PS Petrophysical, XRF Elemental, and Geomechanical Comparison of the Greenhorn and Niobrara Formations, Wattenberg Field, Denver Basin*

Steve Sonnenberg[1], John D. Humphrey[1], Hannah Durkee[1], and Kazumi Nakamura[1]

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[1]Colorado School of Mines, Golden, Colorado (ssonnenb@mines.edu)

Abstract

The Niobrara and Greenhorn formations are two carbonate intervals within the Upper Cretaceous strata of the Western Interior Basin. The carbonates are dominantly coccolith/foraminiferal chalks and shaly chalks/marls. The Niobrara is subdivided into four main chalk benches (A, B, C, and Fort Hays). The Greenhorn is subdivided into the Bridge Creek Limestone, Hartland Shale, and Lincoln Limestone members. The limestone members are foraminiferal chalks and shaly chalks/marls. These two formations are compared to each other on the basis of petrophysical, XRF elemental, and geomechanical data. The chalk beds in the Niobrara (A, B, C, Fort Hays) have relatively low abundances of detrital-related elements (Al, Ti, K, Si) and elevated values of the biogenic indicator element (Ca). The Bridge Creek Member of the Greenhorn has similar low detrital elemental indicators and elevated Ca values (chalk indicator). The Lincoln Limestone Member has higher values of the detrital indicators, lower values for Ca, and thus is more clay rich. From a petrophysical analysis, the Bridge Creek is similar to the chalk beds in the Niobrara. The Bridge Creek has elevated resistivity and similar Neutron-Density porosity readings. The Lincoln Member has lower resistivity and separation in the Neutron-Density curves, indicating an increase in clay content. Poisson's Ratio and Young's Modulus data are also compared between the Niobrara and Greenhorn formations. The Bridge Creek has elevated and similar Young's Modulus values compared to chalk beds in the Niobrara. The brittleness index for the Bridge Creek is also similar to the Niobrara chalk beds. The interpretation of the well-log geomechanical data suggests that the Bridge Creek Member is more brittle than the Lincoln Member and is similar to Niobrara chalk beds. This comparison suggests that the Bridge Creek is similar to the Niobrara chalk beds and should be targeted as a possible unconventional play.

References Cited

Gilbert, G.K., 1895, Sedimentary measurement of geologic time: J. Geol., v. 3, p. 121-127.

Hattin, D.E., 1979, Stratigraphy and depositional environment of Greenhorn Limestone (Upper Cretaceous) of Kansas: Kansas Geological Survey, Bulletin 209, 128 p.

Kauffman, E.G., 1969, Cretaceous marine cycles of the western interior: The Mountain Geologist, v. 6, p. 227-245.

Lockridge, J.P., and R.M. Pollastro, 1988, Shallow Upper Cretaceous Niobrara gas fields in the eastern Denver Basin, *in* S.M. Goolsby, and M.W. Longman, (eds.), Occurrence and petrophysical properties of carbonate reservoirs in the Rocky Mountain region: RMAG Guidebook, p. 63-74.

Longman, M.W., B.A. Luneau, and S.M. Landon, 1998, Nature and Distribution of Niobrara Lithologies in the Cretaceous Western Interior Seaway of the Rocky Mountain Region: RMAG, v. 35/4, p. 137-170.

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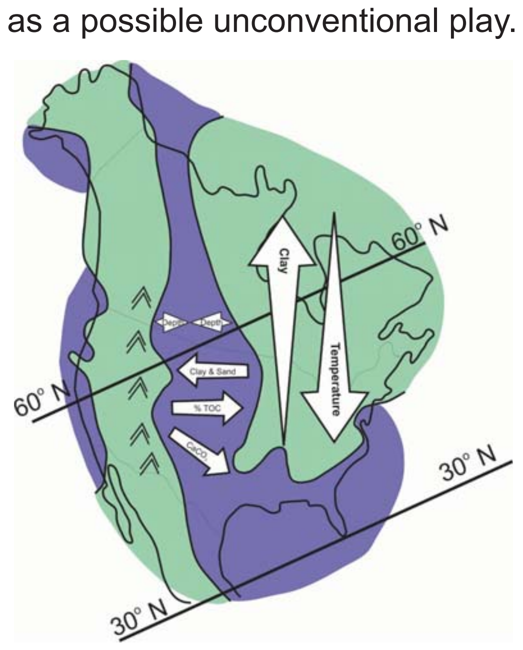
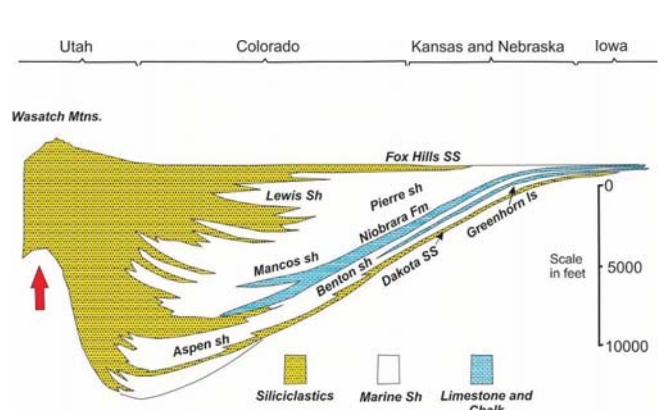
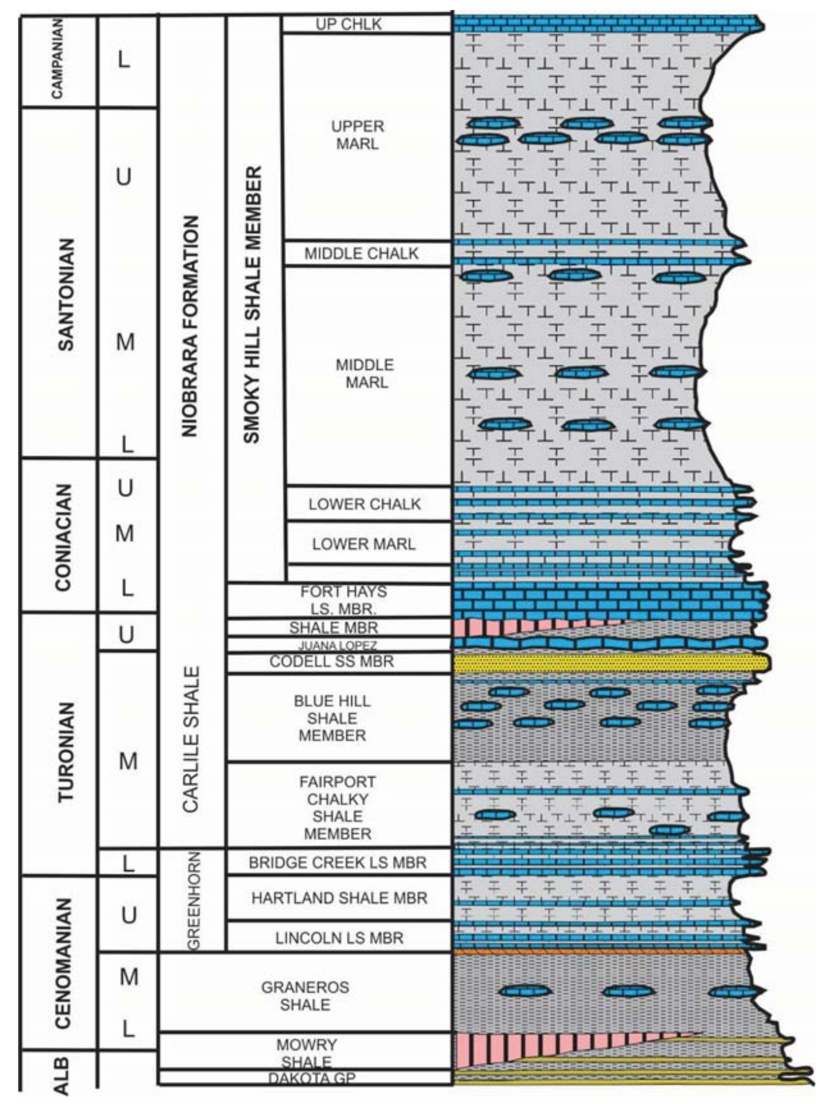


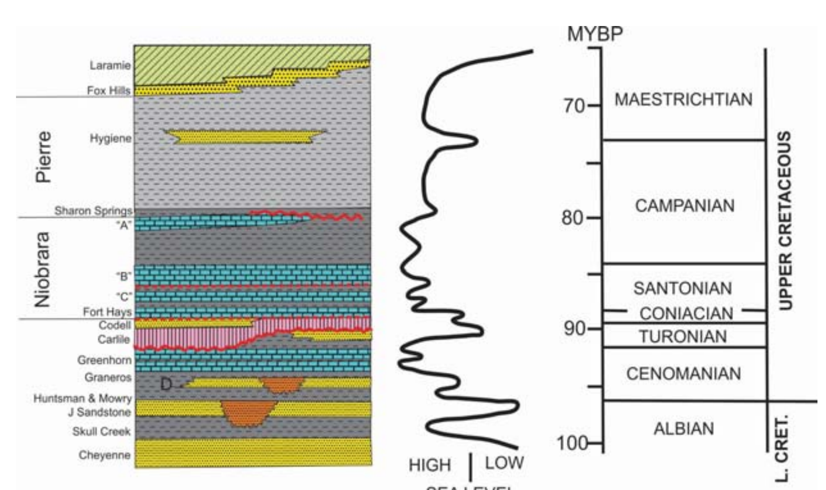
- ***Western Interior Cretaceous Basin Niobrara time (Longman et al., 1998)***



- ***Cross section across WIC basin showing Cretaceous strata.***



- ***Stratigraphic Column Cretaceous Formations Eastern Colorado (Kauffman, 1969)***

