PRACTICAL RESERVOIR CHARACTERIZATION FOR THE INDEPENDENT OPERATOR

Presented by
Roger M. Slatt
School of Geology and Geophysics
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June 24-25, 2002
Norman, Oklahoma

(CD of presentation will not be provided)
APPLIED RESERVOIR CHARACTERIZATION FOR THE INDEPENDENT OPERATOR: WITH EMPHASIS ON COMPARTMENTALIZED RESERVOIRS AND ROUTINE TECHNIQUES FOR DETECTING COMPARTMENTS

UNIT 1: INTRODUCTION TO RESERVOIR CHARACTERIZATION
UNIT 2: EXAMPLES OF COMPARTMENTALIZED RESERVOIRS
UNIT 3: GEOLOGIC CONTROLS ON POROSITY AND PERMEABILITY
UNIT 3A: SEISMIC POROSITY DETECTION IN A CARBONATE RESERVOIR
UNIT 4: FLOW UNIT DETERMINATION & CHARACTERIZATION
UNIT 5: BASICS OF SEQUENCE STRATIGRAPHY
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UNIT 11: BOREHOLE IMAGE LOGS AND APPLICATIONS
UNIT 12: DIPMETER LOGS AND APPLICATIONS
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DAY 1:
APPLIED RESERVOIR CHARACTERIZATION
FOR THE INDEPENDENT OPERATOR
WITH EMPHASIS ON COMPARTMENTALIZED RESERVOIRS AND ROUTINE TECHNIQUES FOR DETECTING COMPARTMENTS

Roger M. Slatt
School of Geology and Geophysics
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DAY 1 COURSE OUTLINE

UNIT 1: INTRODUCTION
UNIT 2: EXAMPLES OF COMPARTMENTALIZED RESERVOIRS
UNIT 3: GEOLOGIC CONTROLS ON POROSITY & PERMEABILITY
UNIT 4: FLOW UNIT DETERMINATION & CHARACTERIZATION
UNIT 5: BASICS OF SEQUENCE STRATIGRAPHY
UNIT 6: INCISED VALLEY FILL RESERVOIRS
UNIT 7: SHOREFACE RESERVOIRS
UNIT 8: DEEP-WATER (TURBIDITE) RESERVOIRS

DAY 1 COURSE OUTLINE (Cont.)

UNIT 9: BOREHOLE IMAGE & DIPMETER LOGS: APPLICATIONS
UNIT 10: STRUCTURALLY COMPARTMENTED RESERVOIRS
UNIT 11: BASICS OF GEOLOGICAL MODELING
UNIT 12: CARBONATE POROSITY DETECTION FROM 3D SEISMIC
UNIT 13: THE LEWIS SHALE AS A PETROLEUM SYSTEM

KEY REFERENCES TO INDIVIDUAL UNITS
RESERVOIR CHARACTERIZATION:

"THE PROCESS OF CREATING AN INTERDISCIPLINARY HIGH-RESOLUTION GEOSCIENCE MODEL THAT INCORPORATES, INTERRELATES, AND RECONCILES VARIOUS TYPES OF GEOLOGICAL AND ENGINEERING INFORMATION FROM PORE TO BASIN SCALE.

AAPG Memoir 71
THE SNEIDER FOCUS

Robert Sneider’s company moved from exploration to property acquisition during 1980’s downturn. Acquisition possibilities had the following traits:

• Might be a waterflood candidate;
• Existing waterflood yielding poor results with existing spacing;
• Unrecognized pay in low resistivity reservoir rocks;
• Unrecognized structural or stratigraphic compartments;
• Unrecognized field extensions that might be defined by new 2D or 3D seismic surveys;

Results: purchase of 46 mature fields with >625 MMBOE added at cost of $2.69/BOE

(Durham, May, 2001, AAPG Explorer, p. 28)

COMPARTMENTALIZED RESERVOIR

A compartmentalized reservoir is defined as a reservoir that is segmented into discrete, isolated geologic units, with each unit commonly having its own production characteristics.
FROM CONCEPTUAL TO QUANTITATIVE RESERVOIR CHARACTERIZATION

- HOW BIG IS THE CONTAINER?
- HOW WILL THIS RESERVOIR STYLE PERFORM?
- HOW WIDELY MUST WE SPACE OUR EXPENSIVE DEVELOPMENT WELLS IN THIS GEOLOGIC SETTING?
- SHOULD WE DRILL A VERTICAL, SLANT, OR HORIZONTAL WELL?
- HOW CAN WE FAST-TRACK DEVELOPMENT OF THIS RESERVOIR?
- WHAT WENT WRONG??

(Bashore, et al., 1994)
Lithostratigraphic Correlation
Delta-Front Sand and Silt
Sea Level

Original Depositional Surface

How do you know the geology between two wells???

Chronostratigraphic Correlation
T1
T2
T3

Sea level

(Bashore, et al., 1994)

WATERFLOOD

INJECTION WELL

PRODUCTION WELL

Water

Water

Water

Water
Reservoir performance is governed by features that are often beneath seismic resolution or detection ("sub-seismic scale")
RECOGNIZING COMPARTMENTALIZED RESERVOIRS

DYNAMIC RESERVOIR PROPERTIES

- Pressures (RFT, DST, PTA)
- 4D Seismic (Time lapse surveys)
- Fluid geochemistry (Produced fluids)
- Saturations (Well logs, cores)
- Fluid Contacts (Well logs, cores, seismic)
- GOR/WOR (IP, other tests)
RECOGNIZING
COMPARTMENTALIZED
RESERVOIRS

STATIC RESERVOIR PROPERTIES

- Stratigraphy
- Geometry
- Lithology
- Porosity and Permeability
- Capillarity
- Structure

Determined by subsurface well log mapping and
correlations, sample analysis, seismic,
borehole imaging, outcrop analogs
ROGER’S RULES OF RESERVOIR CHARACTERIZATION

• THINK SMALL
• THINK IN TERMS OF THE ROCKS (INSTEAD OF PAPER OR SCREEN IMAGES)
• THINK IN TERMS OF NUMBERS
• SEEING IS BELIEVING
• COMPUTERS ARE TOOLS, NOT BRAINS (DON’T BECOME A NINTENDO GEOLOGIST!!)
• ”WHERE OIL IS FIRST FOUND IN THE MINDS OF MEN (AND WOMEN)” by Wallace Pratt
• ”SWEAT THE ASSET” by Andrew Cullen

RESERVOIR CHARACTERIZATION DISCIPLINES

• GEOLOGY
• GEOPHYSICS
• PETROPHYSICS
• PETROLEUM ENGINEERING
• GEOSTATISTICS
• GEOCHEMISTRY
• COMPUTER SCIENCE
• BEHAVIORAL SCIENCE
Two stonecutters were asked what they were doing. The first said, "I'm cutting this stone into blocks." The second replied, "I'm on a team that's building a cathedral."

--Author unknown
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KEY REFERENCES TO INDIVIDUAL UNITS
EXAMPLES OF COMPARTMENTALIZED RESERVOIRS AND THEIR IDENTIFICATION AND CHARACTERIZATION
COMPARTMENTALIZED RESERVOIRS

- THE RULE, RATHER THAN THE EXCEPTION (SLATT, 1998)

- COMMON TO MOST TYPES OF SEDIMENTARY DEPOSITS

- STRUCTURAL COMPARTMENTS ALSO COMMON

- CAN BE DETECTED BY A VARIETY OF METHODS
  - STATIC RESERVOIR PROPERTIES
  - DYNAMIC RESERVOIR PROPERTIES
# ECONOMICS

TARGETED VS BLANKET INFILL DRILLING

<table>
<thead>
<tr>
<th>Targeted Wells</th>
<th>Infill Wells</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 Targeted Wells</td>
<td>20 Infill Wells</td>
</tr>
<tr>
<td>640,000 bbl</td>
<td>768,000 bbl</td>
</tr>
<tr>
<td>9% of OOIP</td>
<td>11% of OOIP</td>
</tr>
<tr>
<td>$1,800,000 Cap Ex</td>
<td>$4,500,000 Cap Ex</td>
</tr>
<tr>
<td>$1,902,000 LOE</td>
<td>$3,262,000 LOE</td>
</tr>
<tr>
<td>$5,068,000 Profit</td>
<td>$2,788,000 Profit</td>
</tr>
</tbody>
</table>

$2,280,000 Incremental

3D Seismic Cost $250,000
$17.00 per BBL  $225,000 per Completed Well

(Kendrick, 2000)
- S Sand, Auger Field; Gulf of Mexico

- 120MMBE assigned to S Sand
- As of 2000, 7 wells have produced 110 MMBE
- Field occurs within a salt-withdrawal mini-basin
- Combination fault-stratigraphic pinchout trap
- Layered/amalgamated sheet sands, and shales extend across entire basin
- Oil-bearing zones beneath water-bearing zones
- Excellent aquifer support
- Pulsed Neutron Capture (PNC) logs record replacement of oil by water during development; indicate that some shales isolate sands and others do not
- PNC data do not confirm that the 20ft. thick shale separating S1 and S2 sands is a barrier; however, other shales are barriers
- Different types of shales with different sealing potential?? Can these be recognized??

(Kendrick, 2000)
(McGee et al., 1994)
Auger Pink (S) Sand Wells One Mile Apart

(Modified from Balinski et al., 1994)

-Pulsed Neutron Capture (PNC) logs record replacement of oil by water during development; indicate that some shales isolate sands and others do not

(Kendrick, 2000)
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KEY REFERENCES TO INDIVIDUAL UNITS
GEOLOGIC CONTROLS
ON POROSITY AND
PERMEABILITY

LESSONS LEARNED
• KNOW HOW MEASUREMENTS ARE MADE;
• POROSITY & PERMEABILITY ARE
  CONTROLLED BY GRAIN SIZE DIST.
  AND SED. PROCESSES;
• POROSITY AND PERMEABILITY ARE
  MODIFIED BY DIAGENESIS, BUT
  USUALLY RETAIN ORIGINAL GRAIN
  SIZE VS. PORO./PERM RELATIONS;
• PERMEABILITY IS MORE SENSITIVE TO
  GRAIN SIZE VARIATIONS THAN IS
  POROSITY;
• GROSS INTERVAL POROSITY CAN BE
  MAPPED SEISMICALLY.
A WORD ABOUT HOW THE MEASUREMENTS ARE MADE

CORE PLUG SAMPLING BIAS

POOR CORE PLUG RECOVERY

INTERBEDDED LITHOLOGIES

POOR CORE RECOVERY

HIGH PERMEABILITY SANDSTONE

LOW PERMEABILITY SANDSTONE

Vavra & Kaldi
Pressure-decay mini-permeameter takes spot measurement of perm.
GRAIN-SIZE CONTROL ON POROSITY & PERMEABILITY

Figure 1 - Green Canyon 205 Unit location in the North Central Gulf of Mexico.

