Linking Stratigraphic Architecture and Petroleum System Elements of the Niobrara Formation to Oceanographic and Far-Field Tectonic Events

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Search and Discovery Article #11354 (2021)**
Posted December 9, 2021

*Adapted from oral presentation accepted for the 2019 AAPG RMS Annual Meeting. Cheyenne, Wyoming, September 15-18, 2019
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Abstract

The Niobrara Formation was deposited in the Western Interior Seaway (WIS), which filled an active foreland basin during the Upper Cretaceous. The WIS experienced important oceanographic variations and tectonic events during Niobrara time, and resolving their influence is critical to mapping petroleum system elements of the greater Denver-Julesburg (D-J) Basin area. To unravel stratigraphic complexity through time, sequence stratigraphic surfaces suited to the distal carbonate ramp, and in the context of biozone and isotope geochronology data, were correlated through basin-scale well control to create a series of age-constrained isochore maps. At a WIS scale, thickness patterns suggest that the basin’s flexural forebulge had migrated eastward to a position along trend with the future Rocky Mountains where it defined the western edge of the distal carbonate ramp that developed in the backbulge of the basin. At the D-J Basin scale, early Niobrara deposition (Upper Turonian - Lower Santonian) was dominated by patterns of differential sediment accumulation with compensational infilling in the form of systematic reversals of stratigraphic thicks and thins through time. This pattern was interrupted in the Lower Santonian by the development of sublinear basement uplifts along the trend of the emergent Transcontinental Arch. As a result, sediment accumulation became dominated by patterns of draping over the long-lived seafloor paleohighs. Absolute timing of architectural changes in the Niobrara suggests a link between Sevier thrusting episodes, a migrating flexural forebulge, and uplifts along reactivated basement shear zones in the distal foreland. The well-known transgressive-regressive cycles of the Niobrara in the D-J Basin appear to be broadly overprinted by two distinct influences: circulation-related bottom currents and deposits and the later interference of tectonic uplifts. This dynamic paleo-seafloor morphology was a first-order control that shaped the depositional patterns of Niobrara source rock and reservoir rock intervals.

Conclusions

• Sequence stratigraphic-based mapping techniques are critical to understanding the stratigraphic architecture and evolution of the Niobrara Formation in the D-J Basin region.
• The timing of sequence-stratigraphic intervals is constrained by radiometric ages and biostratigraphy

• Age-constrained isochore maps suggest the following key findings:
  
  ➢ Regional scale: the basin’s flexural forebulge was positioned along trend with the future Rocky Mountains where it defined the western edge of the Niobrara distal carbonate ramp
  
  ➢ D-J Basin scale: Lower Niobrara (Upper Turonian -Lower Santonian) differential sediment accumulation with compensational infilling, suggesting oceanographic processes with little evidence of tectonic uplifts
  
  ➢ D-J Basin Scale: Upper Niobrara (Lower Santonian -Lower Campanian) development of sublinear basement uplifts along reactivated shear zones on the emergent TCA; dominance of sediment draping over the long-lived seafloor paleohighs

• Comparison of stratigraphic and petrophysical maps suggests that tectonic/geomorphic features were important controls on the distribution and facies of source-prone and reservoir-prone intervals of the Niobrara

• Proterozoic shear zones reactivated in the Lower Santonian are directly responsible for -and co-located with -key Niobrara architectural and facies trends, thermal maturity patterns, and hydrocarbon accumulations.

References


Deacon, M., and McDonough, K.J., 2018, Depositional and Stratigraphic Complexities of the Niobrara Formation and the Relationship to Producibility, DJ Basin, Colorado: AAPG Annual Convention & Exhibition, Salt Lake City, May 20-23, 2018, Search and Discovery Article #51529


Deep water analog?

- **Abyssal erosion** driven by the intensification of deep-water circulation during glaciation periods (e.g., Tucholke and Embley, 1984; Mountain and Tucholke, 1985).

- **Tectonic events and regional basement uplifts** can also magnify the erosional capacity of bottom currents (Gomes and Viana, 2002).
Outline

- Sequence stratigraphy, isotopic ages, and chronostratigraphy
- Age-constrained isochore maps and interpretive cross sections
- Oceanographic influence vs tectonic influence
- Far-field tectonics and basement faulting
- Petrophysical analysis and original oil in place (OOIP) maps
- Architecture & petroleum system elements
- Conclusions

Western Interior Seaway at 85 Ma (licensed from North American Key Time Slices ©2013 Colorado Plateau Geosystems Inc.)
Transgressions and Regressions

**Open Ocean (WIS)**
- Increasing dilution by siliciclastics
- Decreasing biogenic productivity
- Maximum Flooding Surface
- Decreasing dilution by siliciclastics
- Increasing biogenic productivity