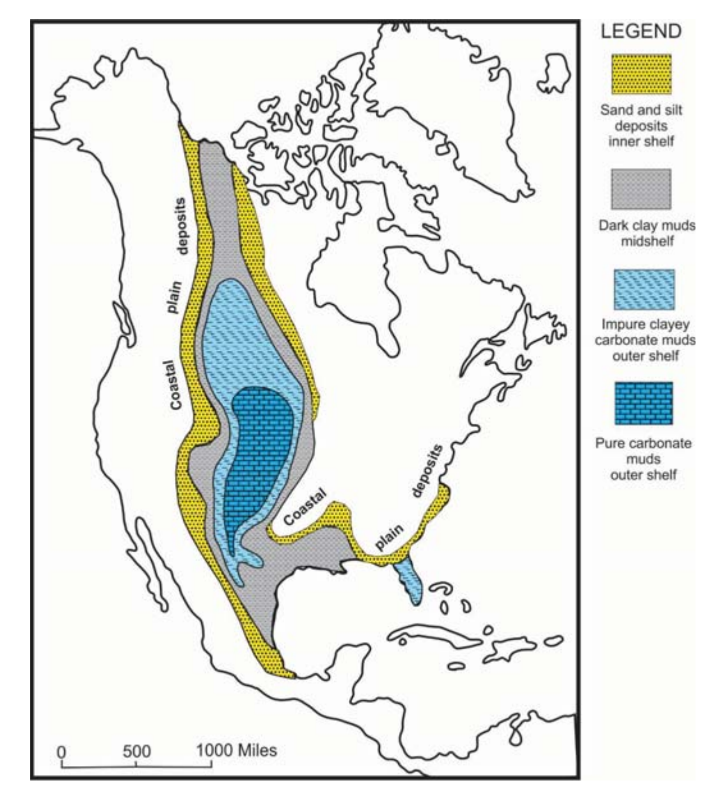


- ***Sea level curve for Cretaceous Formations, Denver Basin.***

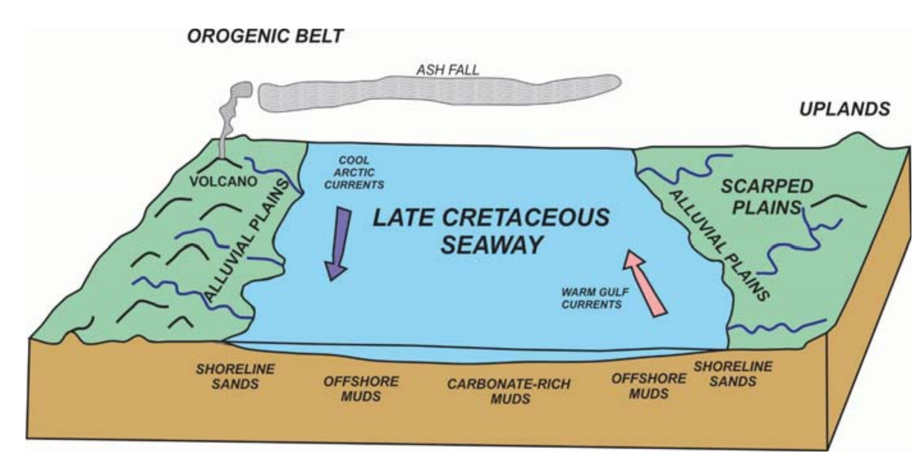
❖ Greenhorn Stratigraphy

Greenhorn

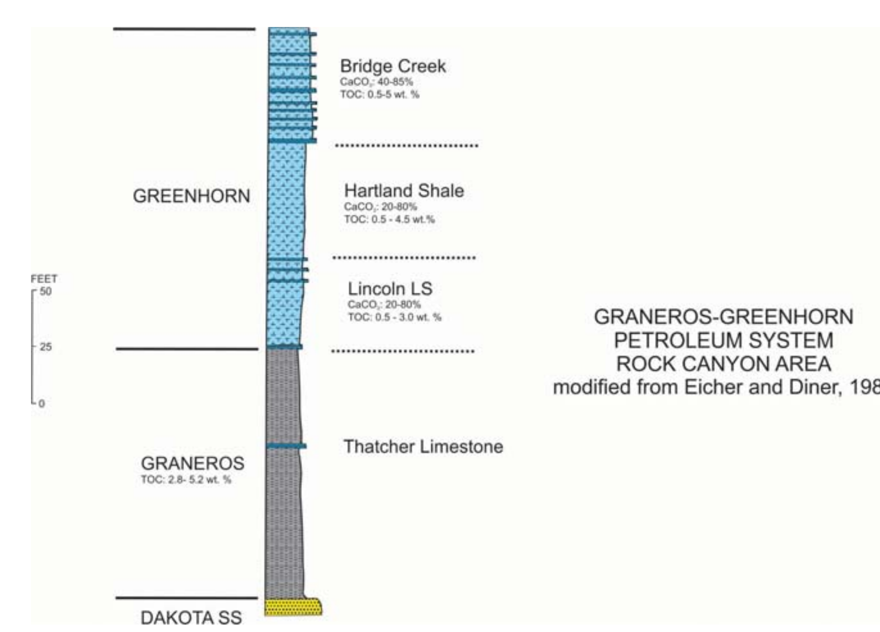
- Greenhorn was named by Gilbert (1896) for exposures near Greenhorn Station, 28 miles south of Pueblo
- Subdivided into Bridge Creek, Hartland, and Lincoln members
- ~ 95 ft thick in Kansas; 153 ft Rock Canyon anticline
- Carbonates predominantly of pelagic origin (i.e., coccoliths & forams)
- Water depths less than 600 ft (90 to 300 ft)
- Inoceramid bivalves are ubiquitous Greenhorn macroinvertebrates, almost everywhere represented by prismatic shell layer



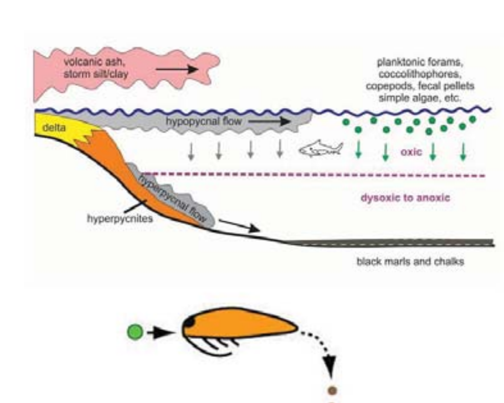
- ***Greenhorn Paleogeography (Kauffman, 1969)***



- ***Water movement Greenhorn Seaway (Hattin, 1975)***



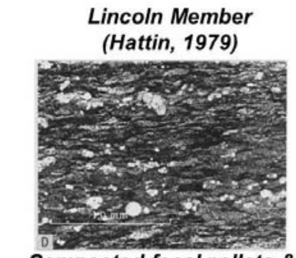
Graneros-Greenhorn Petroleum System



Lincoln Member (Hattin, 1979)

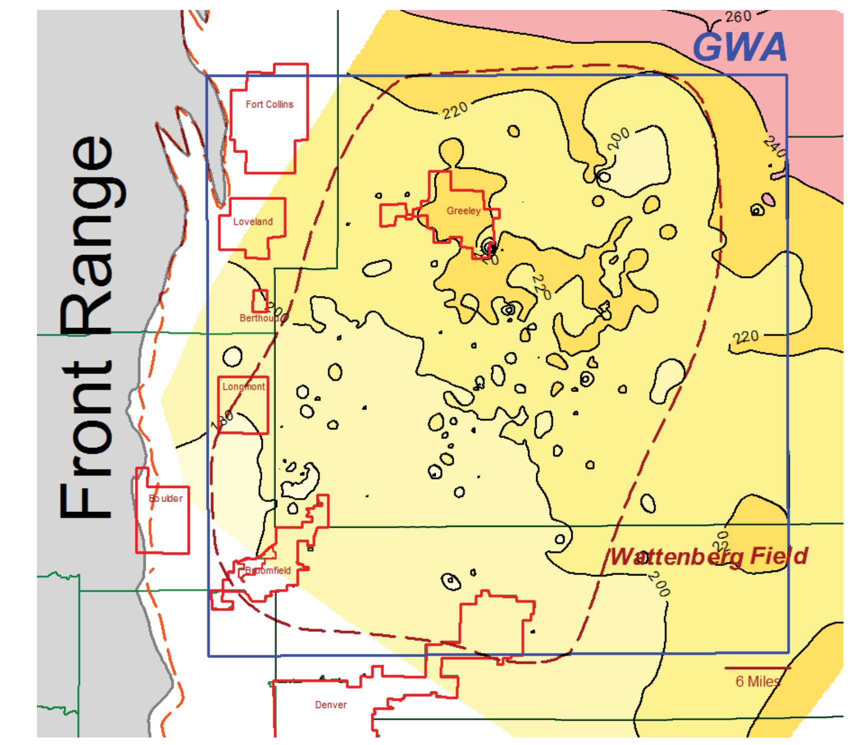
Abundant coccoliths

Lincoln Member (Hattin, 1979)

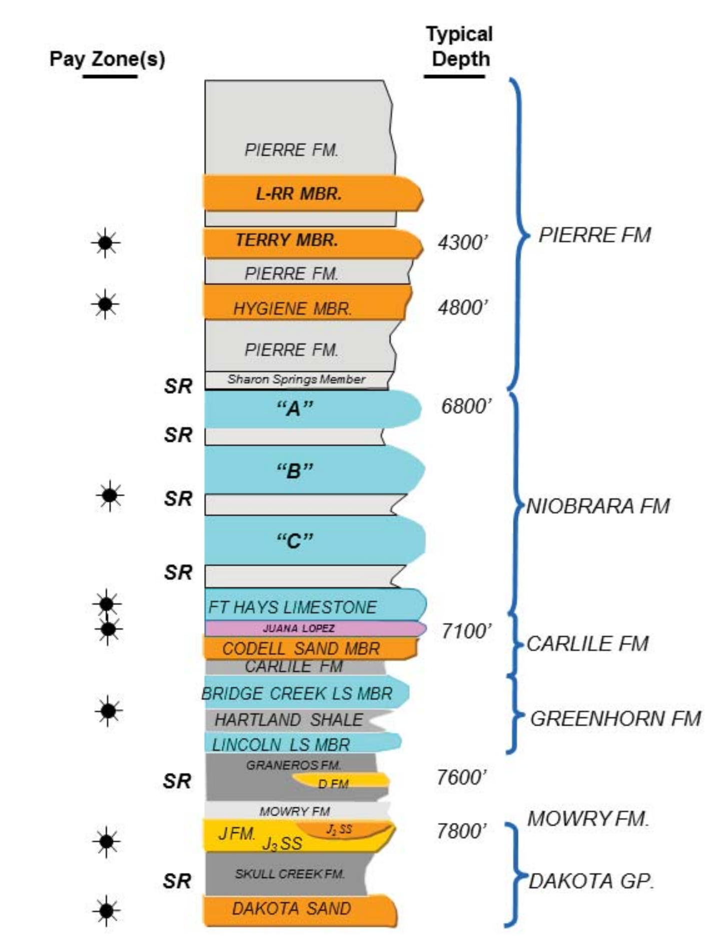


Compacted fecal pellets & forams

- ***Pelleted chalk deposition model***



- ***Greenhorn Isopach, greater Wattenberg Field area***



- ***Stratigraphic column with vertical drilling depths, greater Wattenberg area.***

