Visual and Analytical Comparisons of Upper Bakken “Shale” Cores from a West-to-East Transect, McKenzie and McLean Counties, North Dakota*

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Abstract

Data from six lowermost Mississippian (Kinderhookian) upper Bakken “shale“ cores along a 52-mile-long transect in the Williston Basin in North Dakota provide a rich suite of stratigraphic and analytical information for detailed comparisons. Thickness of this silty, organic-rich mudrock varies from 14 to 21 feet with no consistent regional trend evident along the transect. A visual display alone of three slabbed cores reveals some color variations but fails to show the subtle compositional and textural components of this interval. Analytical results from all six cores, however, serve to characterize and contrast these world-class source rocks as they change from peak oil generation to thermally immature. Detrital silt, disseminated throughout the interval, occurs as scattered grains and thin, locally discontinuous laminae that are visible in the slabbed core. These eolian silt grains, along with a variety of pelagic fossil fragments and fecal pellets, settled through the stratified water column and accumulated on a mostly anoxic seafloor, although there were some minor periods of dysoxia indicated by burrowing. Mineral assemblages identified in thin sections and by SEM EDS are surprisingly diverse. X-ray diffraction results show that the major components that are relatively constant along the transect include quartz (30–50%, detrital, biogenic, and authigenic), kerogen (10–20 wt. %, mostly Type II), illite/mica (15–25%), and K-feldspar (4–8%). The constituents that vary the most include dolomite (2–13%, both detrital and authigenic), albite (2–9%), mixed-layer illite/smectite (1–17%, increasing eastward), pyrite (3–14%, all authigenic), and calcite (1–7%, mostly as skeletal fragments). Present-day as well as estimated original TOC values highlight the well-known westward increase in thermal maturity of the Upper Bakken from east to west with a few interesting exceptions close to the Nesson anticline. Corresponding organic pore development is also related to increasing thermal maturity. Elemental data from hand-held X-ray fluorescence show considerable vertical and lateral variability. The resulting chemostratigraphic interpretation of key elements has defined recognizable, geographically continuous sequences that offer new insights into depositional processes and environments.
VISUAL AND ANALYTICAL COMPARISONS OF UPPER AND LOWER BAKKEN "SHALE" & UPPER PRONGHORN "SHALE" CORES ALONG A WEST-TO-EAST TRANSECT, MCKENZIE & MCLEAN COUNTIES, NORTH DAKOTA

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UPPER BAKKEN HAND HELD X-RAY FLUORESCENCE DATA

West-to-East cross sections showing the distribution of hand held X-ray fluorescence elemental data for the Upper Bakken (A) and the Lower Bakken and the Pronghorn (B). From left to right, elemental tracks include: Cr (light brown), Zn (teal), Mo (gray), V (pink), Ni (light blue), U (light yellow), Fe (red), S (dark yellow), Al (brown), Ti (green), K (light orange), Si (bright yellow). Sequence correlations are based upon vertical profiles that reflect varying degrees of anoxic, organic, and detrital elements.

LATE DEVONIAN PALEOGEOGRAPHIC MAP OF NORTH AMERICA WITH RELATIVE POSITION OF CORES

Late Devonian paleogeographic map of North America with relative position of cores shown with the red star. Organic accumulation and preservation in the Bakken may be attributed to anoxic environments, abundant organic source and productivity, sparsity of diluting inorganic elements, rapid sedimentation and burial rates, and lack of biodegradation in the water column. (C Kaplan and Bustin, 1996)

THREE FORKS                  BAKKEN

Regional map of the Williston Basin showing major structural features as well as the study area. (from http://en.wikipedia.org/wiki/File:WillistonStratCol.jpg)

UPPER BAKKEN STRUCTURE MAP OF N. DAKOTA AND MONTANA

Study area shown in the rectangle contains the locations of the six cored wells analyzed for this core poster presentation. Three of the cores are displayed in a West-to-East orientation.

UPPER BAKKEN ISOCHORE MAP

Upper Bakken Tmax closely mirrors the Upper Bakken structure map above, except where a thermal anomaly appears over the area of the Nesson Anticline (outlined). Note that maturity increases to the west.

COMPARISON OF VOL % X-RAY DIFFRACTION DATA FROM BAKKEN TO THREE FORKS

Most of the available XRD data was measured in volume percent shown to the right. In the Upper and Lower Bakken intervals, much of the red "total other minerals" track is composed of organic material which can be computed as weight percent XRD.

West-to-East log cross section of the six cored wells analyzed for this presentation. Actual cores on display are marked on the section with a blue dot.

Track 1: Shaded gamma ray curve (0 to 800 API scale); Caliper (dashed green on 6 to 16" scale).
Track 2: Core TOC (black dots on 0 to 20% scale). Track 3: Measured depth (in feet); PEF (dashed pink on 0 to 10 B/E scale). Track 4: Deep resistivity (black with shaded red >20 ohm-m) on 0.2 to 2000 ohm-m scale.
Track 5: Density porosity (black and shaded red >6% on LS matrix) on 0 to 20% scale; Core porosity (black dots on 0 to 20% scale); Neutron porosity (blue dashed on 0-20% scale).
Track 6: Core oil saturation (green dots on 0 to 100% scale); Core water saturation (blue dots on 0-100% scale).
VISUAL AND ANALYTICAL COMPARISON OF UPPER BAKKEN "SHALE" CORES FROM A WEST-TO-EAST TRANSECT, MCKENZIE AND MCLEAN COUNTIES, NORTH DAKOTA

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**UPPER BAKKEN UNCONNECTED NANO-POROSITY WITHIN ORGANIC MATTER**

*Average TOC: 10.3%*

Graph at right illustrates the increase in maturity from east to west as represented by lower TOC and ILLITE/SMECTITE. Values for higher thermal maturity are interpreted to be due to differences in organic maturation.

