APPLIED GEOLOGY FOR THE PETROLEUM ENGINEER

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Norman, Oklahoma
One day PTTC course on characterization of sandstone reservoirs, with emphasis on compartmentalization and its effects on reservoir performance

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-Scales of reservoir characterization and classification
-Fluvial reservoirs
-Eolian reservoirs
-Structural compartmentalization
-Shoreface reservoirs
-Barrier Island reservoirs
-Deltaic reservoirs
-Deepwater reservoirs
Reservoir
Perception.

Architectural elements” of a reservoir
Reality.

(Modified from OIPA, October, 2001)
Phases of a Typical Oil Field Life Cycle

- Mapping & reconnaissance
- Acquire/divest
- Prospect generation
- Enhanced recovery
- Discovery
- Primary production
- Reservoir delineation
- Facilities

(Modified from Oil and Gas Journal)
"I thought
I knew this field . . .

. . . but even with a 3D survey,
the reservoir pressure isn’t what
I expected.

What happened to the
injected gas?"

(WesternGeco ad, July, 2002, AAPG Explorer)
Reservoir performance is governed by features that are often beneath seismic resolution or detection (‘sub-seismic scale’).
Geology vs. Seismic Resolution

Buyl, M., et al., 1988

Typical Seismic Resolution Limit for GoM data sets
Tools for reservoir characterization

- Conventional logs
- Conceptual model
- Seismic reflection
- Outcrops
- Cores & borehole image logs
- Computer 3D geologic models
WATERFLOOD

INJECTION WELL

PRODUCTION WELL

Water

INJECTION

PRODUCTION (?)

The "Real World"
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
Scales of geological heterogeneity of sandstone reservoirs:

What the geophysicists (and reservoir engineers) need to know!!

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Geologic features of sandstone reservoirs which control reservoir performance

- Size
- Geometry (shape)
- Architecture (internal makeup)
- Bed dimensions, continuity, & connectivity
- Structural attributes (faults, fractures, folds)
- Grain size and composition
- Porosity, permeability, and capillarity
- Burial depth and history
- Drive mechanism
“Three geophysical components:
- Source
- Medium
- Receiver”

Geologic Reservoir Characterization:

Levels of:
1 (big)
heterogeneity
2
3
4
5
6
7 (small)

Quote from: Evgeni Chesnokov
Level 1: My reservoir is made of:

Sandstone:

Carbonate:

Shale (fractured):

Etc:
Level 2: *My sandstone reservoir is made of:*

- Continental deposits:
- Mixed deposits:
- Marine deposits:

*Environmental setting of clastic stratigraphic traps*

(Brown, 1972)
Level 3: My continental **sandstone reservoir** is made of:

- Fluvial deposits
- Eolian deposits
- Lacustrine deposits

**ENVIRONMENTAL SETTING OF CLASTIC STRATIGRAPHIC TRAPS**

Alluvial fan deposits

*(BROWN, 1972)*
Level 4: My continental, fluvial sandstone reservoir is made of:

- Meandering River deposits
- Incised Valley Fill deposits
- Braided River deposits
Level 5: My continental, fluvial, meandering river sandstone reservoir is made of:

Meandering River
Overbank (floodplain)

Vertical stratigraphy

Cross bedded sand

Mud plug
Point bar
Cutbank

3D architecture
Level 6: Reservoir Quality: Porosity & Permeability

Permeability varies with sediment grain size (even after cementation)

MEANDERING RIVER FACIES MODEL

Remaining oil saturation after watermark within a sandstone body varies with grain size, and thus, permeability.

Gamma or SP log

Regression

Transgressive

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

Remaining oil saturation after waterflood
Level 7: Structure

**Feature** | **Seismic** | **Sub-seismic**

**Fault**

**Fold**

**Diapir**

**Fracture**

See next images
"Three geophysical components:
-Source
-Medium
-Receiver"

Geologic Reservoir Characterization:
Levels of heterogeneity: 1 2 3 4 5 6 7

Communications
Person – Person

These are the important levels for reservoir development

Quote from: Evgeni Chesn
ENVIRONMENTAL SETTING OF CLASTIC STRATIGRAPHIC TRAPS

(BROWN, 1972)
Level 2: My sandstone reservoir is made of:

- Continental deposits:
- Mixed deposits:
- Marine deposits:

ENVIRONMENTAL SETTING OF CLASTIC STRATIGRAPHIC TRAPS

(BROWN, 1972)
Level 3: My continental sandstone reservoir is made of:

- Fluvial deposits
- Eolian deposits
- Lacustrine deposits

Alluvial fan deposits

Environmental setting of clastic stratigraphic traps

(Brown, 1972)
Level 4: My **continental, fluvial sandstone reservoir** is made of:

- **Meandering River deposits**
- **Incised Valley Fill deposits**
- **Braided River deposits**
Level 5: My continental, fluvial, meandering river sandstone reservoir is made of:

- Meandering River
- Overbank (floodplain)
- Mud plug
- Point bar
- Cutbank

Cross bedded sand

Vertical stratigraphy

3D architecture
Meander bend in river, showing ripples and cutbank and point bar

(LeBlanc, 1972)
Level 6: Reservoir Quality: Porosity & Permeability

Permeability varies with sediment grain size (even after cementation)