Water Depths

- Highly debated!
  - Eicher 1969: 1640 ft (planktonic benthonic ratios)
  - Asquith 1970: 2000 ft (depositional topography)
  - Kauffman 1969: 100 to 500 ft
  - Sageman and Arthur: 150 to 900 ft
  - Hattin, 1975: 80 to 300 ft
- Benthonic forams rare
- Preservation of thin laminae
- Poor circulation, oxygen deficiency
- Inoceramus – broad-valved, suspension feeding organisms thrived, dissolved oxygen levels too low for other macroinvertebrates
  - Low taxonomic diversity

- ***Greenhorn water depths and the debate.***

Greenhorn Stratigraphy
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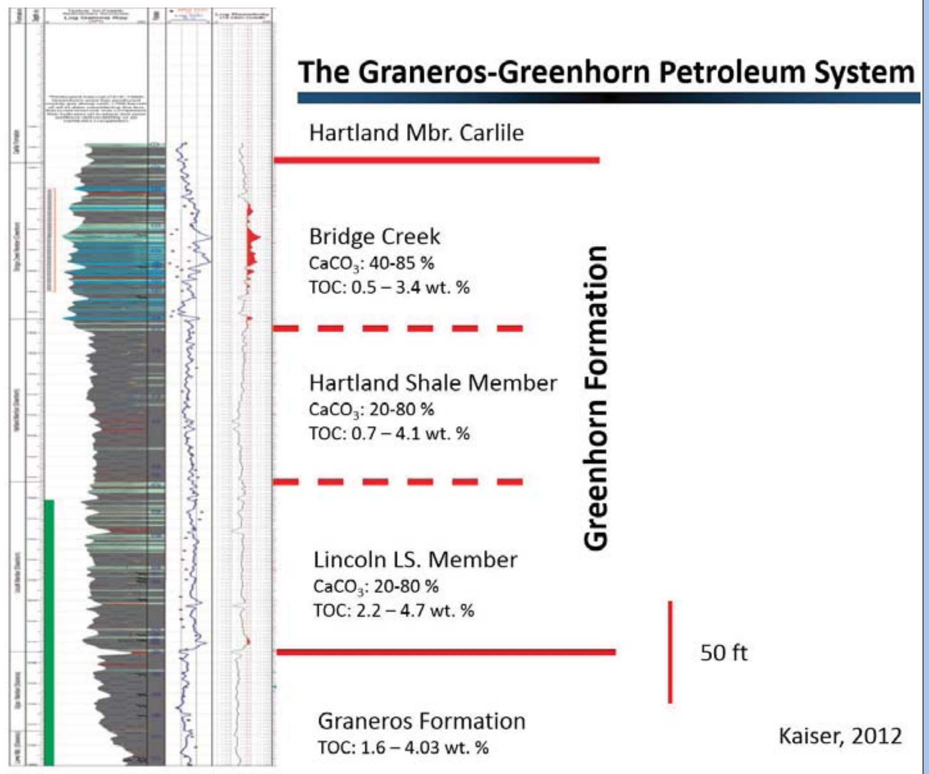
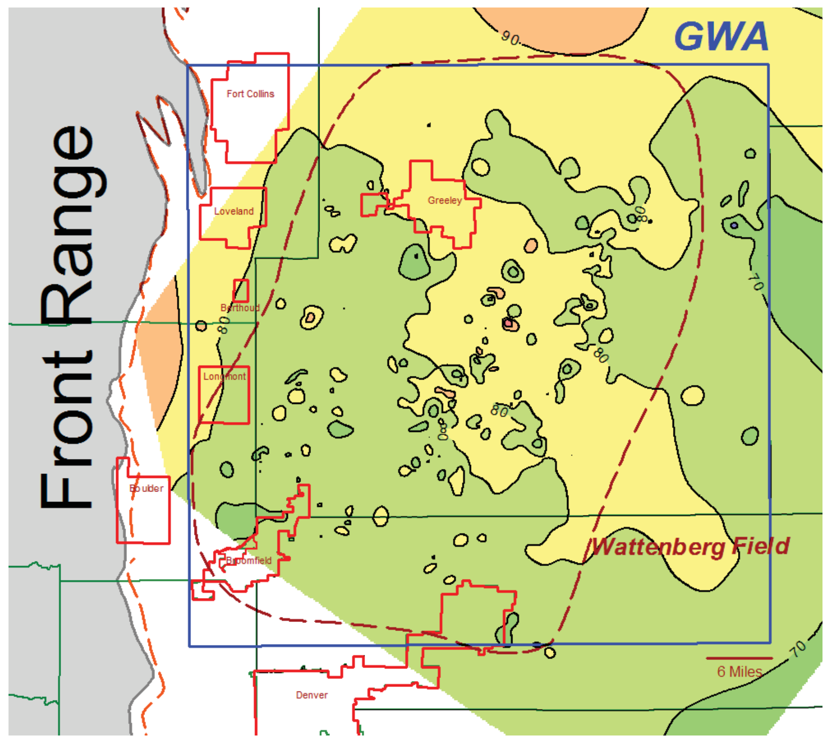
Lincoln Member

- First called Lincoln Marble (Logan, 1897)
- Renamed Lincoln Limestone Member (Rubey and Bass, 1925)
- Shaly chalk with thin beds of skeletal limestone seams (inoceramites and oyster valves), seams of bentonite



- ***TOC and well logs, Greenhorn Formation, Wattenberg Field (AA well)***

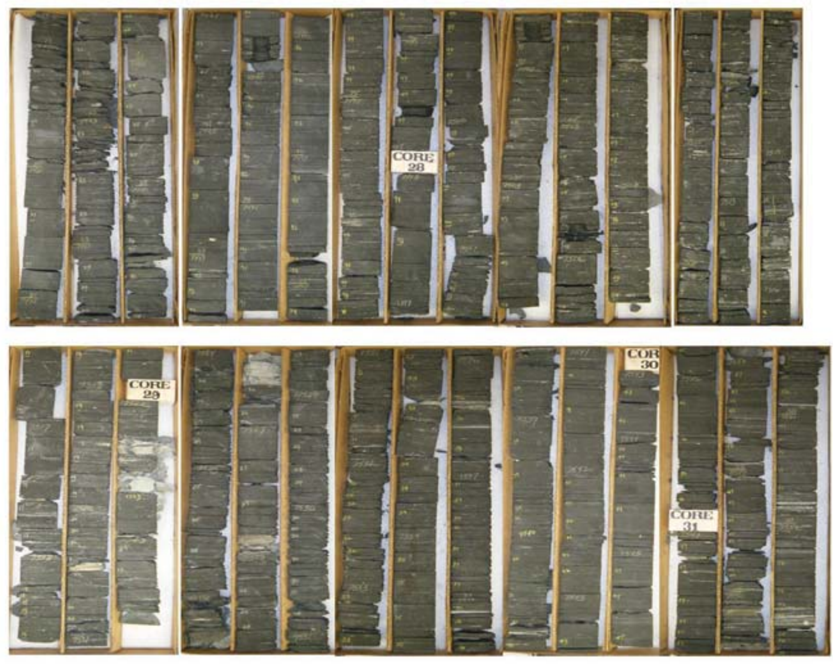
- ***Core photos, Lincoln Member***



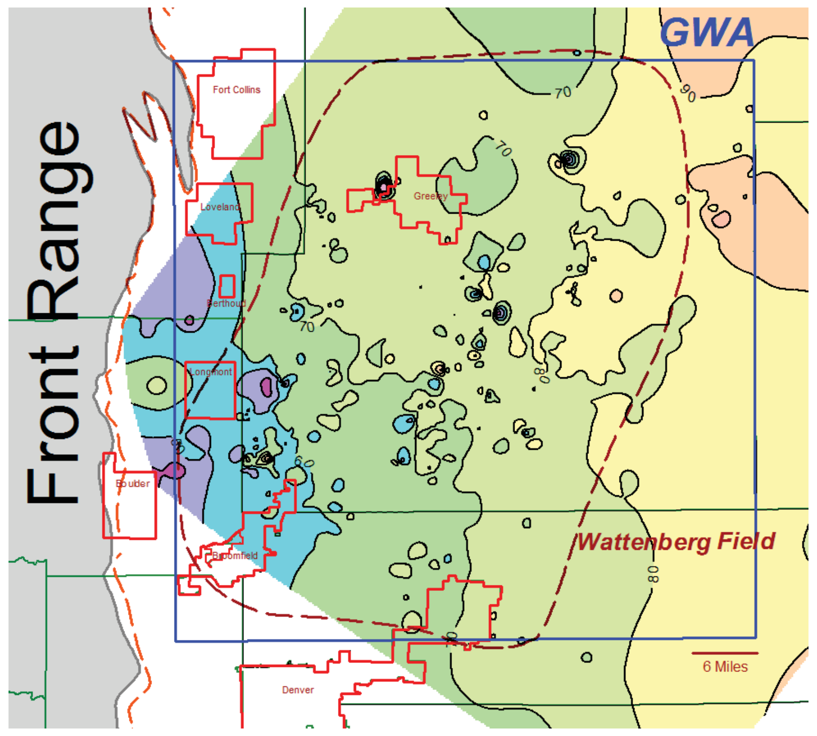
- ***Lincoln Member Isopach***

Hartland Member

- Named by Bass (1926)
- Finely laminated calcareous shale
- High levels of organic carbon
- Low levels of fossil diversity and abundance
- Non-bioturbated
- Probable low oxygen or anoxic event (Sageman, 1985)



