[PS]Assessment of Scale on Permeability Estimates in Late Cretaceous Reservoirs, Denver Basin, Colorado*

Christopher M. Rybowiak[1] and Matthew J. Pranter[1]

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Abstract

This study addresses how reservoir-scale permeability models vary depending on the scale of investigation of the input permeability values. A common practice in reservoir modeling is to directly use permeability measurements from core-plugs or probe permeametry in petrophysical modeling. The petrophysical models may have varying grid sizes but are often 5-7 orders of magnitude larger than scale of investigation (volume support) of the permeability measurement. This scale difference can produce unrealistic results in the petrophysical model and may not be representative of the reservoir heterogeneity.

To explore this issue, two stratigraphic intervals, the Sussex (Terry) and Shannon (Hygiene) sandstones of the Denver Basin (within Wattenberg and Spindle fields), were selected for permeability analysis, near-wellbore modeling for effective properties, and 3-D reservoir-scale modeling. The stratigraphic units represent shoreline sandstones and exhibit six common lithofacies. Permeability values by lithofacies (N=520 per core) from four cores were measured using probe permeametry and used as inputs for near-wellbore modeling to generate effective-permeability values using flow-based upscaling. The effective-permeability values exhibit a narrower distribution as compared to the original permeameter-scale values. Reservoir-scale, three-dimensional models [1 mi^2 (1.6 km^2)] of lithofacies, porosity, and permeability for the Shannon and Sussex were constructed for an area in the Spindle Field. Separate permeability models were generated using the original- and effective-permeability values. Using porosity and permeability cutoffs (>10% and >0.05md), the models were explored in terms of static connectivity of reservoir-quality sandstone and show the differences in connected volumes as a function of the input permeability values (original vs. effective). The models show differences in static "reservoir" connectivity as related to original- and effective-permeability that can be significant in terms of properly representing reservoir heterogeneity. The models illustrate the importance of scale of investigation when creating 3-D reservoir models of petrophysical properties.

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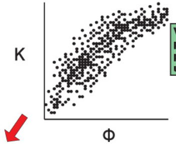
Abstract:

This study addresses how reservoir-scale permeability models vary depending on the scale of investigation of the input permeability values. A common practice in reservoir modeling is to directly use permeability measurements from core-plugs or probe permeametry in petrophysical modeling. The petrophysical models may have varying grid sizes but are often 5-7 orders of magnitude larger than scale of investigation (volume support) of the permeability measurement. This scale difference can produce unrealistic results in the petrophysical model and may not be representative of the reservoir heterogeneity.

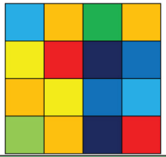
To explore this issue, one stratigraphic interval, the Terry Sandstone of the Denver Basin (within Wattenberg and Spindle fields), was selected for permeability analysis, near-wellbore modeling for effective properties, and 3-D reservoir-scale modeling. This stratigraphic unit represents a shoreline sandstone and exhibit four common lithofacies. Permeability values by lithofacies (N=520 per core) from four cores were measured using probe permeametry and used as inputs for near-wellbore modeling to generate effective-permeability values using flow-based upscaling. The effective-permeability values exhibit a narrower distribution as compared to the original permeameter-scale values as well as truncating the higher and lower values. Reservoir-scale, three-dimensional models [1 mi2 (1.6 km2)] of lithofacies, porosity, and permeability for Terry Sandstone were constructed for an area within Spindle Field. Separate permeability models were generated using the original- and effective-permeability values. Using porosity and permeability cutoffs were imposed on the models to explored, in terms of static connectivity of reservoir-quality sandstone, the differences in connected volumes as a function of the input permeability values (original vs. effective). The models show differences in static "reservoir" connectivity as related to original- and effective-permeability that are significant in terms of properly representing reservoir heterogeneity. The models illustrate the importance of scale of investigation when creating 3-D reservoir models of petrophysical properties.

Research Purpose

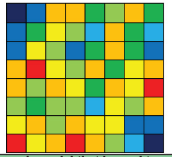
Geologic models today are initially based on petrophysical measurements from small-scale samples such as core plugs or core samples. In terms of permeability these measurements may come from Hassler sleeves or probe-permeameters that have investigation sizes of several cubic inches. Often when these are applied to large scale models, property values may not be representative of what is actually happening in the rock.



Values of permeability and porosity from core plugs, mini-permeametry, and well logs are used in geologic models.

