[PS]Integrated Chemostratigraphy of the Bakken Formation, Williston Basin, North Dakota-Montana*

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Abstract

The Bakken Formation of the Williston Basin is one of the largest hydrocarbon producers in the U.S. Although several studies have characterized the middle Bakken, the mudrocks of the upper and lower Bakken are understudied. The upper and lower Bakken are both low-oxygen, high-TOC, visually cryptic mudrocks. Like most mudrock successions, however, these rocks are complex mineralogical assemblages that contain a detailed record of the depositional and oceanographic history of the basin. Integration of geochemical analysis, visual core description, and borehole geophysical logs reveals marked changes both within and between the upper and lower Bakken. These observations offer new insights into changes in sediment flux and sea floor oxygenation during Bakken deposition. The goal of this study is to define variations in the rock attributes of the upper and lower Bakken that may relate to reservoir performance, e.g. organic matter distribution, pore characteristics, and brittleness. These attributes correspond to mineralogy and sediment type, which can be defined at high resolution by X-ray fluorescence major element analysis and X-ray diffraction techniques. XRF data provide a superior record of vertical mineralogical facies stacking. XRF trace elements reveal information about oceanographic oxygenation and circulation, which affects the production and preservation of organic matter. Stable isotopes of nitrogen and carbon will help define changes in nutrient supply, which may relate to significant changes in TOC and mineralogy, and serve as a potential basis for local and regional correlation. The study is based on seven cores from North Dakota and Montana. Four of the cores form an east-west cross section in the southwestern part of the basin, which is an approximate proximal to distal succession; the other three cores offer off-axis support. Preliminary study of thin sections from these cores reveals microfractures and some sedimentary structures such as thin laminations, along with abundant pyrite, particularly in the lower Bakken. Bioturbation is rare in the upper and lower Bakken, but common in the coarser-grained middle Bakken, which shows that it represents a much higher-energy, better-oxygenated environment than the mudrocks. Integrated characterization of the Bakken mudrocks provides important clues about both basin history and refined targeting for hydrocarbon exploration.

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Introduction

The Bakken Formation is a Devonian-Mississippian mudstone-siltstone succession that acts as a major source rock and oil producer in the Williston intracratonic basin. It is generally divided into three members: the descriptively named Upper, Middle and Lower Bakken. In some cores a silty-dolomitic member called the Pronghorn is also present.

The Upper and Lower Bakken are black, laminated mudrocks with little visible structure. Pyrite lags and occasional coarser-grained laminae are the most visible features. The Middle Bakken is a siltstone to fine sandstone and includes intervals dominated by current structures and intervals in which evidence of bioturbation dominates.

The Bakken Formation's high degree of variability in major and trace elements can be used to understand the changing oceanographic and sedimentological regimes under which it was deposited. This poster focuses on the Charlie Sorenson 17-8 3TFH core, which was taken by Statoil.

Regional Setting

Figure 1. Paleogeographic reconstruction of North America during the late Devonian (Blakey 2013). Modern political boundaries are shown in gray. Arrow points to the study area. Note that the Bakken was deposited slightly south of the equator, potentially affecting water circulation due to a decreased thermocline. Exposed areas to the south and east provide the most likely source of detrital sediment.

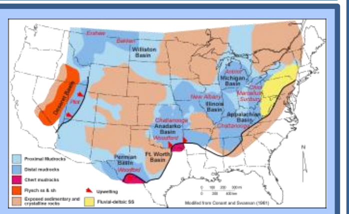


Figure 2. North American tectonics and depocenters during the Devonian. Modified by S. Ruppel from Conant and Swanson (1961).

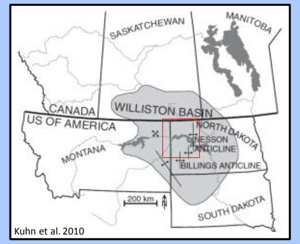


Figure 3. Geologic context and major structural features of the Williston basin. Study area is in red.

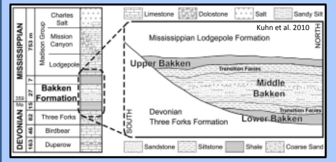


Figure 4. Schematic stratigraphic section of the Bakken formation, including interpreted Bakken extent as a depositional limit onlapping the basin margin. The Bakken formation in this area unconformably overlies the Three Forks formation and conformably underlies the Scallion member of the Lodgepole limestone.