Figure 2 - Productive area (shaded) and exploration depletion and locations within the West Black CC 205 Unit.

(Reedy & Pepper, 1996)

Figure 3 - Wirelogs from the GC 295-11 discovery well showing five of the recognized productive sands. Arrows indicate the depths for the core photographs on Figure 8.
Laser Particle Size Distributions GC 205 #3 ST1 Well

Perm. (md)
- 5078
- 1957
- 102

Relative Volume (%)

Grain Size (mm)

(modified from Reedy and Pepper, 1996)
Reservoir Model with Well Data
Depth slice showing fault traces

E-W REGIONAL CROSS SECTION

Depth scale:

- 4000 FT
- 4700 FT
- 5300 FT
- 6000 FT
- 6700 FT

Legend:

- A-771
- B-7771
- B-1371
- B-2101
- C-774
- C-814UA
- C-110

Layers:

- G
- G5
- H31
- CORE

Faults:

- JUNIPERO FAULT
- TEMPLE AVENUE FAULT
- LONG BEACH UNIT FAULT
- BELMONT A-1 FAULT
- BELMONT FAULT

other coordinates:

- F0
- M1
- H1
- X
(Slatt et al., 1990)
### Average Properties of Sand Facies

<table>
<thead>
<tr>
<th></th>
<th>Porosity (%)</th>
<th>Permeability (md)</th>
<th>MZ (mm)</th>
<th>SD</th>
<th>Bed Thickness (ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin-Bedded</td>
<td>28.3</td>
<td>288</td>
<td>2.6</td>
<td>1.6</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.143)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thick-Bedded</td>
<td>28.1</td>
<td>457</td>
<td>2.6</td>
<td>1.6</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.160)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Slatt et al., 1991)
THICK - BEDDED SAND

THIN - BEDDED SAND

Yellow = grains
Purple = pores

The two areas are equal

(Shatt et al., 1990)
BURROWING ORGANISMS AFFECT POROSITY-PERM.
Biogenic Structures can increase or decrease K

Pemberton (1999)
POST-DEPOSITIONAL BURIAL COMPACTION & CEMENTATION REDUCE POROSITY-PERMEABILITY
<table>
<thead>
<tr>
<th>FACIES</th>
<th>DESCRIPTION</th>
<th>Aver. % SAND</th>
<th>Aver. PERM (md)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bioturbated mudstone</td>
<td>13</td>
<td>0.8</td>
</tr>
<tr>
<td>2</td>
<td>Burrowed to bioturbated sandy mudstone</td>
<td>38</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>Burrowed to bioturbated muddy sandstone</td>
<td>63</td>
<td>1.1</td>
</tr>
<tr>
<td>4</td>
<td>Planar/x-bedded sandstone</td>
<td>89</td>
<td>1.7</td>
</tr>
<tr>
<td>5</td>
<td>Rippled-bedded sandstone</td>
<td>93</td>
<td>2.1</td>
</tr>
<tr>
<td>6</td>
<td>Mudstone/sandstone clasts in mudstone/sandstone matrix</td>
<td>48</td>
<td>1.4</td>
</tr>
</tbody>
</table>
APPLICATION OF KNOWING POROSITY & PERMEABILITY DISTRIBUTION
Gamma or SP log

Regressive

Transgressive

Black dots refer to relative grain-size of sands at each strat. level

Oil saturation (%)

Remaining oil saturation after waterflood

SEISMIC POROSITY DETECTION
Pickerill Field
Porosity vs Rotliegend Amplitude
From Phase Corrected Volume

- slope = 1.292
- const = 6.124
- R^2 = 0.783
LESSONS LEARNED

- KNOW HOW MEASUREMENTS ARE MADE;
- POROSITY & PERMEABILITY ARE CONTROLLED BY GRAIN SIZE DIST. AND SED. PROCESSES;
- POROSITY AND PERMEABILITY ARE MODIFIED BY DIAGENESIS, BUT USUALLY RETAIN ORIGINAL GRAIN SIZE VS. PORO./PERM RELATIONS;
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KEY REFERENCES TO INDIVIDUAL UNITS
CARBONATE POROSITY DETECTION FROM 3D SEISMIC:
ORDOVICIAN RED RIVER, WILLISTON BASIN

COMPLIMENTS OF:
MARK A. SIPPEL

Williston Basin - Area of Interest

Ordovician Red River
8500 to 9500 ft
Statement of Problem

- Does a single crestal well drain all reserves on a small Red River structure?
- Where are optimum drilling locations on Red River structures and how are they identified?
- What are potential reserves related to seismic attribute anomalies?
Winnipeg Time Structure with T1 Amplitude

Grand River School
Bowman Co., ND

160 acres

1 mile

1 km

Grand River School
Bowman CO., ND

Old Well

Winnipeg Time Contours

New Well

1 mile

Red River D Amplitude

Excellent Porosity

Poor Porosity
CONCLUSION

ONCE SEISMIC AMPLITUDE WAS CALIBRATED TO POROSITY, 3D SEISMIC COULD DETECT POROUS RESERVOIR ZONES
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LESSONS LEARNED

- RESERVOIRS CAN BE CHARACTERIZED BY A COMBINATION OF GEOLOGICAL AND PETROPHYSICAL PROPERTIES

- MODIFIED LORENZ PLOT REDUCES VARIABLES, AND QUANTIFIES ZONATION FOR SIMULATION

- NEURAL NET USEFUL FOR DEVELOPING PERMEABILITY LOG FOR FLOW UNIT ZONATION. CORE IS REQUIRED FOR CALIBRATION.
Gamma or SP log

Regressive

Transgressive

Black dots refer to relative grain-size of sands at each strat. level

Oil saturation (%)

Remaining oil saturation after waterflood

APPLICATION OF RFT TO RESERVOIR CONNECTIVITY STUDIES

Lithostratigraphic Correlation

Hydrodynamic Correlation based on RFT data
FLOW UNIT:
"VOLUME OF ROCK SUBDIVIDED ACCORDING TO GEOLOGICAL AND PETROPHYSICAL PROPERTIES THAT INFLUENCE THE FLOW OF FLUIDS THROUGH IT" (Ebanks, 1987)

<table>
<thead>
<tr>
<th>FLOW FLOW</th>
<th>PERM. (md)</th>
<th>POR. (%)</th>
<th>Md. GRAIN SIZE (mm)</th>
<th>Md. PORE THROAT SIZE (mm)</th>
<th>Sg @ 200 psf (%)</th>
<th>CHARACTERISTICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>c</td>
<td>&gt;1000</td>
<td>23-34</td>
<td>0.182-0.304</td>
<td>0.010-0.013</td>
<td>6-12</td>
<td>MASSIVE SAND. CHANNEL FACIES.</td>
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<tr>
<td>G</td>
<td>100-1000</td>
<td>20-34</td>
<td>0.083-0.242</td>
<td>0.007</td>
<td>11-24</td>
<td>MASSIVE SAND. CHANNEL / LOBE FACIES.</td>
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<tr>
<td>P1</td>
<td>0.1-100</td>
<td>7-32</td>
<td>0.100-0.230</td>
<td>0.002</td>
<td>31</td>
<td>INTERBEDDED SAND / MUD. CHANNEL / LOBE FACIES.</td>
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<tr>
<td>P2</td>
<td>0.01-100</td>
<td>4-28</td>
<td>0.113-0.245</td>
<td>0.002</td>
<td>30-37</td>
<td>MASSIVE SAND w/ CALCITE CEMENTED ZONES. CHANNEL / LOBE FACIES.</td>
</tr>
<tr>
<td>PM</td>
<td>Imperme.</td>
<td>Non-porous</td>
<td></td>
<td></td>
<td></td>
<td>CLAY / MUDSTONE</td>
</tr>
</tbody>
</table>
GUNTER (1997) METHOD OF FLOW UNIT CHARACTERIZATION

- 'STRATIGRAPHIC MODIFIED LORENZ PLOT' (SML)
- 'CUMULATIVE FLOW CAPACITY' (PRODUCT OF AVER. PERM. AND INTERVAL THICKNESS)
- 'CUMULATIVE STORAGE CAPACITY' (PRODUCT OF AVER. POROSITY AND INTERVAL THICKNESS)
- CROSS PLOT THE TWO, WITH CUM. STORAGE CAP. ON HORIZONTAL AXIS AND CUM. FLOW CAP. ON VERTICAL AXIS.
- PLOT BEGINS (LOWER LEFT CORNER) AT STRATIGRAPHIC BASE
<table>
<thead>
<tr>
<th>Depth (ft.)</th>
<th>Por.</th>
<th>(Por.) (H)</th>
<th>K</th>
<th>(K)(H)</th>
</tr>
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<tbody>
<tr>
<td>1805</td>
<td>0.15</td>
<td>(0.15)(1)=0.15</td>
<td>10</td>
<td>(10)(1)=10</td>
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<tr>
<td>1804</td>
<td>0.20</td>
<td>(0.20)(1)=0.20</td>
<td>20</td>
<td>(20)(1)=20</td>
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<tr>
<td>1803</td>
<td>0.15</td>
<td>(0.15)(1)=0.15</td>
<td>10</td>
<td>(10)(1)=10</td>
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<tr>
<td>1802</td>
<td>0.10</td>
<td>(0.10)(1)=0.10</td>
<td>5</td>
<td>(5)(1)=5</td>
</tr>
<tr>
<td>1801</td>
<td>0.05</td>
<td>(0.05)(1)=0.05</td>
<td>2</td>
<td>(2)(1)=2</td>
</tr>
<tr>
<td>Summation=</td>
<td>-0.65</td>
<td>= 47</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depth (ft.)</th>
<th>Fract. (Por.) (H)=(X)/0.65</th>
<th>Fract. (K) (H) = (Y)/47</th>
</tr>
</thead>
<tbody>
<tr>
<td>1805</td>
<td>(0.15)/0.65=0.23</td>
<td>(10)/47 = 0.21</td>
</tr>
<tr>
<td>1804</td>
<td>(0.20)/0.65=0.31</td>
<td>(20)/47 = 0.43</td>
</tr>
<tr>
<td>1803</td>
<td>(0.15)/0.65=0.23</td>
<td>(10)/47 = 0.21</td>
</tr>
<tr>
<td>1802</td>
<td>(0.10)/0.65=0.15</td>
<td>(5)/47 = 0.11</td>
</tr>
<tr>
<td>1801</td>
<td>(0.05)/0.65=0.08</td>
<td>(2)/47 = 0.04</td>
</tr>
<tr>
<td>Summation=</td>
<td>=1.00</td>
<td>= 1.00</td>
</tr>
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<table>
<thead>
<tr>
<th>Depth</th>
<th>Cumulative (Por) (H)</th>
<th>Cumulative (K) (H)</th>
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<tbody>
<tr>
<td>(Cum. Storage Capacity)</td>
<td>(Cum. Flow Capacity)</td>
<td></td>
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<tr>
<td>1805</td>
<td>0.23</td>
<td>0.21</td>
</tr>
<tr>
<td>1804</td>
<td>0.54</td>
<td>0.64</td>
</tr>
<tr>
<td>1803</td>
<td>0.77</td>
<td>0.85</td>
</tr>
<tr>
<td>1802</td>
<td>0.92</td>
<td>0.96</td>
</tr>
<tr>
<td>1801</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>
NNLAP™
Neural Network Core Permeability Example

TRAINING WELL
TENSLIP FM, WYOMING
Core Permeability From Neutron & Density Porosity

PERMEABILITY DATA WHERE NO CORE WAS RECOVERED

Difficult Problem in Cross-bedded Sandstone with Carbonate Cement
Core Permeability Ranges Over 5 Decades (0.01 to 500 md)
Neural Network Predictions are Accurate to Within One Half of a Decade Using Only 4 Training Examples (Plus the Depth Interval Sample).
CONFIRMATION WELL
TENSPLEEP FM, WYOMING
Core Permeability from Neutron & Density Porosity

Neural Network Solution from the Training Well was Applied to another Well which had Core Permeability Data and the Results Were Compared.