MEANDERING RIVER FACIES MODEL

Gammaray/SP log response

Increasing mud content

DECREASING GRAIN SIZE

Low K

High K

METERS

INCREASING GRAIN SIZE

GAMMA RAY/SP LOG RESPONSE

LITHOLOGIC VERTICAL SEQUENCE

ORIGIN

CHANNEL FLOOR

BASAL SCOUR

OVERBANK MUDS

POINT BAR TOP

POINT BAR

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

Remaining oil saturation after waterflood within a sandstone body varies with grain size, and thus, permeability.
Level 4: My continental, fluvial sandstone reservoir is made of:

- Meandering River deposits
- Incised Valley Fill deposits
- Braided River deposits
Braided river deposit
Gross thickness

Net Sand
Porosity and permeability vary with grain size and depositional environment.
<table>
<thead>
<tr>
<th>ENVIRONMENT TYPE</th>
<th>PREDOMINANT LITHOLOGY</th>
<th>GRAIN SIZE TREND</th>
<th>SORTING TREND</th>
<th>PERMEABILITY TREND</th>
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<tbody>
<tr>
<td>MID-BRAIDED STREAM</td>
<td>SANDY CONGLOMERATE CONGLOMERATIC SS</td>
<td>DECREASE</td>
<td>DECREASE</td>
<td>LOW</td>
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<tr>
<td>DISTAL BRAIDED STREAM</td>
<td>MEDIUM-GRAINED SANDSTONE</td>
<td></td>
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<td>HIGH</td>
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<tr>
<td>DELTA FRONT</td>
<td>FINE- TO VERY FINE-GRAINED SS</td>
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</table>

Illustration: Diagram of a braided fluvial system with proximal, mid, and distal sections, showing marine shales and floodplain shales.
Conglomerate is reservoir. Some conglomerates are good reservoir, but others are not!!! Why???
Location of Glenn Pool Field

Production History of the Self Unit Glenn Pool Field, Oklahoma
Note changes in production as new Recovery techniques are begun in field
<table>
<thead>
<tr>
<th>Gamma Ray (API)</th>
<th>Depth (ft)</th>
<th>SFL Resistivity (ohm m)</th>
<th>Stratigraphic Units</th>
<th>Oil Staining</th>
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<td>0.2</td>
<td>Inola marker</td>
<td>dead oil</td>
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<td>1450</td>
<td>20</td>
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<td></td>
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<td>DGI C</td>
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<td>DGI D</td>
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<td>DGI E</td>
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<td>DGI F</td>
<td></td>
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<tr>
<td></td>
<td>1600</td>
<td></td>
<td>Brown lime marker</td>
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</table>

Uplands Resources WB Sell 82 (API #35-037-2844.)
Sec. 21, T17N, R12E (G.L. 728 ft)
Core: 1420 to 1575 ft in 3 runs; rec. 153 ft; lost 2 ft from bottom
Other logs include: SP, ILM, ILD, FMI, Density, Neutron, Sonic.

- **flood-plain mudstone**
- **meandering channel fill**
- **splay**
- **braided channel fill**
Braided River Sandstone

Meandering River Sandstone

Structural cross section. Note that 'updip' is to the northeast. Oil will migrate in the updip direction, and be more abundant there.
Meandering River sandstones are laterally discontinuous with interlayered mudstone, and highly compartmented.

Braided River sandstones are laterally continuous without much mudstone, and are not highly compartmented.
INCISED VALLEY FILL RESERVOIRS

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

- VALLEY IS FILLED DURING TURNDOWN 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
Incised valley and its partial fill

(WEIMER, 1994)
Valley carved (incised) into shelf strata (often mudstones) during drop in sea level.

Valley begins to fill with fluvial (lag) gravels and associated deposits during turnaround and early rise in sea level. Later fill may become estuarine.

Idealized incised valley fill: incision during falling stage, fluvial during turnaround and early rise, and estuarine with later rise. Marine muds cap the sequence when the valley is filled.

Tillman and Pittman (1994)
Location of 20-mile-long "Stateline Trend" Morrow Sandstone fields, which produce from valley-fill sandstone reservoirs. Southwest Stockholm field, Kansas, is located in Greeley and Wallace counties, Kansas. (Tillman and Pittman, 1993)

Base map, outlining borders of Southwest Stockholm field, Kansas. Location of stratigraphic cross sections X-X', Y-Y' and W-W' is indicated. Cored wells described in this study are indicated by circles. Type log well (Fig. 5) is indicated by a triangle. A list of all numbered wells on this map is available from the senior author. (Tillman and Pittman, 1993)
TYPE LOG
Texas Oil and Gas 4 Evans E, NW NE SE 11-16s-43w

System | Series | Formation/subsurface name | SP 35-155 | Depth ft | Resistivity, ohm m | Lithology
--- | --- | --- | --- | --- | --- | ---
Mississippian | Manatarian | Sra. Garazmje b | - | - | - | -

Pennsylvanian

Adakian

- Lennow sh
- Aoksa ls

- 5,000
- 5,100
- 5,200
- 5,300

Tilman and Pittman (1994)
### TABLE III

PETROPHYSICAL PARAMETERS FOR RESERVOIR FACIES
SOUTHWEST STOCKHOLM FIELD

<table>
<thead>
<tr>
<th></th>
<th>K (md)</th>
<th>Ø (%)</th>
<th>K/Ø</th>
<th>R&lt;sub&gt;35&lt;/sub&gt; (microns)</th>
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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><strong>Tidal Sandstones</strong></td>
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<tr>
<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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</table>
Sandstone Thickness - GR < 75