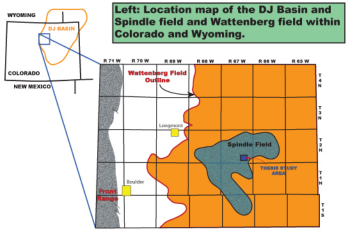


In a coarse-scale geologic model, the range of permeabilities and associated heterogeneity may not be properly represented.

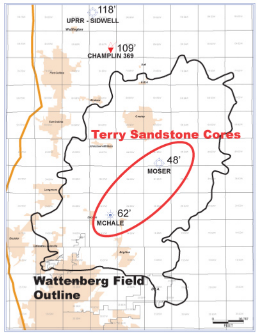


A fine-scale model that is used to create effective permeability can provide a more realistic range of property values that accounts for the scale of observation.

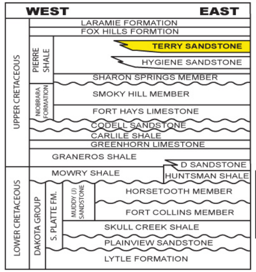
Research Location and Stratigraphy



Left: Location map of the DJ Basin and Spindle field and Wattenberg field within Colorado and Wyoming.

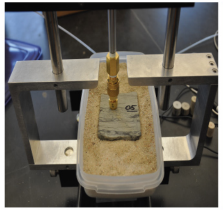


Location map showing the cores used to measure Terry Sandstone permeabilities. The McHale#1 core is the primary core for this research project.



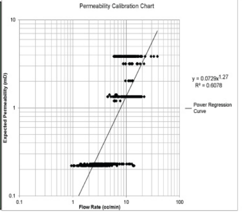
The Terry Sandstone is an Upper Cretaceous member of the Pierre Shale. The Terry Sandstone is primarily present throughout most of the DJ Basin but not all of it. Modified from Higley et al., 2003.

Permeability Acquisition

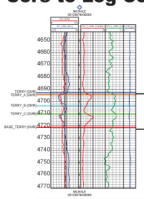


Left: Probe permeameter used to measure permeabilities on core. The tip is lowered onto the core face and has a diameter of 0.125in (3.175 mm). Permeabilities are recorded and calibrated using known standards.

Right: Calibration line using known permeabilities with flow rate of nitrogen gas through permeameter. The displayed cross-plot is used to calibrate measured permeabilities based on the gas flow rate.

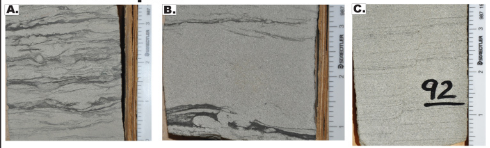


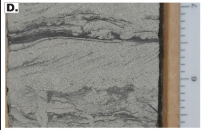
Core-to-Log Comparison



Top: Log suite from the McHale #1 well which was used as the type well for well-log normalization. From core, the top and base of the Terry Sandstone were determined to be 4,689 feet and 4,715 feet, respectively. There is a core-log depth shift of approximately 4 feet. Reservoir intervals include the Terry A and Terry C; these zones are separated by a non-reservoir interval. The environment of deposition of the reservoir sandstones is debated. One interpretation is that they represent delta lobes prograding into the basin (Kiteley, personal comm.).

Facies Description



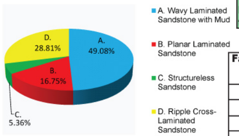


Top: Photos of each of the 4 representative facies that were used in the near-wellbore modeling process. Each facies is based on observed sedimentary structures that were modeled using SBED software. Bioturbation is present throughout the interval, however the impact of bioturbation on permeability was negligible.

Left: Pie chart of facies percentages in the McHale #1 core and resulting fine-scale core model.

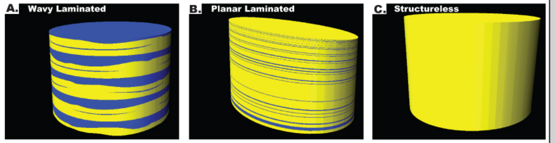
Below: Table of facies statistics used in the near-wellbore modeling process.