- ***Core photos, Hartland Member***



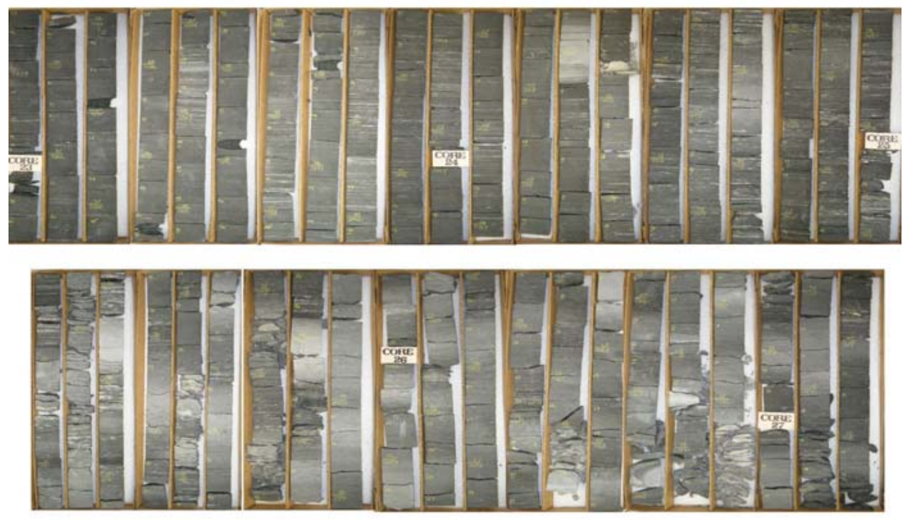
- ***Hartland Shale Member Isopach***

Aristocrat Angus file

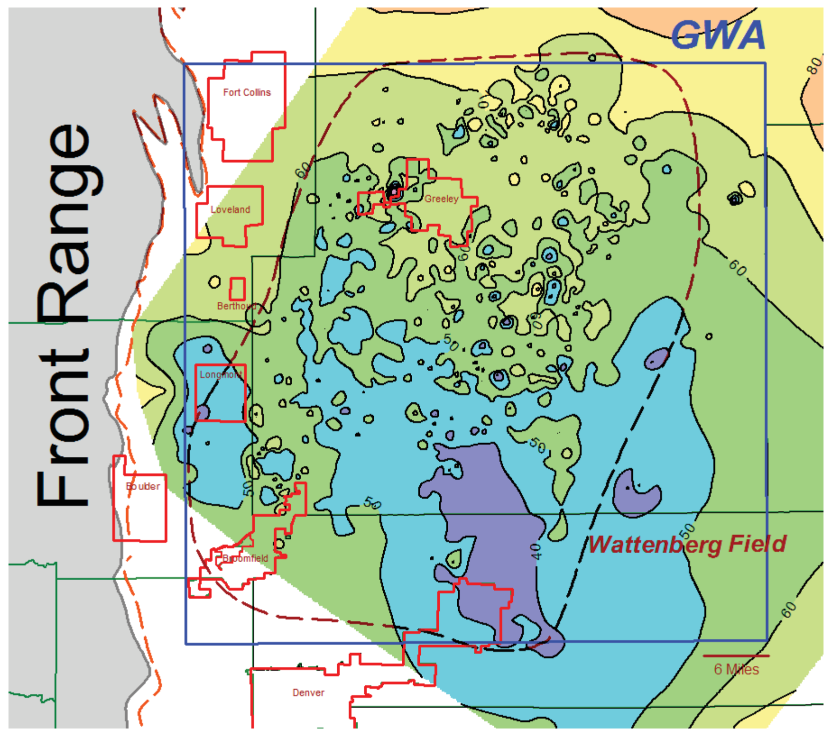
- ***Modified van Krevelen diagram for Graneros Greenhorn Petroleum System***

Bridge Creek Limestone Member

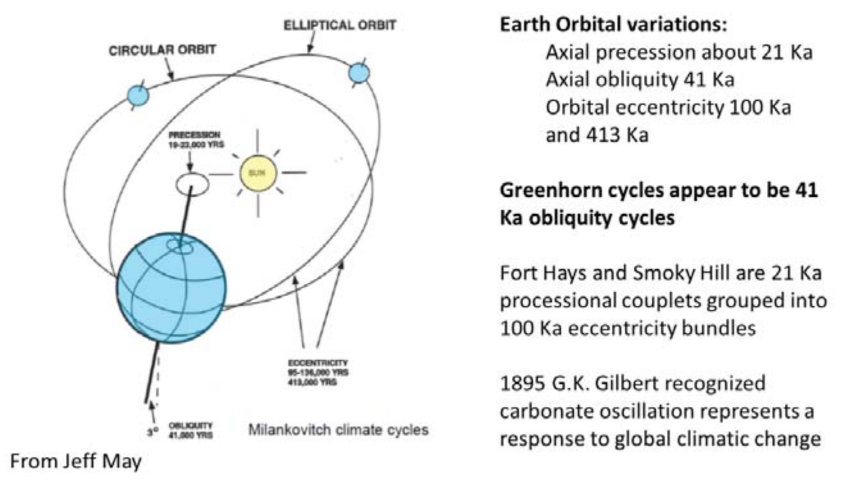
- Rhythmic limestone-shale cycles in response to Milankovitch orbital cycles 20,000 to 100,000 years Barron et al., 1985
- Encompasses Cenomanian-Turonian extinction event and a major Cretaceous oceanic anoxic event
- Named by Bass (1926) for a series of beds at top of Greenhorn limestone near Medway, Kansas
- Bridge Creek correlates to upper Hartland Member, Jetmore Chalk and Pfeifer Shale Member as defined in central Kansas



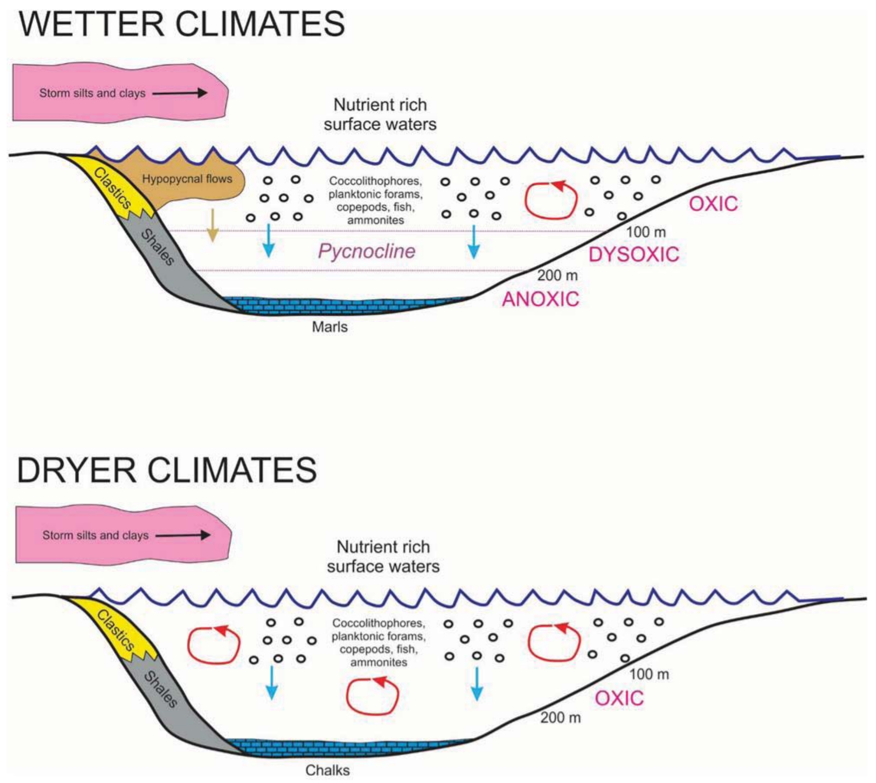
- ***Core photos, Bridge Creek Member***



- ***Bridge Creek Member Isopach***



- ***Earth orbital variations and cyclic deposition***



- ***Climate cycles resulting in chalks and marls***

Major Invertebrate Groups

- Foraminifera
- Ammonites
- Oysters
- Inoceramid bivalves

- ***Greenhorn invertebrate groups***

Salinity

- Normal salinity
- Coccolithophores cannot tolerate seawater having a salinity that departs from open ocean
- All parts of Greenhorn contain ammonites (marine organisms)
- Pycnodont oysters are characteristic of normal marine (found in Bridge Creek/Jetmore member)
- Abundance of *Inoceramus* (not recorded in brackish)

- ***Greenhorn salinity***

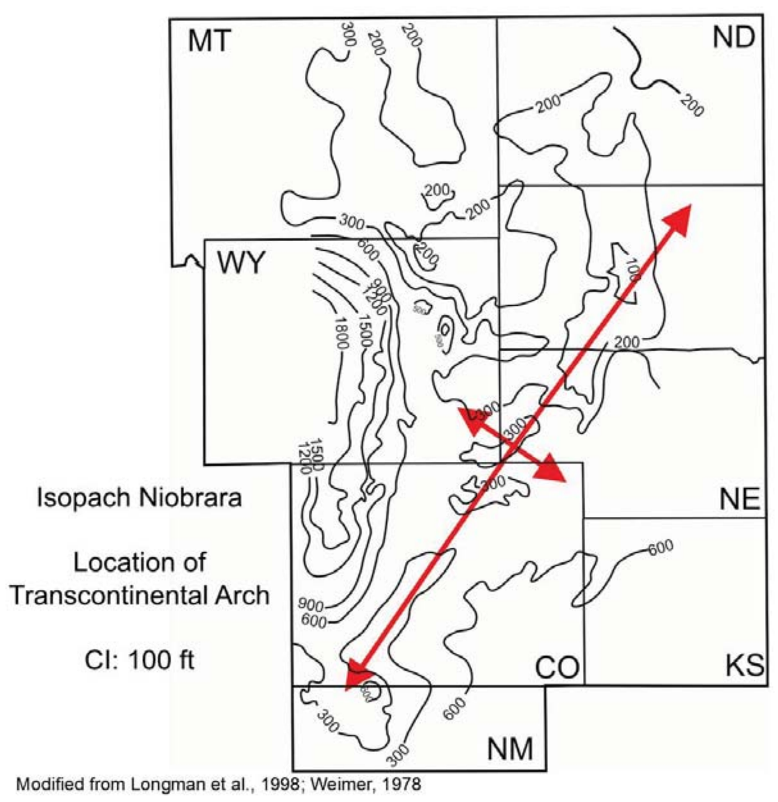
Temperature

- Wide latitudinal range of species
- Broad climate zones of equitable temperatures
- Boreal region referred to as "north temperate zone" by Kauffman
- Pronounced south to north differences in western faunas have been noted

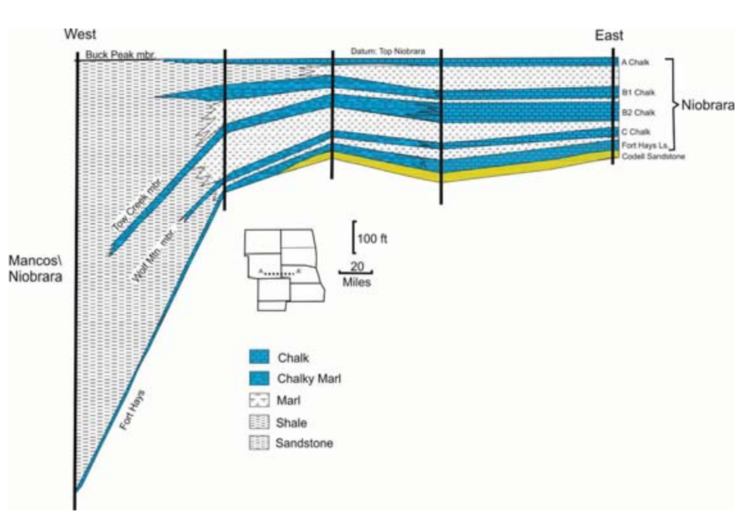
- ***Greenhorn temperature, WIC basin***