Sorrento Field
3-D, 3-C Seismic Survey

Static Pressure Test Results

Mark, 1995
#7 McCormick
Sec 33 T13S / R49W

<table>
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<tr>
<th>Gamma ray</th>
<th>Depth ft</th>
<th>Neutron</th>
<th>Density</th>
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<td>1.95</td>
<td>2.95</td>
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</tbody>
</table>

#7 McCormick Log Display

- **Computed lithology**
  - Gamma ray
  - Neutron
  - Density
  - Profile permeability

- **Facies**
  - Marine shale
  - Reworked sandstone (clay matrix)
  - Channel sandstone (with cemented zones)
  - Lower shoreface siltstone

- **Log scale**
  - 1
  - 1000
Incised Valley Topography and Valley Fill Facies

3000 Feet

Mark, 1995
EOLIAN DEPOSITS & RESERVOIRS
Level 3: My continental sandstone reservoir is made of:

- Fluvial deposits
- Eolian deposits
- Lacustrine deposits

Alluvial fan deposits

Environmental setting of clastic stratigraphic traps

(Brown, 1972)
Dust storms
Inland sand sea
Coastal dune fields
WEBER SANDSTONE,
RANGELY FIELD, CO.
Pickerill Field, North Sea produces from Rotliegendes Sandstone (Permian)
Dipmeter logs applied to eolian reservoirs
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.
Bighorn Basin
Tensleep Sandstone

- Eolian Sandstones
- Marine Sandstones
- Carbonates
- Mudstones

Goose Egg Formation
Upper Tensleep
Lower Tensleep
Ranchester Limestone

Wheeler, 1986
Bounding Surfaces in the Tensleep
GPS (Global Positioning System)
Field Work
Accuracy Control
<table>
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<tr>
<th>Feature</th>
<th>Seismic</th>
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<td>Fault</td>
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<td>Fold</td>
<td><img src="image3" alt="Fold Image" /></td>
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<tr>
<td>Diapir</td>
<td><img src="image5" alt="Diapir Image" /></td>
<td><img src="image6" alt="Sub-seismic Diapir Image" /></td>
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<tr>
<td>Fracture</td>
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Pickerill Field, North Sea produces from Rotliegendes Sandstone (Permian)
### Well #1 RFT RESULTS

<table>
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<tr>
<th>MDRKB (FT)</th>
<th>TVDSS (FT)</th>
<th>HYDROSTATIC PRESSURE (PSIA)</th>
<th>FORMATION PRESSURE (PSIA)</th>
<th>REMARKS</th>
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<td>8596</td>
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<td>3983.2</td>
<td>Good Test</td>
</tr>
<tr>
<td>8745</td>
<td>8620</td>
<td>4565.8</td>
<td>3984.2</td>
<td>Good Test</td>
</tr>
<tr>
<td>8760</td>
<td>--</td>
<td>4572.2</td>
<td>--</td>
<td>Tight</td>
</tr>
<tr>
<td>8764</td>
<td>--</td>
<td>4550.2</td>
<td>--</td>
<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; different depth vs. pressure trends on opposite sides of fault zone.
Small faults can compartmentalize a reservoir
Shale Gouge Ratio (SGR)

$$SGR = \frac{\sum (\text{Zone Thickness}) \times (\text{Clay Fraction})}{\text{Fault Throw}} \times 100$$

Note: "x 100" is a modification, generating whole numbers.

Codell Shale Gouge Ratio vs. Fault Throw (ft)

SGR = Sum [(Zone Thickness) X (Clay Fraction)] X 100
Fault Throw
Pre Drill
Post Drill, Pre FMS log
Post Drill, post FMS log
CRETACEOUS FORMATIONS, DENVER BASIN, COLORADO
(after Porter and Weimer, 1982)
Pre-seismic map based on well control
Post-seismic map with well control
Gas or oil at same structural elevations in different wells

Green = oil

Pink = gas
523: Normalized GOR values (cf/bbl) based on first year of production
Interpretation line for GOR = 15,000cf/bbl
Fault

Numbers are normalized GOR's
Structure cross section

Faults Viewed from South

Hambert-Aristocrat Field, Colorado
Faults Viewed from South

Structural Contours on D2
STRUCTURE CROSS-SECTION ON D2 BENTONITE
Each fault is a seal, so that each fault block is a reservoir compartment!

Seismic horizon slice

Structure cross section

GOR = 100,000

GOR = 2,000
**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. 13 00ft. (420 m)</td>
</tr>
<tr>
<td>14079</td>
<td>200</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** = \( \frac{150 \text{ ft.} \times 15}{433 - 380} \) = 42

Assume SGR = 25 for fault gouge to occur, therefore there is gouge present.
Simulation matched production for a number of wells, indicating the faults are sealing.
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.
SHOREFACE
DEPOSITS & RESERVOIRS
Hambert-Aristocrat Field, Colorado

Hambert Field

Aristocrat Field

CRETACEOUS FORMATIONS, DENVER BASIN, COLORADO

(after Porter and Weinan, 1982)
Level 5, 6, & 7: My mixed, shoreface sandstone reservoir is highly faulted:

(Environmental Setting of Clastic Stratigraphic Traps)