Catuneanu, 2006

D-J Niobrara: yields opposite GR & ResD response

<table>
<thead>
<tr>
<th>Transgressions</th>
<th>Highstand to Lowstand Regressions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoreward shift in facies</td>
<td>Basinward shift in facies</td>
</tr>
<tr>
<td>Warm Tethyan water extends northward into the WIS</td>
<td>Retreat of Tethyan water and carbonate-promoting conditions</td>
</tr>
<tr>
<td>Increased biogenic pelagic productivity</td>
<td>Reduced biogenic production, increased siliciclastic input</td>
</tr>
<tr>
<td>Oxygenated bottom water</td>
<td>Dysoxic to anoxic bottom water (preserved organic carbon)</td>
</tr>
<tr>
<td>Concentrated chalk (biogenic and skeletal)</td>
<td>Dilution of chalk by siliciclastic (silt, clay) sediments</td>
</tr>
<tr>
<td>accumulation</td>
<td></td>
</tr>
<tr>
<td>Lower rate of deposition</td>
<td>Higher rate of deposition</td>
</tr>
<tr>
<td>Dominantly pelletal chalk, interbedded with pelletal chalk</td>
<td>Dominantly organic-rich marlstone, interbedded with pelletal chalks</td>
</tr>
</tbody>
</table>

Typical GR response at siliciclastic margin

Drake and Hawkins, in press

Lange, 2003

Transgressive shale

MFS

FS

MFS

FS

FS

FS

MFS

FS

FS

FS

FS

V-Shale

Fleming Coal

Mineral Coal

Transgressive shale

Lange, 2003
Sequence Stratigraphic Interpretation


Modified from Drake and Hawkins, in press
Projected Isotopic Ages and Biostratigraphy

<table>
<thead>
<tr>
<th>Stage</th>
<th>Substage</th>
<th>Fm.</th>
<th>Mbr.</th>
<th>Core Lith.</th>
<th>(^{40}\text{Ar}/^{39}\text{Ar} ) age</th>
<th>(^{206}\text{Pb}/^{238}\text{U} ) age</th>
<th>Interpolated stage boundary ages</th>
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</thead>
<tbody>
<tr>
<td>Tur.</td>
<td>Upper</td>
<td>Carlile Shale</td>
<td>FHLS</td>
<td></td>
<td>89.32 ± 0.24 Ma</td>
<td>89.37 ± 0.15 Ma</td>
<td>89.75 ± 0.38 Ma</td>
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<td></td>
<td></td>
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<td>89.87 ± 0.18 Ma</td>
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<td>S. corvensis</td>
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<tr>
<td>Conian.</td>
<td>Mid.</td>
<td>Niobrara</td>
<td>Smoky Hill Member</td>
<td></td>
<td>85.84 ± 0.22 Ma</td>
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<td>86.49 ± 0.44 Ma</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>85.66 ± 0.19 Ma</td>
<td></td>
<td>C. saxitonianus</td>
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<tr>
<td></td>
<td>Low.</td>
<td>Mariacolea</td>
<td>Fm.</td>
<td></td>
<td>85.84 ± 0.24 Ma</td>
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<td>86.52 ± 0.31 Ma</td>
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<td>87.11 ± 0.15 Ma</td>
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<tr>
<td>Santonian</td>
<td>Mid.</td>
<td>Low, Mid.</td>
<td>Upper</td>
<td>Pierre Shale</td>
<td>84.41 ± 0.24 Ma</td>
<td>84.43 ± 0.15 Ma</td>
<td>84.19 ± 0.38 Ma</td>
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<td>Upper</td>
<td>Niobrara</td>
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<td>84.55 ± 0.37 Ma</td>
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<td>D. bassleri</td>
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<td>87.11 ± 0.15 Ma</td>
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<tr>
<td>Camp.</td>
<td>Lower</td>
<td></td>
<td>Lower</td>
<td>Fm.</td>
<td>81.84 ± 0.22 Ma</td>
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<td>84.19 ± 0.38 Ma</td>
<td>S. hippocrepis II</td>
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<td></td>
<td></td>
<td></td>
<td>86.52 ± 0.31 Ma</td>
<td>S. hippocrepis I</td>
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<td></td>
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<td></td>
<td></td>
<td>84.43 ± 0.15 Ma</td>
<td>S. leei III</td>
</tr>
</tbody>
</table>

Libsack 43-27
API: 0512321838
Weld Co., Colorado

Drake and Hawkins, in press (modified from Locklair and Sageman, 2008; Sageman et al., 2014)
Age-Constrained Third-Order Sequences

*All ages, including interpolated stage boundary ages in italics, from Sageman et al. (2014)

