Application of Sequence Stratigraphy in the Minnelusa Fm:
A Method to Optimize Production

Stephen T. Whitaker
Wyoming Oil & Gas Fair/EORI Joint Conference: Sept 13, 2018
Paleogeography of North America in Early Pennsylvanian

315 Ma

Ancestral Rockies

Lusk Embayment

Alleghanian Orögeny

Blakey, 2010
Paleogeography of North America in Middle Pennsylvanian

300 Ma

Minnelusa
Lusk Embayment
Alleganian Orogeny
Ancestral Rockies

Blakey, 2010
Paleogeography of North America in Earliest Permian

290 Ma

- Tensleep
- Weber
- Minnelusa
- Lusk Embayment
- Ancestral Rockies
- Alleghanian Orogeny

Blakey, 2010
Paleogeography: Early Permian Period

Modified from Gene George, 2010

Figure 11: Upper Minnelusa paleogeography — The Northern Rockies area is oriented to illustrate the latitude position during Late Pennsylvanian-Early Permian times. The trade wind direction coincides with paleocurrent directions measured in the eolian sands. (After Heckel, 1980 and Peterson, 1980.)
• Ephemeral deposits such as sand dunes are generally not preserved in the sedimentary record unless inundated.

• Minnelusa reservoirs are limited to an area corresponding to an extension of the Lusk Embayment.

• Traps within the Minnelusa are dependent on inter-dune, shallow marine and sabkha facies and on incised, pre-Opeche channels infilled with Opeche shale.

Fryberger, S., 1984

Figure 3: Summary of paleocurrents inferred from dipmeter surveys, Powder River Basin. Most of the present Minnelusa exploration fairway is in an extension of the ancient Lusk Embayment.
Litho-Stratigraphic and Sequence Stratigraphic Correlations

Modern Analog to Permo-Penn Minnelusa Formation
Litho-Stratigraphic and Sequence Stratigraphic Correlations

Modern Analog to Permo-Penn Minnelusa Formation
Litho-Stratigraphic and Sequence Stratigraphic Correlations

Modern Analog to Permo-Penn Minnelusa Formation

Next View
Litho-Stratigraphic and Sequence Stratigraphic Correlations

Modern Analog to Permo-Penn Minnelusa Formation

Shamal winds
Litho-Stratigraphic and Sequence Stratigraphic Correlations

Modern Analog to Permo-Penn Minnelusa Formation

Shamal winds
Global studies reveal that there were significant glacial periods and numerous corresponding sea level fluctuations throughout the late Carboniferous and Permian periods.

The Minnelusa was deposited in and around a shallow marine embayment that was subjected to a fluctuating sea level.
Typical Litho-Stratigraphic concept for the Minnelusa

Figure 24: Origins of stratigraphically-derived petroleum trapping in the Upper Minnelusa sandstones.

Fryberger, S., 1984
• What correlative facies were being deposited in lower areas?
• What is depositional explanation for how the “B” and “D” dolomites climb in the stratigraphic section?
Litho-stratigraphic correlations tend to link similar rock types. This method commonly leads to erroneously connecting different, isolated reservoir units.

Sequence-stratigraphic correlations try to link flooding surfaces and can thereby better represent varying lithofacies within a similar depositional time setting. This method has the potential to better represent isolated sandstone units, such as in the Minnelusa.

Litho-Stratigraphic and Sequence Stratigraphic Correlations

Ranch A Minnelusa outcrop. Lower slope with black shales is Middle Minnelusa. Upper slope with trees and collapsed sands is the Upper Minnelusa. Assignment of Middle cliffy sands, the “Upper Red Zone” of the measured section is uncertain in assignment.

Pahasapa Fm. limestone in Sand Canyon. It is very fossiliferous with many broken shells and crinoid stem fragments.

Fryberger, Jones, and Johnson, 2014
Litho-Stratigraphic and Sequence Stratigraphic Correlations

Bounding Surface Sketch Ranch A

Fryberger, Jones and Johnson, 2014
Litho-Stratigraphic and Sequence Stratigraphic Correlations

Casper Formation dune interfingering with interdunal sabkha facies

Expect to see similar relationships in the subsurface
• Diastems are defined as interruptions in deposition
  o for our purposes are generally equivalent to flooding surfaces
• Flooding surfaces are commonly expressed by low-permeability beds (algal mats with high gamma counts, cemented zones within sandstones, dolomites, and anhydrites

Fryberger, 1984
- Model for preservation of Minnelusa sand deposits circa 1990
- Each rise in base level would preserve those deposits now inundated
- Commonly each surface of flooding would exhibit any of the following: algal mats, thin interbedded shales, well-cemented beds, or facies changes to a more marine-like environment (dolomites and anhydrites)
- This model, although not used for correlations, illustrates the concept of Sequence Stratigraphy as presented in this talk.

