Characterization and Simulation of the Panoma Field (Wolfcampian); *a Tight, Thin-Bedded Carbonate Reservoir System, Southwest Kansas*

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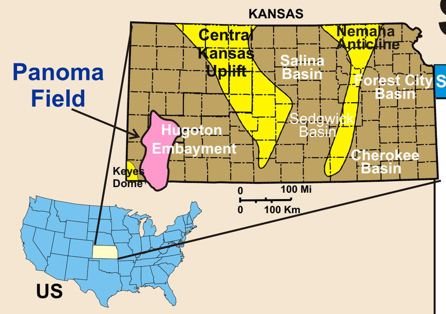
AAPG Hedberg Conference, 2002
Carbonate Characterization and Simulation:
From Facies to Flow Units

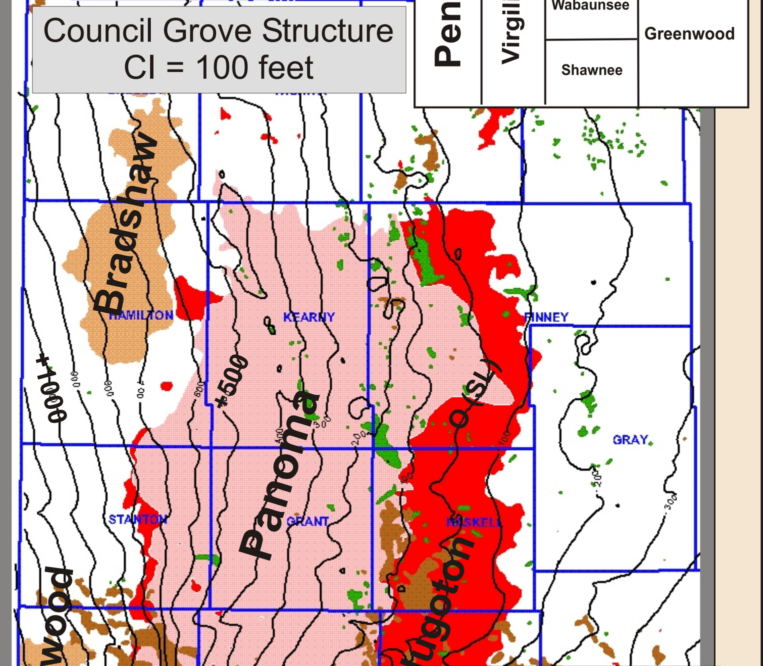
Setting and History

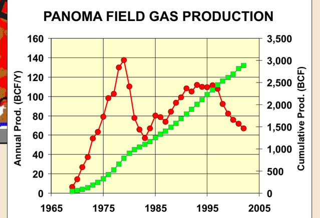
The Panoma Field (2.9 TCF gas) produces from Permian Council Grove Group marine carbonates and nonmarine silicilastics in the Hugoton embayment of the Anadarko Basin. It and the Hugoton Field (Chase Group) have combined for 27 TCF gas, making this the largest gas producing area in North America. Both fields are stratigraphic traps with updip west and northwest limits nearly coincident. Maximum recoveries in the Panoma are attained west of center of the field. Deeper production includes oil and gas from Pennsylvanian Lansing-Kansas City, Marmaton, and Morrow and the Mississippian.

Stratigraphy



System	Series	Group	Field
Permian	Leonardian	Sumner	
	Wolfcampian	Chase	Hugoton, Byerly, Bradshaw
		Council Grove	Panoma
Penn.	Virgilian	Admire	
		Wabaunsee	Greenwood
		Shawnee	



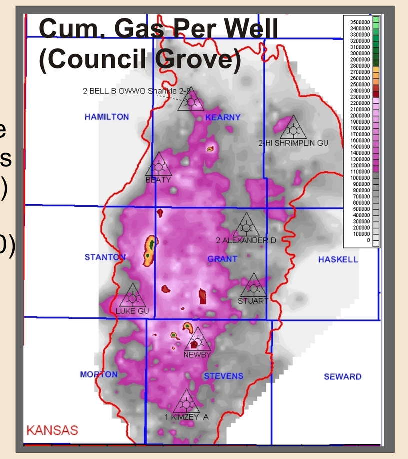


Panoma Statistics

Initial Prod	1959
2002 Prod	67 BCF
Cum. Prod	2.88 TCF gas
Well count	2600
Per well avg.	1.1 BCF to date
Area	1.7 million acres (1 well per sect)
Top of pay	2500-3200 feet (+800 to 100)
Current SIP	~60#
Original SIP	~440#

Hugoton

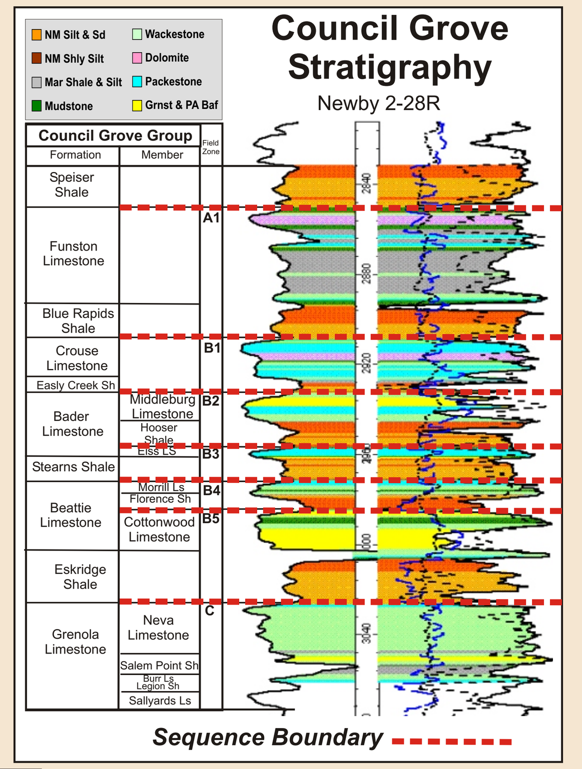
Initial Prod	1929
2002 Prod	264 BCF
Cum. Prod	24 TCF gas