Hambert Field
Aristocrat Field
Hambert-Aristocrat Field, Colorado
Figure 3.10: The offshore to coastal plain cross sections, and distribution of the facies relative to seaward wave base. Note the distribution of the Cruises and Skelettina facies relative to the coastal zone of the Western interior the way of North America. A) The Cruises/Skelettina facies comprises: 1) Cruisesa, 2) Cruisesb, 3) Plainlandia, 4) Skelettinaa, 5) Skelettinab, 6) Skelettinac. B) Offshore, Middle, Upper, and Backshore. The vein features marked with asterisks are not represented in the offshore. 2. The offshore facies are: 1) Cruises facies, 2) Skelettina facies, 3) Plainlandia facies, 4) Jonassiana facies. The offshore facies are: 1) Cruises facies, 2) Skelettina facies, 3) Plainlandia facies, 4) Jonassiana facies (H.W. - High Water, M.L.W. - Mean Low Water, M.W.B. - Mean Water Base). (Modified from Pritchard et al., 1997).
Figure 1. This figure (based on figure 1, p. 64, in Vail et al., 1977) illustrates the original relationship between cycle and paracycle, as defined by Vail, Mitchum, and Thompson. According to the original figure, "cycles consist of relative rises and falls of sea level, commonly containing several paracycles, which are smaller scale pulses of relative rises to stillstands" (Vail et al., 1977, p. 64). Cycles deposit sequences (Vail et al., 1977), paracycles deposit parasequences (Van Wagoner, 1985). (Kamola, P. Van Wagoner, 1995)
Seaward to right

Figure 1. This figure (based on figure 1, p. 64, in Vail et al., 1977) illustrates the original relationship between cycle and paracycle, as defined by Vail, Mitchum, and Thompson. According to the original figure, "cycles consist of relative rises and falls of sea level, commonly containing several paracycles, which are smaller scale pulses of relative rises to stillstands" (Vail et al., 1977, p. 64). Cycles deposit sequences (Vail et al., 1977), paracycles deposit parasequences (Van Wagoner et al., 1985). (Kamola, P. Van Wagoner, 1995)

Seaward progradation during relative stillstand of sea level (Van Wagoner et al., 1990)
Vertical sequence indicates progradation followed by rapid deepening (transgression) of water.

**Offshore shelf**

**Upper shoreface**

**Lower shoreface**

**Offshore shelf**

---

*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

Figure 4—Progressive development of a parasequence boundary.
Four cycles to give four parasequences

Figure 10—Parasequence-stacking patterns in parasequence sets; cross-section and well-log expression.
STRATIGRAPHIC CROSS SECTION
TERRY SANDSTONE

Parasequence G
SHOREFACE RESERVOIRS

• HAMBERT FIELD EXAMPLE FORMED DURING OVERALL PERIOD OF MARINE TRANSGRESSION

• INDIVIDUAL SANDSTONES DEVELOPED DURING PERIODS OF RELATIVE STILLSTAND OF SEA (BASE) LEVEL WHEN SEDIMENT SUPPLY EXCEEDED SEA (BASE)LEVEL RISE. RESULTED IN PROGRADATION.

• END RESULT IS A SERIES OF SHOREFACE SANDSTONES SEPARATED BY LATERALLY CONTINUOUS SHALES; i.e. COMPLEXELY COMPARTMENTALIZED RESERVOIR
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
BARRIER
ISLAND DEPOSITS & RESERVOIRS
Figure 9.14
Subenvironments in a barrier-island system. (From Walker, 1984.)
Figure 9.14
Subenvironments in a barrier-island system. (From Walter, 1984.)

Flood tidal delta
Figure 9.14
Subenvironments in a barrier island system. (From Nather, 1984.)

**Ebb tidal delta**

**Lagoon**

**Ocean**
Washover Sand

Beach Sand
<table>
<thead>
<tr>
<th>Name</th>
<th>Discovery date (mo/yr)</th>
<th>Producing wells (Total Jan. 1, 1977)</th>
<th>Production&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Production&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Annual 1976)</td>
<td>(Cumulative Jan. 1, 1977)</td>
</tr>
<tr>
<td>Bell Creek</td>
<td>6/67</td>
<td>196</td>
<td>8.75</td>
<td>86.3</td>
</tr>
<tr>
<td>Hilight</td>
<td>2/69</td>
<td>195</td>
<td>3.82</td>
<td>57.6</td>
</tr>
<tr>
<td>Recluse</td>
<td>8/67</td>
<td>58</td>
<td>8.38</td>
<td>20.8</td>
</tr>
<tr>
<td>Gas Draw</td>
<td>8/68</td>
<td>83</td>
<td>1.8</td>
<td>19.7</td>
</tr>
<tr>
<td>Rozet</td>
<td>4/59</td>
<td>28</td>
<td>0.70</td>
<td>15.7</td>
</tr>
<tr>
<td>Kitty</td>
<td>8/65</td>
<td>175</td>
<td>0.50</td>
<td>15.1</td>
</tr>
<tr>
<td>Springen Ranch</td>
<td>11/68</td>
<td>43</td>
<td>0.70</td>
<td>8.9</td>
</tr>
<tr>
<td>Collums</td>
<td>2/69</td>
<td>42</td>
<td>0.20</td>
<td>5.4</td>
</tr>
<tr>
<td>Sandbar, East</td>
<td>1/68</td>
<td>24</td>
<td>0.10</td>
<td>4.2</td>
</tr>
<tr>
<td>Sandbar, West</td>
<td>2/68</td>
<td>16</td>
<td>0.06</td>
<td>3.3</td>
</tr>
<tr>
<td>Rozet East</td>
<td>6/61</td>
<td>8</td>
<td>0.16</td>
<td>1.7</td>
</tr>
<tr>
<td>Mill</td>
<td>3/69</td>
<td>22</td>
<td>0.01</td>
<td>1.5</td>
</tr>
<tr>
<td>Gillette</td>
<td>10/62</td>
<td>11</td>
<td>0</td>
<td>1.3</td>
</tr>
<tr>
<td>Recluse SE</td>
<td>12/68</td>
<td>5</td>
<td>0.02</td>
<td>0.4</td>
</tr>
<tr>
<td>L-X Bar</td>
<td>2/73</td>
<td>7</td>
<td>0.10</td>
<td>0.6</td>
</tr>
</tbody>
</table>