Fryberger, 1990
Two Rules for Being a Successful Oil & Gas Geologist

1. You must excel at working with incomplete data sets
2.
• Parasequence boundaries (flooding surfaces) commonly indicated by low-porosity / low-permeability beds that can be correlated over many miles
• Flooding surfaces can form barriers to vertical fluid flow - - but not in all cases
### Sequence Stratigraphic Correlations: Core Descriptions

**CORE LOCATION:** NW NE Sec 1 T50N R68W F50-68-1-C1

<table>
<thead>
<tr>
<th>DEPTH (FEET)</th>
<th>GR</th>
<th>ROCK TYPE</th>
<th>SONIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>6350</td>
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<tr>
<td>6400</td>
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</table>

#### Grain Size

<table>
<thead>
<tr>
<th>ROCK TYPE NO.</th>
<th>SAND</th>
<th>SILT</th>
<th>CLAY</th>
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<td>m</td>
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<tr>
<td>121</td>
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<td>m</td>
<td>m</td>
</tr>
<tr>
<td>551</td>
<td></td>
<td>m</td>
<td>m</td>
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<tr>
<td>164</td>
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<tr>
<td>781</td>
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<td>m</td>
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</tr>
<tr>
<td>357</td>
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#### Sedimentary and Biogenic Structure

<table>
<thead>
<tr>
<th>ROCK TYPE NO.</th>
<th>CEMENTS</th>
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<tr>
<td></td>
<td>AN</td>
</tr>
<tr>
<td></td>
<td>D</td>
</tr>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>D</td>
</tr>
<tr>
<td></td>
<td>D</td>
</tr>
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</table>

#### Comments

- 121: Mix of bioclastic debris
- 551: Bi-modal sorting, Reworked Mnilansa sand
- 164: Red shale
- 781: Disturbed with short patches clay drapes
- 357: Mix of bioclastic debris
- 557/554: Very porous-clean sand. Possible dune
**Sequence Stratigraphic Correlations: Core Descriptions**

**CORE LOCATION:** NW NE Sec 1 T50N R68W
F50-68-1-C1

<table>
<thead>
<tr>
<th>DEPTH (FEET)</th>
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<th>ROCK TYPE</th>
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<tr>
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</table>

**Rudus Mbr-Opeche Fm**

**Top of Minnelusa**

**GRAIN SIZE**

<table>
<thead>
<tr>
<th>ROCK TYPE NO.</th>
<th>SAND</th>
<th>SILT</th>
<th>CLAY</th>
<th>SEDIMENTARY AND BIOGENIC STRUCTURE</th>
<th>CEMENTS</th>
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<tbody>
<tr>
<td>154</td>
<td>I</td>
<td></td>
<td>M</td>
<td></td>
<td></td>
</tr>
<tr>
<td>551</td>
<td>D</td>
<td></td>
<td>M</td>
<td>Bi-modal cutting, Reworked Minnelusa sand.</td>
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</tr>
<tr>
<td>154</td>
<td>D</td>
<td></td>
<td>M</td>
<td>Red shale.</td>
<td></td>
</tr>
<tr>
<td>551</td>
<td>D</td>
<td></td>
<td>M</td>
<td>Disturbed with short patches clay drapes.</td>
<td></td>
</tr>
<tr>
<td>154</td>
<td>D</td>
<td></td>
<td>M</td>
<td></td>
<td></td>
</tr>
<tr>
<td>280</td>
<td>D</td>
<td></td>
<td></td>
<td>Algal laminated.</td>
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</tr>
<tr>
<td>551</td>
<td>D</td>
<td></td>
<td></td>
<td>Very porous-clean sand. Pezzable dune.</td>
<td></td>
</tr>
</tbody>
</table>

**COMMENTS**

- AN: Gastropods.
- C: Moderate to abundant calcite growths.
- D: Algal laminated.
Sequence Stratigraphic Correlations: Core Descriptions
Green lines show apparent flooding surfaces (parasequence boundaries)
• Minnelusa “B” sand, as originally correlated, subdivided into 3 sands
• Operator noted communication between wells was not as predicted
• Minnelusa “B” sand, as originally correlated, subdivided into 3 sands
• Operator noted communication between wells was not as predicted
• Sequence Stratigraphic correlations indicated
Flooding surfaces indicated by base of tight facies or by algal mats (high gamma signatures).