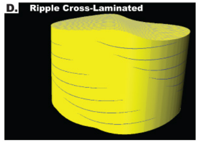
Facies Percentage in Facies Model



Facies	Total Feet	% of Core	Arithmetic Mean of K (mD)	Geomean of K (mD)	Std. Dev.
A	13.27	49.1	0.207	0.158	0.162
B	4.53	16.8	0.146	0.119	0.085
C	1.45	5.4	0.169	0.115	0.136
D	7.79	28.8	0.097	0.084	0.051

Near-wellbore Modeling

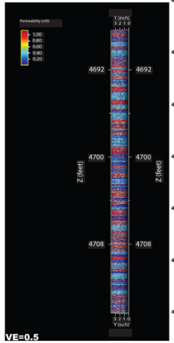


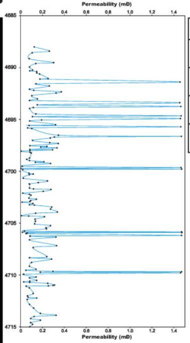


	A	B	C	D
Sand Lamina	0.332	0.660	0.155	1.561
Std. Dev.	0.532	0.570	0.187	0.580
Mud Lamina*	0.701	0.421	0.626	--
Std. Dev.*	0.611	0.437	0.106	--

The McHale #1 core was modeled to create a fine-scale representation of the 4 key facies in three dimensions (a fine-scale 3D model of the core facies). The individual facies are modeled separately and then stacked together to create the vertical facies succession observed in the core. Sandstone=yellow mudrock=blue.

Upscaling Results



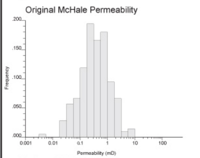


Facies	Geomean Upscaled K	Standard Deviation	N=
A	0.051 mD	0.056 mD	65
B	0.521 mD	0.138 mD	31
C	0.254 mD	0.095 mD	46
D	1.464 mD	0.006 mD	14

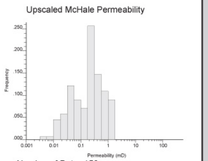
Above: Chart showing statistics of upscaled permeabilities for the McHale #1 core.

Left: 3D representation of effective permeabiliites in the McHale core. Upscaled permeability data are displayed. High permeability values are associated with the structureless sandstone lithofacies.

Upscaling Results Continued

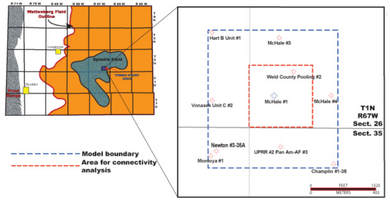


Number of Data 211
Mean 0.6931
Std. Dev. 0.9917
Coef. of Var 1.4309
Maximum 6.7282
Upper Quartile 0.8169
Median 0.3366
Lower Quartile 0.1515
Minimum 0.0040



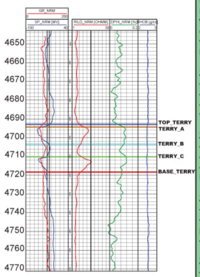
Number of Data 156
Mean 0.3474
Std. Dev. 0.4017
Coef. of Var 1.1565
Maximum 1.4721
Upper Quartile 0.4667
Median 0.2143
Lower Quartile 0.0537
Minimum 0.0043

3-D Spindle Field Reservoir Model



The modeling area for the project is located within Spindle field in the greater Wattenberg field. The model area is a portion of Spindle field that measures approximately 0.5 mi by 0.6 mi (0.8 km x 1 km) (blue box). A smaller area was chosen in the middle of this model area to be the location in which static connectivity is evaluated. The smaller area (red box) was selected to be

Model Zones



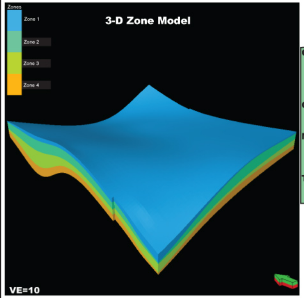
Zones were defined based on core to log comparison. The top of the Terry sandstone is based on the transition from interbedded sandstone and mudrock to dominently sandstone and the base from sandstone to heavily bioturbated sandy shale.

Zone 1:
-Top Terry to Terry A
-Increasing Resistivity and porosity
-Interpretated as transition from quiet water to sandstone delta lobe

Zone 2:
-Terry A to Terry B
-Negative SP kick, high resistivity, GR
-Offshore sandstone, possible delta lobe

Zone 3:
-Terry B to Terry C
-Decreased resistivity, GR, and SP, low porosity
-Offshore, quiet water setting

Zone 4:
-Terry C to Base Terry
-Negative SP kick, high resistivity, GR



Cell Size:
30 ft x 30 ft x 1ft (9.1m x 9.1m x 0.3m)