Study Area

The cores used in this study come primarily from northwestern North Dakota, with an additional two cores in Montana.

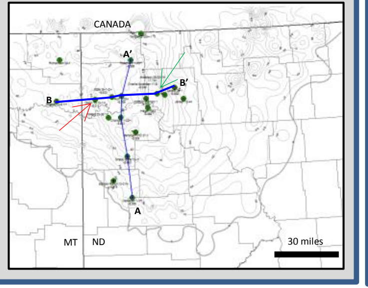
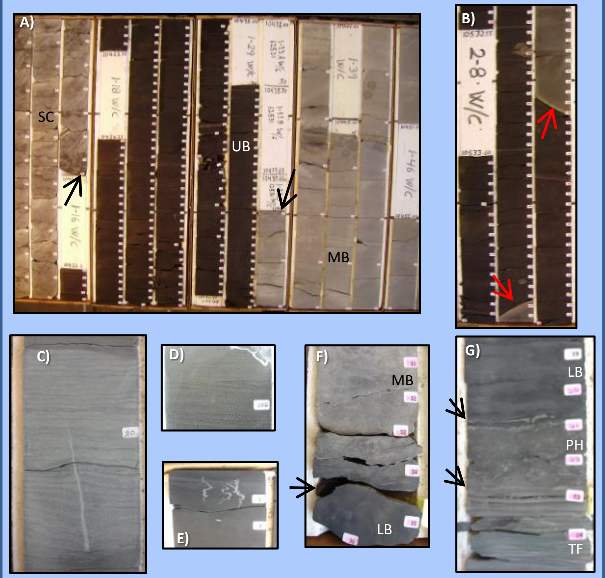


Figure 5. Isopach map of total Bakken Fm., courtesy of Julie Lefever and the North Dakota Geological Survey. Green dots show the location of 18 cores used in this study. Green arrow highlights the Charlie Sorenson 17-8 3TFH core location. Blue lines show cross sections A-A' and B-B'. Red arrow points to the Olson 10-15-1H well, location of the thin sections shown on Panel 2.



SC = Scallion member, Lodgepole Fm. MB = Middle Bakken member PH = Pronghorn member
UB = Upper Bakken member LB = Lower Bakken member TF = Three Forks Fm.

Figure 6. Core photos from Charlie Sorenson 17-8 3TFH. Black arrows point to contacts. Labels show XRF sample locations; pink highlights show powder sample locations (XRD, TOC, isotopes). **A)** Scallion, Upper Bakken and Middle Bakken members. 10414-10453 ft. **B)** Red arrow points to large calcite concretion, 18" maximum cored thickness, LB. 10538 ft. **C)** Wavy laminae, MB. 10486.7 ft. **D)** Cross-stratified ripple features, MB. 10449.5 ft. **E)** Burrowed MB-LB contact, incl. pyritized fossil fragments. 10520.8 ft. **F)** Ptygmatic fractures accompanying coarser-grained laminae, LB. 10550 ft. **G)** Contacts between LB, PH, and TF. 10575.8 ft.

Data and Methods

A total of 961 data points in the Charlie Sorenson 17-8 3TFH core were collected with a handheld Bruker Energy-Dispersive X-Ray Fluorescence (ED-XRF) instrument at a resolution of 1 inch in the shales and at 2-6 inches in the other parts of the system. The handheld XRF instrument collects a suite of 26 major and trace elements which are calibrated to a mudrock reference standard (Rowe 2012). These elemental data are composed of major elements (Na-Fe), which largely correspond to mineralogy, and trace elements (Ba-Mo), which respond to changes in oceanographic conditions.

A statistical method called hierarchical cluster analysis was performed using TIBCO Spotfire software. This method was developed for use in This method groups samples by degree of similarity over the whole suite of 26 elements and helps identify high-frequency variations in chemical composition. These 'clusters,' when combined with X-Ray diffraction mineralogy, TOC values, and organic carbon and nitrogen isotope data, form the basis for defining facies within the Bakken mudrocks. The relationships between clusters are shown in a dendrogram (Figure 9).