- Upper B parasequences are generally parallel to top of Opeche.
- Lower B parasequences are generally not parallel to the top of Opeche but are parallel to each other - suggesting an unconformity between the “Upper B” and “Lower B”.

Colored bands within parasequences indicate porosity >18%.
• Flooding surfaces indicated by base of tight facies or by algal mats (high gamma signatures)
• Upper B parasequences are generally parallel to top of Opeche
• Lower B parasequences are generally not parallel to the top of Opeche but are parallel to each other - suggesting an unconformity between the “Upper B” and “Lower B”
Flooding surfaces indicated by base of tight facies or algal mats (high gamma signatures)

Upper B parasequences are generally parallel to top of Opeche

Lower B parasequences are generally not parallel to the top of Opeche but are parallel to each other - suggesting an unconformity between the “Upper B” and “Lower B”
Litho-Stratigraphic Correlations in Minnelusa Field “B”

From G. George, 2009

* This section is 30 miles from previous example
Litho-Stratigraphic and Sequence Stratigraphic Correlations in Minnelusa Field “B”

Why did the northwest-most well (#1) make so much less water than the SE offset (#6) if in same sand and downdip?

From G. George, 2009

- upper B sand
- lower B sand
• Why did the northwest-most well (#1) make so much less water than the SE offset (#6) if in same sand and downdip?

<table>
<thead>
<tr>
<th>Well</th>
<th>Upper B Sand (mi³)</th>
<th>Lower B Sand (mi³)</th>
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<tbody>
<tr>
<td>1</td>
<td>407,128</td>
<td>17,634</td>
</tr>
<tr>
<td></td>
<td>19,559</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1,808,092</td>
<td>5,700</td>
</tr>
<tr>
<td></td>
<td>1,100,000</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>653,838</td>
<td>3,196</td>
</tr>
<tr>
<td></td>
<td>2,059,644</td>
<td></td>
</tr>
<tr>
<td>10</td>
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<tr>
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<td></td>
<td>2,504,043</td>
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</tr>
<tr>
<td>16</td>
<td>1,935,845</td>
<td>10,494</td>
</tr>
<tr>
<td></td>
<td>1,594,348</td>
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</tbody>
</table>

From G. George, 2009
As noted earlier, water production in the #1 well is anomalously low compared to other wells in the same mapped reservoir.
Litho-Stratigraphic Correlations – Stratigraphic Section

As noted earlier, water production in the #1 well is anomalously low compared to other wells in the same mapped reservoir.
As noted earlier, water production in the #1 well is anomalously low compared to other wells in the same mapped reservoir.
By correlating flooding surfaces (indicated by cemented zones, algal mats (high-gamma), carbonate beds), it is apparent the #1 well is producing from a porous interval in the sequence below that which is producing from the #6 well, which explains the water production discrepancy.
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**Sequence Stratigraphic Correlations Minnelusa Field “’B”**

- Stratigraphic correlations *above* the light green line more or less parallel the top of Opeche.
- Note that stratigraphic correlations below the light green line (Top of Lower B) were roughly parallel to the black dashed line (sometimes called the C-marker).

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<td>W</td>
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<td>6</td>
<td>7</td>
<td>26</td>
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<tr>
<td>E</td>
<td>28</td>
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**Minnekahta Datum = Top of Opeche**

**“C marker”**

### Coordinates

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<td>653,838</td>
<td>446,554</td>
<td>185,300</td>
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<tr>
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<td>2,059,644</td>
<td>340,322</td>
<td>3,089</td>
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</table>
When the datum is shifted to a consistent marker bed ("C marker") well below the green line, the different orientation of the flooding surfaces in the "Lower B" section become more apparent.

This relationship suggests the green line represents an unconformable surface (Sequence Boundary) and that some tectonic shifting in the basin occurred prior to "Upper B" deposition.
• When the datum is shifted to a consistent marker bed ("C marker") well below the green line, the different orientation of the flooding surfaces in the "Lower B" section become more apparent.