The Favorable Match Indicates That We Have a Robust Solution.

We Can Now Feel Confident That We Can Apply the Neural Network Solution to Other Wells (Located Between Our Training and Confirmation Well) Which Do Not Have Core Data.

Neural network synthetic permeability compared to core permeability. NNKcore is the synthetic permeability derived from the core measurements. It correlates to the core permeability at high permeability values relatively well.
LESSONS LEARNED

• RESERVOIRS CAN BE CHARACTERIZED BY A COMBINATION OF GEOLOGICAL AND PETROPHYSICAL PROPERTIES

• MODIFIED LORENZ PLOT REDUCES VARIABLES, AND QUANTIFIES ZONATION FOR SIMULATION

• NEURAL NET USEFUL FOR DEVELOPING PERMEABILITY LOG FOR FLOW UNIT ZONATION. CORE IS REQUIRED FOR CALIBRATION.
APPLIED RESERVOIR CHARACTERIZATION FOR THE INDEPENDENT OPERATOR: WITH EMPHASIS ON COMPARTMENTALIZED RESERVOIRS AND ROUTINE TECHNIQUES FOR DETECTING COMPARTMENTS

UNIT 1: INTRODUCTION TO RESERVOIR CHARACTERIZATION
UNIT 2: EXAMPLES OF COMPARTMENTALIZED RESERVOIRS
UNIT 3: GEOLOGIC CONTROLS ON POROSITY AND PERMEABILITY
UNIT 3A: SEISMIC POROSITY DETECTION IN A CARBONATE RESERVOIR
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UNIT 10: DEEP-WATER (TURBIDITE) DEPOSITS AND RESERVOIRS
UNIT 11: BOREHOLE IMAGE LOGS AND APPLICATIONS
UNIT 12: DIPMETER LOGS AND APPLICATIONS
UNIT 13: STRUCTURALLY COMPARTMENTALIZED RESERVOIRS

KEY REFERENCES TO INDIVIDUAL UNITS
Global Sea level Curves

- Global cycle: relative rise and fall occurs on a global scale
- Global cycle charts illustrate different cycles at three orders
  - First order
    - Precambrian to Early Triassic, 300 Ma
    - Middle Triassic to present, 225 Ma
  - Second order
    - 10 to 80 Ma duration—now considered as 9-10 Ma; stacked second order: 29-30 Ma
  - Third order
    - 1 to 10 Ma duration—now considered as 1-3 Ma
- These curves are asymmetric; again they are now considered to be coastal onlap curves
### Figure 1

First- and second-order global cycles of relative change of sea level during Phanerzoic time.

<table>
<thead>
<tr>
<th>PERIODS</th>
<th>EPOCHS</th>
<th>2ND ORDER CYCLES</th>
<th>RELATIVE CHANGES OF SEA LEVEL</th>
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<tbody>
<tr>
<td>PRECAMBRIAN</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>ORDOVICAN</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAMBRIAN</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MISSISSIPPIAN</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DEVONIAN</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SILURIAN</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PERMIAN</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>PENNSYLVANIAN</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>TRIASSIC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JURASSIC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRETACEOUS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TERTIARY</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Geologic Time in Millions of Years**

- PRESENT SEA LEVEL
- RELATIVE CHANGES OF SEA LEVEL: RISING, FALLING

**Notations**

- STRK
- KA
- TD
- TP
- DM
- CR

**Relative Changes of Sea Level**

- 0
- 100
- 200
- 300
- 400
- 500

**Geologic Time in Millions of Years**

- 0
- 100
- 200
- 300
- 400
- 500

**Graphical Representation**

- Composite Eustatic Curve
- 4th Order Eustatic Cycle
- 3rd Order Eustatic Cycle

**Notes**

- 10,000 x YEARS
- FEET

- 0
- +100
- -100
- 0
- +100
- -100
Figure 1. Elements of eustatic change. Maximum rates of rise and fall coincide with R- and F-inflexion points. From Posamentier and others, 1988. Reprinted by permission of SEPM.
Falling sea level

A. Lowstand Fan

Turnaround in sea level

B. Early Lowstand Wedge
Channel-Levee Complex

Prograding Complex

Early rise in sea level

C. Late Lowstand Wedge
Prograding Complex

Late Lowstand Wedge
(Prograding Complex)

Prograding complex

Lowstand wedge

Complete lowstand systems tract

D. Axial Section through Canyon and Slope
Figure 1. Elements of eustatic change. Maximum rates of rise and fall coincide with R- and F-inflection points. From Posamentier and others, 1988. Reprinted by permission of SEPM.
Figure 1. Elements of eustatic change. Maximum rates of rise and fall coincide with R- and F-inflexion points. From Posamentier and others, 1988. Reprinted by permission of SEPM.
Figure 1. Elements of eustatic change. Maximum rates of rise and fall coincide with R- and F-inflection points. From Posamentier and others, 1988. Reprinted by permission of SEPM.
DEPOSITIONAL SEQUENCE MODEL
SYSTEMS TRACTS

SURFACES:
B = SEQUENCE BOUNDARIES
(SB 1) = TYPE 1
(SB 2) = TYPE 2
LS = DOWNLAP SURFACES
S = TRANSgressive SURFACE

SYSTEMS TRACTS:
HST = HIGH SYSTEMS TRACT
DLS = DEEP LOW SYSTEMS TRACT
ID = INTERVALユニフォーム
HSD = HIGH STAND DUNFORD
INCISED VALLEY = HIGH STAND DUNFORD
CANYON = DEEP FAN

DEPOSITIONAL SEQUENCE MODEL
CLASTIC FACIES

SAND = PRONE FACIES
STACKING PATTERNS
• A COMPLETE VERTICAL SEQUENCE CONSISTS OF:

Sequence Boundary
- Highstand systems tract (thin sh. in deep water; deltas)
- Transgressive systems tract, including condensed section
  (thin, organic rich sh. in deep water; shoreface sands)
- Prograding complex or early lowstand wedge (mud-prone)
- Leveed channel complex, slope fan or early lowstand wedge
- Sheet sandstones, basin floor fan, or lowstand fan
- Mass transport complex

Sequence Boundary
• COMPLETE VERTICAL SEQUENCE MAY NOT BE
  PRESENT; DEPENDS UPON POSITION OF
  DEPOSITION WITHIN BASIN
ROCK vs. TIME STRATIGRAPHY

- **LITHOSTRATIGRAPHY**: CORRELATION OF ROCK UNITS ON THE BASIS OF CHARACTERISTICS;

- **SEQUENCE STRATIGRAPHY**: CORRELATION OF UNITS ON THE BASIS OF TIME-EQUIVALENT SURFACES;

- OWING TO TIME-TRANSGRESSION NATURE OF STRATA, TIME-EQUIVALENT SURFACES CROSS-CUT LITHOSTRATIGRAPHIC BOUNDARIES
Figure 2.1. The difference between sequence stratigraphy, which has a geological time significance and lithostratigraphy, which correlates rocks of similar type. A lithostratigraphic correlation would correlate conglomerate units 1 and 2, sandstone units 3, 4 and 5 and mudstone units 6, 7 and 8. A sequence stratigraphic correlation would correlate time lines A-A', B-B' and C-C'. Used with permission of Blackwell Science.
### Electrofacies Classification

#### Upper Contact of Sand

<table>
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<th>Gradual</th>
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<td>Cylinder Shape</td>
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<tr>
<td>Serrated</td>
<td>Smooth</td>
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<td>Smooth</td>
<td>Serrated</td>
</tr>
<tr>
<td>Smooth</td>
<td>Serrated</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lower Contact of Sand</th>
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</thead>
<tbody>
<tr>
<td>Funnel Shape</td>
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<tr>
<td>Serrated</td>
</tr>
<tr>
<td>Smooth</td>
</tr>
<tr>
<td>Smooth</td>
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</table>

*Fig. 3-21. Relationship between SP curve shape and grain size or shaliness (adapted from SHELL's documents).*

---

#### Stratigraphic Units

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<tr>
<td>Zones (both)</td>
</tr>
<tr>
<td>Upper boundary</td>
</tr>
<tr>
<td>Lower boundary</td>
</tr>
<tr>
<td>Interbedded sand</td>
</tr>
<tr>
<td>Shellmark</td>
</tr>
<tr>
<td>Common thickness: 0.0-10.0 ft (0-3 m)</td>
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</table>

<table>
<thead>
<tr>
<th>SW Vertical</th>
</tr>
</thead>
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<tr>
<td>Elongated mark</td>
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<td>Lower boundary</td>
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<tr>
<td>Interbedded sand</td>
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<tr>
<td>Shellmark</td>
</tr>
<tr>
<td>Common thickness: 0.0-10.0 ft (0-3 m)</td>
</tr>
</tbody>
</table>

*Figure 17.6: Idealized examples of stratigraphic units and self-potential (SP) logs for (A) a funnel-shaped unit, (B) a channel-barrier, (C) a barrier-bar, and (D) a distributary channel mouth. Note that the SP log shows an increase in resistivity with increasing distance from the channel mouth. The IF curve shows the corresponding upward barrier-shelf sequence also noted upward. (After following, 1976).*
Figure 19—Idealized patterns in a type-3 sequence deposited in a basin with a shelf break.
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KEY REFERENCES TO INDIVIDUAL UNITS
Figure 19 - Sediment patterns in a typical sequence depended on a basin with a shelf break.
FLUVIAL (RIVER) DEPOSITS