**Fourth 3rd order cycle**
84.6 Ma – 81.7 Ma

**Third 3rd order cycle**
85.7 – 84.6 Ma

**Second 3rd order cycle**
88.7 – 85.7 Ma

**First 3rd order cycle**
90.0 – 88.7 Ma

Modified from Drake and Hawkins 2012
Well Control and Preferred Type Log

>2300 wells correlated across D-J Basin

11 tops – four 3rd order sequences, plus sub-intervals

Supron-UPRR 27-1
0512310188
27-8N-65W, Weld Co., CO

Modified from Drake and Hawkins 2012
Isochore Controls: Paleohighs and Basement Structures

- Isochore thins associated with paleohighs, and thicks associated with paleolows (e.g., Weimer, 1986)
- Paleohighs align with structural trends (Precambrian shear zones) along Front Range

Drake and Hawkins 2012
Sediments and Paleohighs and Paleolows

- Sediment draping
- Accumulation adjacent to paleohigh
- Bypassed sedimentation, unconformity, disconformity, and hardground
- *No thick occurring on top of a paleohigh*

- Underlying thin caused by lack of sediment accumulation (bypassed sedimentation, erosion, channeling?)
- Sediment accumulation in accommodation space

Note that isochore maps of the blue units in a) and b) would be nearly identical, but:

Thin-thick trends can have very different origins – key factors:
  - *Relationship to underlying architecture*
  - *Scale and morphology of features*
  - *Duration of features*
First 3\textsuperscript{rd} Order Sequences

- Dominantly \textbf{NW-SE-oriented stratigraphic architecture}
- More uniform thickness than subsequent sequences (note contour values): relatively broad ramp deposition compared to later sequences
- \textbf{No evidence of TCA}

\textit{Interpretive conceptual cross section}

\begin{itemize}
  \item Present outcrops and counties for reference
  \item Stratigraphic thick
  \item Stratigraphic thin
  \item C.I. = 20 ft
  \item \textbf{Dominantly NW-SE-oriented stratigraphic architecture}
  \item More uniform thickness than subsequent sequences (note contour values): relatively broad ramp deposition compared to later sequences
  \item \textbf{No evidence of TCA}
\end{itemize}

Dashed thin arrows mark the major stratigraphic thick (yellow) and thins (red) with arrows pointing in the direction of thickening and thinning, respectively. TCA: Transcontinental Arch

\textbf{Modified from Drake and Hawkins, in press}

\textbf{Drake and Hawkins 2012}

\textbf{Fourth 3\textsuperscript{rd} order cycle}

\textbf{Third 3\textsuperscript{rd} order cycle}

\textbf{Second 3\textsuperscript{rd} order cycle}

\textbf{First 3\textsuperscript{rd} order cycle}

\textbf{Supron-UPRR 27-1}

\textbf{Res}

\textbf{GR}
Second 3rd Order Sequence

- Persistent NW-SE-oriented stratigraphic architecture
- Patterns of thick and thin are mostly reversed: compensational infilling of accommodation space provided by previous sequence
- First broad TCA influence during Niobrara time?
- No evidence of individual paleohighs

Interpretive conceptual cross section

- Fourth 3rd order cycle
- Third 3rd order cycle
- Second 3rd order cycle
- First 3rd order cycle

Solid thin arrows mark where compensational infilling has occurred, thus reversing the colors of the earlier features. Dashed circle marks a bisection (thin) of the dominant NW-SE trending thick.
Third 3rd Order Sequence

- Earlier NW-SE-oriented stratigraphic architecture disrupted by SW-NE-oriented architecture: First significant uplifts are recorded ~86.0 – 84.6 Ma
- 3 uplifts are apparent
- Stratigraphic thickss are shifted laterally: forced reorganization of depocenters
- Persistent stratigraphic thickss along flanks of TCA

Interpretive conceptual cross section

- Fourth 3rd order cycle
- Third 3rd order cycle
- Second 3rd order cycle
- First 3rd order cycle

Modified from Drake and Hawkins, in press
Fourth 3rd Order Sequence

- SW-NE-oriented architecture is more pronounced - **long-lived thinning** and less compensational infilling
- Major stratigraphic thins align with noted paleohighs (i.e., Wattenberg, Morrill County, Hartville, and Turkey Creek highs): **long-lived paleohighs**
- New stratigraphic thins emerge - possibly due to sequence boundary marking end of Niobrara Supr

**Interpretive conceptual cross section**

- Fourth 3rd order cycle
- Third 3rd order cycle
- Second 3rd order cycle
- First 3rd order cycle

Present outcrops and counties for reference

C.I. = 20 ft

Stratigraphic thick
Stratigraphic thin

MCH: Morrill County High, MWLH: Morgan-Washington County High, LAA: Las Animas Arch

Modified from Drake and Hawkins, in press
**Analogous Scale?**

**Alternative explanations:**

**Differential subsidence?**
- Salt dissolution post-dated Niobrara.

**Compaction?**
- Observed thickness patterns are dynamic; do not correlate to basin depth/morphology.

**Sediment drift?**
- Unlikely that thicks would fortuitously be located above basement uplifts (thins) like (a), so (b) is favored.