Niobrara Stratigraphy
3

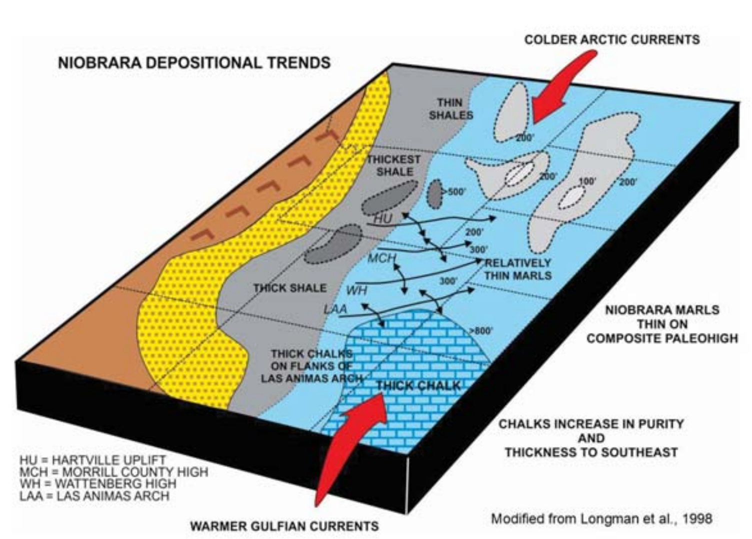
❖ Niobrara Stratigraphy



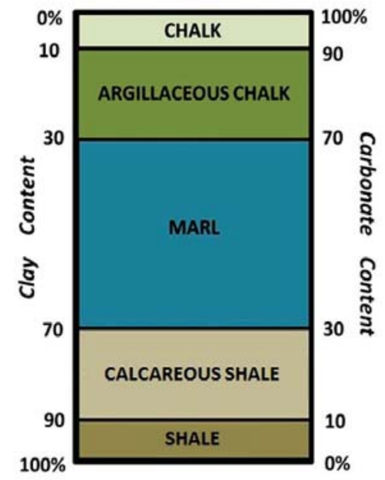
- ***Isopach Niobrara Formation, WIC basin; location of Transcontinental Arch from Weimer, 1978***



- ***West east cross section WIC basin showing correlations of chalk and marl units (modified from Longman et al., 1998)***

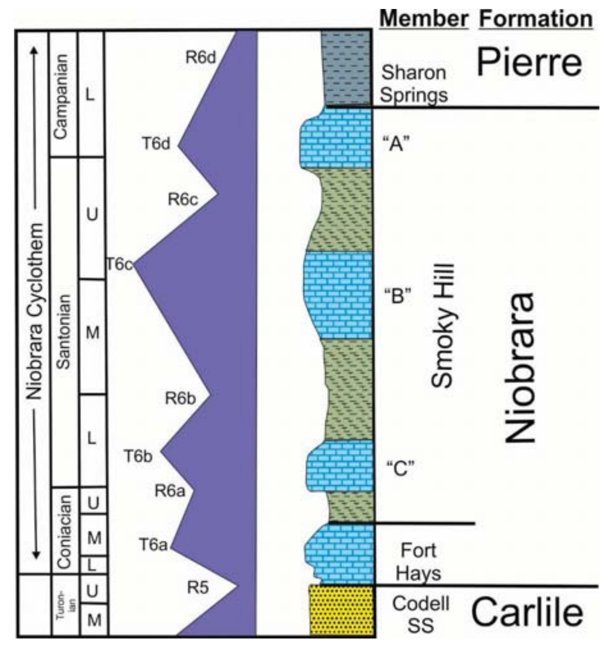


- ***Depositional model and facies changes for Smoky Hill member Niobrara Formation***

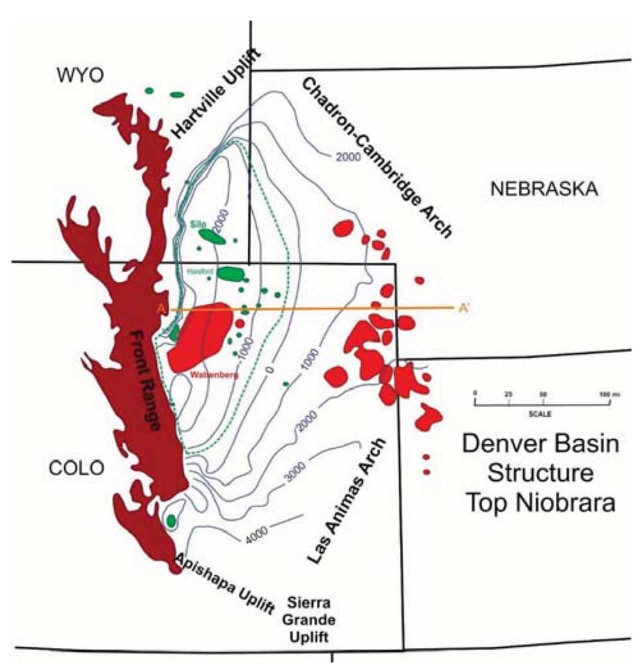


CSM Niobrara Consortium – 'Unlock the Chalk'

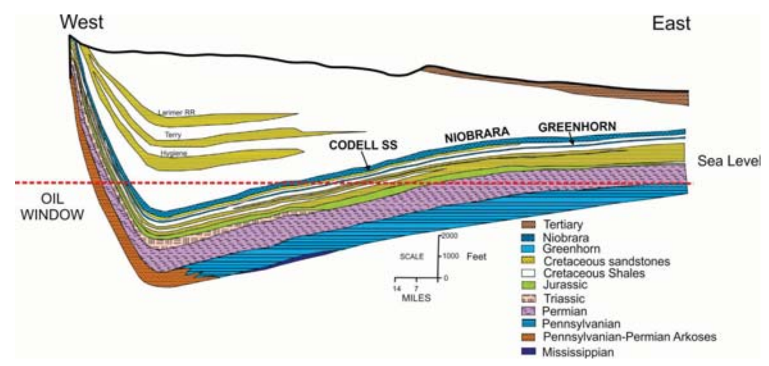
- ***Chalk, marls, and shales; some general definitions***



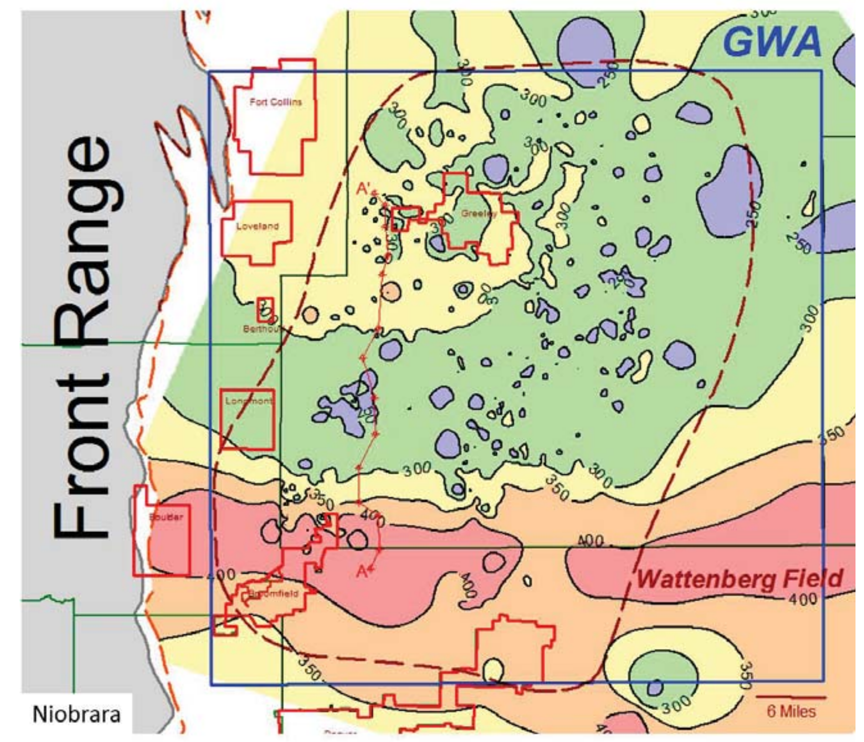
- ***Niobrara Formation and possible sea level changes for chalk and marl deposition (Kauffman, 1969)***



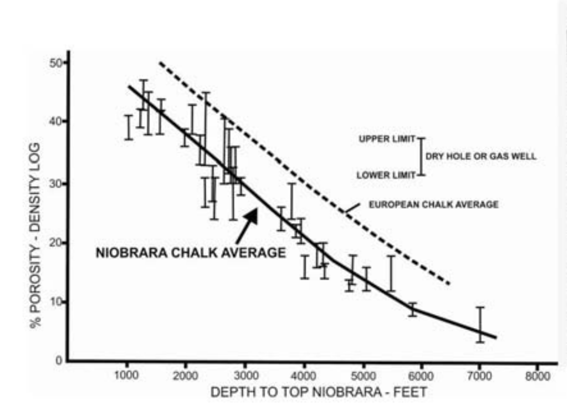
- ***Structure contour map top Niobrara Formation, Denver Basin. Niobrara production for gas fields shown in red; oil fields shown in green.***