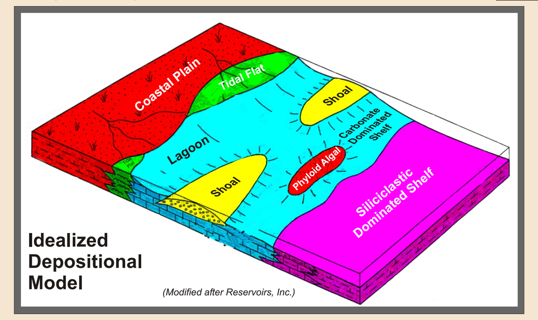


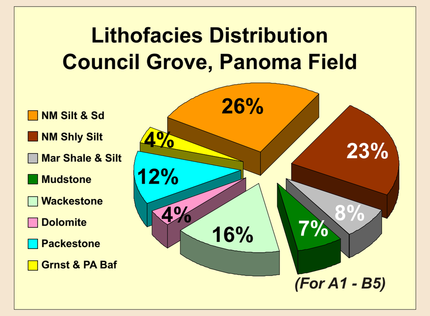
Seven Sequences, Eight Lithofacies

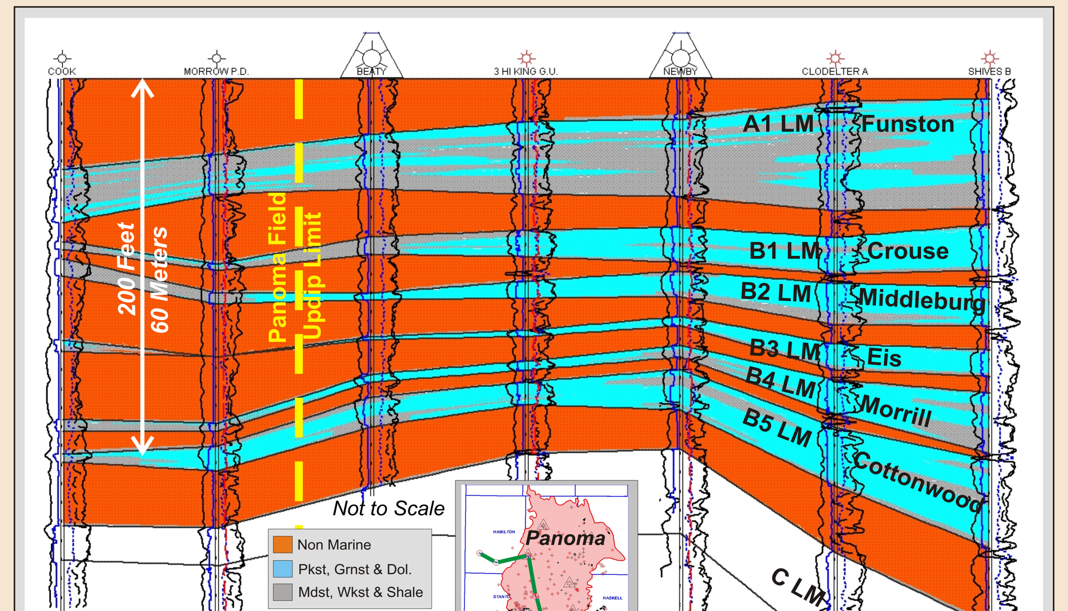
Lithofacies and Depositional Environments

In the Panoma Field of southwest Kansas the Council Grove Group includes nine fourth-order marine-nonmarine sequences, the top seven of which are gas productive. Through core studies, eight major lithofacies were identified and characterized. During Council Grove deposition, the Panoma area was on a broad shallow shelf or ramp that dipped gently southward into the Anadarko basin. The geometry was conducive for broad, parallel depositional environments and associated lithofacies belts. In response to cyclical sea level fluctuations, facies belts migrated across the shelf resulting in a predictable vertical succession of eight major lithofacies.



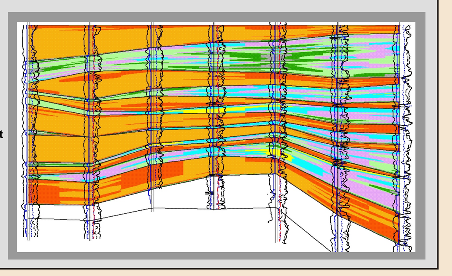






Stratigraphic Cross Section
Datum: Top of Council Grove

- Lithofacies by core description are shown in wells with triangles. Other lithofacies were predicted by neural net models.
- Panoma updip limit coincides with thinned marine carbonates and reciprocally thicker nonmarine silts.
- Smaller scale cross section of same wells shows 8 lithofacies using Petra's interpretive colorfill.

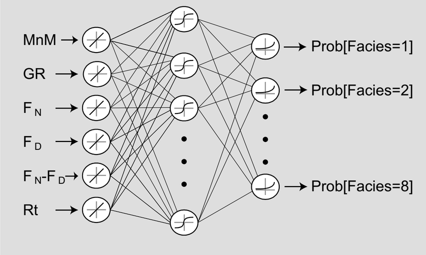


Lithofacies Prediction using Neural Network

Lithofacies Prediction Steps

1. Define eight core-based lithofacies
2. Select e-log predictor variables (GR, Nphi, Dphi, PE, Rta. N-Dphi)
3. Add knowledge through geologic constraining variables
4. Train/test Neural Networks on cored wells; measure accuracy and error
5. Choose Nnet models and predict facies in non-cored wells (~500)
6. AUTOMATE process throughout

