The Graneros-Greenhorn Petroleum System, a Possible New Resource Play, Rocky Mountain Region, USA*

Steve Sonnenberg[1], Hannah Durkee[2], and Craig Kaiser[3]

Search and Discovery Article #10898 (2016)**
Posted December 19, 2016

*Adapted from oral presentation given at AAPG Pacific Section and Rocky Mountain Section Joint Meeting, Las Vegas, Nevada, October 2-5, 2016

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

Abstract

High total organic carbon content (TOC) in the Graneros and Greenhorn formations and limestone reservoirs in the Greenhorn suggest potential for a new resource play in the Rocky Mountain region. Operators are currently testing new horizontal wells in the play. The source rocks are dominantly Type II with a mixture of Type III. The Greenhorn is a pelagic carbonate deposit and consists of three members: Bridge Creek, Hartland, and Lincoln. Pelagic constituents consist of nannofossils (coccoliths and calcispheres) and foraminifera (mainly planktonic). The formation ranges in thickness in the northern Denver Basin from 200 to 290 feet. The Bridge Creek and Lincoln are largely chalk units or chalky marl units (40-85% $CaCO_3$). The Hartland is a chalky marl (20-80% $CaCO_3$). TOC in the Bridge Creek, Hartland, and Lincoln members ranges from 0.5 to 5 wt. %. The Hartland contains the high levels of organic carbon and has the lowest levels of fossil diversity and abundance, suggesting low oxygen or anoxic conditions during deposition. Depositional depths for the chalk units is probably 100 to 300 feet.

The Graneros interval occurs between the Greenhorn and the D Sandstone over much of the Denver Basin. Where the D pinches out the Graneros terminology is extended down to the top of the Mowry Shale. The Graneros to Mowry interval ranges in thickness from 150 to 400 feet across the northern Denver Dasin. TOC in the Graneros ranges from 0.5 to 5.3 wt. %. The overall all distribution of the TOC in the Graneros is more consistent (not as cyclic) than in the Greenhorn. Production from vertical Greenhorn wells has been encountered in the general Denver Basin area. Production comes mainly from the Lincoln member.

References Cited

Barron, E.J., M.A. Arthur, and E.G. Kauffman, 1985, Cretaceous rhythmic bedding sequences: A plausible link between orbital variations and climate: Earth Planet. Sci. Lett., v. 72, p. 327-340.

Bass, N.W., 1926, Geologic investigations in western Kansas: Kansas Geol. Survey, Bull. 11, parts 1 and 2, p. 1-83.

Durkee, H., 2016, Reservoir characterization and geomechanical evaluation of the Greenhorn Formation in the Northern Denver Basin, Colorado: M.S. Thesis, Colorado School of Mines, Golden, CO, 153 p.

Eicher, D., 1969, Paleobathymetry of Cretaceous Greenhorn Sea in Eastern Colorado: AAPG Bull., v. 53, p. 1075-1090.

Eicher, D.L., and R. Diner, 1985, Origin of the Cretaceous Bridge Creek cycles in the Western Interior, United States: Paleogeography, Paleoclimatology, Paleoecology, v. 74, p. 127-146.

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.

Kaiser, C.A., 2012, The Graneros-Greenhorn Petroleum System: Greater Wattenberg Area, Denver Basin, Colorado: M.S. Thesis, Colorado School of Mines, Golden, CO, 132 p.

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

Kauffman, E.G., 1977, Geological and biological overview: Western Interior Cretaceous Basin: The Mountain Geologist, v. 14/3-4, p. 75-99.

Logan, W.N., 1897, The Upper Cretaceous of Kansas: Kansas Geol. Survey, v. 2, p. 195-234.

Nakamura, K., 2015, Chemostratigraphy of the late Cretaceous western interior (Greenhorn, Carlile, and Niobrara Formations), Denver Basin, CO, USA: Thesis submitted to Colorado School of Mines.

Rubey, W.W., and N.W. Bass, 1925, The Geology of Russell County, Kansas: Kansas Geol. Survey, Bull. 10, pt. 1, p. 1-86.