**LOWER BAKKEN UNCONNECTED NANO-POROSITY WITHIN ORGANIC MATTER**

*Average TOC: 10.9%*

Graph at right illustrates the increase in maturity from east to west as represented by lower TOC and ILLITE/SMECTITE. Values for higher thermal maturity are interpreted to be due to differences in organic maturation.

**OTHER CHARACTERISTICS OF THE UPPER BAKKEN**

The Upper Bakken is a black, shale, massive, organic-rich mudrock or kerogenite with relatively low clay content.

- **Detrital Suite**
  - A wide range of detrital minerals (quartz, feldspars, micas, chlorite, titanite, biotite, muscovite, and chlorite) and diagenetic minerals (quartz, calcite, dolomite, pyrite, and illite) in the silt-sized fraction.
  - Detrital silt laminae are sparse, thin, laterally continuous (except where disrupted by compaction fluids), and deposited from eolian dust storms rather than bottom traction currents.
  - Redox elements (U, Mo, V, Ni) are abundant as is diagenetic pyrite (FeS2) locally.

- **Anoxic Suite**
  - Typical silt lamination throughout.
  - Deposition occurred below storm wavebase under anoxic conditions interrupted by brief periods of dysoxia near the base and top of interval.

- **Organic Suite**
  - Siliceous, clay-rich kerogenite with radiolarians, Tasmanites, and calcitic fossil fragments.
  - Radiolarians, phosphatic fossil fragments, and phosphatic fossil fragments are locally common but not abundant. Tasmanites were filled with authigenic minerals (pyrite, calcite, silica) prior to compaction. Tasmanites are "burned out" to the west in areas of higher thermal maturity.
CT Scans of Slabbed Core from 3 Wells in Transect (Linseth, George Evans, MHA 2-05-04H):

CT Scan Key Points:
1. Density-based images provide bulk composition and textural differences between the lower Bakken and upper Pronghorn in the transect.
2. The lower Bakken and upper Pronghorn contact is easily recognizable on e-logs, but visual differences are subtle.
3. The upper Pronghorn is classified as a shaly organic mudstone.
4. The lower Bakken and upper Pronghorn contact is easily recognizable on e-logs, but visual differences are subtle.
5. The lower Bakken and upper Pronghorn contact is easily recognizable on e-logs, but visual differences are subtle.
6. Key differences between the upper Pronghorn and the lower Bakken include (Peterson based on averages from Bernice):
   - Lower TOC (5% Pronghorn vs. 16% lower Bakken), Hydrogen Index (10 vs 23), and Oxygen Index (30 vs 15).
   - More clay (4% vs 9%), hematite (1% vs 6%), and carbonate (4% vs 9%).
   - Slightly more organic carbon.
   - More phosphatic fossil debris including conodonts.
   - More abundant silt laminae.
   - Detrital and biogenic quartz.
   - Lack of current transported beds.
   - Sparse fossil debris that appears to rafted into basin rather than transported.

Photomicrographs (Bernice, Linseth, George Evans):

Photomicrographs Key Points:
1. Photomicrographs highlight the mineralogical and textural similarities and differences between the upper Pronghorn, lower Bakken and upper Pronghorn.
2. Visually see more silt laminae, calcite fossil fragments, filamentous/flattened kerogen particles as well as lower organic content and randomly distributed quartz in the upper Pronghorn.
3. Visually see key similarities randomly distributed silt grains, detrital and biogenic quartz, lack of current transported beds, sparse fossil debris that appears to rafted into basin rather than transported into the basin.
4. Along the W-E transect overall XRF in the upper Pronghorn was higher than the lower Bakken and Pronghorn.
5. The upper Pronghorn essentially has no Mn, Ti and very low Fe, Mg, Na, Si.
6. This data indicates that the upper Pronghorn was essentially in a basinal setting below storm wave base.
7. The upper Pronghorn was deposited in a basinal setting below storm wave base.
8. Slightly more organic carbon is preserved in the upper Pronghorn.
9. A lower TOC and hydrogen index in the upper Pronghorn supports a thicker basinal water column where increased oxidation and biodegradation of organic matter affected organic matter preservation and quality.
10. Vertical variability of geochemical parameters is likely due to redox conditions, static input, and organic carbon flux during deposition.

Discussion:
1. The upper Pronghorn was deposited in a basinal setting below storm wave base.
2. The water column during upper Pronghorn deposition was thicker compared to the lower Bakken and Pronghorn deposition.
3. As the transgression continued into lower Bakken deposition, the rate of organic input increased and the reduction zone moved shallower which increased the organic water column and allowed for more organic matter accumulation and preservation.
4. Lower TOC and hydrogen index in the upper Pronghorn supports a thicker basinal water column where increased oxidation and biodegradation of organic matter affected organic matter preservation and quality.
5. Detrital Suite:
   - Organic Suite:
   - Anoxic Suite:

Key Poster Points:
1. The upper Pronghorn is classified as a shaly organic mudstone.
2. The lower Bakken and upper Pronghorn contact is easily recognizable on e-logs, but visual differences are subtle.
3. Key differences between the upper Pronghorn and the lower Bakken include (Peterson based on averages from Bernice):
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   - More phosphatic fossil debris including conodonts.
   - More abundant silt laminae.
   - Detrital and biogenic quartz.
   - Lack of current transported beds.
   - Sparse fossil debris that appears to rafted instead of transported into basin.

Depositional Models:
1. Upper Pronghorn deposition is likely associated with basin filling processes.
2. Lower TOC and hydrogen index in the upper Pronghorn supports a thicker basinal water column where increased oxidation and biodegradation of organic matter affected organic matter preservation and quality.