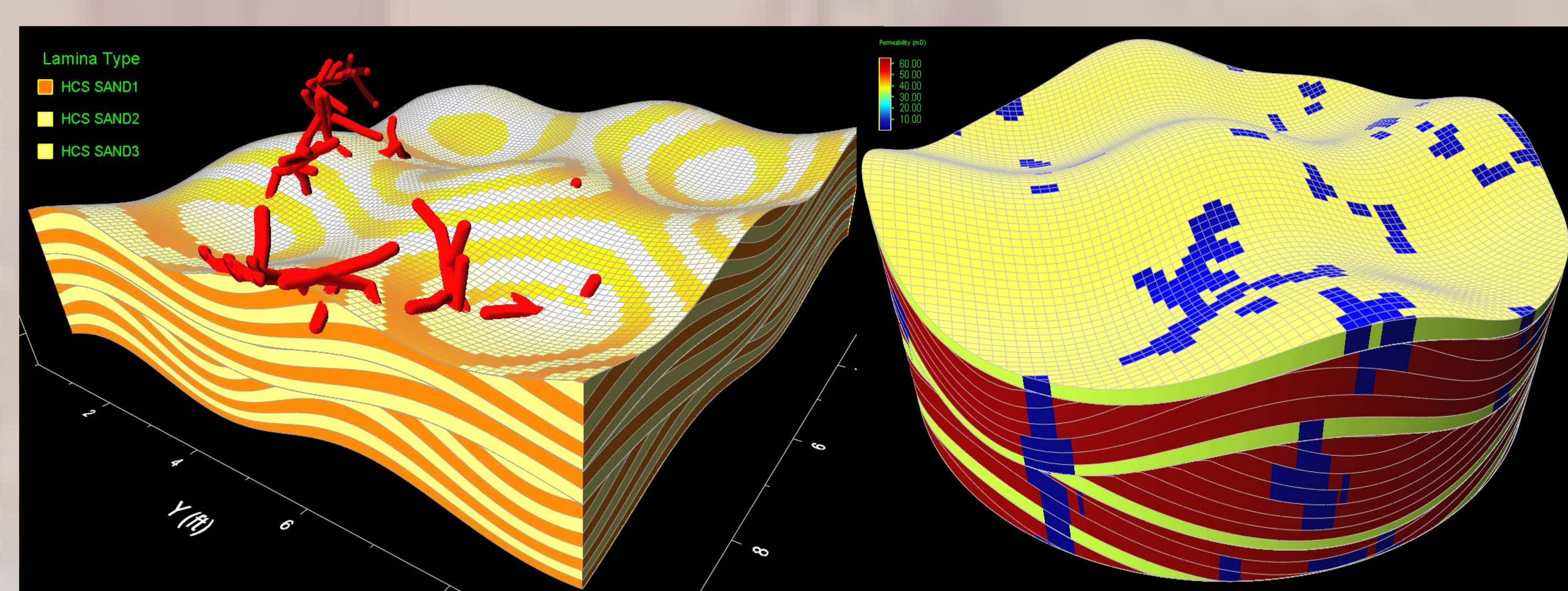
Single Phase flow-based upscaling was calculated for controlled variables (matrix models) containing independent variables (biogenic structures) resulting in tensor permeabilities (*kx, ky, kz*) for each controlled variable.