Sageman, B.B., 1985, High-resolution stratigraphy and paleobiology of the Hartland Shale Member: Analysis of an oxygen-deficient epicontinental sea, *in* L.M. Pratt, E.G. Kauffman, and F.B. Zelt, eds., Fine-grained deposits and biofacies of the Cretaceous Western Interior Seaway: Evidence of cyclic sedimentary processes: SEPM Field Trip Guidebook, v. 4, p. 110-121.

The Graneros-Greenhorn Petroleum System, A Possible Resource Play

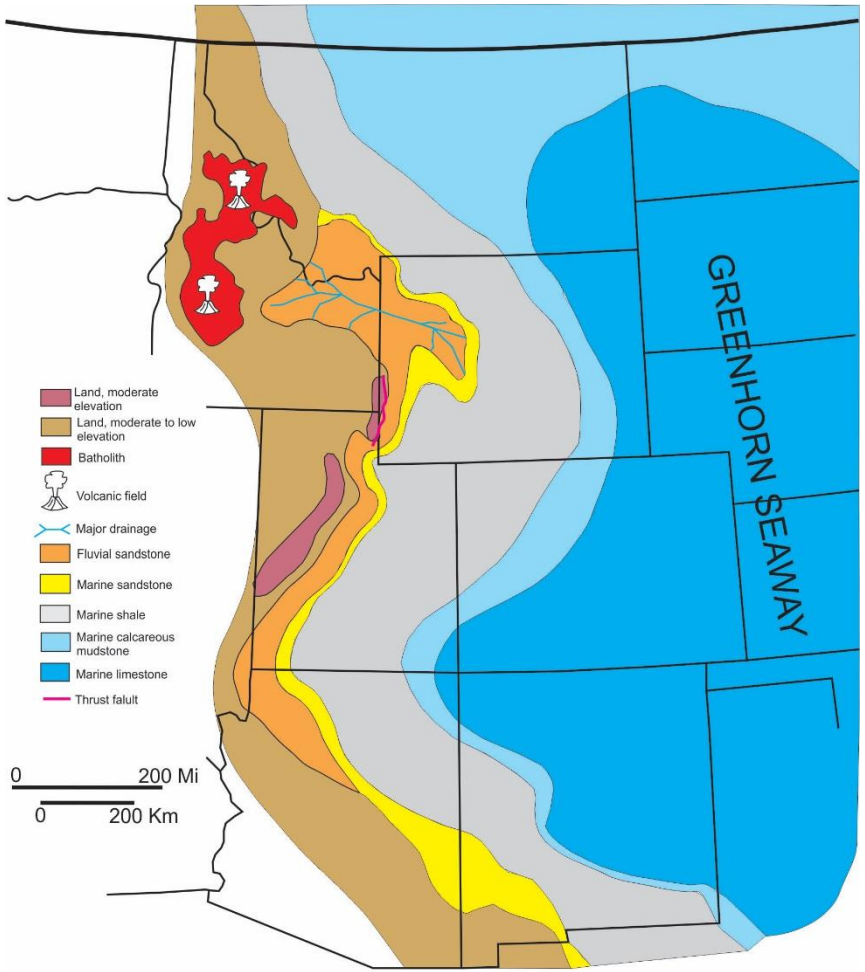
Steve Sonnenberg
Colorado School of Mines