246 powder samples were drilled for TOC, X-Ray Diffraction (XRD), and organic carbon and nitrogen isotope analysis. XRD 2θ diffraction values were calibrated to an international standard and a customized Bakken mineral library was built. Figure 8 shows an example of an XRD diffraction spectrum.

The core focused on this panel is part of a larger dataset of 18 cores located in western North Dakota and eastern Montana (Figure 5). Data for five of these cores were collected by Maldonado (2012) at lower resolution; data for the remaining twelve cores were collected at the same resolution as the Charlie Sorenson.

Panel 2 shows seven facies within the Upper, Lower, and Pronghorn members defined by hierarchical cluster analysis over the entire 18-core dataset; these facies are not the same as those shown in Panel 1.

Chemostratigraphy

Elemental Proxies – Mineralogy and Oceanographic Conditions

	Major Elements - Mineralogy
Al (K, Na)	Clay minerals (illite), feldspars
Si	Quartz, clay minerals, feldspars
Ca	Calcite, dolomite
Mg	Dolomite, clays
Ti (Zr)	Detrital material; ilmenite, rutile, zircons
P	Apatite (bone), collophane, francolite, fish scales
S	Pyrite, barite, gypsum

	Redox-sensitive Trace Elements – Oceanographic Conditions and Preservation Potential
U	Often partitions with organic material
V	Suboxia to anoxia
Mo	Anoxia-euxinia

Figure 7. Major elements reflect the mineral makeup of a rock. Trace elements record organic productivity, sediment anoxia, and water restriction.

X-Ray Diffraction - Mineral Species

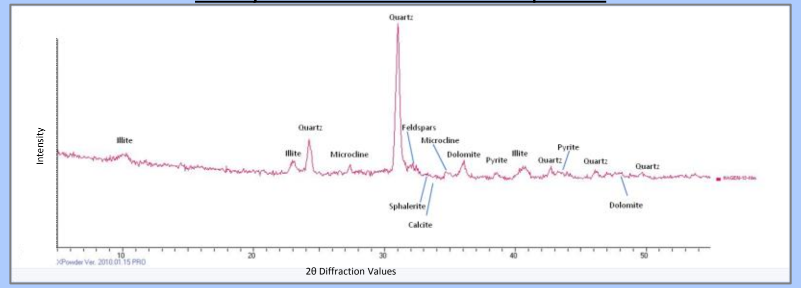
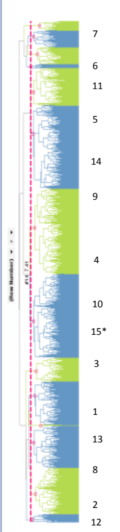


Figure 8. Example of an X-Ray Diffraction spectrum. Major minerals in the Bakken include quartz, illite, potassium feldspar, and dolomite.

Hierarchical Cluster Analysis



Average Concentration of Elements in Each Cluster

Statistical Clusters	% Al	% Si	% Ca	% Mg	% P	% S	% Ti	Zr (ppm)	U (ppm)	V (ppm)	Mo (ppm)
1 (n = 54)	7.36	24.25	2.50	0.92	0.06	1.36	0.29	124.11	26.86	81.69	56.12
2 (n=51)	6.53	27.00	1.35	0.94	0.06	1.94	0.28	109.84	70.87	1279.90	498.48
3 (n=132)	5.32	29.69	1.59	0.96	0.10	2.06	0.24	93.86	66.03	301.20	253.32
4 (n=106)	3.99	32.64	1.38	0.83	0.11	2.08	0.20	75.48	53.34	315.71	243.38
5 (n=113)	3.57	20.58	11.79	1.14	0.04	0.66	0.21	280.44	1.96	53.10	22.25
6 (n=47)	1.89	10.09	25.23	1.05	0.02	0.61	0.10	127.00	0.00	56.01	7.22
7 (n=79)	0.21	4.16	34.04	1.05	0.00	0.54	0.03	37.15	0.00	47.97	1.36
8 (n=77)	5.31	29.63	1.68	0.95	0.08	1.85	0.24	94.57	61.60	1037.17	437.67
9 (n=121)	3.08	35.12	0.83	0.55	0.09	1.46	0.16	61.95	44.04	354.37	204.17
10 (n=82)	3.88	32.48	1.72	0.85	0.09	1.60	0.20	79.15	51.08	842.30	335.66
11 (n=27)	3.30	13.27	16.10	5.44	0.004	0.46	0.17	110.64	0.00	57.04	5.87
12 (n=6)	4.72	27.90	3.02	0.98	0.10	2.37	0.22	82.65	67.70	571.50	343.52
13 (n=44)	6.95	25.61	2.43	1.09	0.06	1.52	0.29	116.63	42.80	1128.24	205.16
14 (n=20)	5.79	18.23	9.38	2.67	0.02	0.70	0.27	132.84	5.31	21.16	6.89
15 (n=1)	1.84	28.15	0.78	7.71	0.71	16.31	0.10	56.60	8.63	313.50	61.02
Core average	**4.17**	**25.45**	**7.17**	**1.09**	**0.07**	**1.44**	**0.20**	**110.30**	**37.42**	**419.26**	**195.86**