-ORIGIN

-TYPES
  -Point Bar (Meandering)
  -Braided
  -Alluvial fan
  -Incised valley fill

-CHARACTERISTICS

-RESERVOIR EXAMPLES
Meander bend in river, showing ripples and cutbank and point bar
MOVEMENT OF ROCK PARTICLES IN A STREAM

SURFACE OF STREAM

SCHEMATIC VELOCITY PROFILE
FLUVIAL (RIVER) DEPOSITS

-ORIGIN

-TYPES
  -Point Bar
  -Braided
  -Alluvial fan
  -Incised valley fill

-CHARACTERISTICS

-RESERVOIR EXAMPLES
FLUVIAL (RIVER) DEPOSITS

-ORIGIN

-TYPES
  -Point Bar
  -Braided
  -Alluvial fan
  -Incised valley fill

-CHARACTERISTICS

-RESERVOIR EXAMPLES
FLUVIAL (RIVER) DEPOSITS

-ORIGIN

-TYPES
  -Point Bar
  -Braided
  -Alluvial fan
  -Incised valley fill

-CHARACTERISTICS

-RESERVOIR EXAMPLES
INCISED VALLEY FILL RESERVOIRS

- VALLEY IS INCISED DURING FALL IN SEA (BASE) LEVEL

- VALLEY IS FILLED DURING TURNAROUND AND RISE IN SEA (BASE) LEVEL

- IDEAL VERTICAL SEQUENCE:
  - BASAL FLUVIAL LAG
  - ESTUARINE STRATA
  - OPEN MARINE STRATA

- LATERAL SEQUENCE: ESTUARINE TO FLUVIAL IN THE PALEO-LANDWARD DIRECTION

- ENCASED IN MARINE SHALE, SO GOOD STRAT. TRAP

(Welmer, 1994)
Valley cut into sediment during sea-level drop. At this time the valley is an open conduit in which no sediment is accumulated.

Tillman and Pittman (1994)
Valley-fill during period of sea-level rise. Valley is filled with fluvial (potential sandstone reservoir) and swamp and marsh deposits (non-reservoir). Fill may be a mixture of marine and river deposits deposited at or slightly below sea level.

Tillman and Pittman (1994)
FLUVIAL (RIVER) DEPOSITS

-ORIGIN

-TYPES
  -Point Bar
  -Braided
  -Alluvial fan
  -Incised valley fill

-CHARACTERISTICS

-RESERVOIR EXAMPLES
  -Peco Field, Alberta
  -Murdoch Field, North Sea
FLUVIAL (RIVER) DEPOSITS

- ORIGIN

-TYPES
  - Point Bar
  - Braided
  - Alluvial fan
  - Incised valley fill

- CHARACTERISTICS

- RESERVOIR EXAMPLES
  - Sorrento Field
  - Stockholm Field
#7 McCormick Log Display

<table>
<thead>
<tr>
<th>Computed lithology</th>
<th>Gamma ray</th>
<th>Neutron</th>
<th>Density</th>
<th>Profile permeability</th>
<th>Facies</th>
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<td></td>
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<tr>
<td>Flow unit 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/55</td>
<td>1000</td>
<td></td>
<td></td>
<td></td>
<td>Lower shoreface</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td>siltstone</td>
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Log scale: 1:1000

---

**Complete Depositional Sequence**

- Younger Unconformity (UUC)
- Sequence boundary and transgressive surface
- Complete sequence in areas outside valleys
- Unconformity (sequence boundary)
- Transgressive surface (TS)
- Marine muds
- Older sequence
- Lowstand erosional surface
- Unconformity of sequence boundary

*Wermer (1994)*
Incised Valley Topography and Valley Fill Facies

3000 feet
Mark, 1995

Static Pressure Test Results

Mark, 1995
Vertical Units of Flow-Units May Represent Cycles of Channel Stacking Events

After Bowen et al., 1990
Compressional Wave Mid-Morrow Amplitudes

Vp/Vs Top of Morrow to Mississippian Interval
Sorrento Field
Flow Unit Model

Developed by integrating sequence stratigraphy, 3-D compressional seismic interpretation, and production data:

- Sequence stratigraphy explains the development of the reservoir
- Reservoir is compartmentalized vertically by diagenetic events associated with stacked channel sequences
- 3-D compressional seismic data reveals the valley outline and lateral barriers to flow
- Production data corroborates geologic and geophysical interpretations of reservoir compartmentalization
- The reservoir consists of four flow units that display separate fluid contacts but maintain a baffled pressure relationship with other flow units

Mark, 1995

Location of 20-mile-long "State line Trend" Morrow Sandstone fields, which produce from valley-fill sandstone reservoirs. Southwest Stockham Field, Kansas, is located in Greeley and Wallace counties, Kansas.

(Tillmand and Patman, 1953)
SANDSTONE FACIES STOCKHOLM SANDSTONE SOUTHWEST STOCKHOLM FIELD

- Fluvial Sandstones
  - Channel Fill
  - Fluvially reworked tidal Sandstone
- Tidally Deposited Sandstones
  - Estuary Channels
    - Sandstone Fill
    - Low-Energy Fill
  - Fluvial Channel Sandstones Reworked by Tides
  - Tidal Bar or Tidal Flat
  - Tidal Channels
  - Ponded Tidal-Creek Fill
  - Tidal Sandstone
- Marine Shelf Sandstones

(Tillman and Pittman, 1993)

---

TABLE III
PETROPHYSICAL PARAMETERS FOR RESERVOIR FACIES SOUTHWEST STOCKHOLM FIELD

<table>
<thead>
<tr>
<th></th>
<th>K (md)</th>
<th>$\theta$ (%)</th>
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<th>$R_{35}$ (microns)</th>
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<td>Range</td>
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<td>11.7-20.6</td>
<td>11.0-92.2</td>
<td>11.2-33.5</td>
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<tr>
<td>Tidal Sandstones</td>
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<tr>
<td>Mean</td>
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<td>14.4</td>
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<td>Range</td>
<td>50-111</td>
<td>11.5-17.8</td>
<td>4.1-7.2</td>
<td>6.0-8.4</td>
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</tbody>
</table>
FLUVIAL (RIVER) DEPOSITS

-ORIGIN

-TYPES
  -Point Bar
  -Braided
  -Alluvial fan
  -Incised valley fill

-CHARACTERISTICS

-RESERVOIR EXAMPLES
  -Glen Pool Field
Isopach map of Bartlesville Sandstone near Glenn Pool Field (contour interval is 50ft.)

Production History of the Self Unit Glenn Pool Field, Oklahoma
Note changes in production as new Recovery techniques are begun in field
CONCLUSIONS

• INCISED VALLEY FILL DEPOSITS ARE INTERNALLY COMPLEX AND CAN BE STRATIGRAPHICALLY COMPARTMENTALIZED BY CHANNEL INCISEMENT AND/OR CEMENTATION

• FLUVIAL AND ESTUARINE/MARINE FACIES WILL EXHIBIT DIFFERENT PORO./PERM. VALUES, RESULTING IN VARIABLE RESERVOIR VOLUMETRICS AND PERFORMANCE

• COMPLEXITIES CAN BE IMAGED SEISMICALLY AND DETERMINED BY CORE ANALYSIS AND PRESSURE TESTS
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KEY REFERENCES TO INDIVIDUAL UNITS
EOLIAN (WIND-BLOWN, SAND SEA) DEPOSITS AND RESERVOIRS

EOLIAN DEPOSITS & RESERVOIRS
ENVIRONMENTAL SETTING OF CLASTIC STRATIGRAPHIC TRAPS
Dust devil entraining sediment into atmosphere.

Dust storm descending on Phoenix, Arizona
Sand transport from top to bottom of screen.
PROCESS OF DUNE MIGRATION
IDEALIZED BARCHANOID SAND DUNES

FACIES ASSOCIATION 1 - TRANSVERSE DRAA

- E Crabbing scour pit
- A Transverse dune
- C Oblique crescentic dune
- F Linear dune

Scale: 100m
Dune cross bedding due to fluctuating wind direction
WEBER SANDSTONE, RANGELY FIELD, CO.

Pickerill Field,
North Sea produces from
Rotliegendes
Sandstone (Permian)
### Well #1 RFT RESULTS

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<th>MD&amp;RKB (FT)</th>
<th>TVDSS (FT)</th>
<th>HYDROSTATIC PRESSURE (PSIA)</th>
<th>FORMATION PRESSURE (PSIA)</th>
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### Well #2 RFT RESULTS

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<td>Tight</td>
</tr>
<tr>
<td>8770</td>
<td>--</td>
<td>4575.8</td>
<td>--</td>
<td>Tight</td>
</tr>
</tbody>
</table>
Fault zone compartmentalizes the reservoir

TOP ROTLIEGEND
REFLECTION AMPLITUDE

2 km
Recent Advances in Outcrop-Based 3-D Modeling

Neil Hurley
Bozkurt Ciftci
Ali Raba’a
Chris Zahm
Colorado School of Mines

Research Objectives: Tensleep Sandstone

Use superb outcrop exposures in parallel canyon walls to identify the geometry and volumetric sizes of dune-related reservoir compartments.
Bounding Surfaces in the Tensleep

1st Order Bounding Surfaces
- A: across the surface 0.0289 md
  - above the surface 0.283 md
  - below the surface 0.592 md

2nd Order Bounding Surfaces
- B: across the surface 0.0273 md
  - above the surface 0.621 md
  - below the surface 0.888 md

3rd Order Bounding Surfaces
- C: across the surface 0.230 md
  - above the surface 1.12 md
  - below the surface 0.680 md
GPS (Global Positioning System)

Field Work
APPLIED RESERVOIR CHARACTERIZATION FOR THE INDEPENDENT OPERATOR: WITH EMPHASIS ON COMPARTMENTALIZED RESERVOIRS AND ROUTINE TECHNIQUES FOR DETECTING COMPARTMENTS

UNIT 1: INTRODUCTION TO RESERVOIR CHARACTERIZATION
UNIT 2: EXAMPLES OF COMPARTMENTALIZED RESERVOIRS
UNIT 3: GEOLOGIC CONTROLS ON POROSITY AND PERMEABILITY
UNIT 3A: SEISMIC POROSITY DETECTION IN A CARBONATE RESERVOIR
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UNIT 6: FLUVIAL DEPOSITS AND RESERVOIRS
UNIT 7: EOLIAN DEPOSITS AND RESERVOIRS

*UNIT 8: SHOREFACE DEPOSITS AND RESERVOIRS
UNIT 9: DELTAIC DEPOSITS AND RESERVOIRS
UNIT 10: DEEP-WATER (TURbidite) DEPOSITS AND RESERVOIRS
UNIT 11: BOREHOLE IMAGE LOGS AND APPLICATIONS
UNIT 12: DIPMETER LOGS AND APPLICATIONS
UNIT 13: STRUCTURALLY COMPARTMENTALIZED RESERVOIRS

KEY REFERENCES TO INDIVIDUAL UNITS
SHOREFACE & BARRIER
ISLAND DEPOSITS & RESERVOIRS

ENVIRONMENTAL SETTING OF
CLASTIC STRATIGRAPHIC TRAPS

(BROWN, 1972)
Figure 19—Nodal patterns in a type 3 sequence deposited in a basin with a shelf break.