Hannah Durkee
EOG

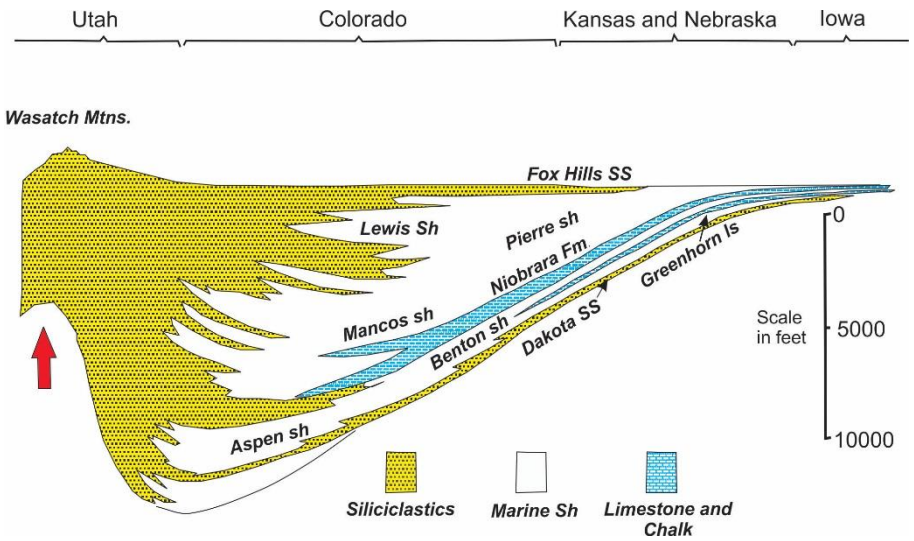
Craig Kaiser
Anadarko

Outline

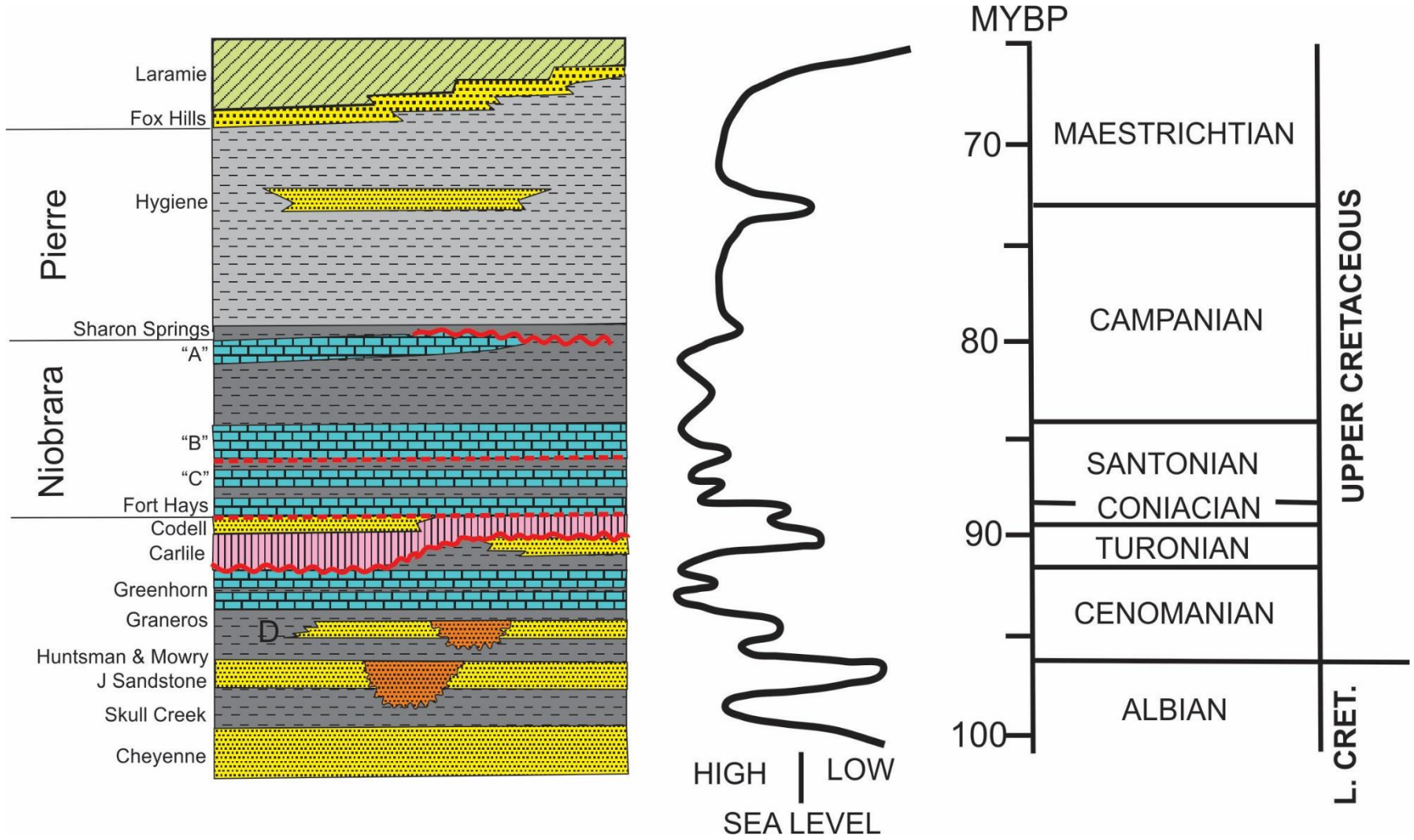
- Regional geology
- Graneros-Greenhorn Petroleum System
- Analysis of Greenhorn
  - XRF
  - Petrophysics
  - Geomechanics
- Shows and Greenhorn completions
- Screening criteria for unconventional plays
- Summary