Figure 9. **Left)** Dendrogram of hierarchical statistical clusters. Samples are not in stratigraphic order but grouped by degree of overall chemical similarity . **Above)** Table showing the number of samples in each cluster and average concentrations of several elements with a strong correlation to mineralogy or redox conditions.

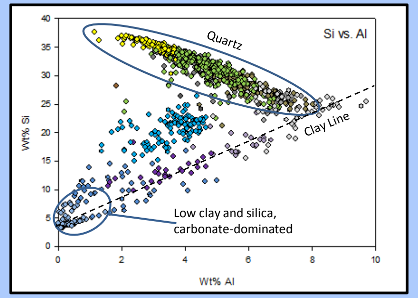


Figure 10. Crossplot of Aluminum and Silicon from XRF. Positive correlation is interpreted as clay minerals (clay line); a trend towards the silicon axis represents quartz. Colored by the facies scheme shown in Figures 11 and 12.

Figure 11 shows that the Middle Bakken member is dominated by three main facies, shown in shades of blue. Thin section analysis reveals that abundant quartz is present in the Middle Bakken as detrital silt and very fine sand-sized grains (Figure 12).

The Upper and Lower Bakken, by contrast, are dominated by shades of green, gray, and gold. Most of these samples trend away from the 'clay line' in Figure 10, but do not significantly overlap with the detrital quartz-dominated Middle Bakken. This suggests that much of the quartz in the Upper and Lower Bakken is biogenic in nature and unaccompanied by significant clay.