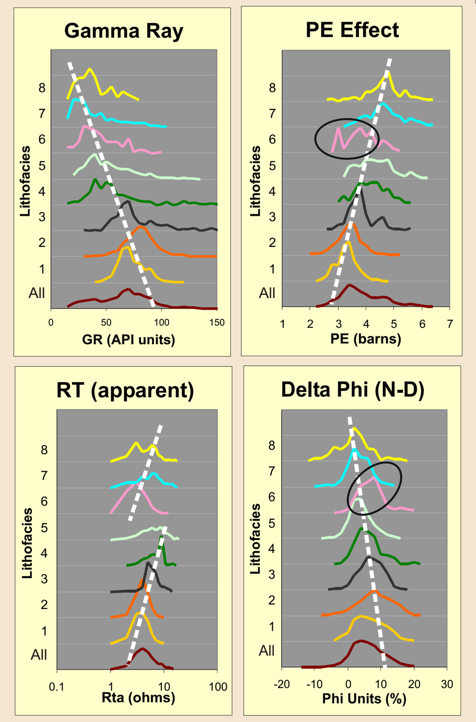
Neural Network



Predicted lithofacies probabilities using 6-8 log and geologic constraining variables. (PE and RelPos curve not shown.) Standard single hidden-layer neural network was used (Duda et al., 2001). Model calibration efforts focused on selection of appropriate number of hidden-layer nodes (governs richness of model) and damping parameter (constrains magnitude of network weights to prevent overtraining).

Log Response and Lithofacies

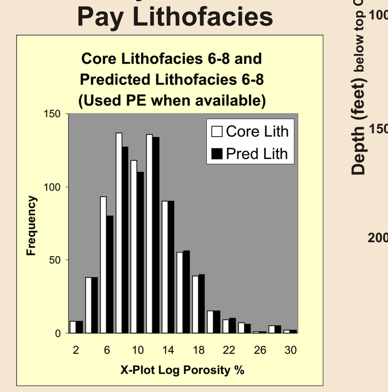
The eight lithofacies can be discriminated effectively by combination of log properties (GR, Nphi, Dphi, PE, Rta. N-Dphi) and geologic constraining variables (Nonmarine-Marine and Relative Position curves).



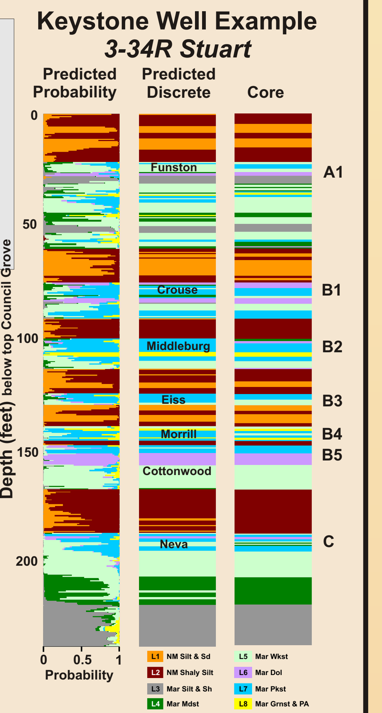
Effectiveness Metrics

- Absolute accuracy
- Accuracy within one facies
- Proportional representation
- Porosity (and perm) distribution in facies populations

Porosity Distribution Pay Lithofacies



Keystone Well Example *3-34R Stuart*



Predicted Lithofacies Scorecard (Counts)

Core Lithofacies (Actual) — *(Nnet mod1, no RelPos, w/ PE)* — rows: *Predicted Lithofacies*

Facies	1	2	3	4	5	6	7	8	Total	Within 1 Facies
1	465	89							554	100%
2	71	523							594	100%
3			149	5	11	1	4		170	91%
4			12	101	26	4	7	2	152	91%
5			9	20	353	3	34	4	423	89%
6			1	3	6	69	8		87	95%
7			4	9	36	3	204	8	264	95%
8			2	2	8	5	7	72	96	88%
Total	536	612	177	140	440	85	264	86	2340	
Pred/Actual	97%	103%	104%	92%	104%	98%	100%	90%		

Correct

97.3% of actual predicted for L6,7,8

Resolving Volumetric OGIP

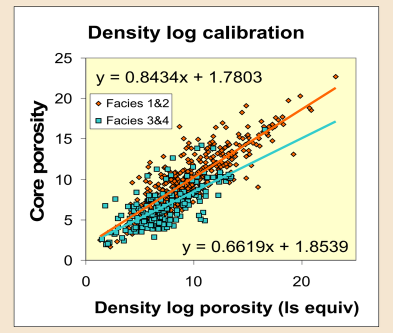
Log Porosity Corrections

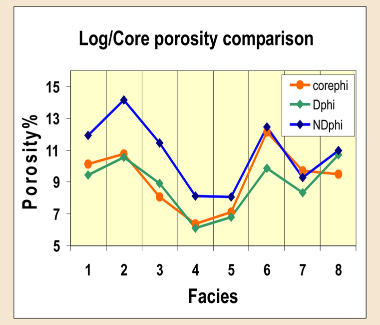
Log porosity corrections (Doveton) based on log to core relationships (360 wc 790 plug) tied to core-defined lithofacies.

Lith 1 and 2: PHI_F12 = 0.8434 * DPHI + 0.017803
Lith 3 and 4: PHI_F34 = 0.6619 * DPHI + 0.018539
Lith 5 thru 8: PHI_F5-8= (NPHI + DPHI)/2

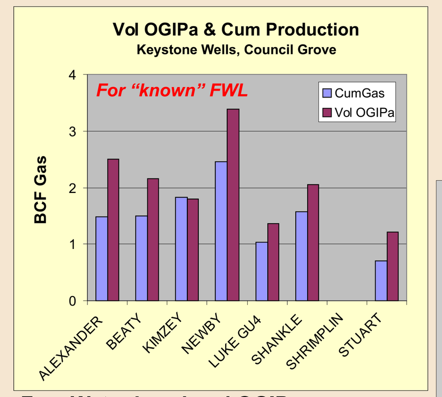
Elimination of bad phi due to washouts

Lith1-5: PhiND > 0.20Phi = 0.03
Lith 6-8: PhiND > 0.225 Phi = 0.10 (mean phi of L6-8)