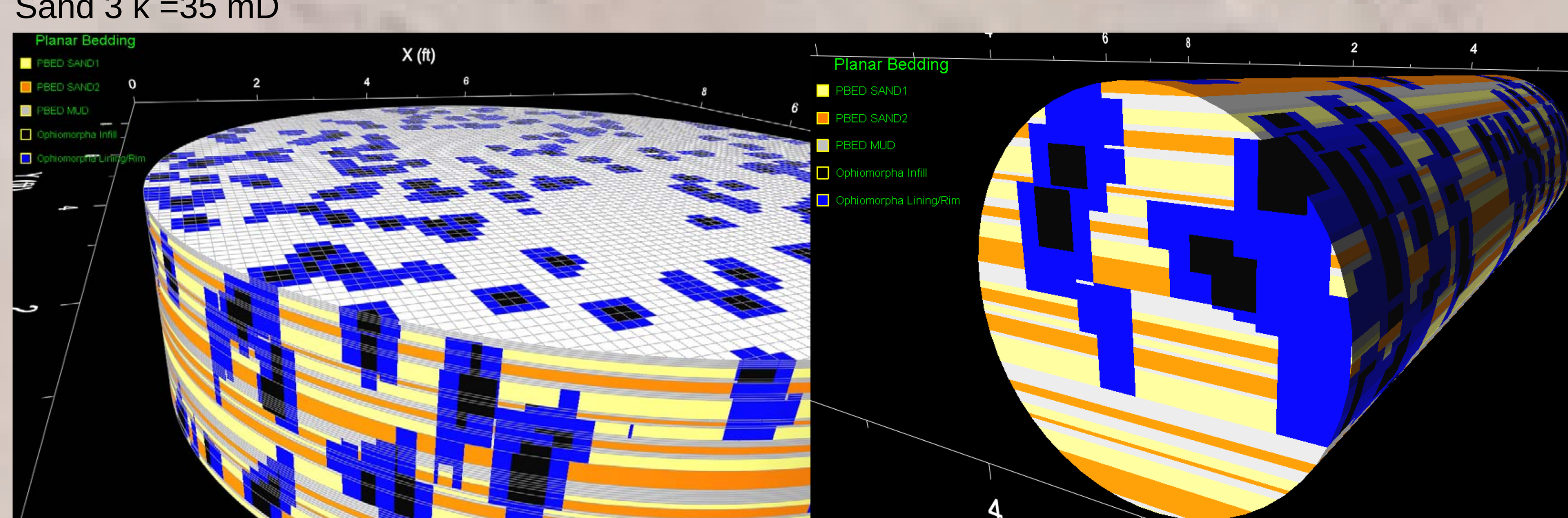
Process oriented model of *Ophiomorpha* (light blue) in planar bedding


Core plug model of *Ophiomorpha* in planar bedding. Burrows : k = 0.01 mD; Matrix: k = 300 mD