Figure 1. Elements of eustatic change. Maximum rates of rise and fall coincide with R- and P-inflexion points. From Posamentier and others, 1988. Reprinted by permission of SEPM.
SHOREFACE DEPOSITS & RESERVOIRS
Vertical ophiomorpha burrows in side view.

**Figure 3A.** Stratal characteristics of an upward-coarsening parasequence. This type of parasequence is interpreted to form in a beach environment on a sandy, wave- or tidal-dominated shoreline.

**Upward-coarsening/thickening shoreface parasequence**
Seaward progradation during relative stillstand of sea level

Vertical sequence indicates progradation followed by rapid deepening (transgression) of water

Offshore shelf

Upper shoreface

Lower shoreface

Offshore shelf

Within each parasequence:
- Sandstone beds and muds thin upward
- Sandstone/mudstone ratio thickens upward
- Grain size increases upward
- Laminae geometry become steeper upward in general
- Bioturbation decreases upward to the parasequence boundary
- Facies within each parasequence shallow upward
- Parasequence boundary marked by:
  - Abrupt change in lithology from sandstone below the boundary to mudstone up section
  - Abrupt decrease in bed thickness
  - Possible major truncation of underlying laminae
  - Horizon of bioturbation, bioturbation intensity diminishes downward
  - Sulfates, phosphates, and carbonates of organic-rich shale, shale pelloids
  - Abrupt deepening in depositional environment across the boundary

Figure 3A—Stratal characteristics of an upward-coarsening parasequence. This type of parasequence is interpreted to form in a beach environment on a sandy, wave- or fluvial-dominated shoreline.

Upward-coarsening/thickening shoreface parasequence
Two cycles of progradation and transgression to give two parasequences

Four cycles to give four parasequences
Coastal plain
Coral/reef platform
Beach
Breaker zone - ridge B
runnel / rip channels

Shoreface - Swaley cross-stratification

Lower shoreface - inner shelf transition -
Hummocky cross-stratification

Mid-shelf - bioturbated sandy siltstone

Outer shelf - bioturbated mudstone

"Normal" gradational based shoreface succession

Sharp-based shoreface succession deposited during
relative sea level fall

Relatively thin, erosive-based shoreface sandbody.

Mudstone introclasts
Gutter casts

(Walker, 1992)
EXERCISE ON HAMBERT-ARISTOCRAT FIELD

CONCLUSIONS

• SHOREFACE SEQUENCES ARE INTERNALLY COMPLEX

• INDIVIDUAL SANDSTONES ARE SEPARATED BY LATERALLY CONTINUOUS TRANSGRESSIVE MARINE SHALES WHICH CAN VERTICALLY ISOLATE INDIVIDUAL SANDSTONES

• PORO./PERM. VALUES WILL VARY WITH FACIES (UPPER, MIDDLE, LOWER SHOREFACE)

• HIGH RESOLUTION SEQUENCE STRATIGRAPHY SHOULD BE APPLIED TO SHOREFACE SEQUENCES
Figure 9.14
Subenvironments in a barrier-island system. (From Walker, 1984.)
Flood tidal delta
Figure 7.13 Structure on top of the Muddy Formation, northeastern Powder River basin, and location of Muddy stratigraphic oil fields. Contour interval 1000 ft (300 m). [Map drawn by L. D. Recker.] Map area shown in Figure 7.12.
### TABLE 7-1. OIL PRODUCTION FROM SELECTED MUDDY FIELDS, NORTHEASTERN POWDER RIVER BASIN, MONTANA AND WYOMING

<table>
<thead>
<tr>
<th>Name</th>
<th>Discovery date (mo/yr)</th>
<th>Producing wells (Total Jan. 1, 1977)</th>
<th>Production $^a$ (Annual 1976)</th>
<th>Production $^a$ (Cumulative Jan. 1, 1977)</th>
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<tr>
<td>Bell Creek B</td>
<td>6/67</td>
<td>196 180</td>
<td>8.75</td>
<td>86.3</td>
</tr>
<tr>
<td>Hilight R</td>
<td>2/69</td>
<td>195 176</td>
<td>3.82</td>
<td>57.6</td>
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<tr>
<td>Recluse R</td>
<td>8/67</td>
<td>58 46</td>
<td>8.38</td>
<td>20.8</td>
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<tr>
<td>Gas Draw</td>
<td>8/68</td>
<td>83 47</td>
<td>1.8</td>
<td>19.7</td>
</tr>
<tr>
<td>Rozet</td>
<td>4/59</td>
<td>28 28</td>
<td>0.70</td>
<td>15.7</td>
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<tr>
<td>Kitty</td>
<td>8/65</td>
<td>175 161</td>
<td>0.50</td>
<td>15.1</td>
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<tr>
<td>Springen Ranch</td>
<td>11/68</td>
<td>43 28</td>
<td>0.70</td>
<td>8.9</td>
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<td>Collums</td>
<td>2/69</td>
<td>42 23</td>
<td>0.20</td>
<td>5.4</td>
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<td>Sandbar, East</td>
<td>1/68</td>
<td>24 12</td>
<td>0.10</td>
<td>4.2</td>
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<tr>
<td>Sandbar, West</td>
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<td>0.06</td>
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<td>L-X Bar</td>
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<td>0.6</td>
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</table>

Source: Data from International Oil Scouts Association, *Yearbook 1977.*

Production in million barrels of crude oil.

---

**Figure 7-27.** Thickness of Muddy sandstones at Bell Creek field, Montana, showing linear barrier-island sandstones partly overlapped in the center of the field. Regional dip is toward the northwest at 100 ft/mi (19 m/km). [Modified from Berg and Davies 1968.]
Sedimentary structures. The Muddy sandstone shows a sequence similar to that of the barrier island, and a typical section is shown in a core from the well Boekel 21-14, as follows:

<table>
<thead>
<tr>
<th>Unit</th>
<th>Thickness ft (m)</th>
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<tbody>
<tr>
<td>1. Eolian sandstone, very fine grained, massive.</td>
<td>5 (1.5)</td>
</tr>
<tr>
<td>2. Beach and upper-shoreface sandstone, fine grained,</td>
<td></td>
</tr>
<tr>
<td>laminated.</td>
<td>5 (1.5)</td>
</tr>
<tr>
<td>3. Middle-shoreface sandstone, fine grained, massive</td>
<td></td>
</tr>
<tr>
<td>or with discontinuous laminae.</td>
<td>10 (3)</td>
</tr>
<tr>
<td>4. Lower-shoreface mudstone, shaly, highly bioturbated.</td>
<td>3 (0.9)</td>
</tr>
<tr>
<td>Total</td>
<td>23 (7)</td>
</tr>
</tbody>
</table>

This sequence is identical to that of the modern barrier island at Galveston Island (Figure 7-4).

Figure 7-31  Correlation of electric logs from cored wells across Bell Creek field showing overlap of two barrier-island sandstones and adjoining lagoonal facies. No horizontal scale. *Cross-hatched intervals are shales which separate sandstones.*
Figure 7-29 Electric logs, texture, and composition of typical barrier-island and lagoonal sections, Bell Creek field. Location of wells shown in Figure 7-27. Sedimentary structures for these wells are shown in Figure 7-28.

Figure 7-31 Permeabilities, porosities, and fluid saturations in barrier-island and lagoonal sandstones, Bell Creek field. Texture and composition for the sections are illustrated in Figures 7-29 and 7-30. Note change in scales.
Figure 7-13 Structure on top of the Muddy Formation, northeastern Powder River basin, and location of Muddy stratigraphic oil fields. Contour interval 1000 ft (300 m). [Map drawn by L. D. Recker.] Map area shown in Figure 7-12.

Figure 7-14 Correlation of electric logs showing six zones within the Muddy Formation from Bell Creek field on the northeast to the vicinity of Recluse field on the southwest. Location of Bell Creek and Recluse fields given in Figure 7-12. No horizontal scale.
Figure 7-24  Gross thickness of sixth Muddy sandstones (A) and Fifth Muddy sandstones (B) at Recluse field. Contour interval 10 ft (3 m). Cores or samples were examined from circled and named wells. The north Recluse area is shown in Figure 7-25. [Maps and published with the permission of the Wyoming Geological Association.]

Figure 7-18  Electric logs, texture, and composition of the fifth and sixth Muddy sandstones in the ARCO Bow and Arrow 3 core. Location of well shown in Figure 7-25.
Figure 7-19 Electric logs, texture, and composition of the fourth and fifth Muddy sandstones, Apache State 1 well, Recluse field. Location of well shown in Figure 7-25.

Figure 7-21 Electric logs, texture, and composition of the third Muddy sandstone, Stuarco Federal 1 well, Recluse field. Location of well shown in Figure 7-25.
Note upward (structurally) increase in IPF oil, then water.

Figure 7-26 Cross sections AA’ and BB’ in the north part of Recluse field showing water recovery adjacent to oil production and an oil column greater than 100 ft (30 m). Location of cross sections shown in Figure 7-25. BOPD = bbls oil/day; BWPD = bbls water/day. [From Berg 1976a and published with the permission of the Wyoming Geological Association.]