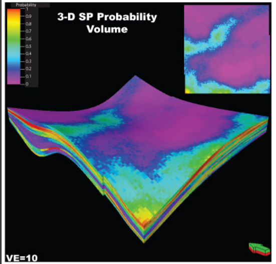
Grid Size:
95 x 97 x 40 cells

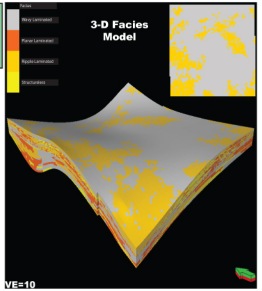
Model Dimensions:
~2725 ft x 2900 ft (830 m x 884 m)

Thickness:
Max: 64 ft (20 m)
Min: 28 ft (9 m)

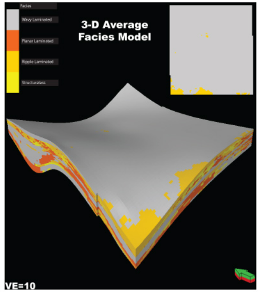
3-D Facies Modeling

Facies models were generated using Sequential Indicator Simulation (SIS) and constrained to 9 wells and a lithology probability volume. SP logs were used to create the lithology probability volume (below). The probability volume was used to control the spatial distribution of sandstone-rich facies.



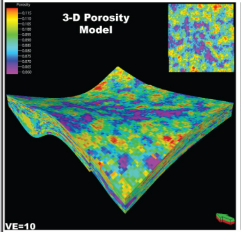


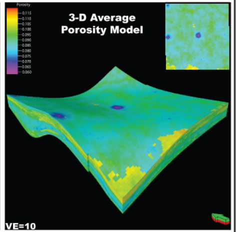
30 facies realizations were generated to account for uncertainty in the spatial distribution of lithofacies between the wells.



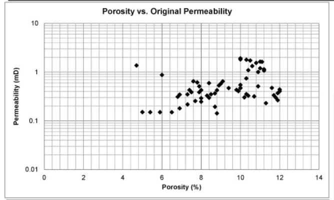
The 30 facies realizations were used to create an "average" facies model.

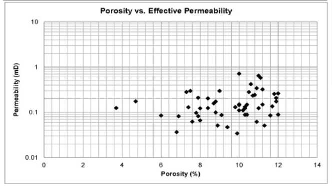
3-D Petrophysical Modeling





Porosity and permeability were both modeled and constrained to facies. Similar to facies modeling, 30 realizations of different porosity models were generated to account for uncertainty in spatial distribution of porosity. Displayed top left, is one realization of a porosity model using Sequential Gaussian Simulation (SGS). To the right is the average porosity model of 30 individual SGS realizations.

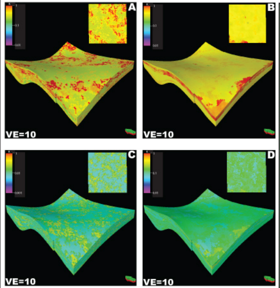




A cloud transformation was used to model permeability based on the generated porosity models.

Top: Original permeability cross-plot

Bottom: Effective permeability cross-plot



4 permeability models were generated with two representing original (non-upscaled) measurements and two representing the effective (upscaled) permeabilities generated through near-wellbore modeling. Models A and B are original permeabiliity models and C and D are effective permeability models. Models A and C are generated from a single porosity model realization and B and D are generated using the average porosity model described previously. These were generated using the above cloud transformations.

A-Original permeability model
-referenced to single SGS Φ model

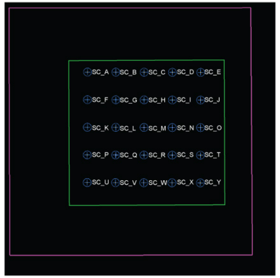
B-Original permeabilty model
-referenced to average SGS Φ model

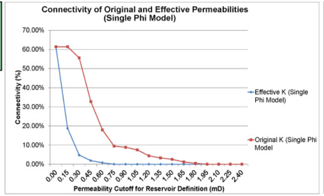
C-Effective permeability model
-referenced to single SGS Φ model

D-Effective Permeability model
-referenced to average SGS Φ model

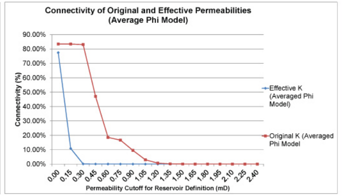
3-D Static Connectivity Analysis

Well-based static connectivity analysis was used to compare the original and effective permeability models. Sandstone connectivity was evaluated using pseudo-wells on a 10-acre spacing (distance between wells is 660 ft).