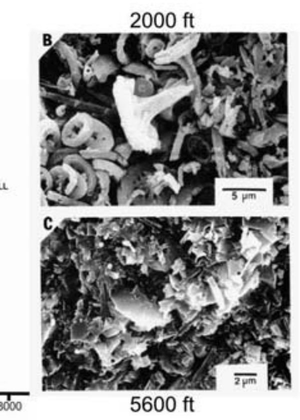


- ***Generalized west to east cross section Denver Basin***

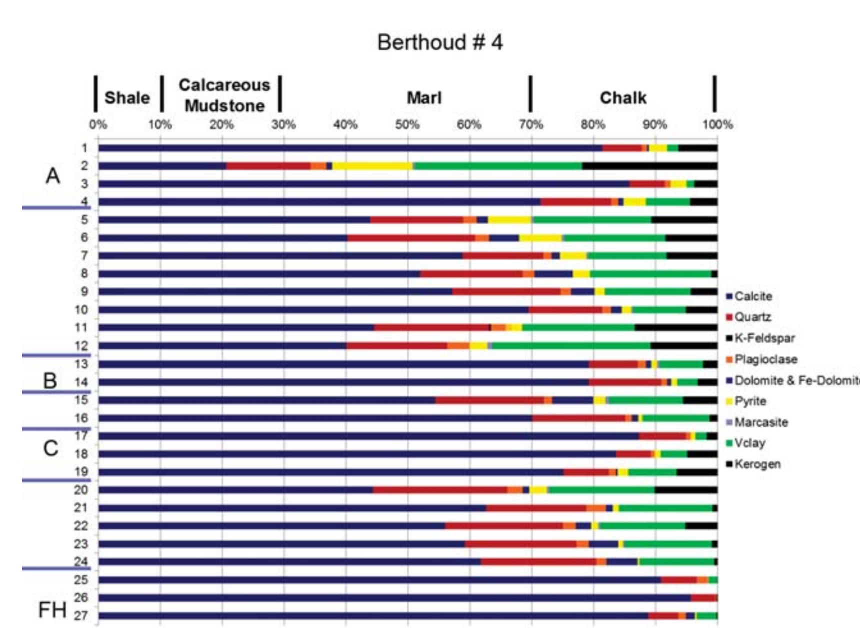


- ***Isopach map Niobrara Formation, Wattenberg Field area.***

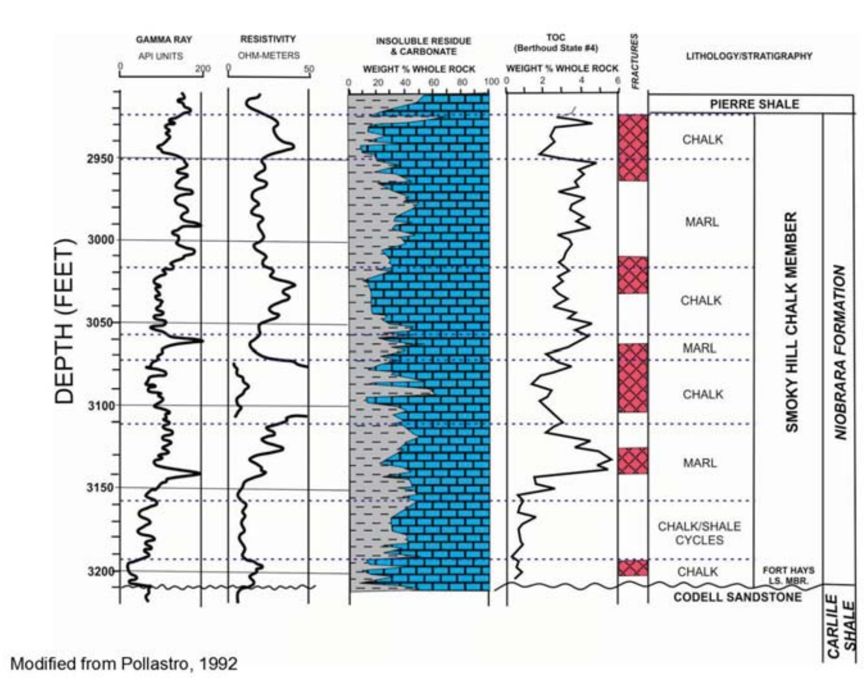




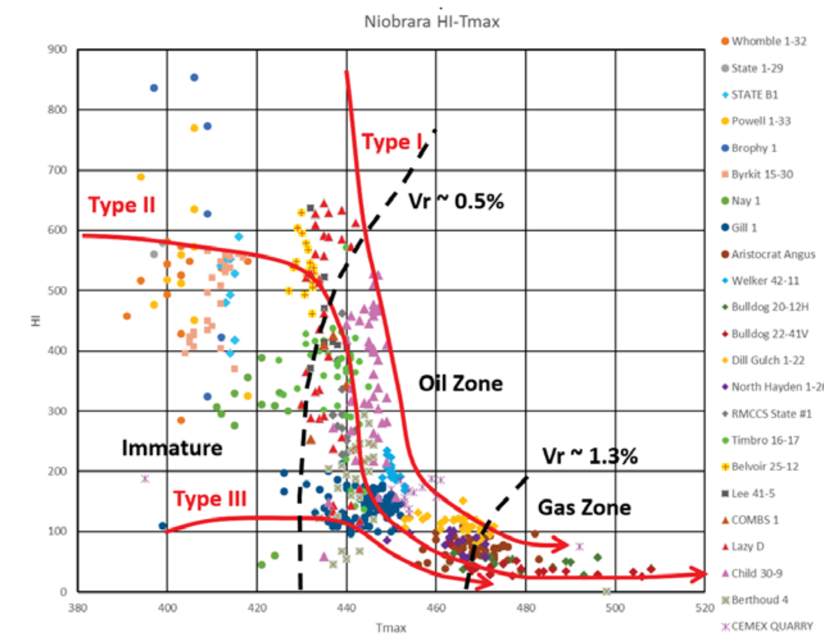
- ***Porosity with depth Niobrara Formation, Denver Basin (from Lockridge and Pollastro, 1988)***



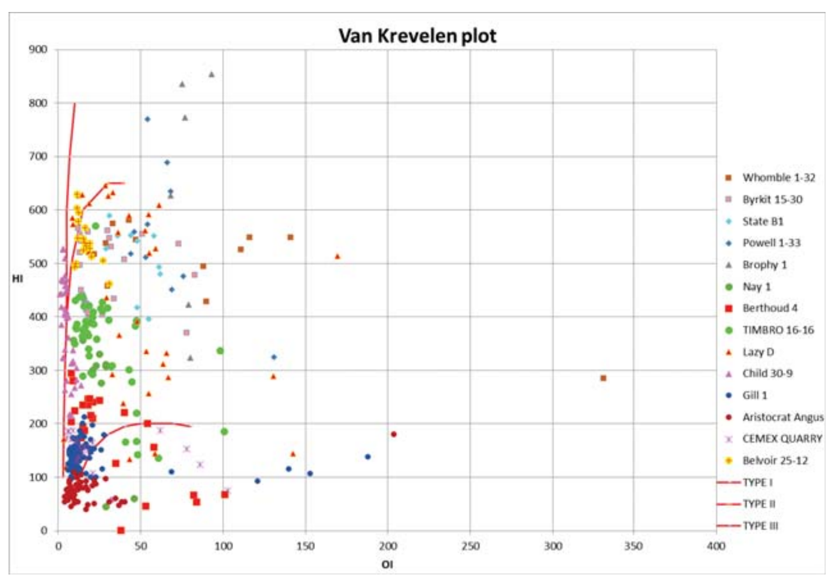
- ***XRD data for Niobrara Formation, Berthoud # 4 well, Denver Basin***



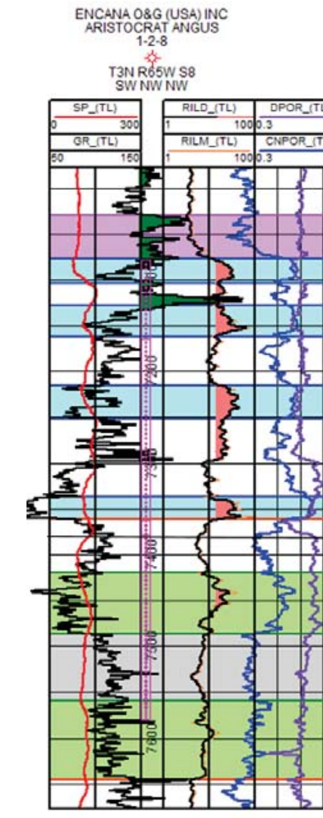
- ***Mechanical stratigraphy, Niobrara Formation***



- ***Espitalie diagram, Niobrara Formation. Red line for Type II kerogen maturity. Oil generation starts at approximately ~435°F Tmax; gas zone starts at ~465°F***



- ***Modified Van Krevelen diagram, Niobrara Formation. Organic matter is dominantly Type II in origin (some mixing of Type III)***



Niobrara Properties

	H (ft)	TOC (wt.%)	CaCO3 (%)	PHI (%)	K (md)
Sharon Springs	47	2.9		8.2	.00013
A Chalk	27	2.1	82	9.1	.00033
A Marl	24	5.8	64	9.4	.00038
B Chalk	33	2.8	73	9.2	.00057
B Marl	55	3.5	68	7.6	.00013
C Chalk	30	2.7	80	8.3	.00029
C Marl	56	4.4	52	8.3	.00024
Lower Marl	35	3.6	42	6.0	.00008
Fort Hays	24	0.06	94		
Codell	15	1.5	1.5	11.8	.02