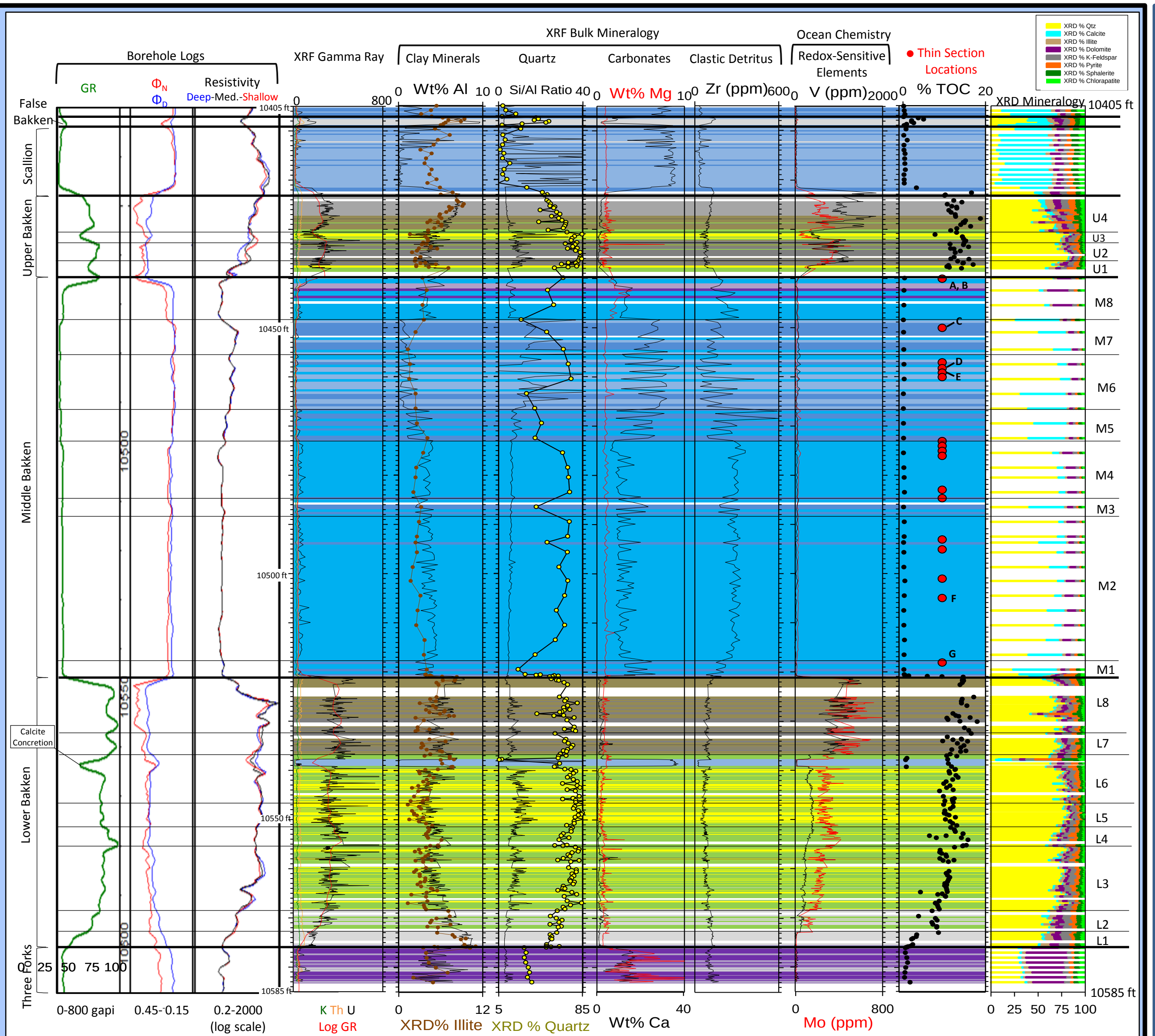


Figure 11. Chemostratigraphy from XRF, TOC, and XRD data. X marks show XRD sample locations. TOC values (black dots) correlate well with indicators of anoxia (V, Mo). Background color shows vertical distribution of samples within the facies developed through hierarchical cluster analysis.

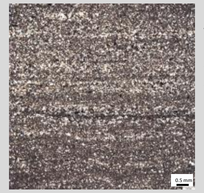
Facies Key

Name	Interpreted Mineralogy (XRF + XRD)
Euxinic Argillaceous Siliceous Organic-rich Mudstone	Clay minerals, some quartz
Euxinic Siliceous Mudstone	Quartz, clay minerals
Euxinic Organic Phosphatic Siliceous Mudstone	Quartz, clay minerals, phosphates
Euxinic-dysoxic Organic Biogenic-Siliceous Mudstone	Quartz-dominated
Dysoxic Detrital Argillaceous Mudstone	Clay minerals, detrital quartz
Oxic Detrital Argillaceous Mudstone	Clay mineral-dominated, some quartz
Dolomitic Mudstone-siltstone	Dolomite, some clay minerals, phosphates
Detrital Argillaceous Dolomitic Mudstone-Siltstone	Dolomite, clay minerals, quartz, feldspars
Calcite-cemented siltstone	Quartz, calcite cement, dolomite
Mixed carbonate-clastic siltstone	Calcite, detrital material, quartz
Limestone	Calcite, phosphates, clay minerals

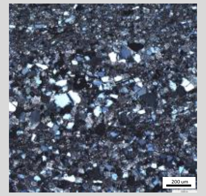
Facies names were defined by combining hierarchical cluster analysis of XRF elemental concentrations with XRD mineralogy, visual description, and TOC data. This facies scheme highlights the high-frequency facies changes within the mudrocks of the Upper and Lower Bakken members.

Thin Section Petrography

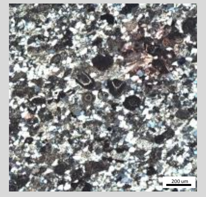
Figure 12. Photomicrographs of thin sections from the Middle Bakken interval. Thin section locations are shown in red on the TOC plot in Figure 11.



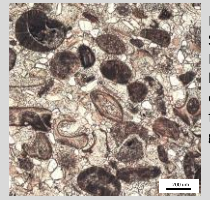
A) 10440.2 ft. XPL.. Laminated quartz siltstone to fine sandstone.