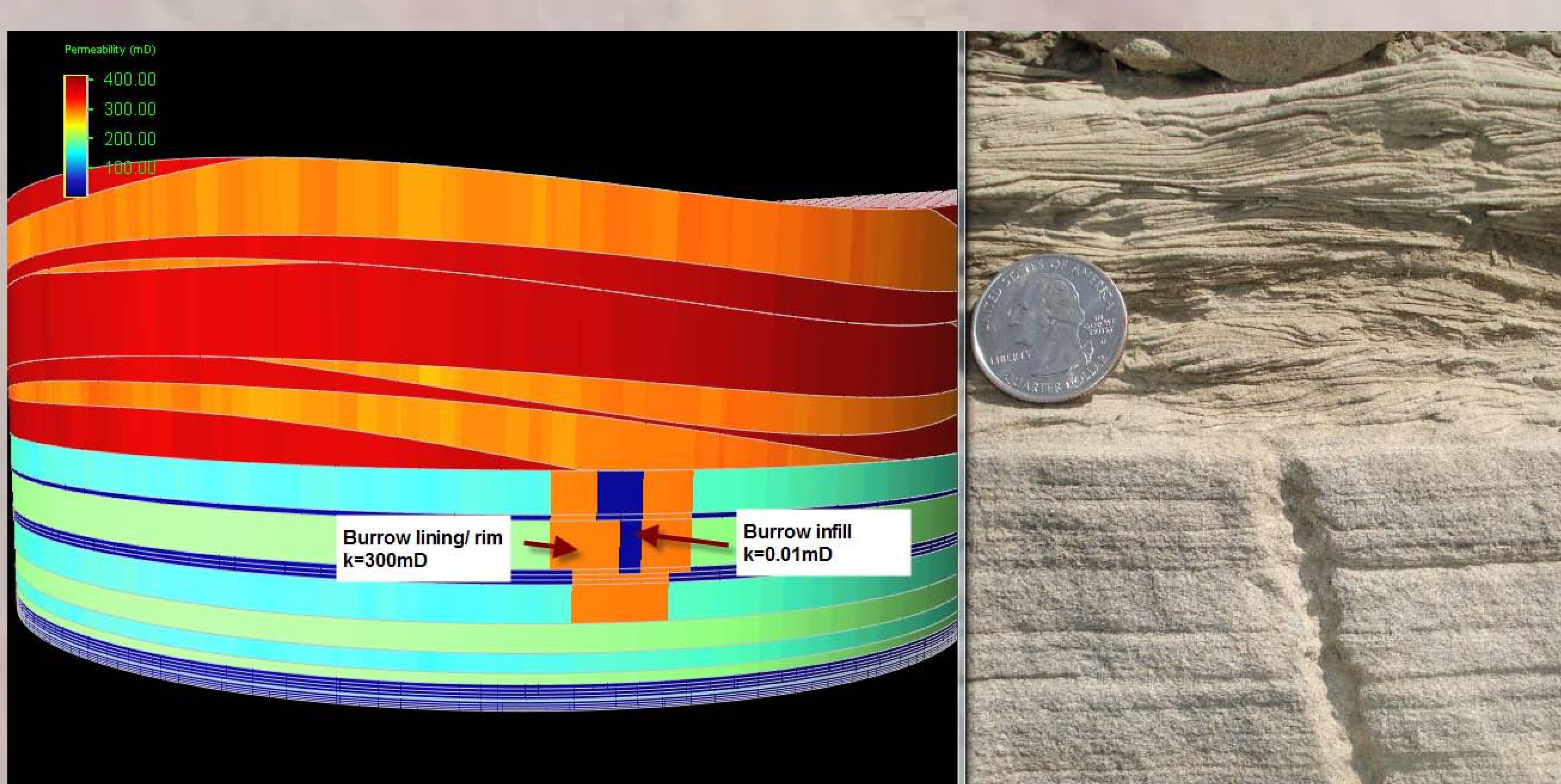

Process oriented model of *Ophiomorpha* burrows (red) in hummocky cross bedding (left). Core plug model of *Ophiomorpha* in hummocky cross bedding; Burrows : k = 0.01 mD; Sand 1, 2: k = 300 mD, Sand 3 k =0.5 mD