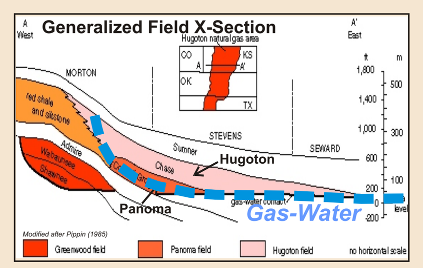
OGIP validated where FWL is known



Free Water Level and OGIP *(key wells)*

Key wells	Cum	OGIPa	FWLa	OGIPmb	FWLmb
KIMZEY	1.83	1.80	50	2.5	12
SHRIMPLIN	0.00	0.00	50	0.0	26
NEWBY	2.46	3.38	50	3.4	48
ALEXANDER	1.48	2.50	50	2.1	63
STUART	0.70	1.21	50	1.0	65
BEATY	1.50	2.16	300	2.1	305
SHANKLE	1.57	2.05	350	2.2	344
LUKE GU4	1.03	1.36	450	1.4	446

Cum — Cumulative gas production 2002 (BCF)
OGIPa — OGIP based on FWLa
FWLa — "Best guess"; anecdotal data (perfs, tests, lowest prod perfs), Pippin (1985
OGIPmb — OGIP assuming cumprod = 80% EUR and EUR = 90% OGIP (1.39*cumprod)
FWLmb — Back-calculated from OGIPmb using Excel goal seek function



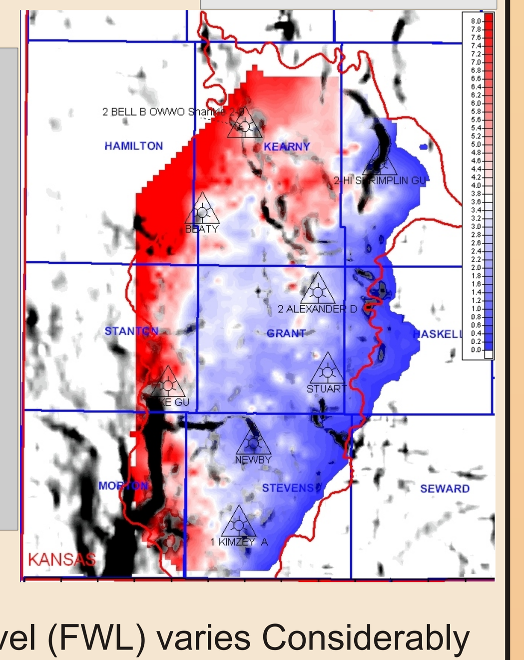
Outline of Problem:

Comparison of Volumetric OGIP with material balance OGIP is critical to fundamental reservoir evaluation. Volumetric calculations by measured values of Sw (log petrophysics) is problematic due to deep invasion. Lithofacies property based volumetric OGIP is possible with appropriate data:

- Lithofacies and lith-based capillary pressure data
- Height above free water level
- Correct porosity
- Reservoir parameters (P, Z, T)

Volumetric GIP calculated for 400 wells using FWL=50', PHIcor, Nnet lithofacies, Sw from Byrnes' transform equations and vol engineering equation, all done in batch mode. Since the field is uniformly produced the ratio is a surrogate for FWL.

$OGIP_{50}$/CumGas overlain by "Faults"



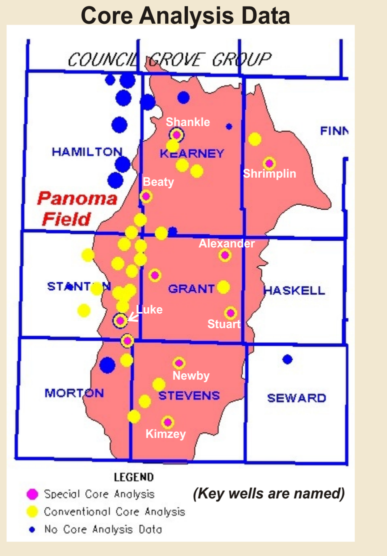
Free water level (FWL) varies Considerably

across the field (+600? to west and sea level to east, but is not well established. An estimated FWL can be "back" calculated if other variables are known, particularly EUR and material balance OGIP. ***Map above*** indicates FWL may be fault controled in places.

Lithofacies Classification

Rock properties data represent analyses from 33 wells (below) that have attempted to sample the complete range in porosity, permeability, geographic distribution, and formational unit for each of the major lithofacies. Lithofacies were described for core using a digital classification system to facilitate data management and because it offered the ability to use non-parametric categorical analysis. Digits generally represent continuous variation of a lithologic property that may be correlated with petrophysical properties. Final petrophysical trends used the eight major lithofacies shown below (selection process is discussed further on).

Core Analysis Data



Digital Rock Classification System

by: Alan Byrnes, Martin Dubois

CODE ↓ / DIGIT # →	1 Rock Type	2 Dunham/Folk Classification	3 Consolidation/Fracturing	4 Argillaceous Content	5 Grain Size	6 Principal Pore Type
9	Evaporite	cobble conglomerate	unconsolidated	Frac-fill 10-50%	vcrs rudite/cobble congl (>64mm)	cavern vmf (>64mm)
8	Dolomite	sucrosic/pebble conglomerate	poorly cemented, high porosity	Frac-fill 5-10%	med-crs rudite/pebble congl (4-64mm)	med-lrg vmf (4-64mm)
7	Dolomite-Limestone	baffle-boundstone/vcrs sandstone	cemented, >10% porosity, highly fractured	Shale >90%	fn rudite/vcrs sand (1-4mm)	sm vmf (1-4mm)
6	Dolomite-Clastic	grainstone/crs sandstone	cemented, >10% porosity, fractured	Shale 75-90%	arenite/crs sand (500-1000um)	crs(500-1000um)
5	Limestone	packstone-grainstone/med sandstone	cemented, >10% porosity, unfractured	Shale 50-75%	arenite/med sand (250-500um)	med(250-500um)
4	Carbonate-Clastic	packstone/fn sandstone	well cemented, 3-10% porosity, highly fractured	Shale 25-50%	arenite/fn sand (125-250um)	fn (125-250um)
3	Clastic-Carbonate	wackestone-packstone/vfn sandstone	well cemented, >3-10% porosity, fractured	Shale 10-25%	arenite/vfn sand (62-125um)	pin-vf (62-125um)
2	Marine Clastic	wackestone/crs siltstone	well cemented, >3-10% porosity, unfractured	wispy 5-10%	crs lutite/crs silt (31-62um)	pinpoint (31-62um)
1	Nonmarine Clastic	mudstone-wackestone/vf-m siltstone	highly cemented, fractured	trace 1-5%	fn-med lutite/vf-m silt (4-31um)	microporous (<31um)
0	Shale	mudstone/shale/clay	totally cemented, dense, unfractured	Clean <1%	clay (<4um)	nonporous