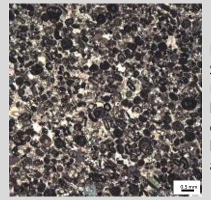
B) 10440.2 ft. XPL. Silty dolomitic quartz sandstone. Includes rare feldspars and muscovite fragments.



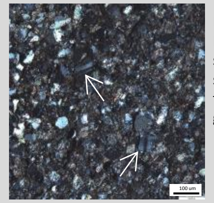
C) 10450.2 ft. XPL. Very fine dolomitic quartz sandstone. Includes scattered fossil fragments.



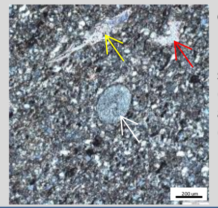
D) 10457.2 ft. PPL.. Skeletal grainstone. Fossils include brachiopod spines, ooids, and ostracodes; fine sand-sized quartz grains are also present.



E) 10458.4 ft. XPL.. Skeletal grainstone. Includs crinoids, brachiopod spines, ooids, and scattered bryzoans and green algae.



F) 10505.1 ft. XPL. Dolomitic quartz siltstone-fine sandstone with rare twinned plagioclase grains (white arrows).



G) 10518.2 ft. XPL.. Basal Middle Bakken. Dolomitic quartz siltstone with echinoid (white), crinoid (red), and brachiopod (yellow) fragments.

Observations and Interpretation

Lower Bakken
- can be subdivided into 8+ distinct units in this core (thin black lines, L1-L8)
  - L1 and L2: transitional facies from heavily dolomitized Three Forks
    - L1: comparatively low TOC values and redox-sensitive elements
      - suggest depositional conditions not fully anoxic; possibly episodic
  - L3-L6: Clay minerals inversely correlated with quartz (Figure 10, trend towards y-axis)
    - L3 and L4 dominated by facies enriched in phosphorus
      - may imply significant organic detritus, e.g. fish bones
    - High TOC, Mo, and V values imply overall reducing environment
    - L6 includes rounded carbonate concretion 1.5-2 ft in diameter
      - Deformed laminae above and below suggest early diagenesis
  - Units L7 and L8 mineralogically similar to L1
    - similar sediment at beginning and end of Lower Bakken deposition, but dissimilar conditions at the sediment-water interface

Middle Bakken
- XRD data and thin sections (Figure 12) show dominantly siliceous character with a few, thin limestone beds
- Units M5-M7 show ooid-crinoid-brachiopod grainstone facies interbedded with quartz silt and fine sand-dominated facies
- Dolomite rhombs visible in all detrital quartz-dominated thin sections from the Middle Bakken, esp. uppermost unit (M8)

Upper Bakken
- Just above base to top, increasingly argillaceous and decreasingly siliceous
  - Corresponding increasing trend in resistivity may or may not be related
- TOC not strongly correlated with XRD mineralogy
- U3: redox-sensitive elements and TOC plummet, indicating a relatively well-mixed water column or increased sediment influx
- Decreasing trend in redox-sensitive elements from U2 to U3; in U4 V reverses trend but Mo does not
  - TOC remains high; combined with enrichment in V suggests dysoxic bottom waters
  - clay content, calcite, and dolomite increase as quartz drops off
  - Probable transitional environment into oxygenated conditions for Lodgepole deposition.

Basal Bakken Facies

Figure 13. Photomicrographs of the basal Lower Bakken-upper Pronghorn in the Olson10-15-1H well (red arrow, Figure 5), between the Rogney 17-8 1H and the State 36-1 wells on cross section B-B'.

Figure 13A. 10658.5 ft. PPL. Laminated mudrock grading into very fine sandstone.

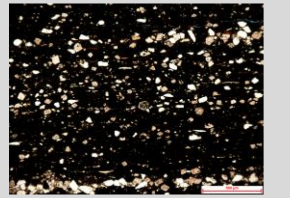


Figure 13C. 10658.5 ft. PPL. Abundant silt-sized euhedral dolomite rhombs mix with poorly rounded, elongate quartz grains and scattered phosphates.

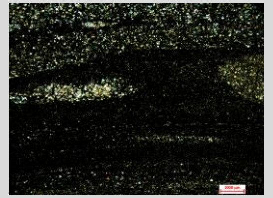


Figure 13B. 10658.5 ft. XPL. Lenticular sandstone intervals suggest presence of burrowing organisms.