CONCLUSIONS

- BARRIER ISLAND DEPOSITS ARE INTERNALLY COMPLEX

- INDIVIDUAL SANDSTONES MAY BE SEPARATED BY LAGOONAL SHALES WHICH CAN ISOLATE INDIVIDUAL SANDSTONES

- PORO./PERM. VALUES WILL VARY WITH FACIES AND GRAIN SIZE
APPLIED RESERVOIR CHARACTERIZATION FOR THE INDEPENDENT OPERATOR: WITH EMPHASIS ON COMPARTMENTALIZED RESERVOIRS AND ROUTINE TECHNIQUES FOR DETECTING COMPARTMENTS

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KEY REFERENCES TO INDIVIDUAL UNITS
DELTAIC DEPOSITS & RESERVOIRS

ENVIRONMENTAL SETTING OF CLASTIC STRATIGRAPHIC TRAPS
Figure 1. Elements of eustatic change. Maximum rates of rise and fall coincide with R- and F-inflection points. From Posamentier and others, 1988. Reprinted by permission of SEPM.
DELTA ENVIRONMENTS AND THEIR PROGRADATION WITH TIME
- Delta Plain
- Delta Front
- Prodelta
- River channels, marine influenced
- Channel Mouth Bars

RIVER, WAVE, AND TIDAL INFLUENCE ON DELTAS AND DELTA TYPES
- River Dominated (Miss. R. Delta type example)
  - Environments, deposits, and processes
  - Subsidence and delta switching
  - Vertical Sequence
- Wave Dominated (Nile Delta type example)
  - Environments, deposits, and processes
  - Vertical Sequence
- Tide Dominated
  - Environments, deposits, and processes
  - Vertical Sequence

DIFFERENTIATING DELTA TYPES IN THE STRATIGRAPHIC RECORD
RESERVOIR EXAMPLES

I. Deltaic Environments

Deltaic coasts have three principal gradational bathymetric zones and related facies. 1) the delta plain, comprised largely of fresh and brackish water muds, sands and peats; 2) the delta front, comprised of sands reflecting decreasing energy to the depth of effective wave base (EWB = 10-15m); and 3) the prodelta, comprised largely of mud with minor sand. Farther offshore, prodelta muds grade into shelf muds.
Delta Types - Shoreline Embayment

(Modified from Reading, 1996, Sedimentary Environments and Facies p. 117)
Fig. 7-11 Block diagram indicating geometric arrangement of bar-finger sand, fine-grained sediments, and topset marsh deposits of the modern Birdfoot delta of the Mississippi River. (After Fisk et al., 1954.)
Figure 3: Cross-sections of (A) the coastal plain progradation near the mouth of the Thames River, showing the natural development of the barrier island system. (B) The evolution of the coastal plain progradation near the mouth of the Thames River, showing the natural development of the barrier island system.
Figure 5.11: Conventional vertical profile through a channel mouth bar body. As in fluvial system profiles, sedimentary structures are illustrated schematically, grain size increases to the right on the average grain size plot, and the log profile is drawn to resemble either an S.P. or gamma-ray curve.
Tertiary subsurface deltaic reservoirs, south Texas (yellow)

Figure 20—Sequence B net-sandstone distribution resembling that of sequence A; dip-dominated trends in the Houston and Rio Grande embayments and strike-oriented pattern in the San Marcos arch. Highest values in the updip area reflect the main fluvial or distributary-channel axes; however, sequence B depocenters have prograded further seaward.
Delta Types - Shoreline Embayment

WAVE DOMINATED DELTAS

EXPOSED SHORE

WAVES

SHELTERED SHORE

WAVES

Delta Types - Shoreline Embayment

WAVE DOMINATED DELTA

Beach-barrier shoreline

Potential Reservoir sand

- Sandstone
- Siltstone
- Shale
- Scour surface with lag deposit
- Coal with roots
- Low angle crossbedding
- Herringbone crossbedding
- Trough, festoon crossbedding
- Ripple marks
- Shell, shell fragments
- Bioturbation, trace fossils

Delta marsh
Distributary channel
Delta marsh
Stacked beach ridges
Shoreface deposits
Pro-delta shale

meters

70
Nile Delta

Good potential reservoir

- Mudstone
- Sandstone
- Conglomerate
Delta Types - Shoreline Embayment

TIDE DOMINATED DELTA

Potential reservoir

sand

Delta marsh
Tidal channel deposits
Tidal flat
Tidal channel
Offshore tidal sand ridges

- Sandstone
- Siltstone
- Shale
- Scour surface with lag deposit
- Coal with roots
- Low angle crossbedding

Herringbone crossbedding
Trough, festoon crossbedding
Ripple marks
Shells, shell fragments
Bioturbation, trace fossils
Characteristics of tidal sand-ridge sandstones

<table>
<thead>
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<th>Feature</th>
<th>Description</th>
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<tr>
<td>Thickness:</td>
<td>Range 3-12 ft, average 6 ft.</td>
</tr>
<tr>
<td>Basal contact:</td>
<td>Transitional with marine shales.</td>
</tr>
<tr>
<td>Texture and Composition:</td>
<td></td>
</tr>
<tr>
<td>Grain size:</td>
<td>Upward-coursering from siltstone/very fine-grained sandstone at the base to upper fine-grained sandstone at the top.</td>
</tr>
<tr>
<td>Sorting:</td>
<td>Well to very well.</td>
</tr>
<tr>
<td>Clay interbeds:</td>
<td>Very common and gradually decreasing toward the top. Their relative content defines the upward-coursering, thickening trend.</td>
</tr>
<tr>
<td>Clay clasts and wood fragments:</td>
<td>Common in the upper half.</td>
</tr>
<tr>
<td>Shell clasts:</td>
<td>Mainly in the sandier levels of the upper part. Frequently in high concentrations at the top.</td>
</tr>
<tr>
<td>Sedimentary Structures:</td>
<td>Wavy lamination and ripples are dominant in the lower two thirds of the facies.</td>
</tr>
<tr>
<td></td>
<td>Small-scale trough cross-stratification is usually present in the upper one-third facies.</td>
</tr>
<tr>
<td>Burrows:</td>
<td>Most common within the lower half or at the very top of the facies. Frequently muddy sandstones are homogenized by bioturbation. Ophiomorpha traces are common in sand-rich levels.</td>
</tr>
</tbody>
</table>

TIDAL SAND-RIDGE AND PRODELTA/ SHELF FACIES

- SAND
- CLAY

- TIDAL SAND RIDGE
  - B
  - C
  - D

- PRODELTA SHELF FACIES
  - A
  - 10'
(Modified from Reading, 1986, Sedimentary Environments and Facies p. 117)
CONCLUSIONS

• DELTAS ARE COMPLEX SEDIMENT BODIES

• DIFFERENT DELTA TYPES HAVE DIFFERENT TYPES OF SAND BODIES WITH DIFFERENT TRENDS

• IT IS IMPORTANT TO UNDERSTAND WHICH DELTA TYPE YOUR RESERVOIR IS IN IF YOU WANT TO MAXIMIZE OR IMPROVE PRODUCTION AND RESERVOIR MANAGEMENT
APPLIED RESERVOIR CHARACTERIZATION FOR THE INDEPENDENT OPERATOR: WITH EMPHASIS ON COMPARTMENTALIZED RESERVOIRS AND ROUTINE TECHNIQUES FOR DETECTING COMPARTMENTS

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DEEPWATER (TURBIDITE) DEPOSITS & RESERVOIRS

Deepwater Discovered Reserves

Total Discovered
57 BBOE
37 BBOE + 120 TCF

>500m water
as of Sept. 2001

Recoverable Resources in BBOE
(yellow = oil, red = gas)
GEOLOGIC DEFINITION: Clastic sediments transported beyond the shelf edge into deep water by sediment gravity flow processes and deposited on the continental slope and in the basin. They are later buried and become part of a basin fill. Engineering and geologic “deep water” are usually the same.

SIX RESERVOIR TYPES

* Canyon (C)
* Channel (Ch)
*sheeted Channel (LC)
* Reservoirs we’ll look at today

Modified from Bouma (2000)
GEOLOGIC DEFINITION: Clastic sediments transported beyond the shelf edge into deep water by sediment gravity flow processes and deposited on the continental slope and in the basin. They are later buried and become part of a basin fill. Engineering and geologic 'deep water' are usually the same.

SIX RESERVOIR TYPES

* Reservoirs we'll look at today

Modified from Bouma (2000)
Figure 19—Stratal patterns in a type 1 sequence deposited in a basin with a shelf break.

A. Lowstand Fan

B. Early Lowstand Wedge
Channel-Levee Complex

Pramanik & Stueber, 1991
Figure 1. Elements of eustatic change. Maximum rates of rise and fall coincide with R- and F-inflection points. From Posamentier and others, 1988. Reprinted by permission of SEPM.
Figure 1. Elements of eustatic change. Maximum rates of rise and fall coincide with R- and F-inflection points. From Posamentier and others, 1988. Reprinted by permission of SEPM.

CHAINS

SHEETS
RESERVOIR PERFORMANCE ISSUES WITH DIFFERENT SANDSTONE TYPES

**Sheet Sandstones**
- Good reservoirs
- Good lateral continuity
- Good reservoir quality
- Sandstones separated by continuous shales; can give rise to compartments & multiple fluid contacts

**Channel Sandstones**
- Internally complex
- Unpredictable internal continuity & connectivity; can give rise to compartments & multiple fluid contacts

**Channel-Levee/Overbank Deposits**
- Thin-beded, low resistivity, low contrast 'pay'
- Continuity & connectivity are variable
- Pressure communication between channel & levees??
- Sometimes yes & sometimes no
- Sometimes sandstone-, and sometimes shale-filled channels
- Levee wedge reservoirs can be isolated from each other & from central channel-fill; gives rise to compartments & multiple fluid contacts
SHEET SANDSTONE EXAMPLES

• *S* Sand, *Auger Field; Gulf of Mexico* (Kendrick, 1998)
  - Since 1994, >200 MMBOE produced
  - layered/amalgamated sheet sands across basin
  - oil-bearing zones above water-bearing zones

• *450’ Sand, Garden Banks 236; Gulf of Mexico* (Fugitt et al., 2000)
  - Since 6/94, 93BCFG produced
  - layered/amalgamated sheet sandstones
  - shale intervals subdivide sandy intervals into different production zones
  - strong water drive

• *Martin, Viosca Knoll; Gulf of Mexico* (Clemenceau et al., 2000)
  - amalgamated sheet sandstones
  - limited vertical connectivity due to laterally continuous shales

• *Magnus; North Sea* (Leonard et al., 2000)
  - 1.28 BBOIP
  - Sandstones separated by 1-5m thick shale

• *Andrew Field; North Sea* (Leonard et al., 2000)
  - 292 MBOIP
  - Well performance strongly influenced by shales, which impact gas migration toward producing wells

• *Long Beach Unit; S. California* (Slott et al., 1993)
  - 3.88 BBOIP
  - Laterally continuous shales extend across fault blocks
CHANNEL-FILL SANDSTONE EXAMPLES

*N Sand, Ram Powell, Gulf of Mexico (Kendricks, 2000)
- Cumulative production is 12MMBE
- Variable thickness over short distances
- Numerous perched water levels
- Reservoir is composed of multiple, laterally offset stacked,
  lenticular channel-fill sandstones incised into
  slope shales

*8500' Sand, Garden Banks 236, Gulf of Mexico (Fugitt et al., 2000)
- 12BCFG produced through 4/98
- Good vertical connectivity, but lateral continuity of sand
  is variable
- Multiple shales, but shales are not laterally continuous
- Multiple perched water contacts
- Due to complexities, recovery efficiency would be less
  if the reservoir were oil-bearing

Jackfork Sandstone, Big Rock Quarry, Arkansas
Cut-and-fill structures. Most cuts are mud-lined
Levee Wedge      Slumped       Channel Thalweg
Channel margin  Margin

(Intra-canyon channel fill and adjacent (left) channel-margin slump)
Ram Powell ‘N’ Sand