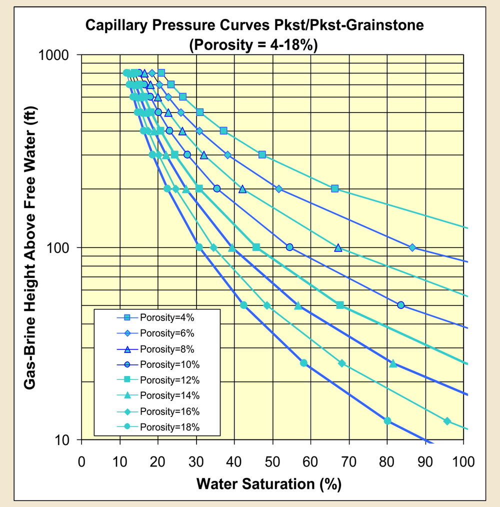
CODE ↓ / DIGIT # →	7 Subsidiary Pore Type	8 Cement/Pore-Filling Mineral	9 Bedding	10 Water Depth	11 Faunal Assemblages	12 Color
9	cavern vmf (>64mm)	sulfide =3.85-5.0	massive/structureless	Bathyal	Normal, one dominant (<3)	black
8	med-lrg vmf (4-64mm)	siderite =3.89	planar, low angle X-bed	Slope	Normal, not diverse (2-4)	dark gray
7	sm vmf (1-4mm)	phosphate =3.13-3.21	lrg X-bed (>4mm), trough	Outer Shelf	Normal, diverse (4+)	gray
6	crs(500-1000um)	anhydrite =2.35-2.98	sm X-bed (<4mm), ripple	Mid-shelf	Mixed, diverse (5+)	light gray
5	med(250-500um)	dolomite =2.87	flasier	L. Upper Shelf	Mixed, not diverse (<4)	shades of green
4	fn (125-250um)	calcite =2.71	wavy bedded/cont. layers	U. Upper Shelf	Restricted, diverse (5+)	white
3	pin-vf (62-125um)	quartz =2.65	lenticular/discont. layers	Intertidal	Restrict., not diverse(2-4)	tan
2	pinpoint (31-62um)	clay =2.0-2.7	convolute/lrg burrows	Supratidal Carb.	Restrict., one dom. +2-4	brown
1	microporous (<31um)	carbonaceous =2.0	churned/bioturbated	Supratidal Clastic	Restrict., one dom. +0-1	red-brown
0	nonporous	uncemented =1.0	vertical k barriers	Nonmarine	Absent	red

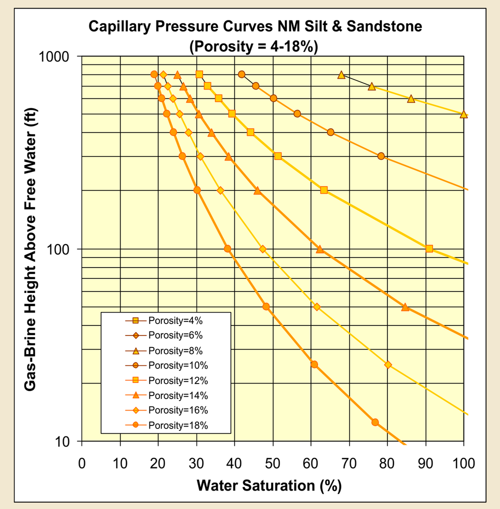
Litho-facies	Council Grove Lithofacies	Digital Code 1st Digit	Digital Code 2nd Digit
1	NM Silt & Sand	1	2-3
2	NM Shaly Silt	1	0-1
3	Mar Shale & Silt	0,2	all
4	Mdst / Mdst-Wkst	3-8	0-1
5	Wkst / Wkst-Pkst	3-8	2-3
6	Sucrosic (Dol)	3-8	8
7	Pkst / Pkst-Grnst	3-8	4-5
8	Grnst / PhAlg Baff	3-8	6-7

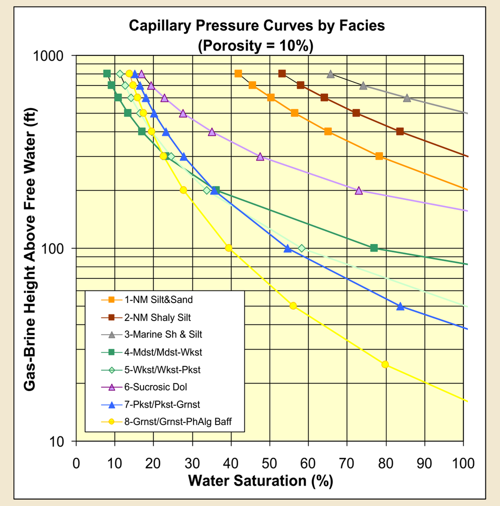
Examples:

12-322-215-9001
Nonmarine clastic, coarse siltstone, well cemented/fractured, wispy clay (5-10% clay), coarse silt sized (31-62um), pipoint primary pores (31-62um), microporous subsidiary pores (<31um), dolomite cement, massive bedded, nonmarine, absent of fauna, red-brown in color

52-505-534-9444
Limestone, grainstone, cemented/ unfractured, clean (<1% clay,) medium arenite (250-500um), medium sized principle pore (250-500um), pinpoint-very fine subsidiary pore size (31-62um), calcite cement, massive bedded, upper shelf, restricted-diverse fauna, white in color.