- ***Reservoir properties Niobrara Formation, Wattenberg Field***

Petrophysical, XRF Elemental, and Geomechanical Comparison

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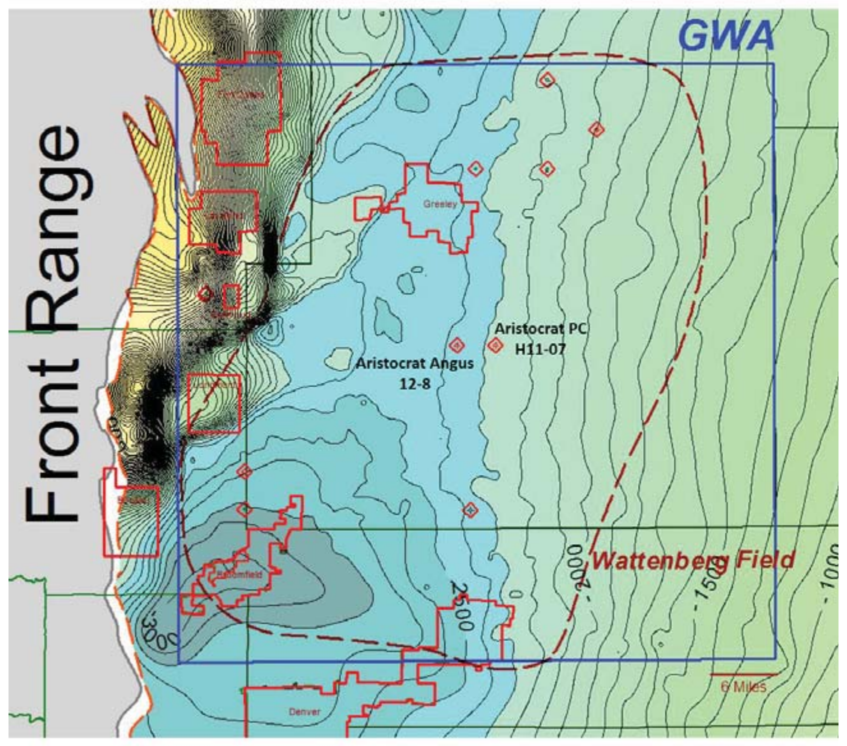
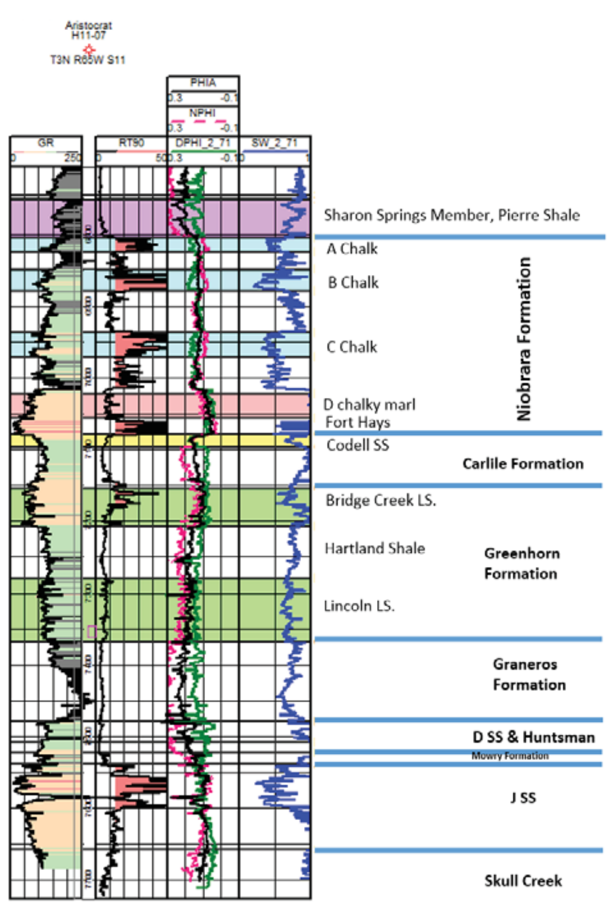
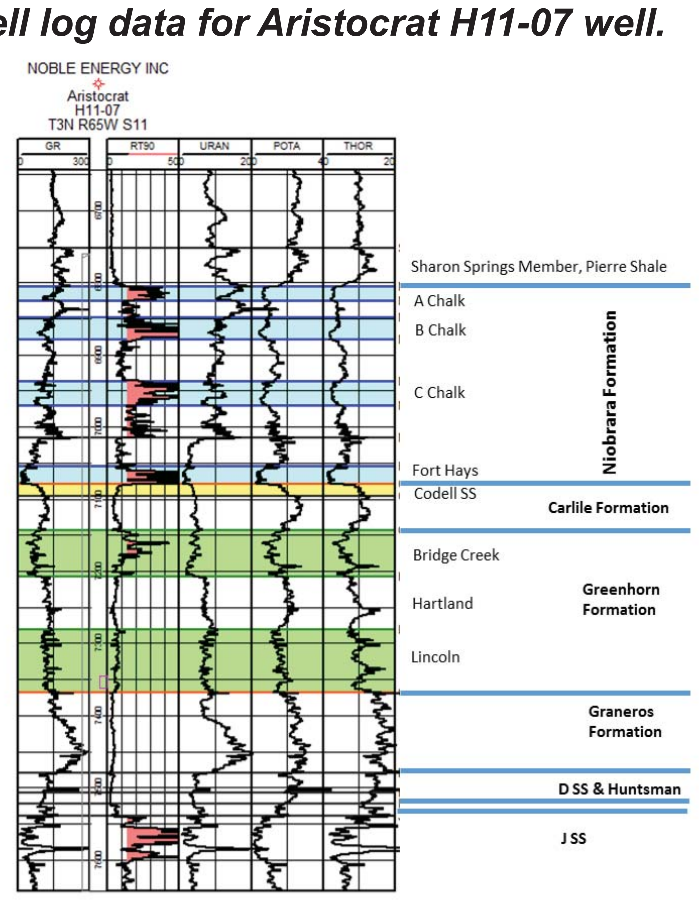


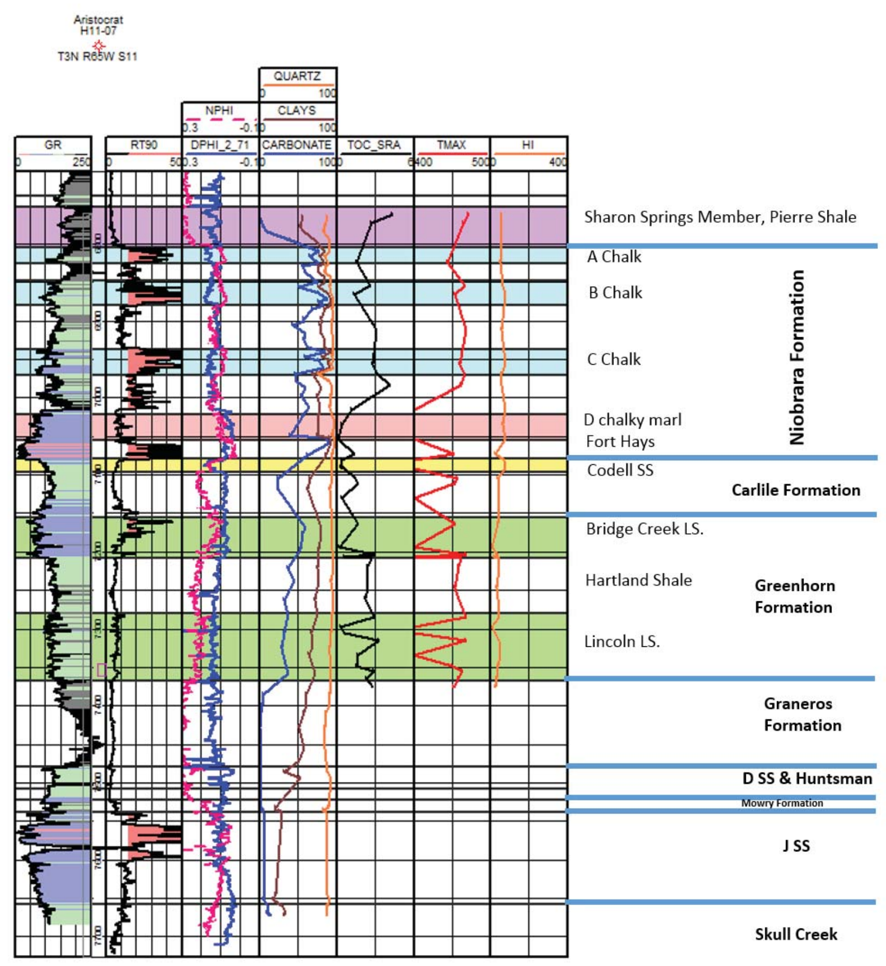
- *Structure contour map, top Codell Sandstone, greater Wattenberg area. Wells with XRD, XRF, and various log curves also shown.*



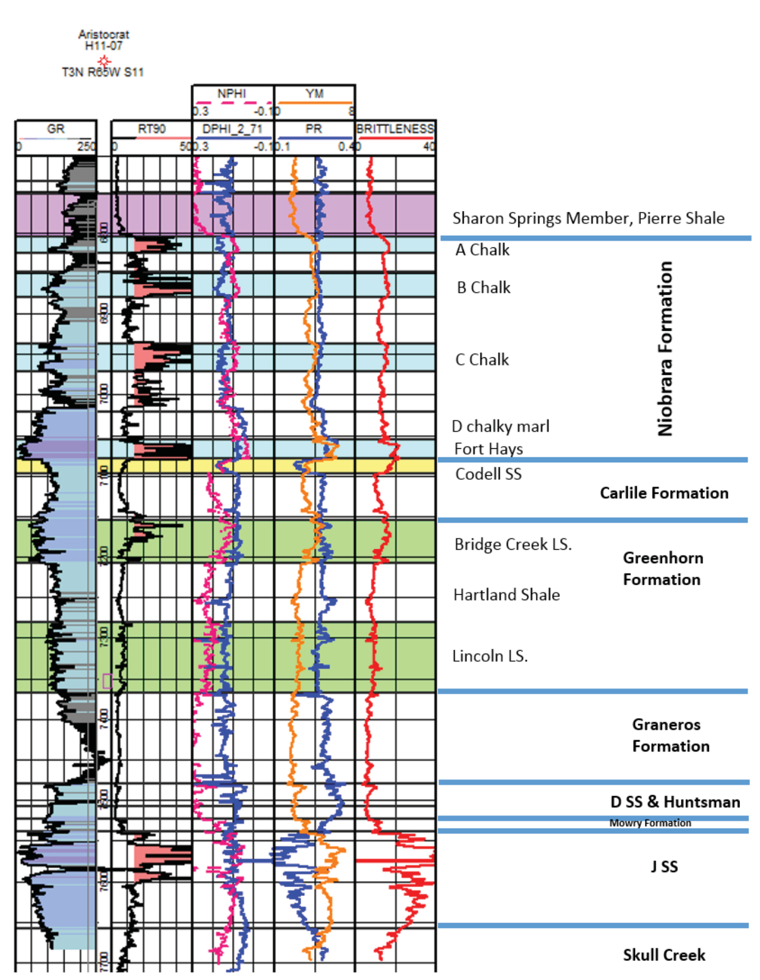
- *Well log data for Aristocrat H11-07 well.*



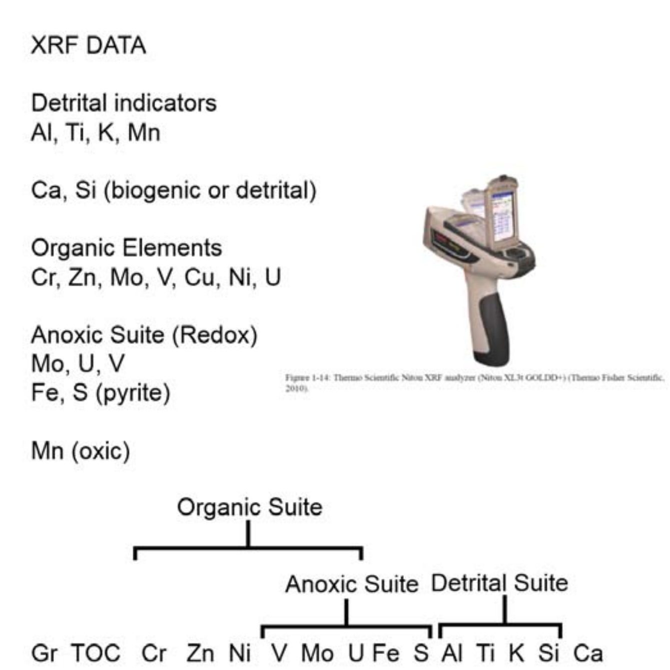
- *Well log and spectral gamma ray data for Aristocrat H11-07 well. Source beds generally show higher GR values (Niobrara marls and Graneros)*