K cutoff	SIS Single - Original K	SIS Single - Effective K	Bulk Model	Original K - Connectivity	Effective K - Connectivity
(md)	(cells)			(Connected %)	(Connected %)
0.00	51307312	51307312	83615056	61.36%	61.36%
0.15	51307312	15718164	83615056	61.36%	18.80%
0.30	46498524	3990217	83615056	55.61%	4.77%
0.45	27377846	1585681	83615056	32.74%	1.90%
0.60	15009833	650371	83615056	17.95%	0.78%
0.75	7937865	1004	83615056	9.49%	0.00%
0.90	7396993	502	83615056	8.85%	0.00%
1.05	6274338	502	83615056	7.50%	0.00%
1.20	3669397	502	83615056	4.39%	0.00%
1.35	2767767	502	83615056	3.31%	0.00%
1.50	2144226	502	83615056	2.56%	0.00%
1.65	1014086	502	83615056	1.21%	0.00%
1.80	393099	502	83615056	0.47%	0.00%
1.95	502	502	83615056	0.00%	0.00%
2.10	502	502	83615056	0.00%	0.00%
2.25	502	502	83615056	0.00%	0.00%
2.40	502	502	83615056	0.00%	0.00%



K cutoff	SIS Average - Original K	SIS Average - Effective K	Bulk Model	Original K - Connectivity	Effective K - Connectivity
(md)	(cells)			(Connected %)	(Connected %)
0.00	69791064	64793036	83615056	83.47%	77.49%
0.15	69791064	9102157	83615056	83.47%	10.89%
0.30	69494208	101243	83615056	83.11%	0.12%
0.45	39320728	31403	83615056	47.03%	0.04%
0.60	15518851	11569	83615056	18.56%	0.01%
0.75	13916971	1004	83615056	16.64%	0.00%
0.90	7992335	502	83615056	9.56%	0.00%
1.05	2516950	502	83615056	3.01%	0.00%
1.20	559350	502	83615056	0.67%	0.00%
1.35	141370	502	83615056	0.17%	0.00%
1.50	43906	502	83615056	0.05%	0.00%
1.65	11049	502	83615056	0.01%	0.00%
1.80	1004	502	83615056	0.00%	0.00%
1.95	502	502	83615056	0.00%	0.00%
2.10	502	502	83615056	0.00%	0.00%
2.25	502	502	83615056	0.00%	0.00%
2.40	502	502	83615056	0.00%	0.00%

To determine static reservoir connectivity, reservoirs sandstone was defined as having a porosity greater than 8.75%. Numerous permeability cutoffs were evaluated. Permeability cutoffs ranged from 0 to 2.4 mD using an increments of 0.15 mD.

A. Original K:
-K>0 mD
-Φ>8.75%
-Single Φ model

B. Original K:
-K>0.6 mD
-Φ>8.75%
-Single Φ model

C. Original K:
-K>0 mD
-Φ>8.75%
-Average Φ model

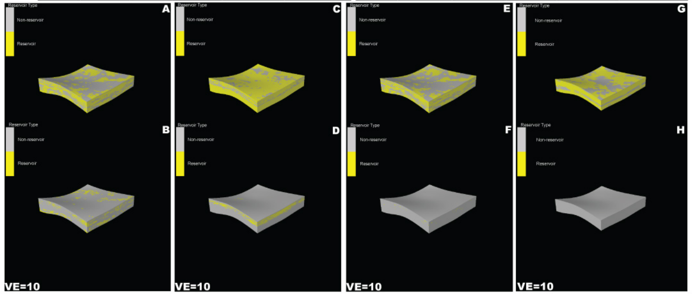
D. Original K:
-K>0.6 mD
-Φ>8.75%
-Average Φ model

E. Effective K:
-K>0 mD
-Φ>8.75%
-Single Φ model

F. Effective K:
-K>0.6 mD
-Φ>8.75%
-Single Φ model

G. Effective K:
-K>0 mD
-Φ>8.75%
-Average Φ model

H. Effective K:
-K>0.6 mD
-Φ>8.75%
-Average Φ model



Conclusions

-The Terry Sandstone in the Spindle field area (McHale #1 core) consists of 4 key lithofacies: wavy laminated sandstone, ripple cross-laminated sandstone, planar laminated sandstone, and structureless sandstone.

-There is a difference in the range between original and effective permeability values.

-Effective (upscaled) permeabilities exhibit a narrower range compared to original permeability values.

-For lower permeability cutoffs, there is a distinct difference in static connectivity between models based original and upscaled permeability values.

-For higher permeability cuttoffs, the differences in static connectivity between models based on original and upscaled permeability values is negligible.

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