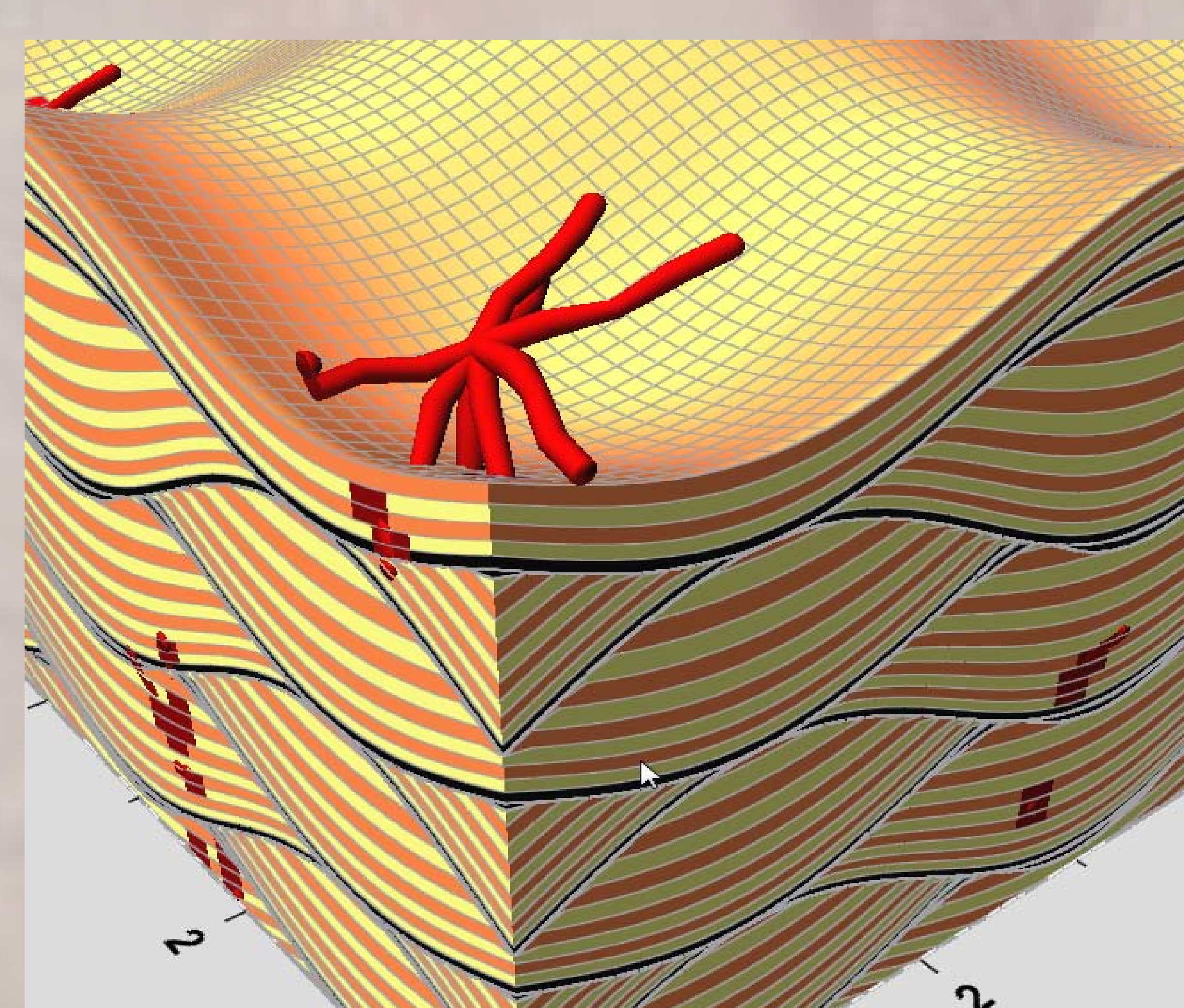
Process oriented model of *Thalassinoides* (red) in swaley cross bedding (left). Core plug model of *Thalassinoides* in swaley cross bedding; Burrows (blue) : k = 0.01 mD; Sand 1, 2: k = 65 mD, Sand 3 k =35 mD