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

*Production in million barrels of crude oil.*
**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>
</tr>
</thead>
<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, laminated.</td>
<td>5 (1.5)</td>
</tr>
<tr>
<td>3. Middle-shoreface sandstone, fine grained, massive 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><strong>Total</strong></td>
<td><strong>23 (7)</strong></td>
</tr>
</tbody>
</table>

This sequence is identical to that of the modern barrier island at Galveston Island (Figure 7-4).
Typical logs for different facies; Bell Creek Field
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 from Berg 1976a and published with the permission of the Wyoming Geological Association.]
Recluse Field
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
DELTAIC DEPOSITS & RESERVOIRS
FLUVIAL PROCESSES AND SEDIMENT INFLUX

CUSPATE

STRANDPLAIN  WAVE-DOMINATED (High-destructive)

LOBATE

RIVER-DOMINATED (High-constructive)

Elongate

Marine Processes (Waves and Longshore Currents)

Arrows point in direction of increasing influence

(after Scott, 1969; Fisher et al, 1969)
FLUVIAL PROCESSES AND SEDIMENT INFLUX

CUSPATE

STRANDPLAIN

WAVE-DOMINATED

HIGHER Destructive)

LOBATE

RIVER-DOMINATED

(High-constructive)

ELONGATE

MARINE PROCESSES (WAVES AND LONGSHORE CURRENTS)

Arrows point in direction of increasing influence

(after Scott, 1969; Fisher et al. 1969)

Mississippi River delta

Nile River delta
River dominated deltas

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.
<table>
<thead>
<tr>
<th>Environment Type</th>
<th>Predominant Lithology</th>
<th>Grain Size Trend</th>
<th>Sorting Trend</th>
<th>Permeability Trend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-Braided Stream</td>
<td>Sandy Conglomerate Conglomeratic SS</td>
<td>Decrease</td>
<td>Decrease</td>
<td>Low</td>
</tr>
<tr>
<td>Distal Braided Stream</td>
<td>Medium-Grained Sandstone</td>
<td></td>
<td></td>
<td>High</td>
</tr>
<tr>
<td>Delta Front</td>
<td>Fine- to Very Fine-Grained SS</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The diagram illustrates the transition from marine shales at the bottom to braided fluvial systems at the top, with corresponding changes in grain size, sorting, and permeability trend.

- **Braided Fluvial System**: Shows the transition from proximal to mid to distal areas.
- **Floodplain Shales**: Represented at the bottom of the diagram.
- **Marine Shales**: Represented at the bottom of the diagram.
### A. DELTAIC
- DISTAL BRAIDED STREAM / MOUTH BAR
- MOUTH-BAR / DELTA FRONT
- DELTA FRONT

### B. FLUVIAL
- MID BRAIDED STREAM
- MID-DISTAL BRAIDED STREAM
- DISTAL FLUVIAL AND FLOODPLAIN

<table>
<thead>
<tr>
<th>FACIES</th>
<th>FLOW UNIT</th>
<th>TYPICAL GAMMA-RAY RESPONSE (API)</th>
<th>PETRO-PHYSICAL ZONATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>DISTAL FLUVIAL SANDSTONE</td>
<td>Z</td>
<td>0</td>
<td>ZONE 4</td>
</tr>
<tr>
<td>EXTENSIVE FLOOD-PLAIN SHALE</td>
<td>BARRIER</td>
<td></td>
<td>ZONE 4</td>
</tr>
<tr>
<td>MID-BRAIDED STREAM CONGLOMERATE</td>
<td>V3</td>
<td></td>
<td>ZONE 3</td>
</tr>
<tr>
<td>MID-DISTAL FLUVIAL CONGLOMERATE AND SANDSTONE</td>
<td>V2</td>
<td></td>
<td>ZONE 3</td>
</tr>
<tr>
<td>PROXIMAL-MID FLUVIAL CONGLOMERATE</td>
<td>V1</td>
<td></td>
<td>ZONE 2</td>
</tr>
<tr>
<td>FLOODPLAIN SHALE</td>
<td>BARRIER</td>
<td></td>
<td>ZONE 2</td>
</tr>
<tr>
<td>MID-DISTAL FLUVIAL SANDSTONE AND CONGLOMERATE</td>
<td>T</td>
<td></td>
<td>ZONE 2</td>
</tr>
<tr>
<td>FLOODPLAIN SHALE</td>
<td>BARRIER</td>
<td></td>
<td>ZONE 2</td>
</tr>
<tr>
<td>DISTAL FLUVIAL AND MOUTHBAR SANDSTONE</td>
<td>R2</td>
<td></td>
<td>ZONE 1</td>
</tr>
<tr>
<td>MOUTHBAR SANDSTONE AND DELTA FRONT SILTSTONE AND SHALE</td>
<td>R1</td>
<td></td>
<td>ZONE 1</td>
</tr>
</tbody>
</table>
**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 Embayments

WAVE DOMINATED
DELTAS

Modern Nile Delta
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

meters

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

Mudstone

Sandstone

Conglomerate

Gamma Ray Log (Core)

Delta Front Sequence

Porosity

Air Permeability

Coastal Plain

Possible Distributary Channel

Keniwlorth Delta Canyon

Storm Bar

* Minor core-to-log depth adjustment relates to removal of coals from core.
Characteristics of tidal sand-ridge sandstones

Thickness: Range 3-12 ft. average 6 ft.
Basal contact: Transitional with marine shales.