PALEOENVIRONMENT IN MIDDLE GREENHORN (BRIDGE CREEK) TIME
RMAG ATLAS 1972

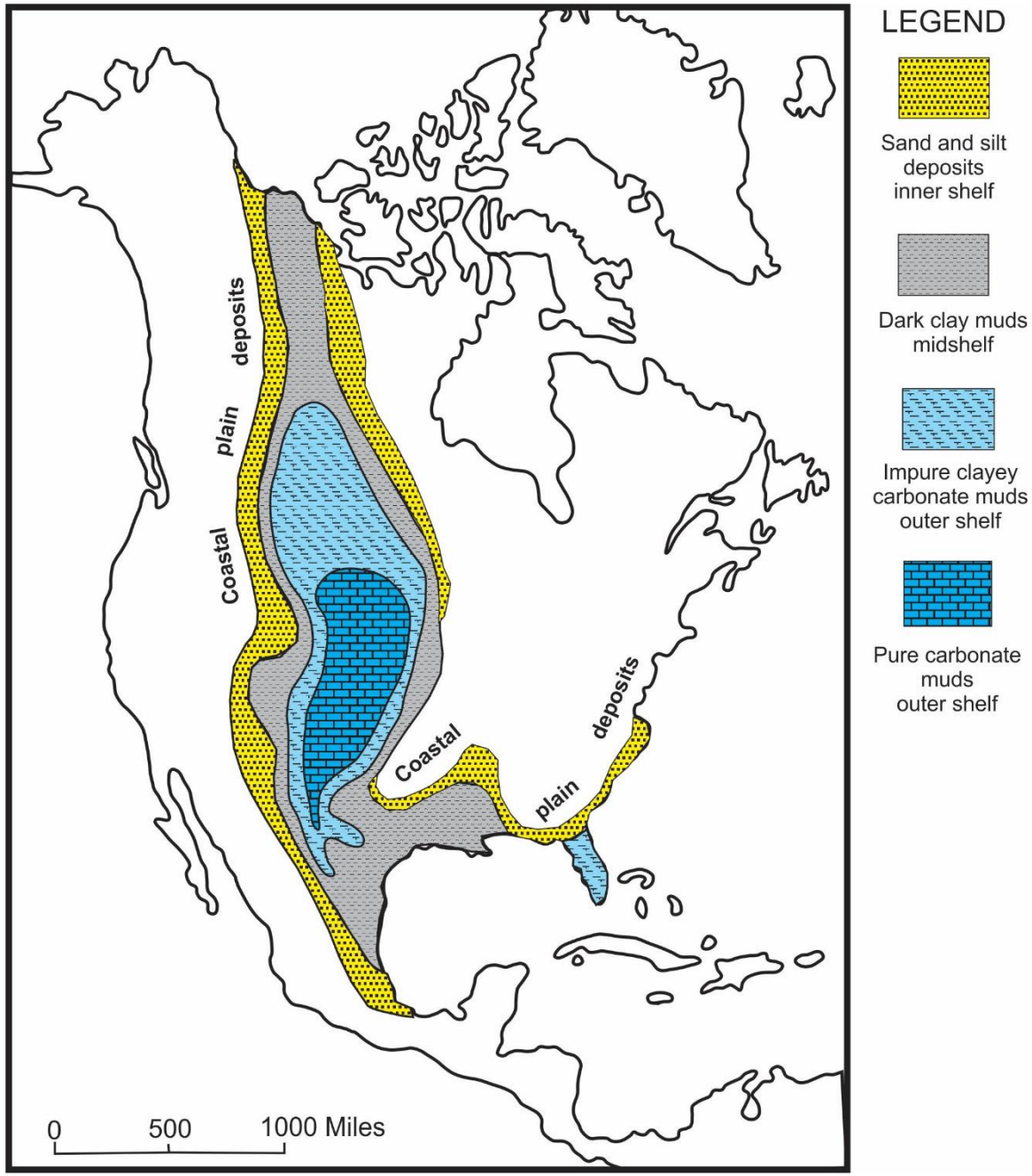


Modified from Kauffman, 1977


Laramie
Fox Hills
Pierre
Hygiene
Sharon Springs
"A"
Niobrara
"B"
"C"
Fort Hays
Codell
Carlile
Greenhorn
Graneros
D
Huntsman & Mowry
J Sandstone
Skull Creek
Cheyenne
HIGH
LOW
SEA LEVEL
MYBP
70
80
90
100
MAESTRICHTIAN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
CENOMANIAN
ALBIAN
UPPER CRETACEOUS
L. CRET.

STAGE	GROUP	FORMATION	MEMBER
CONIACIAN		NIOBRARA	Fort Hays
TURONIAN	BENTON	CARLILE	Codell SS Blue Hill Fairport
CENOMANIAN		GREENHORN	Bridge Creek Hartland Lincoln
		GRANEROS	
ALBIAN	DAKOTA	J SANDSTONE	
		SKULL CREEK	
		PLAINVIEW LYTLE	