Core plug model of *Ophiomorpha* (fill in black, lining/rims in blue) in planar bedding (left). Core plug model of *Ophiomorpha* in planar bedding; fill (black), lining/rims (blue)



Generic model of observation in Sowbelly parasequence, Utah. (Left) core plug permeability model of *Ophiomorpha* (fill in blue (k = 0.01 mD), lining/rims in orange (k = 300 mD) hosted in planar bedding and overlain by ripple laminated beds. (Right) outcrop photograph of *Ophiomorpha* in planar sandstone overlain by current to wave ripple sandstone. US quarter for scale

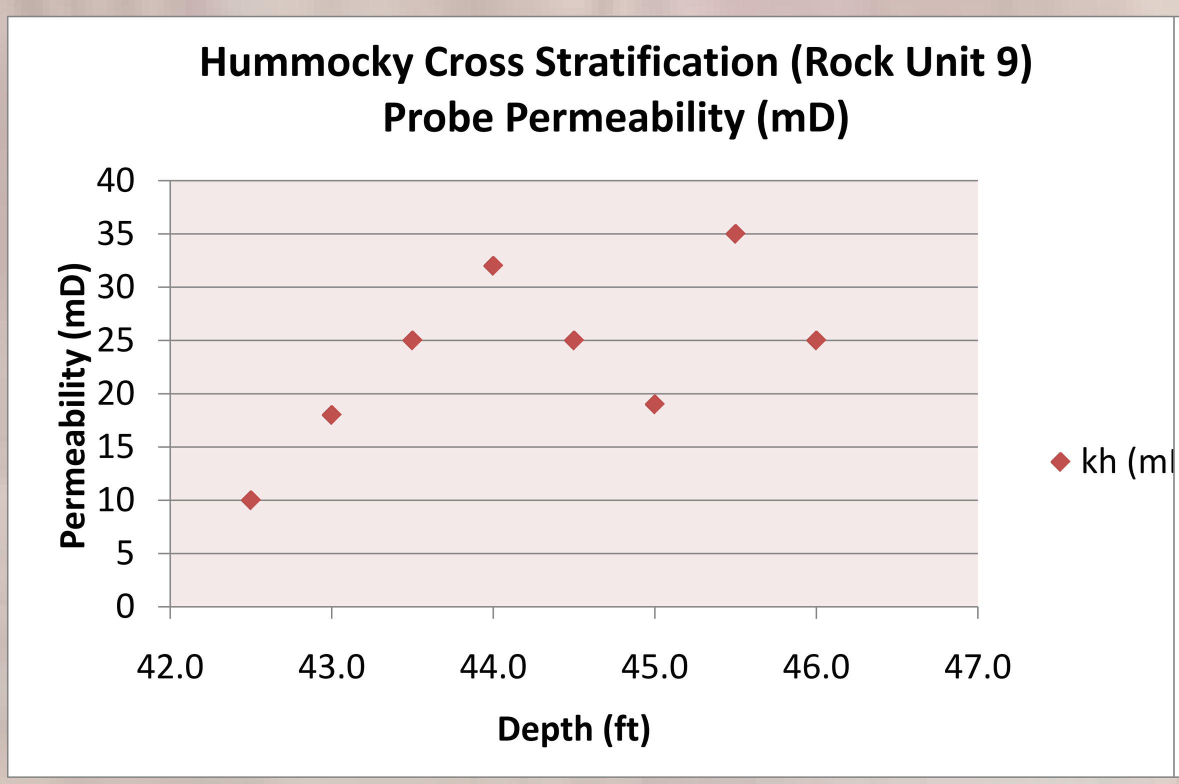

Generic hummocky cross bedding model with *Asterosoma* biogenic structure

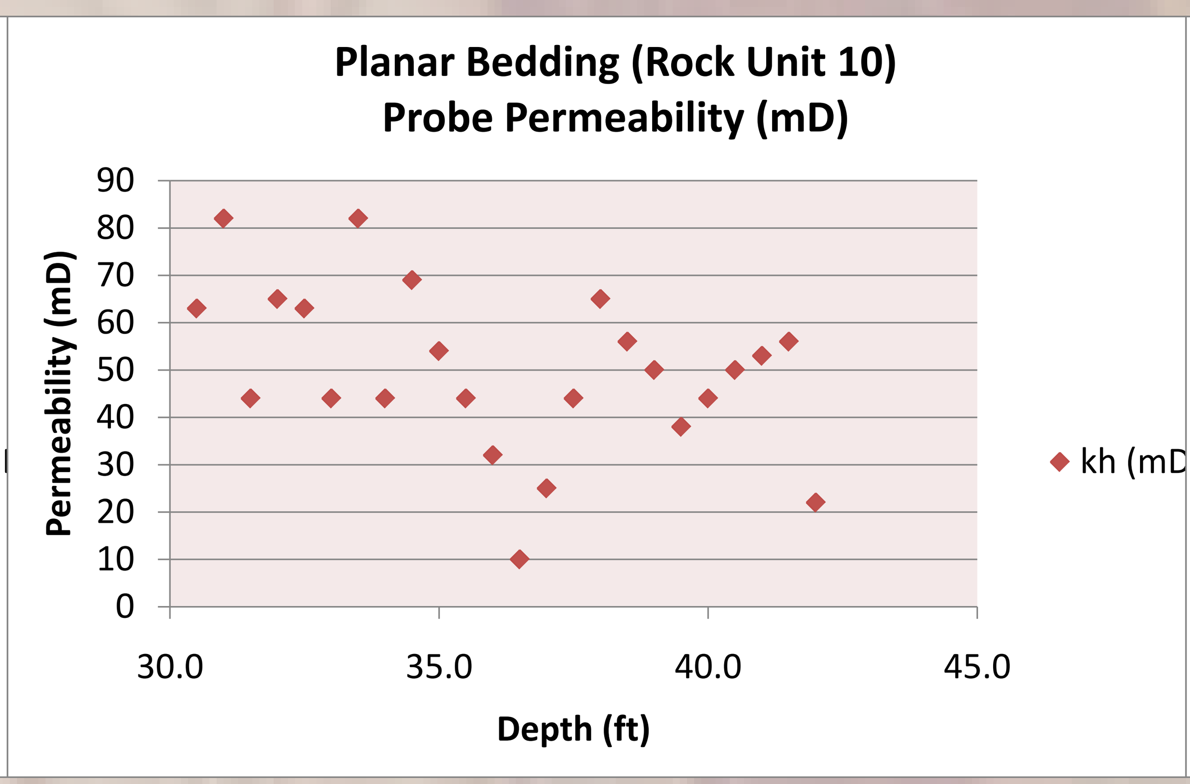
6. Petrophysical Modeling

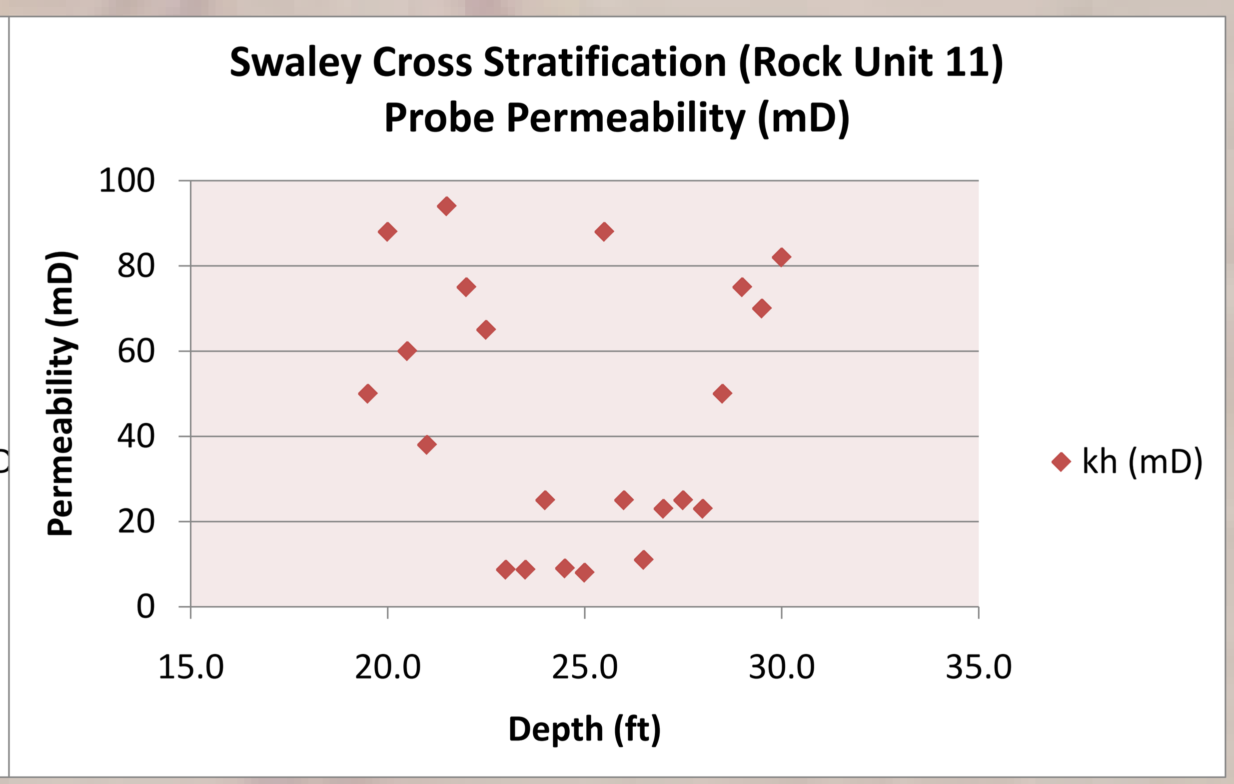
Controlled Variable - Model Statistics

Three wave - dominated lithofacies were selected as controlled variables: (i) hummocky cross stratification (rock unit 9), (ii) planar bedding (rock units 10) and (iii) swaley cross stratification (rock unit 11). Bedding structure models were completed for each lithofacies , followed by the assignment of mean permeability and porosity values to sand and mud laminae in each bedding structure model. A simulation of porosity and permeability models was followed by single phase upscaling to calculate directional effective permeability (kx, ky and kz), porosity, and netgross.

Probe permeameter samples from the Gilson Gulch No. 2 vertical section indicate permeability values are highest in upper shoreface lrocks and decrease progressively downward into lower shoreface rocks (Shanley *et al., (*2003). This observation is validated in plots of permeability vs depth of Gilson Gulch No. 2 probe permeameter samples. From these plots the mean value of permeability was used for hummocky cross stratification and swaley cross stratification controlled variables. The mean permeability value for planar bedding was not used. Instead, permeability values of 300 mD (for sand) and 0.01 mD (for mud) were used for planar bedding controlled variable to provide a greater contrast in permeability between laminae.