• This relationship suggests the green line represents an unconformable surface (Sequence Boundary) and that some tectonic shifting in the basin occurred prior to "Upper B" deposition.
Sequence-Stratigraphic Correlations: Truncation Trap

Colored bands within parasequences indicate porosity >18%

datum = top of Opechee

Minnekahta

1,469,833
97,145
4,804,706

407,128
17,634
19,559
Using Sequence Stratigraphy to Help Water Flood Optimization in Minnelusa Field “B”
Sequence Stratigraphic Correlations

Opeche Shale Isopach
Sequence Stratigraphic Correlations

“A” Parasequence Isopach
Sequence Stratigraphic Correlations

A Sand Isopach > 10% Porosity
Sequence Stratigraphic Correlations

A Sand Isopach > 10% Porosity

Red Circles Indicate Perforations in the Parasequence
Sequence Stratigraphic Correlations

A Sand Isopach >18% Porosity

Red Circles Indicate Perforations in the Parasequence
Sequence Stratigraphic Correlations

Upper B1 Isopach
Sequence Stratigraphic Correlations

Upper B1 Isopach >10% Porosity
Sequence Stratigraphic Correlations

Upper B1 Isopach >10% Porosity

Red Circles Indicate Perforations in the Parasequence

No good pressure support
Sequence Stratigraphic Correlations

**Upper B1 Isopach >18% Porosity**

Red Circles Indicate Perforations in the Parasequence

No good pressure support
Sequence Stratigraphic Correlations

Upper B2 Isopach >10% Porosity
Sequence Stratigraphic Correlations

Upper B2 Isopach >10% Porosity

Red Circles Indicate Perforations in the Parasequence

No good pressure support
Sequence Stratigraphic Correlations

Upper B2 Isopach >18% Porosity

No good pressure support

Red Circles Indicate Perforations in the Parasequence
Sequence Stratigraphic Correlations

Upper B3 Isopach
Sequence Stratigraphic Correlations

Upper B3 Isopach >10% Porosity
Sequence Stratigraphic Correlations

Upper B3 Isopach >10% Porosity

Red Circles Indicate Perforations in the Parasequence
Sequence Stratigraphic Correlations

Upper B3 Isopach >18% Porosity

Red Circles Indicate Perforations in the Parasequence
Sequence Stratigraphic Correlations

Upper B4 Isopach >10% Porosity
Sequence Stratigraphic Correlations

Upper B4 Isopach >10% Porosity

Red Circles Indicate Perforations in the Parasequence
Sequence Stratigraphic Correlations

Upper B4 Isopach >18% Porosity

Red Circles Indicate Perforations in the Parasequence
Sequence Stratigraphic Correlations

Upper B5 Isopach >10% Porosity
Sequence Stratigraphic Correlations

Upper B5 Isopach >10% Porosity

Red Circles Indicate Perforations in the Parasequence
Sequence Stratigraphic Correlations

Upper B5 Isopach >18% Porosity

Red Circles Indicate Perforations in the Parasequence
Sequence Stratigraphic Correlations

Lower B1 Isopach >10% Porosity
Sequence Stratigraphic Correlations

Lower B1 Isopach >10% Porosity

Red Circles Indicate Perforations in the Parasequence
Sequence Stratigraphic Correlations

Lower B1 Isopach >18% Porosity

Red Circles Indicate Perforations in the Parasequence

No pressure support
Sequence Stratigraphic Correlations

Lower B2 Isopach >10% Porosity
Sequence Stratigraphic Correlations

Lower B2 Isopach >10% Porosity

Red Circles Indicate Perforations in the Parasequence
Sequence Stratigraphic Correlations

Lower B2 Isopach $>18\%$ Porosity

Red Circles Indicate Perforations in the Parasequence

No pressure support

no pressure support
Sequence Stratigraphic Correlations

Lower B3 Isopach >10% Porosity
Sequence Stratigraphic Correlations

Lower B3 Isopach >10% Porosity

no pressure support

Red Circles Indicate Perforations in the Parasequence
Sequence Stratigraphic Correlations

Lower B3 Isopach >18% Porosity

Red Circles Indicate Perforations in the Parasequence
Sequence Stratigraphic Correlations

Lower B4 Isopach >10% Porosity
Red Circles Indicate Perforations in the Parasequence

No sands within this parasequence has porosity > 18%

no pressure support
Sequence Stratigraphic Correlations

Lower B5 Isopach >10% Porosity
Sequence Stratigraphic Correlations

Lower B5 Isopach >18% Porosity
Slice-map of lithostratigraphic variance within a mapped parasequence of the upper Minnelusa using sonic log travel time data in a 40 mi² area. Porous sands are white; tight facies are purple, blue and green. Fields productive from this parasequence are indicated by red arrows.

• **Fryberger, Steven G.**, L. Krystanik, 1990, Modern and ancient eolian deposits: petroleum exploration and production; SEPM Rocky Mountain Section, Christopher Schenk ed., 250 p.


• **George, Gene R.**, 2010, Minnelusa Formation excellent EOR opportunity; *Enhanced Oil Recovery Institute Advisory Board, Denver, CO, January 13, 2010.*


Thank You

Questions, Comments, Concerns

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