Texture and Composition
- Grain size: Upward-coursening from siltstone/very fine-grained sandstone at the base to upper fine-grained sandstone at the top.
- Sorting: Well to very well.
- Clay interbeds: Very common and gradually decreasing toward the top. Their relative content defines the upward-coursening, thickening trend.
- Clay clasts and wood fragments: Common in the upper half.
- Shell clasis: Mainly in the sandier levels of the upper part. Frequently in high concentrations at the top.

Sedimentary Structures
- Wavy lamination and ripples are dominant in the lower two thirds of the facies.
- Small-scale trough cross-stratification is usually present in the upper one-third facies.

Burrows
- 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.
Delta Types - Shoreline Embayment

Different delta types due to different processes and environments of deposition. Each of the three types exhibits different orientations and types of reservoir sands.

(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
Figure 5-19. Interpretable facies cross-sections of (A) progradational channel mouth bar and (B) distributary channel-fill sand bodies of an elongate, fluvial-dominated delta lobe. Geochemical log profiles are based on bore hole data from the Wilcox (Eocene) Holly Springs delta system of the northern Gulf Coast basin. (Modified from Galloway, 1968.)
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 5-11. Generalized vertical profile through a channel mouth bar sand 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.
**Delta Lobes**

One delta lobe

*Fig. 7-11* Block diagram indicating geometric arrangement of bar-dagger sand, fine-grained sediments, and upper marsh deposits of the modern Birdfoot delta of the Mississippi River. (After Fisk et al., 1954.)
PRINCIPAL DELTA ENVIRONMENTS
DEEPWATER (TURBIDITE) DEPOSITS & RESERVOIRS
**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.

**“DEEP WATER”**

Engineering and geologic ‘deep water’ are usually the same, but for different reasons.
Deepwater (>500m) discovered reserves

- Cumulative Gas
- Cumulative Oil/Cond.
- Cumulative BBOE in Ultra-Deep Water (>2000m)
- Portion of BBOE Developed or under development

Discoveries mainly from:
- Gulf of Mexico, offshore W.
- Africa and Brazil, N. Sea,
- SW shelf
- Australia, SE Asia

< 25% Developed or In Development

Year

Source: Various
Deepwater discoveries exceeding 500 MMBOE, announced as of September 2001. The South Atlantic and Gulf of Mexico are oil and gas; Europe, Asia and Australia are predominantly gas discoveries. Data from IHS Energy Group (2000, used with permission) and other published references as noted.
Three major elements:

-Sheets
-Channel-fill
-Levee/overbank

(Pirmez et al., 2000)
Seismic Facies Mapping: Turbidites

FINE-GRAINED, DEEPWATER ARCHITECTURAL ELEMENTS

Slatt, R.M., 2002

Mitchum, R.M., 1985
DEEPWATER (TURBIDITE) DEPOSITS & RESERVOIRS:

Sheet Sandstones & Reservoirs
Amalgamated Sheets
(Mutti, 1979)

Layered Sheets

Amalgamated sheets

Layered sheets

Brushy Canyon Fm., Texas
SHEET SANDSTONE EXAMPLES

• *S Sand, Auger Field; Gulf of Mexico (Kendrick, 1998)*

  - 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??
Auger 'S' Sand

(Kendrick, 2000)
Auger Field: GoM

(Modified from Balinski et al., 1994)

(McGee et al., 1994)

Bilinski et al., 1995

Slatt and Weimer, 1999
-Pulsed Neutron Capture (PNC) logs record replacement of oil by water during development; indicate that some shales isolate sands and others do not.
Axis of deposition

Time 1
Time 2
Time 3

(Fischer and Cherven, 1989)
“Compensation style” deposition as seen on seismic; Brazil
SHEET SANDSTONE EXAMPLES

- 4500’ Sand, Garden Banks 236; Gulf of Mexico
  (Fugitt et al., 2000)
  - Since 6/94, 93BCFG produced
  - layered/amalgamated sheet sandstones
  - shaley intervals subdivide sandy intervals into different production zones
  - strong water drive
  - Porosity: 16.7-33.5%
  - Permeability: 0.6-2520 md (Aver. = 427)
  - Porosity and permeability vary with grain size (best reservoir quality in thicker, cleaner sands)
Original Gas/water contact

(Fugitt et al., 2000)
Long Beach Unit; S. California (Slatt et al., 1993)

-Part of the larger Wilmington Oil Field of southern California

-3.8BBOOIP

-Laterally continuous shales extend across fault blocks

-Ranger Zone is most prolific unit

-Sands are unconsolidated except where held together by oil

-Porosites and permeabilities are high

-Long distant continuity of sands
Structure of the Longshore Currents

West Wilmington

East Wilmington
Reservoir Model with Well Data
Depth slice showing fault traces
E-W REGIONAL CROSS SECTION

(Slatt et al., 1990)
DEEPWATER (TURBIDITE) DEPOSITS & RESERVOIRS:

Channel-fill Sandstones & Reservoirs
EROSIONAL CHANNELS

- intrachannel mounds
- channel terraces
- second-order mound elements
- channel thalweg

DEPOSITIONAL (AGGRADATIONAL) CHANNELS

- second-order mound elements at channel bends
- intrachannel slump
- levee margin growth faults
- channel thalweg coarse-grained deposits

(Clark & Pickering, 1996)
Figure 1: Comparison between the stratigraphic hierarchy of confined channels proposed by Sprague et al. (2002) and the stratigraphic hierarchy for the Dalia M9 Upper Channel System

(Abreu et al., in press)
Channel-fill sandstones
Channel-margin sandstones
Slope mudstones
Estimated 1 Billion BOE in offshore west Africa field
CHANNEL-FILL SANDSTONE EXAMPLES

- *N Sand, Ram Powell, Gulf of Mexico (Kendricks, 2000)*
  - Cumulative production is 12MMBE
  - Elongate geometry of N sand and adjacent shales indicate sand was deposited in pre-existing erosional depression, with turbidity currents entering at the northern apex of the depression
  - Reservoir is composed of multiple, laterally offset stacked, lenticular channel-fill sandstones of variable thickness and numerous perched water levels
  - Pre-development geologic modeling indicated an amalgamated channel sand reservoir with a single oil-water contact
  - Development drilling and early production revealed water bearing sands beneath oil sands in individual wells updip of the presumed oil-water contact. Each development well encountered a perched water level.
  - Water legs occur in depressions within the field which could not be displaced by oil as it migrated in
West
Ram/Powell Field
East
J sand
L sand
M sand
N sand
Tertiary Cretaceous Unconformity

(Kendrick, 2000)

RAM POWELL VIOSCA KNOLL 956 FIELD
COMPOSITE TYPE LOG
NET PAY

(Craig et al., 2003)
DEEPWATER (TURBIDITE) DEPOSITS & RESERVOIRS:

Levee Sandstones & Reservoirs
Leveed Channel deposits and reservoirs
Potential Reservoir:
--- Channel
--- Levee
--- Splay

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

3D seismic horizon slice of leveed channel, offshore Angola (Kolla et al., 2001)

Offshore Angola
Location Map
Section 25, T16N-R92W

Channel-fill #1 Sandstone

Spine 1
Cross bedded sandstones; “point bar”

Debris flow beds; “cut bank”
Sandstones are various colors; shales are green.

Cross bedded sandstones
Debris flow beds
"I’d like to **extend the life**...

... of this field, because we know there is bypassed pay in thin sands. Conventional seismic can help identify the compartments, but its resolution isn’t good enough for what we need.

**What can we do to locate this pay and increase production?**
Behind-outcrop well on Spine I
Cored intervals
CHANNEL LEVEE/OVERBANK

EXAMPLES

• *M4.1 Sand, Tahoe, Gulf of Mexico (Kendrick, 2000)*
  - Upper Miocene
  - Field is on faulted structural nose
  - Characteristic ‘gull wing’ on seismic
  - Channel is elongate dim area on horizon slice
  - >17MMBE gas and condensate from 4 wells
  - Single well flow rates from thin bedded levees tested 29MMCFGPD and 950BCPD
  - Pressures in west levee depleted over time over entire stratigraphic interval; Pressures in east levee only depleted in upper part; lower part at original pressures, indicating disconnect with west levee.
  - Oil-water contact is shallower in west, than east levee.
  - Early production from upper levees provided optimism that was lost when production began from lower levee interval
M4.1 Sand, Tahoe

(Kendrick, 2000)
M4.1 Sand, Tahoe

(Kendrick, 2000)
- **Ram/Powell, L Sand, Gulf of Mexico** (Clemenceau et al., 2000)
  - L Sand comprised of *channel, proximal and distal levee* facies
    - Channel is 1500-2000ft. wide, contains 25-100ft. water wet sand
    - Gas charged, east levee extends 15,000 ft. to east of channel
    - Reservoir is thin-bedded levee/overbank facies; individual sands are 0.04-1 inch thick!!
    - Sand porosities = 15-32% (X=28%); k = <10-1000md (X=300)
    - Single 2,500ft. horizontal well in proximal levee facies peaked
      at 8.8MBOPD & 108MMCFGD. This well has produced 4.8MMBO & 61.5BCF (15.4MMBOE from 9/97(?)-5/00.
    - 4 day well test in 50ft. thick distal levee flowed 23MMCFGD
      and 2700BC/D with PTA perms of 143md.
    - Good lateral continuity and pressure communication across entire 4000 acre proximal levee reservoir
    - Channel and levee sands are NOT in communication, as determined from pressure data
  - Gas sands give *good* seismic amplitudes, water sands do
Ram-Powell
‘L’ Sand
(Clemenceau et al., 1995;
Kendrick, 2000)
L Sand

(Craig et al., 2003)
3D Seismic Horizon Slice through a reservoir

(Clemenceau et al., 1995)
High and variable dip Magnitude of beds

(Ram-Powell L Sand)

Low and uniform dip magnitudes of beds

(Clemenceau et al., 2000)
Miocene Mt. Messenger Formation, Taranaki Basin of New Zealand

PHOTOMOSAICS FROM HELICOPTER; WELLS; CORES; LOGS; HIGH-RESOLUTION SHALLOW SEISMIC; MEASURED SECTIONS
Mt. Messenger Fm., New Zealand
Bedding style and Dipmeter example