- *Well log, XRD, and Source Rock data for Aristocrat H11-07 well. TOC is highest in the Niobrara A and C marls and the Hartland Shale member of the Greenhorn. Tmax values greater than 450 and HI values less than 100 illustrate that this well is located in the wet gas to gas zones. The highest carbonate contents are found in the Niobrara chalks and Bridge Creek member of the Greenhorn.*



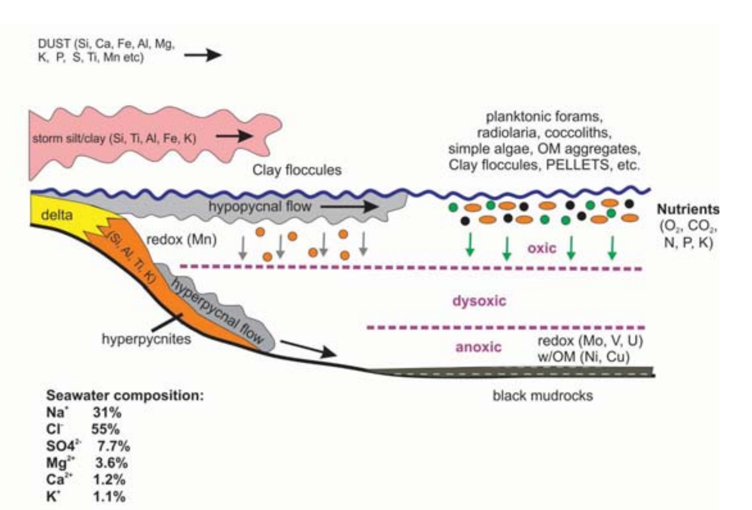
- *Well log and geomechanical data for Aristocrat H11-07 well. The highest Young's modulus and brittleness values are found in the Niobrara chalks and the Bridge Creek member of the Greenhorn Formation. These zones also show neutron and density logs "track" through these zones and diverge in the marls and shales.*



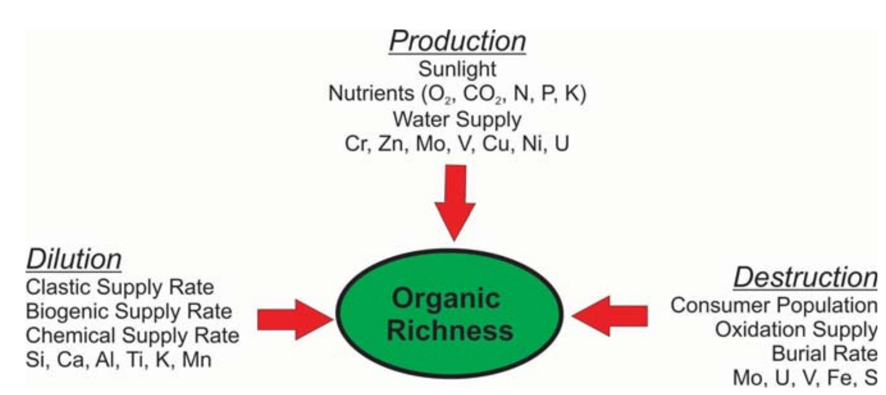
Element	R^2
Ca	0.977
Zr	0.975
Si	0.969
Al	0.958
Mn	0.956
Rb	0.955
Sr	0.952
Ba	0.943
Fe	0.933
Nb	0.877
K	0.858
S	0.856
V	0.853
Ti	0.844
Mo	0.810
Th	0.791
Zn	0.673
As	0.577
P	0.516
Mg	0.511
Ni	0.483
Cu	0.444
Pb	0.314
Cr	0.301
U	0.287
Cs	0.242
Bi	0.228
Sb	0.174
Sc	0.138
Sn	0.059
Ag	0.058
W	0.056
Co	0.037
Hf	-
Ta	-

R2 values for Niton-ICP/LECO relationships. Nakamura, 2015.

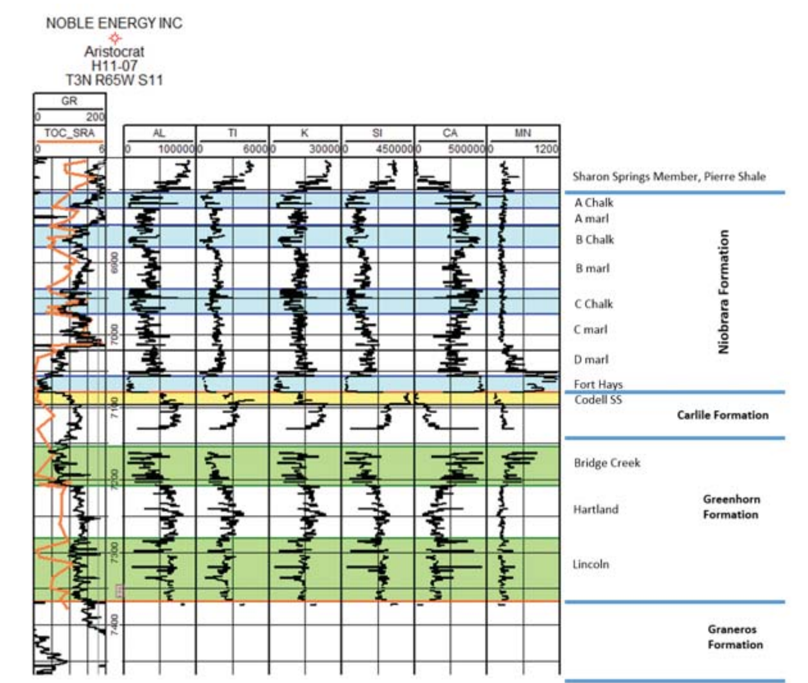
- *XRF data and its use for detrital, anoxic, and organic elemental suites. Detrital elements are Al, Ti, K, and Mn. Ca and Si can be biogenic or detrital. The anoxic suite largely consists of elevated values of Mo, U, and V. Fe and S are related to pyrite which can support anoxic conditions. Elevated values of Cr, Zn, Ni correspond generally to high TOC content.*



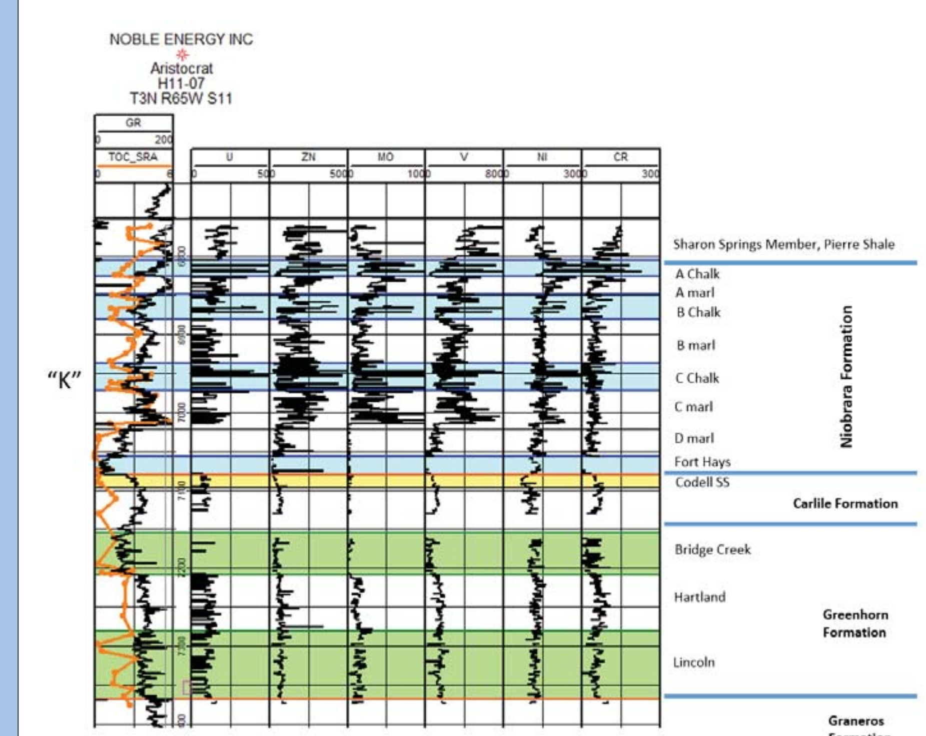
- *Source bed model for Type II kerogen and various elemental suites. O2, CO2, N, P, and K are nutrients that promote organic matter precipitation. Dilution can occur from detrital input of Si, Ca, Fe, Al, Mg, K, P, S, Ti, Mn, etc.*



- *Controls on organic richness and elemental suites used to interpret production, dilution, and destruction. Si, Ca, Al, Ti, K, and Mn are detrital or biogenic indicators. Production is related to nutrient supply (O_2, CO_2, N, P, and K). High organic productivity is associated with Cr, Zn, Mo, V, Cu, Ni, and U. Low oxygen conditions have elevated values of Mo, U, V, Fe, and S.*



- *Elements used for detrital indicators include Al, Ti, K, and Si. Ca is a proxy for carbonate or chalks. Mn appears to be related to redox and the oxic suite. Note high values of Ca in Niobrara chalks and chalk/limestone beds of Greenhorn and corresponding low values of Al, Ti, K, and Si. Marls and shales have higher values of detrital elements when compared to chalks.*



- *Elements used for organic production and redox include: Cr, Zn, V, Mo, U, and Ni. High values of U, V, and Mo suggest reducing conditions (these are more soluble under oxic conditions). Note the extremely low values in the bioturbated Fort Hays member of the Niobrara. Both the Niobrara chalks and marls show spikes in these values as compared to the Greenhorn. High TOC best correlates with CR, V, Mo, Ni, Zn, and U. The Hartland Shale shows elevated values of Mo, V, Ni, and Cr compared to the Bridge Creek and Lincoln members of the Greenhorn. The analysis of the data suggests dysoxic to anoxic deposition for the Niobrara marls and Hartland member of the Greenhorn. More oxic conditions are suggested for bioturbated Fort Hays limestone member of the Niobrara and the Bridge Creek and Lincoln members of the Greenhorn.*