(Kendrick, 2000)

Ram-Powell N Sand

(Kendrick, 2000)
8500' SAND, GARDEN BANKS

(Fugitt et al., 2000)
CHANNEL LEVEE/OVERBANK EXAMPLES

• Ram/Powell, L. Sand, Gulf of Mexico (Clemenceau et al., 2000)
  - 500MMBOESTOIP
  - Reservoir is thin-bedded levee/overbank facies
  - Single 2,500ft Horizontal well in proximal levee facies peaked at
    8.8MBOPD and 198MMCFGD
  - Good lateral continuity and pressure communication across entire
    4000 acre reservoir

• M4.1 Sand, Tahoe, Gulf of Mexico (Kendrick, 2000)
  - ~17MMBE gas and condensate
  - Differential pressure depletion and fluid contacts between
    west and east levees

• P Sand, Mahogany, Gulf of Mexico (Camp, 1998)
  - Peak production of 19,900BOPD and 31MMCFGD
  - Upper P sand forms two wedge shaped, thin-bedded units
    that thin away from a shale-filled channel
  - Better reservoir quality in proximal levee facies
(Shanley et al., 2000)

(Mayall et al., 2000)
3D SEISMIC HORIZON SLICE

Offshore Angola

(Provided by Kolla)

3D Seismic line, offshore Angola

Black = positive seismic reflection
Purple = negative seismic reflection

Kolla et al., 2001
Miocene Mt. Messenger Formation, Taranaki Basin, New Zealand: *Cliff is 250m high and several km long*
C = channel fill (upward dip decrease); P = proximal levee (high & variable angle dips); D = distal levee;
Distal levee bed sets (lower & uniform dip angles)

**Levee Facies**

Proximal levee: Higher net sand; thin bedded; cut-and-fill; mud-lined scours; climbing ripples; good connectivity; **high angle and variable dips of beds**.

Distal levee: Lower net sand; thin bedded; interbedded sand/silt; good continuity; **low angle and uniform dips of beds**.

Channel margins: Complex: slumps, discontinuities, mud-lined; variable fluid communication in leveed channel reservoirs.
Cretaceous Lewis Shale, Wyoming
“Bashful outcrops”

*S1 and S2 are continuous Lewis sheet sandstones
CC is Lewis leveed channel complex on Spine I
F is shallow marine Fox Hills

Spine I
(yellow line is app. 450m on ground; 120m of strat. section)

10 Channel-fill sandstones, each separated by shale/mudstone breaks: i.e. discontinuous reservoirs; not so easy to develop as sheet sandstone reservoirs !!
Laterally discontinuous channel-fill sandstone

Channel-fill #1 Sandstone
(150 m across in outcrop)

Thin-bedded, extra-channel or levee facies
3D Seismic line, offshore Angola

Black = positive seismic reflection
Purple = negative seismic reflection

Kolla et al., 2001
3D Seismic line, offshore Angola

Black = positive seismic reflection  Kolla et al., 2001
Purple = negative seismic reflection

3D Seismic line, offshore Angola

Black = positive seismic reflection  Kolla et al., 2001
Purple = negative seismic reflection
L Sand, Ram/Powell Field, Gulf of Mexico: comprises channel, proximal, & distal levee facies.

(Clemenceau et al., 2000)
Ram Powell 'L' Sand

(Clemenceau et al., 2000)
Ram Powell ‘L’ Sand

Inferred complex channel margin

Datum base of sand

Low resistivity gas pay

100 ft

(Clemenceau et al, 2000)
Drilling Strategy: Horizontal well in proximal levee, parallel to channel: “Well performance exceeded expectations with a peak flow rate of 105 mmcf/d and 9400 bopd.”

SUMMARY

• DEEP WATER (TURBIDITE) RESERVOIRS ARE COMPLEX

• THREE MAIN TYPES OF RESERVOIRS (ARCHITECTURAL ELEMENTS):
  - SHEETS
  - CHANNEL-FILL
  - LEVEE/OVERBANK

• MULTIPLE FLUID CONTACTS AND COMPLEX PRESSURE REGIMES FOR EACH TYPE, BUT DIFFERENT REASONS FOR MULTIPLE CONTACTS & PRESSURES

• THEREFORE IT IS IMPORTANT TO UNDERSTAND THE ARCHITECTURE OF THE SPECIFIC RESERVOIR OF INTEREST

• BECAUSE OF DIFFERENT PRODUCTION ISSUES WITH EACH TYPE:
  - WELL SPACING
  - HORIZONTAL, SLANT, OR VERTICAL WELL
  - WELL ORIENTATION
  - ANTICIPATED FLOW RATES

• OUTCROPS PROVIDE AN EXCELLENT MEANS OF IMPROVING UNDERSTANDING OF RESERVOIR ARCHITECTURE: GIVEN THE PROPER SCALES, OUTCROPS PROVIDE THE ONLY MEANS OF OBTAINING SUB-SEISMIC SCALE CONTINUITY & CONNECTIVITY INFORMATION
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APPLICATIONS OF BOREHOLE IMAGE LOGS

BOREHOLE IMAGE AND DIPMETER LOGS

- PROVIDES ELECTRICAL/ACOUSTIC IMAGE OF BOREHOLE WALL

- WATER-BASED OR SYNTHETIC MUDS REQUIRED
  OBMI Log (TM Schlumberger)
- FIRST USED TO OBSERVE FAULTS AND FRACTURES

- NOW USED FOR SEDIMENTARY/STRATIGRAPHIC INTERPRETATION; PROVIDES INFORMATION ON BEDDING AND STRATIFICATION STYLES, BED CONTINUITY AWAY FROM WELLBORE, ETC.

- DIPMETER DATA CAN BE USED FOR CORRELATION AND INTERPRETATION PURPOSES
Vertical resolution of various logging tools. Modified from Allen et al. (1988).

* = Trademark of Schlumberger

<table>
<thead>
<tr>
<th>Tool</th>
<th>Abbreviation</th>
<th>Intrinsinc Vertical Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formation MicroScanner</td>
<td>FMS*</td>
<td>0.2 in/5 mm</td>
</tr>
<tr>
<td>Formation Microimager</td>
<td>FMU*</td>
<td>0.2 in/5 mm</td>
</tr>
<tr>
<td>Strat. High Res. Dipmeter</td>
<td>SHDT*</td>
<td>0.4 in/10 mm</td>
</tr>
<tr>
<td>High Resolution Dipmeter</td>
<td>HDT*</td>
<td>0.5 in/13 mm</td>
</tr>
<tr>
<td>Microspherically Focused Log</td>
<td>MSFL*</td>
<td>2-3 in/5-7.6 cm</td>
</tr>
<tr>
<td>Medium Induction Log</td>
<td>ILM*</td>
<td>5-6 ft/1.5 m</td>
</tr>
<tr>
<td>Deep Induction Log</td>
<td>ILD*</td>
<td>7-8 ft/2 m</td>
</tr>
<tr>
<td>Spontaneous Potential</td>
<td>SP*</td>
<td>5 ft/1.5 m</td>
</tr>
<tr>
<td>Density Log</td>
<td>LDT*</td>
<td>15 in/38 cm</td>
</tr>
<tr>
<td>Photoelectric Log</td>
<td>PE*</td>
<td>2 in/5 cm</td>
</tr>
<tr>
<td>Neutron Log</td>
<td>CNL*</td>
<td>15 in/38 cm</td>
</tr>
<tr>
<td>Gamma Ray</td>
<td>GR*</td>
<td>8-12 in/20-31 cm</td>
</tr>
<tr>
<td>Sonic Log</td>
<td>BHC*</td>
<td>24 in/61 cm</td>
</tr>
</tbody>
</table>

Dip azimuth is trough of sinusoid

Dip Angle = tan⁻¹(h/d)

Planar feature intersecting a well bore and borehole imaging log of the feature
(modified from Zemansky et al. 1970)
Figure 3.17  Image of induced fractures in the Pilgrim Federal well. The dip of the induced fracture is more vertical compared with the natural fracture. Depth is in ft.
THIN BEDS

1 FT

(Slatt et al., 1994)

Thin bedded low-density turbidity current deposits.

(Slatt et al., 1994)
SHALE-FILLED DEPRESSION

Shale-filled depression (arrow) above sandstone beds.

(Slatt et al., 1994)

Shale-filled topographic depression interpreted as a slump scar on the upper surface of a sandstone bed. The shale has been reworked into the depression.

(Slatt et al., 1994)
(Slatt et al., 1994)

Jackfork Sandstone, DeGray Spillway, Arkansas
General borehole image characteristics of sheet sandstones

"Layered"

(Slatt et al., 1994)

General borehole image characteristics of channel-fill sandstones

"Chaotic"

(Slatt et al., 1994)
Sheet or channel-fill sandstone????
Sheet???

Channel-fill???
Cretaceous Lewis Shale, Wyoming
“Bashful outcrops”

S1 and S2 are continuous Lewis sheet sandstones
CC is Lewis leveed channel complex on Spine I
F is shallow marine Fox Hills
Cretaceous Lewis Shale, Wyoming

S1 and S2 are continuous Lewis sheet sandstones. CC is Lewis leveed channel complex on Spine I. F is shallow marine Fox Hills.

Sheet Sandstones: Laterally continuous for miles; i.e., good potential reservoir facies; individual sandstone intervals are separated by shales.