Deep-water bottom currents: Similar seafloor morphology and scale at greater depths.

**Madeira Abyssal Plain**

**Channeling:** Unconformity, bypassed sedimentation, mounded drift

- From Drake and Hawkins, in press

- Rebesco et al. 2014; Hernandez-Molina et al., 2014
Far-Field Tectonic Events during Niobrara Time

DeCelles, 2004

Chapin, 2012

Atlantic spreading rate

Paxton thrust

Magmatic flux in Sierra Nevada

Brown, 1988

Sevier Orogeny 80 Ma Laramide Orogeny

155 to 80 Ma

8 cm/yr N72E

80 to 40 Ma

14 cm/yr N40E

Kn

80 Ma

N72E

14 cm/yr

N40E

Kn

Magmatic flux in Sierra Nevada
Sevier-Laramide Transition during Niobrara Time

Regional Niobrara Isochore

- **Eastward migration of forebulge** and shifts in flexural subsidence and depozones through the Sevier Orogeny
  - **Coniacian-Santonian Paxton thrust** (e.g., Pang and Nummedal, 1995; DeCelles, 2004; White et al., 2002).
- Interaction between migrating forebulge (Sevier), TCA, Ancestral Rocky Mountains, and earliest flat-slab subduction, Laramide activity (?)
- All led to basement adjustments as **reactivation along basement shear zones** of Proterozoic origin in the WIS
  - Bring anomalous geothermal gradients – *influences maturity*
  - Recorded in Niobrara stratigraphic architecture – *influences facies and oil accumulations*

Approximate edge of Niobrara chalkiest facies

Modified from Drake and Hawkins, in press
Shear Zones and Tectonic Model for Colorado Province

- Inherited Proterozoic discontinuities play a major role in basement structure through time (Sevier and Laramide orogenies)

From Cavosie and Selverstone, 2003
Isostatic Gravity and Magnetic Anomaly Maps

Inherited Proterozoic discontinuities play a major role in basement structure through time (Sevier and Laramide orogenies). Shear zones extend into the basin, align well with uplifts and paleohighs identified in Niobrara isochrones.

Data from Kucks (1999)

Data from Bankey et al. (2002)

Modified from Drake and Hawkins, in press
Anomalous heat flow along shear zones

Magnetic highs & gravity lows are inversely related in map view, and align with elevated geothermal gradients

Magnetic highs + gravity lows suggest hot intrusive rock along deep fracture networks

Potential Fields, SW Nebraska

From Moore, 2002
Maturity is a function of two main factors:
- Geothermal anomalies
- Depth and burial history

Modified from Drake et al., 2013
Basin-Scale Petrophysical Analysis

\[ \Phi * (1 - Sw) * \text{Net Pay} * 7758 * 640 \text{ acres} = \text{OOIP (MMRBO/section)} \]

1,000,000 barrels

Objective: **reconnaissance OOIP maps**

Petrophysical cut offs: \( \Phi A = 6\% \), \( SwA = 60\% \)

*Note: does not include OM-porosity analysis of source-prone intervals*

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Modified from Drake et al., 2013

A Chalk (MMRBO/Sec) + B Chalk (MMRBO/Sec) + C Chalk (MMRBO/Sec)
Architectural Controls on Reservoir-Prone Intervals

Red arrows point to higher oil accumulations (above) that align with isochore thins in reservoir-prone subintervals (below). Dashed yellow lines frame acceptable water saturation.

Where Sw and maturity permit, PhiA_pay dominates.

Thins are co-located with hydrocarbon accumulations
  - High PhiA_pay
  - Mechanical concentration of chalk?
  - But, too thin = little pay

Modified from Drake et al., 2013
Maturity (thermal transformation) is critical; thickness less important.

Sub-intervals 3 and 5 are thin around Wattenberg, but high thermal transformation there. Note thick Sub-interval 8 along this trend.

Adequate thickness, organic richness (not addressed here), and maturity required to charge adjacent (overlying and/or overlying) reservoir-prone sub-intervals.

Modified from Drake et al., 2013

Red arrows point to isochore thicks in source-prone subintervals (below) that might play a role in oil charge of subintervals above. Dashed yellow lines frame acceptable water saturation.