Variance was not assigned to mean permeability and porosity values in controlled variable models in order to quantify the changes in horizontal and vertical permeability, as biogenic structure were added to controlled models. No probe permeameter measurement of mudstone permeability was available, instead a value of 0.01 mD was assigned to each controlled variable model. No measurement of porosity was available for this study, instead static values were assigned to each controlled variable model.

Rock Unit	Matrix Model	Mean Permeability (mD)	Porosity (fraction)
9	Hummocky Cross Stratification	{Sand (1) = 30} ; {Sand (2) = 30}; {Mud = 0.01}	{Sand (1) = 0.3} ; {Sand (2) = 0.3}; {Mud = 0.025}
10	Planar Bedding	{Sand (1) = 300} ; {Sand (2) = 300}; {Mud = 0.01}	{Sand (1) = 0.3} ; {Sand (2) = 0.3}; {Mud = 0.025}
11	Swaley Cross Stratification	{Sand (1) = 65} ; {Sand (2) = 25}; {Sand (3) = 65}	{Sand (1) = 0.3} ; {Sand (2) = 0.25}; {Sand (3) = 0.3}

Independent Variable - Model Statistics

The biogenic structure models represent the independent variable in this study. Models for *Ophiomorpha* and *Thalassinoides* were used to test burrow/matrix permeability contrasts. No permeability measurements were available for burrowing structures, instead controlled variable model mud and sand mean permeability values were assigned to the biogenic structures. Biogenic structure fill and lining/rim permeabilities were varied to identify changes in controlled variable model horizontal and vertical permeability.

Biogenic Structure Model	Low Permeability (mD)	High Permeability (mD)	Porosity Low (fraction)	Porosity High (fraction)
Ophiomorpha (Fill)	0.01	300.0	0.02	0.3
Ophiomorpha (Lining/rim)	0.01	300.0	0.02	0.3
Thalassinoides (Fill)	0.01	30.0, 60.0	0.02	0.3
Thalassinoides (Lining/rim)	0.01	30.0, 60.0	0.02	0.3

7. Upscaling Results

Each property model in this study underwent single phase flow-based upscaling. A total of 10 realizations were created for each property model to capture pertophysical property variation. The mean values for net:gross, porosity, kx, ky, kz from each group of 10 realizations are presented in the tables below for each rock unit. The upscaled controlled variable models with no bioturbation are highlighted in light blue in rows in the tables below. Biogenic structure models assigned fill and lining/rim permeability are highlighted in light yellow in rows in the tables below.

Upscaled Results – Hummocky Cross Stratification (HCS)

Matrix Model-Percentage Biogenic Structure	Fill Permeability (mD)	Lining/rim Permeability (mD)	NTG (fraction)	Porosity (fraction)	Kxx (mD)	Kyy (mD)	Kzz (mD)
HCS - Non Bioturbated	**N/A**	**N/A**	**0.7996**	**0.218**	**18.7636**	**16.4244**	**0.2647**
Ophiomorpha							
HCS - 10% *Ophiomorpha*	0.01	N/A	0.8237	0.1996	16.3079	14.7085	0.2113
HCS - 30% *Ophiomorpha*	0.01	N/A	0.8736	0.1631	11.8542	11.5362	0.1418
HCS - 60% *Ophiomorpha*	0.01	N/A	0.9454	0.1075	7.4009	7.4784	0.0508
HCS - 10% *Ophiomorpha*	0.01	15	0.8247	0.2191	19.3051	17.8427	3.1322
HCS - 10% *Ophiomorpha*	0.01	30	0.8247	0.219	20.3388	18.8593	4.7861
HCS - 10% *Ophiomorpha*	0.01	60	0.8247	0.219	21.4619	19.9632	7.0772
Thalassinoides							
HCS - 10% *Thalassinoides*	0.01	N/A	0.8159	0.1971	14.2559	12.5477	0.2474
HCS - 30% *Thalassinoides*	0.01	N/A	0.8468	0.1552	6.8244	6.8696	0.2031
HCS - 60% *Thalassinoides*	0.01	N/A	0.9053	0.0955	2.3158	2.3286	0.0931