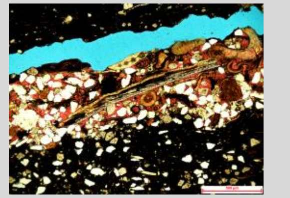
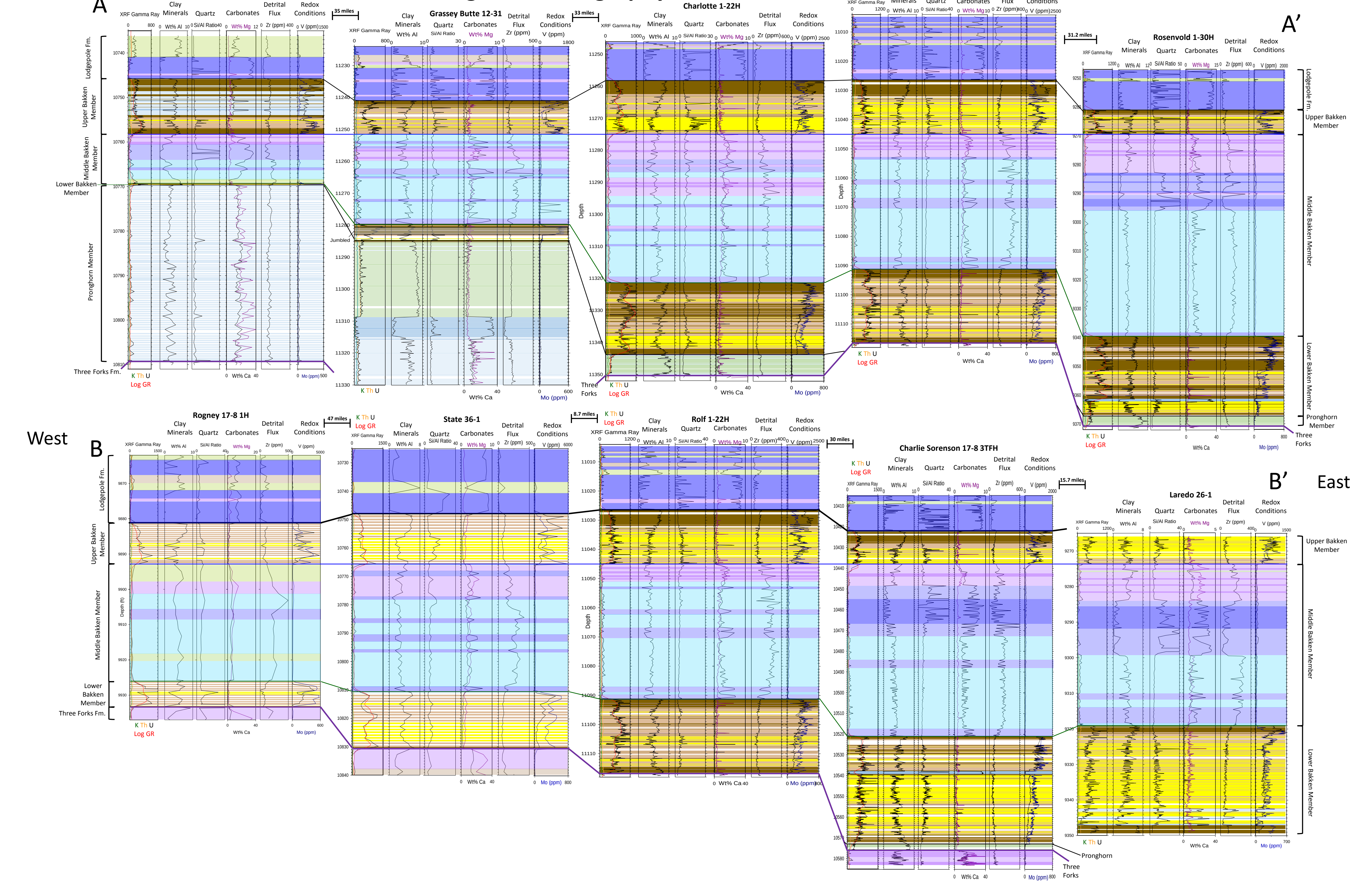


Figure 13D. 10658.5 ft. PPL. Fossiliferous zone typical of the Pronghorn-Lower Bakken transition. Quartz and dolomite dominate the overall grain composition.