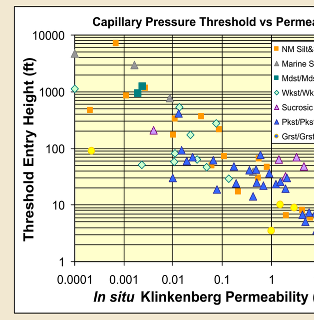






Capillary Pressure and Water Saturation

- Capillary pressures and corresponding water saturations (Sw) vary between facies, and with porosity/permeability and gas column height.
- Threshold entry pressures and corresponding heights above free water level are well correlated with permeability.
- Synthetic capillary pressure curves were constructed from capillary curves from 91 cores representing the range in facies and permeability.
- With decreasing porosity and permeability, threshold entry heights and heights necessary to decrease Sw increase.
- Differences in Sw between facies



Lithofacies and Associated Petrophysical Properties

Lithofacies, Porosity, Permeability

Fundamental to construction of the reservoir geomodel is the population of cells with the basic lithofacies and their associated petrophysical properties- porosity, permeability, and fluid saturation. Petrophysical properties vary between the eight major lithofacies classified. Mean and maximum porosities increase with increasing lithofacies number for the limestones (mud- to grainstone; histograms below). Permeability is a function of several variables including primarily pore throat size, porosity, grain size and packing (which controls pore body size and distribution), and bedding architecture. Equations were developed to predict permeability and water saturation using porosity as the independent variable because porosity data are the most economic and abundant, and because porosity is well correlated with the other variables for a given lithofacies.

Each lithofacies exhibits a relatively unique *k*-ϕ correlation that can be represented using equations of the form:

$$\log k = A \log \phi_i + B \text{ or } k = 10^B \phi_i^A:$$

Lithology Code	Lithology	Permeability Equation A	Permeability Equation B	Permeability Adjusted R^2	Standard Error (log units)	Standard Error * (factor)
1	NM Silt & Sand	7.861	-9.430	0.780	0.769	5.9
2	NM ShlySilt	5.963	-7.895	0.702	0.787	6.1
3	Mar Shale & Silt	8.718	-10.961	0.719	0.847	7.0
4	Mdst/Mdst-Wkst	7.977	-9.680	0.588	0.958	9.1
5	Wkst/Wkst-Pkst	6.260	-7.528	0.774	0.611	4.1
6	Sucrosic (Dol)	7.098	-8.706	0.643	0.673	4.7
7	Pkst/Pkst-Grnst	6.172	-6.816	0.840	0.521	3.3
8	Grnst/PA Baff	8.240	-8.440	0.684	0.600	4.0

Standard error of prediction ranges from a factor of 3.3 to 9.1.

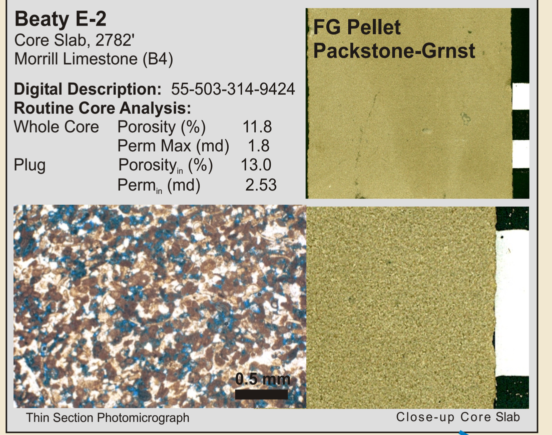
L-7 Packstone and Packstone-Grainstone

Lithofacies Digital Description: 3-8 / 4-5
Primary Depositional Environments:
Shoals on mid to upper shelf in either regressive or transgressive phase, lagoons and tidal flats.

Beaty E-2
Core Slab, 2782'
Morrill Limestone (B4)

Digital Description: 55-503-314-9424
Routine Core Analysis:

Whole Core	Porosity (%)	11.8
	Perm Max (md)	1.8
Plug	$Porosity_{in}$ (%)	13.0
	$Perm_{in}$ (md)	2.53



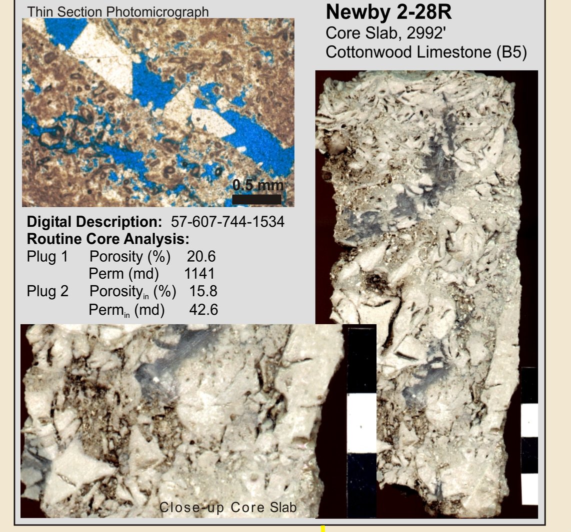
L- 8 Phyloid Algal Bafflestone

Lithofacies Digital Description: 3-8 / 7
Primary Depositional Environments:
Mounds or biostromes on mid to upper shelf.