(Witton, 1999)
Cretaceous Lewis Shale, Wyoming

S1 and S2 are continuous Lewis sheet sandstones
CC is Lewis leveed channel complex on Spine I
F is shallow marine Fox Hills

Cretaceous Lewis Shale, Wyoming

S1 and S2 are continuous Lewis sheet sandstones
CC is Lewis leveed channel complex on Spine I
F is shallow marine Fox Hills
Laterally discontinuous channel-fill sandstone

Channel-fill #1
Sandstone
(150m across in outcrop)

Siltstone, conglomerate pebbles, turbidite

Interbedded turbidites and debris
DIFFERENTIATING SHEET FROM CHANNEL SANDSTONES
(Subseismic scale)

- PRESENCE OR ABSENCE OF COMMON SHALE RIP-UP CLASTS IN SANDSTONES
- SCOUR- vs. FLAT-BASED SANDSTONES
- INTERBEDDED DEBRITES AND TURBIDITES vs. TURBIDITES

- BOREHOLE IMAGE/CORE FEATURES
  - Above features:
  - Small scale continuities vs. discontinuities
  - Vertical bed thickness/orientation trends
    (Hurley techniques)

Behind-outcrop drilling for logs and core
Contorted beds (slump) readily seen on image log but only faintly visible on core

<table>
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<tr>
<th></th>
<th>Statically normalized</th>
<th>Core Photos</th>
<th>Dynamically normalized</th>
</tr>
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<td>3R1</td>
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<td></td>
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<tr>
<td>3R2</td>
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<tr>
<td>3R3</td>
<td></td>
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</tbody>
</table>

(Kuecher, 2000)

Rip-up clasts in small channel fill, Lewis Shale

<table>
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<tr>
<th></th>
<th>Statically normalized</th>
<th>Core Photos</th>
<th>Dynamically normalized</th>
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<td></td>
</tr>
<tr>
<td>085</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Kuecher, 2000)
Channel scour, debris flows, flame structures in the Lewis Shale

(Kuecher, 2000)

Depositional Event

Waning Flow/Suspension
Relatively Higher Energy Flow

fine-grained sandstone and siltstone
Sandstone

one depositional event

Static Image
Figure 3.9  Image of a scoured surface in the Iverson well. The underlying bed was truncated by the scoured surface. Depth is in ft.
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Miocene Mt. Messenger Formation, Taranaki Basin, New Zealand: *Cliff is 250m high and several km long*

PHOTOMOSAICS FROM HELICOPTER; WELLS; CORES; LOGS; HIGH-RESOLUTION SHALLOW SEISMIC; MEASURED SECTIONS
Depositional interval or bed scale
C = channel fill (upward dip decrease); P = proximal levee (high & variable angle dips); D = distal levee;
Distal levee bed sets (lower & uniform dip angles)

Bedding Style Model

North Well  Central Well

148 m

(Spang, 1998)
Behind-outcrop dipmeter logs (by Schlumberger)

(Channel fill)

Proximal levee

Distal levee/overbank

(Slatt et al., 1998)

LEVEE FACIES

Proximal levee: Higher net sand; thin bedded; cut-and-fill; mud-lined scours; climbing ripples; good connectivity; high angle and variable dips of beds.

Distal levee: Lower net sand; thin bedded; interbedded sand/silt; good continuity; low angle and uniform dips of beds.

Channel margins: Complex: slumps, discontinuities, mud-lined; variable fluid communication in leveed channel reservoirs.
L Sand, Ram/Powell Field, Gulf of Mexico: comprises channel, proximal, & distal levee facies.

(Clemenceau et al., 1995)
Ram Powell ‘L’ Sand

datum base of sand

(Clemenceau et al, 2000)

---

Inferred complex channel margin

(Clemenceau et al, 2000)
Ram Powell ‘L’ Sand

Inferred complex channel margin

low resistivity gas pay

datum base of sand

(Clemenceau et al., 2000)

(channel-levee "gull-wing" model)

datum base of sand

distal levee-overbank

(Clemenceau et al., 2000)
Drilling Strategy: Horizontal well in proximal levees, parallel to channel:
"Well performance exceeded expectations with a peak flow rate of 105 mcmcf/d and 9,600 bopd, 3 miles from well."
(Chenevert et al., 2000)
### CUMULATATIVE DIP MAGNITUDE AND DIRECTION CALCULATIONS

<table>
<thead>
<tr>
<th>Sample</th>
<th>Depth (ft.)</th>
<th>Dip (°)</th>
<th>Cum. Dip (°)</th>
<th>Dip Dir. (°)</th>
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<td>7</td>
<td>3797</td>
<td>5</td>
<td>29</td>
<td>230</td>
</tr>
</tbody>
</table>

![Graph](image.png)

- **Scour**
- **High angle cross bedding**
- **Slumps**

- **Dip Azimuth**
  - 0-90 degrees (blue diamonds)
  - 90-180 degrees (pink squares)
  - 180-270 degrees (green triangles)
  - 270-360 degrees (red crosses)

**Cumulative Bedding-Plane Dip (Deg)**

**Sample Number**
Figure 4.3  Vector plot for beds with gamma ray value > 80 API unit in the Dad and upper member of the Lewis Shale in the Pilgrim Federal well. The beds are dipping to the west-northwest. Infillation points are shown. Depth is in ft.
### MODIFIED FISCHER PLOT

<table>
<thead>
<tr>
<th>Cycle No.</th>
<th>Top Thick (ft.)</th>
<th>Thick from MCT (ft.)</th>
<th>Depart. from MCT</th>
<th>Dim. Depart. from MCT</th>
<th>Cum. Dim Depart. from MCT</th>
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<td>-0.64</td>
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<td>258</td>
<td>14046</td>
<td>1.12</td>
<td>0.45</td>
<td>0.67</td>
<td>0.67</td>
</tr>
</tbody>
</table>

- Mean Cycle Thickness (MCT) for this sequence = 0.67 ft.
- Dimensionless Departure from MCT = Depart./MCT
- Cum. Dimensionless Depart from MCT starts at bottom of sequence

---

### Two wells--5 miles apart...

[Graph showing cycle number and interval correlation]

Cumulative Dimensionless Departure from Mean Cycle Thickness
BOREHOLE IMAGE AND DIPMETER LOGS

- PROVIDES ELECTRICAL/AcouSTIC IMAGE OF BOREHOLE WALL

- WATER-BASED OR SYNTHETIC MUDS REQUIRED 
  OBMI Log (™ Schlumberger)
- FIRST USED TO OBSERVE FAULTS AND FRACTURES

- NOW USED FOR SEDIMENTARY/STRATIGRAPHIC INTERPRETATION; PROVIDES INFORMATION ON BEDDING AND STRATIFICATION STYLES, BED CONTINUITY AWAY FROM WELLBORE, ETC.

- DIPMETER DATA CAN BE USED FOR CORRELATION AND INTERPRETATION PURPOSES
APPLIED RESERVOIR CHARACTERIZATION FOR THE INDEPENDENT OPERATOR: WITH EMPHASIS ON COMPARTMENTALIZED RESERVOIRS AND ROUTINE TECHNIQUES FOR DETECTING COMPARTMENTS

UNIT 1: INTRODUCTION TO RESERVOIR CHARACTERIZATION
UNIT 2: EXAMPLES OF COMPARTMENTALIZED RESERVOIRS
UNIT 3: GEOLOGIC CONTROLS ON POROSITY AND PERMEABILITY
UNIT 3A: SEISMIC POROSITY DETECTION IN A CARBONATE RESERVOIR
UNIT 4: FLOW UNIT DETERMINATION & CHARACTERIZATION
UNIT 5: BASICS OF SEQUENCE STRATIGRAPHY
UNIT 6: FLUVIAL DEPOSITS AND RESERVOIRS
UNIT 7: EOLIAN DEPOSITS AND RESERVOIRS
UNIT 8: SHOREFACE DEPOSITS AND RESERVOIRS
UNIT 9: DELTAIC DEPOSITS AND RESERVOIRS
UNIT 10: DEEP-WATER (TURBIDITE) DEPOSITS AND RESERVOIRS
UNIT 11: BOREHOLE IMAGE LOGS AND APPLICATIONS
UNIT 12: DIPMETER LOGS AND APPLICATIONS

*UNIT 13: STRUCTURALLY COMPARTMENTALIZED RESERVOIRS

KEY REFERENCES TO INDIVIDUAL UNITS
STRUCTURAL COMPARTMENTALIZATION

- ROCKY MOUNTAIN EXAMPLES

- MORE COMMON THAN PREVIOUSLY THOUGHT
CRETACEOUS FORMATIONS, DENVER BASIN, COLORADO
After Dutro and Weaver, 1982.
Basement fault map interpreted from a regional grid of seismic control. Substantially more seismic data than just the 3 lines shown in this figure were used to delineate the fault zones. Faults were inferred by observing subtle drone, elastic normal faults, lack of reflection continuity near basement, dikes, etc.

(Davis, 1985)
523: Normalized GOR values (cf/bbl) based on first year of production

Interpreted line for GOR = 15,000 cf/bbl

Fault
Faults Viewed from South

Structural Contours on D2
SGR = \frac{\text{Sum} \left( \text{(Zone Thickness)} \times \text{(Zone Clay Fraction)} \right)}{\text{Fault Throw}} \times 100

Note: \( \times 100 \) is a modification, generating whole numbers.
**SHALE GOUGE RATIO CALCULATION FOR TERRY SANDSTONE**

Two wells in Sec. 20

<table>
<thead>
<tr>
<th>Well</th>
<th>GOR</th>
<th>Spud Date</th>
<th>Distance Apart</th>
</tr>
</thead>
<tbody>
<tr>
<td>12519</td>
<td>104.500</td>
<td>11/88</td>
<td>app. 1300 ft. (420 m)</td>
</tr>
<tr>
<td>14079</td>
<td>20.0</td>
<td>12/88</td>
<td></td>
</tr>
</tbody>
</table>

Assume 15% clay in the Terry Sandstone

Assume 150 ft. thickness of Terry Sandstone

**Shale Gouge Ratio** = \((150 \text{ ft.})(15) / (433 - 380)\) = 42

Assume SGR = 25 for fault gouge to occur, therefore there is **gouge present**.
CONCLUSIONS

- FAULTS MAY BE SEALING IF FILLED WITH CEMENT AND/OR GOUGE
- GOR'S MAY BE USEFUL FOR DETECTING SEALING FAULTS IN THE ABSENCE OF PRESSURE DATA
- FAULTS MAY BE BENEATH SEISMIC RESOLUTION
- TO DETECT SUB-SEISMIC SCALE FAULTS REQUIRES DETAILED MAPPING
- SMALL COMPARTMENTS MAY BE UNTAPPED; CLOSELY SPACED WELLS MAY BE PRODUCTIVE
KEY REFERENCES TO FIGURES AND DISCUSSION

Key References for Unit 1: Introduction


Key References for Unit 2: Examples of compartmentalized reservoirs


**Key References for Unit 3: Porosity and Permeability**


**Key References for Unit 3a: Carbonates and seismic**

Key References for Unit 4: Flow units


Reservoirs, Examples and Analogs, Springer-Verlag, N.Y., p. 263-292


**Key References for Unit 5: Basics of sequence stratigraphy**


**Key references for Unit 6: Incised valley fill reservoirs**


**Tillman, R.W. and Pittman, E.D.,** 1993, Reservoir heterogeneity in valley-fill


Key References for Unit 8: Shoreface sequence stratigraphy


VanWagoner, J.C. and Bertram, G.T., 1995, Sequence stratigraphy of foreland
basin deposits, Amer. Assoc. Petrol. Geol. Mem. 64, 490p.)

Key References for Unit 10: Deep-water Deposits


Key References for Units 11/12: Borehole Image logs


Key References for Unit 13: Structure


Davis, T.L., 1985, Seismic evidence of tectonic influence on development of Cretaceous


**Key References for Unit 14: Geologic modeling**


Fugitt, D.S., C.E. Stelting, W.J. Schweller, G.J. Herricks, and M.R. Wise, 2000, Production characteristics of sheet and channelized turbidite reservoirs, Garden Banks 191, Gulf of Mexico, U.S.A., in Weimer, P. R. Slatt, J. Coleman,