Regional Stratigraphy



Bureau of Economic Geology

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Mudrock Facies

Upper, Lower, Pronghorn Members

- n=325 Argillaceous limestone-dolostone
- n=1288 Euxinic-suboxic argillaceous organic-rich mudrock
- n=1639 Euxinic organic-rich siliceous mudrock
- n=1171 Authigenic/biogenic siliceous mudrock
- n=38 Phosphatic dolostone
- n=235 Argillaceous (oxic) mudstone-siltstone
- n=88 Limestone

Non-mudrock facies

Lodgepole, Middle Bakken, Three Forks

- Moderately argillaceous quartz siltstone-fine sandstone with occasional calcareous allochems
- Mixed argillaceous-calcareous muddy facies
- Dominantly argillaceous facies
- Dominantly calcareous facies
- Limestone; in the Middle Bakken, mixed detrital quartz and abundant calcareous allochems, frequently interbedded as thin grainstones and siltstone-sandstones
- Heavily dolomitized siltstone-fine sandstone; dolomite frequently present as euhedral rhombs
- Dolomite siltstone-fine sandstone

Discussion

Hierarchical cluster analysis of the mudrocks (Upper, Lower, and Pronghorn Members) of all 18 wells (4,860 samples) and grouped into seven clusters shows that three facies dominate the Upper and Lower Bakken (Yellow, dark brown, light brown). The Pronghorn, where present, is mineralogically distinct even where it is visually indistinguishable from the Lower Bakken and is dominated by two facies (green and light blue). The seventh, dolomitic facies (purple) is volumetrically insignificant.

Lower Bakken

- Basal Bakken is highly argillaceous
- Frequently followed by a highly siliceous interval and then overall increasing clay content up to the top of the interval
- Siliceous interval likely dominated by biogenic silica which is not diluted by significant detrital input
- Increase in argillaceous fraction may represent decreasing water depth leading up to the Middle Bakken
- Anoxia (Mo and V) increases through section right up to the contact with the middle Bakken; likely poor water circulation
  - major exception is in brief carbonate-rich features in three northeasternmost cores; also 3 others not shown to N and E
  - Diagenetic features that may not represent oxic conditions

Middle Bakken

- Abrupt change at the base of the Middle Bakken; usually a heavily burrowed, muddy-silty interval
- Significantly more calcareous, heavy influence of detrital silt in thin section (Figure 12G, panel 1)
- Zirconium content (detrital proxy) also shows marked increase
- Probable effect of carbonate and detrital dilution of background sedimentation which dominated in the Lower Bakken
- Middle Bakken generally low-clay, but 3 northwest cores show very distinct low-clay, high-carbonate interval in upper half
  - Same cores as include carbonate features in Lower Bakken
  - Thin sections from the Charlie Sorenson indicate that high-carbonate beds may be skeletal grainstones composed of transported material

Upper Bakken

- Basal Upper Bakken generally mixed siliceous-argillaceous facies; frequently incorporates significant dolomite
- Tends to grade up into the most siliceous facies, esp. near basin center
- More (detrital) clay near basin edge
- Top 1/3 Upper Bakken in most cores shows significant increase in relative abundance of clay minerals to siliceous material
- Similar trend to Lower Bakken; increase in detrital material suggests more proximal sediment source
- Towards center of deposition (e.g Charlotte core) behavior of Mo and V also diverges in upper 1/3 of Upper Bakken
- Suggests a shift to generally suboxic conditions over true euxinia in the leadup to the deposition of the Lodgepole

Though all of the Bakken members are dominantly siliceous, the variance in sediment type tells a story about source, proximity, and energy during the Devonian-Mississippian transition. The more distal Upper and Lower members both appear to record maximum water depth or minimum detrital sediment flux near the base of the section, but increasing redox indicators, especially in the Lower Bakken, suggest that any decrease in water depth was insufficient to affect bottom water circulation until very near the to of the section. The Upper Bakken in several cores tells a slightly different oxidation story; while still dominantly anoxic, several cores suggest a progressive decrease in anoxia to suboxia in the upper part of the Upper Bakken.

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