Newby 2-28R
Core Slab, 2992'
Cottonwood Limestone (B5)

Digital Description: 57-607-744-1534
Routine Core Analysis:

Plug 1	Porosity (%)	20.6
	Perm (md)	1141
Plug 2	$Porosity_{in}$ (%)	15.8
	$Perm_{in}$ (md)	42.6



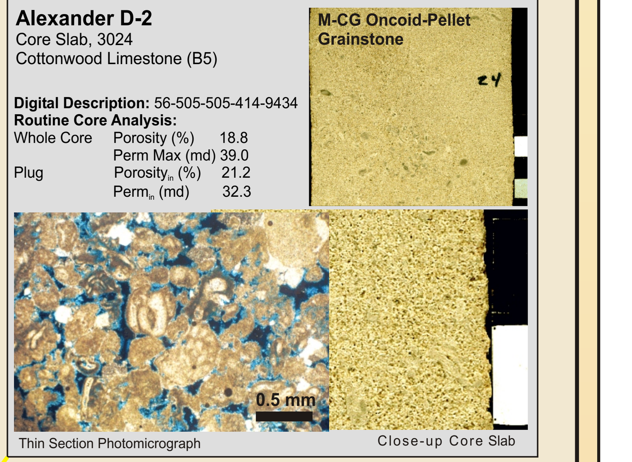
L- 8 Grainstones

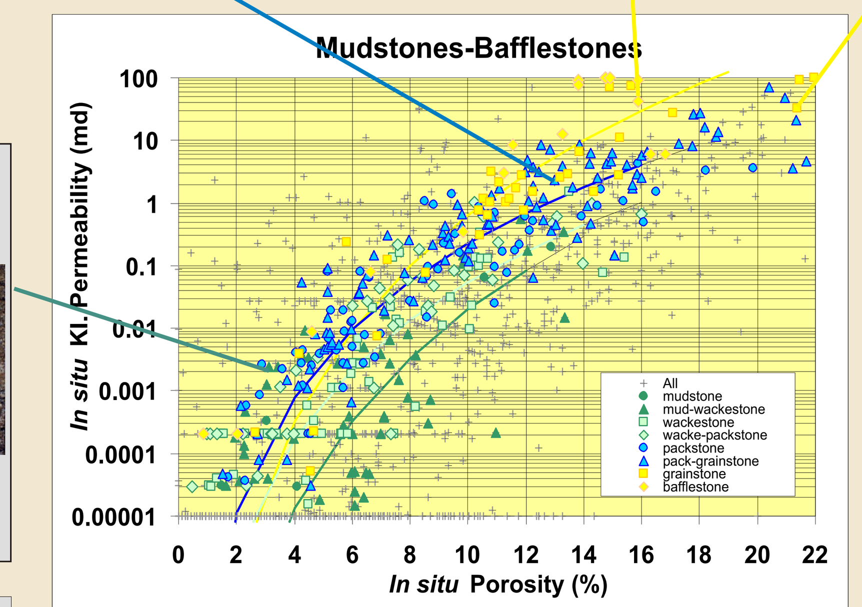
Lithofacies Digital Description: 3-8 / 6
Primary Depositional Environments:
Shoals on mid to upper shelf in either regressive or transgressive phase.

Alexander D-2
Core Slab, 3024
Cottonwood Limestone (B5)

Digital Description: 56-505-505-414-9434
Routine Core Analysis:

Whole Core	Porosity (%)	18.8
	Perm Max (md)	39.0
Plug	$Porosity_{in}$ (%)	21.2
	$Perm_{in}$ (md)	32.3





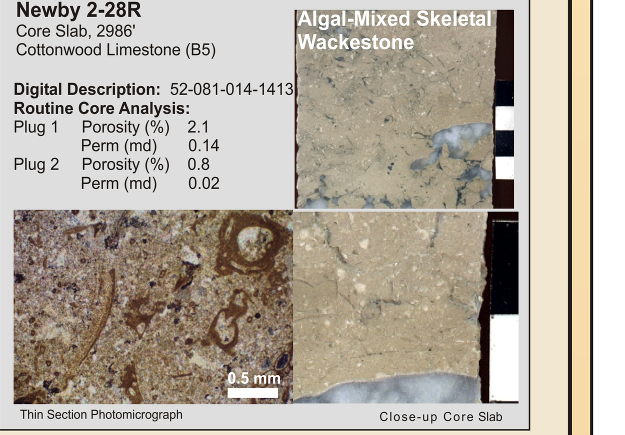
L-5 Wackestones and Wkst-Packstones

Lithofacies Digital Description: 3-8 / 2-3
Primary Depositional Environments:
Mostly in carbonate dominated mid shelf, some lagoon and tidal flat

Newby 2-28R
Core Slab, 2986'
Cottonwood Limestone (B5)

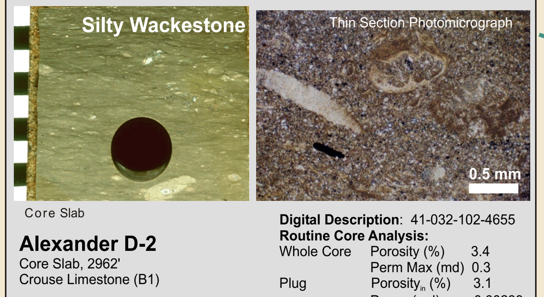
Digital Description: 52-081-014-1413
Routine Core Analysis:

Plug 1	Porosity (%)	2.1
	Perm (md)	0.14
Plug 2	Porosity (%)	0.8
	Perm (md)	0.02



L-4 Mudstones and Mdst- Wackestones

Lithofacies Digital Description: 3-8 / 0-1
Primary Depositional Environments:
Siliciclastic or carbonate dominated mid shelf.