Upscaled Results – Swaley Cross Stratification (SCS)

Matrix Model-Percentage Biogenic Structure	Fill Permeability (mD)	Lining/rim Permeability (mD)	NTG (fraction)	Porosity (fraction)	Kxx (mD)	Kyy (mD)	Kzz (mD)
SCS - Non Bioturbated	**N/A**	**N/A**	**0.8661**	**0.2933**	**61.9588**	**61.943**	**60.0765**
SCS - 10% *Thalassinoides*	0.01	N/A	0.8738	0.2657	47.213	48.5553	51.0623
SCS - 30% *Thalassinoides*	0.01	N/A	0.8952	0.2108	26.5207	28.5361	32.6959
SCS - 60% *Thalassinoides*	0.01	N/A	0.934	0.1289	9.5812	10.0827	4.2187
SCS - 10% *Thalassinoides*	65	N/A	0.8861	0.2944	62.3592	62.3499	60.9313
SCS - 30% *Thalassinoides*	65	N/A	0.924	0.2964	63.1557	63.1582	62.422
SCS - 60% *Thalassinoides*	65	N/A	0.973	0.2989	64.297	64.3011	64.1613

Upscaled Results – Planar Bedding

Matrix Model-Percentage Biogenic Structure	Fill Permeability (mD)	Lining/rim Permeability (mD)	NTG (fraction)	Porosity (fraction)	Kxx (mD)	Kyy (mD)	Kzz (mD)
Planar-Non Bioturbated	**N/A**	**N/A**	**0.8401**	**0.2568**	**252.018**	**252.018**	**0.0625**
Planar - 10% *Ophiomorpha*	0.01	N/A	0.7924	0.216	174.935	176.7187	0.0407
Planar - 30% *Ophiomorpha*	0.01	N/A	0.8286	0.17	78.6808	81.1832	0.0319
Planar - 60% *Ophiomorpha*	0.01	N/A	0.8843	0.103	16.2121	16.9397	0.0214
Planar - 10% *Ophiomorpha*	300	N/A	0.7924	0.2435	235.8674	235.8776	8.5919
Planar - 30% *Ophiomorpha*	300	N/A	0.8286	0.2531	242.7615	242.9195	40.903
Planar - 60% *Ophiomorpha*	300	N/A	0.8843	0.2686	257.4104	257.4292	112.8865
Planar - 10% *Ophiomorpha*	0.01	300	0.781	0.234	220.5166	220.9318	8.2366
Planar - 30% *Ophiomorpha*	0.01	300	0.7996	0.2262	197.9989	198.9428	32.0779
Planar - 60% *Ophiomorpha*	0.01	300	0.8973	0.2127	155.2114	156.0549	47.132

8. Summary and Conclusions

1. Process oriented models of geologically correct clastic sedimentary bedforms with biogenic structures provide an alternative approach to small-scale reservoir facies analysis. This approach is appropriate for hydrocarbon reservoirs with heterogeneous geology that significantly effects fluid flow.

2. The increased presence of burrowing structures within the controlled variable models had a significant impact on permeability anisotropy (kx, ky, and kz) and porosity, specifically evident in all controlled variable models that hosted biogenic structures with low permeability fill. As the biogenic structure percentages increased in the controlled variable model, the permeability and porosity decreased in the controlled variable models. Alternatively, when percentages of biogenic structures with high permeability fill increased in the controlled variable models, the permeability and porosity became elevated in the controlled variable models.

3. Controlled variable models with biogenic structures whose lining/rims were assigned greater permeability values than biogenic structure fill, resulted in elevated vertical permeability (kz) when compared to upscaled non-bioturbated controlled variable models. The burrow linings/rims appear to act as conduits to fluid flow and thus increasing the vertical permeability.

4. Controlled variable models with biogenic structures whose lining/rims were assigned greater permeability values than biogenic structure fill, resulted in lower horizontal permeability (kx, ky) and porosity when compared to upscaled non-bioturbated controlled variable models. This was observed in controlled variable models of planar bedding which contained mudstone laminae. Although the biogenic structures had lining/rims with high permeability values, their fill had low permeability values which impeded horizontal fluid flow between bedform layers.

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