Bedding Style Model
North Well
Central Well
148 m

(Spang, 1998)

Dip Patterns

**Channel-fill**
* Variable Dip
* Decrease Upward

**Proximal Levee**
* Variable Dip & Azimuth
* Relatively High Dip Angles
* High net/gross

**Distal Levee**
* Constant Dip & Azimuth
* Relatively Low Dip Angles
* Lower net/gross
Ram-Powell 
L Sand

Low and uniform dip magnitudes of beds

Proximal levee

High and variable dip magnitudes of beds

Distal levee

(Clemenceau et al., 2000)
VK 956 #1

VK 912 #2

Ram Powell L Sand

J Sand

L Sand

~100' net gas

Channel fill

3000 ft

 Fluid barrier

datum base of sand

100 ft

low resistivity gas pay

2 ohms
Drilling Strategy: Horizontal well in proximal levee beds, parallel to channel: “Well performance exceeded expectations with a peak flow rate of 105mmcf/d and 9600 bopd”

(Clemenceau et al, 2000)
TYPICAL JACKFORK!

Jackfork Gas

H & H STAR
# 1-4 Hope
Sec. 4, T3N, R20E

ARCO
# 1-12 Borne
Sec. 12, T4N, R20E

I.P. = 5.7 MMCTGPD
"Lower" Jackfork

"Lower" Jackfork
Gamma ray and neutron & density porosity logs for productive Jackfork strata in two eastern Oklahoma wells (modified from Paull, 1994).

- Well
  - Monthly Production (Mcf)
    - GHK/Amoco Ratcliff 1-33
      - 200,000+
    - GHK Thompson 1-4
      - 350,000+

- Well
  - Monthly Production (Mcf)
    - GHK Morgan 1-5
      - 900,000
    - GHK Guggenheim 1-6
      - 50,000
JACKFORK GROUP HYDROCARBON RESERVOIR/TRAP TYPES

• LARGE-SCALE STRUCTURES

• FRACTURES

• STRATIGRAPHIC PINCHOUTS??

• UNCONFORMITY??

• DIAGENETIC??

• STRATIGRAPHICALLY CONTROLLED FRACTURE FREQUENCY??
DeGray Lake Spillway, Arkansas

Jackfork Group, mainly sheet sandstones

(Slatt et al., 2000)
Thin bedded low-density turbidity current deposits.
Upper Jackfork near Little Rock, Arkansas

(Jordan et al. 1993)
Big Rock Quarry
North Little Rock, Arkansas

The three numbered vertical yellow lines are locations of outcrop gamma ray logs. Each log is spaced about 200m apart.
Outcrop gamma ray log from location 1. Shell Oil Co. drilled a core behind this outcrop location. Core description is shown alongside outcrop gamma ray log.

(Jordan et al., 1991)
Cut-and-fill structures. Most cuts are mud-lined
Cut-and-fill structures. Most cuts are mud-lined
(Abreu et al., in press)
Orlando’s Distribution of Friable and Cemented Shales in Outcrops of the Pennsylvanian Jackfork Group.
Southeast Oklahoma.

Tosan Omatsola
May 15, 2005
Sandstones in study area are dominated by two main sandstone types:

- Friable sandstones

- Quartz cemented sandstones

The two sandstones are representative of different porosity, permeability and facies types
The area of investigation is in the Ouachita Mountains, southeast Oklahoma; ~4 miles (6.5km) from the Oklahoma – Arkansas border.
Lithostratigraphy

- Quartz cemented sandstones
  - Gray – tan (fresh) and light gray
    - medium brown (when weathered)
  - Very fine to fine-grained; moderately - well sorted
  - Planar-tabular bedded; bulbous contacts, scoured bedding (occasionally)
  - Thick & thin bedded (0.5 – 5ft), (0.8m-1.5m); massive, amalgamated or layered; Bouma Ta-Tc beds
  - Various sedimentary structures and deepwater ichnofacies
  - Highly fractured
Lithostratigraphy

- Friable sandstones
  - Gray – whitish (fresh) and yellow – orange (when weathered)
  - Fine to medium-grained; poorly - moderately sorted
  - Bulbous contacts/bedding; planar bedded (occasionally)
  - Thick & thin bedded (0.5 – 7ft), (0.8m-2.1m); massive, amalgamated or layered (occasionally)
  - Various sedimentary structures
  - Highly porous (and also fractured)
Friable sandstone facies (2A & 2B) (and to a lesser degree cemented sandstone facies 1A)

Levee facies (facies 4)

Cemented sandstone facies (1A, 1B & 3)
Porous channel fill sandstones (matrix porosity)

Tight sheet sandstones (fracture porosity)
Sequence stratigraphy, where applicable, provides a predictive tool for the lateral and vertical distribution of facies.

By identifying channelized (matrix porosity) and non-channelized strata (fracture porosity), explorationists may better predict where these facies may exist and tailor exploration and production plans accordingly.
Jackfork Reservoir Potential - *Porosity*

- Studies show that:
  - Fracture porosity dominates in the cemented sandstones
  - Friable sandstones matrix porosity is dominant.

- In subsurface analog reservoirs, juxtaposition of the different sandstone types with their associated differences in reservoir quality may result in among others:
  - Varying production rates and development operational hazards
  - Challenging development economics for an analog reservoir.
Sheets or channels????
Does it matter????
Sheet or channel-fill sandstones?? Does it matter??

"Lower" Jackfork