Alexander D-2
Core Slab, 2962'
Crouse Limestone (B1)

Digital Description: 41-032-102-4655
Routine Core Analysis:

Whole Core	Porosity (%)	3.4
	Perm Max (md)	0.3
Plug	$Porosity_{in}$ (%)	3.1
	$Perm_{in}$ (md)	0.00239

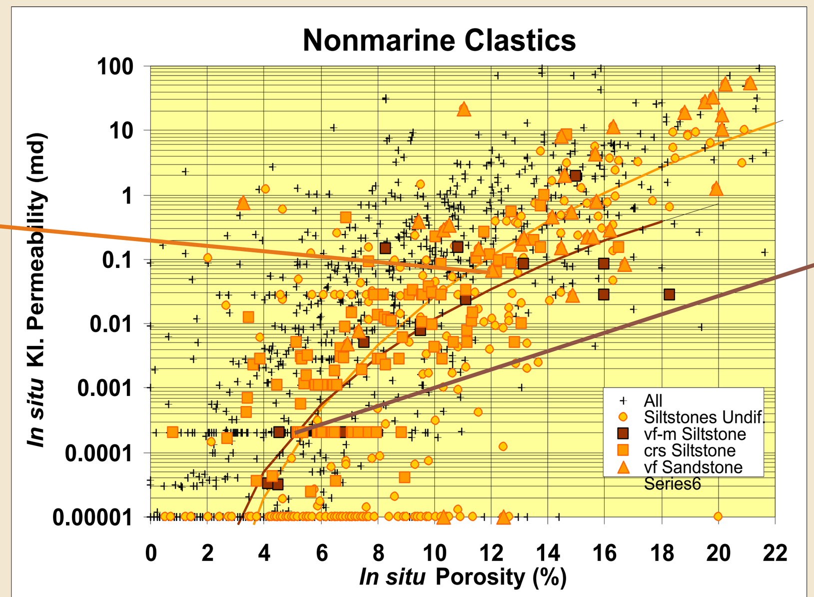
L-1 Nonmarine Siltstone and Sandstone

Lithofacies Digital Description: 1 / 2-3
Primary Depositional Environments:
Coastal Plain and, rarely, tidal flat (supratidal)

Amoco Beaty E-2
Core Slab, 2694',
Blue Rapids Shale (B1sh)

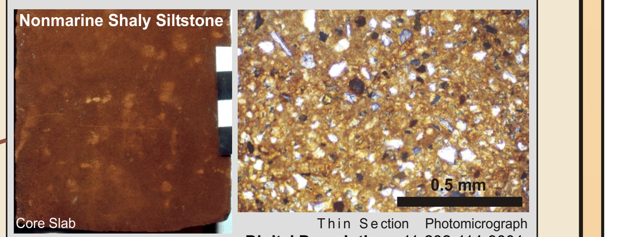
Digital Description: 13-513-214-900-005
Routine Core Analysis:

Whole Core	Porosity (%)	10.8
	Perm Max (md)	0.30
Plug	$Porosity_{in}$ (%)	11.9
	$Perm_{in}$ (md)	0.0667



L-2 Nonmarine Shaly Siltstone

Lithofacies Digital Description: 1 / 0-1
Primary Depositional Environments:
Coastal plain and, rarely, tidal flat (supratidal).



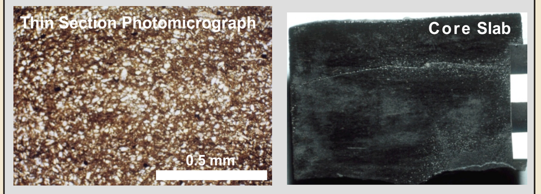
Newby 2-28R
Core Slab, 2949'
Blue Rapids Shale (B1sh)

Digital Description: 11-232-114-9001
Routine Core Analysis:

Plug	Porosity (%)	5.7
	Perm (md)	0.0002

L-3 Marine Siltstone and Shale

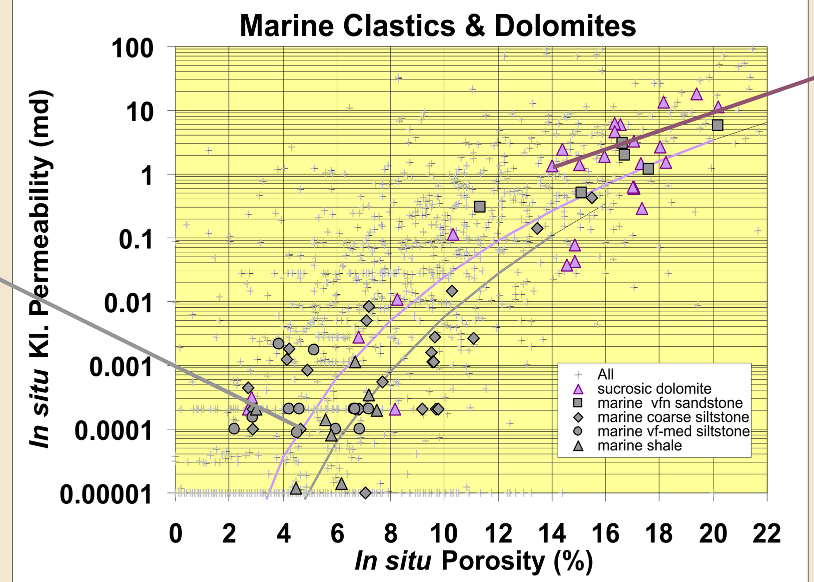
Lithofacies Digital Description: 0,2 / 0-2
Primary Depositional Environments:
Siliciclastic dominated mid shelf to lower shelf.



Newby 2-28R
Core Slab, 2872'
Funston Limestone (A)

Digital Description: 22-032-104-3709
Routine Core Analysis:

Whole Core	Porosity (%)	10.4
	Perm (md)	0.01
Plug	$Porosity_{in}$ (%)	4.6
	$Perm_{in}$ (md)	<0.0001



L- 6 Dolomite

Lithofacies Digital Description: 3-8 / 8
Primary Depositional Environments:
Upper shelf lagoons and tidal flats.

Beaty E-2
Core Slab, 2800'
Cottonwood Limestone (B5)

Digital Description: 68-503-235-9443
Routine Core Analysis:

Whole Core	Porosity (%)	13.3
	Perm Max (md)	1.1
Plug	Porosity (%)	14.0
	Perm (md)	1.3