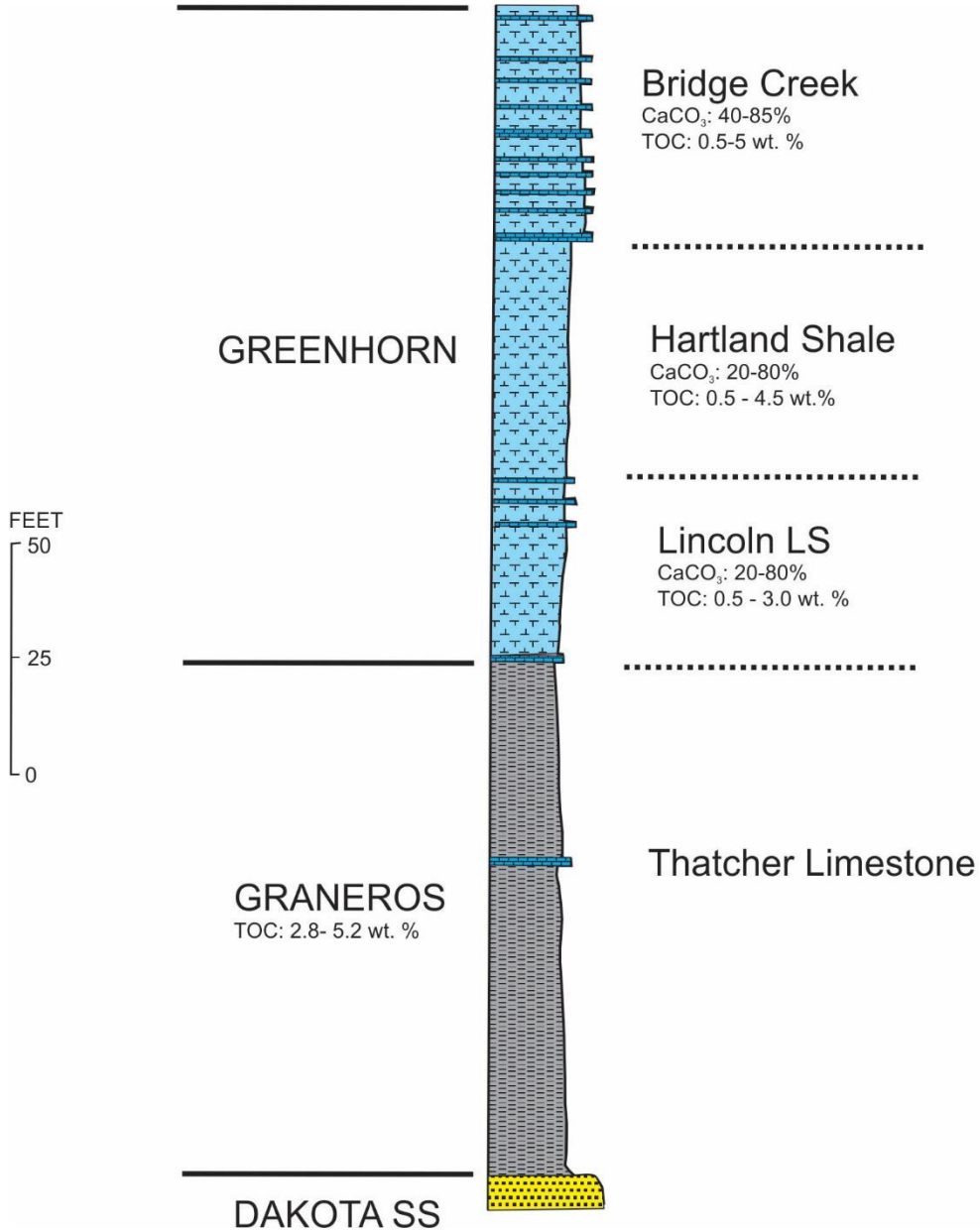
Modified from Eicher, 1969



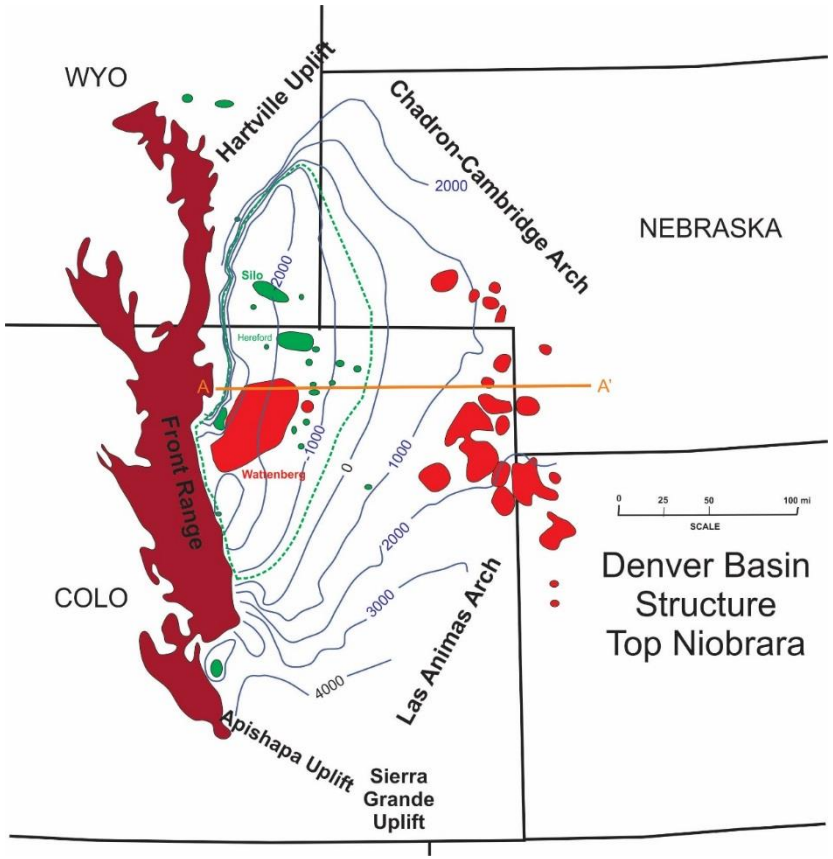
Peak transgression, Cretaceous epeiric sea, Greenhorn marine cycle, from Kauffman, 1969

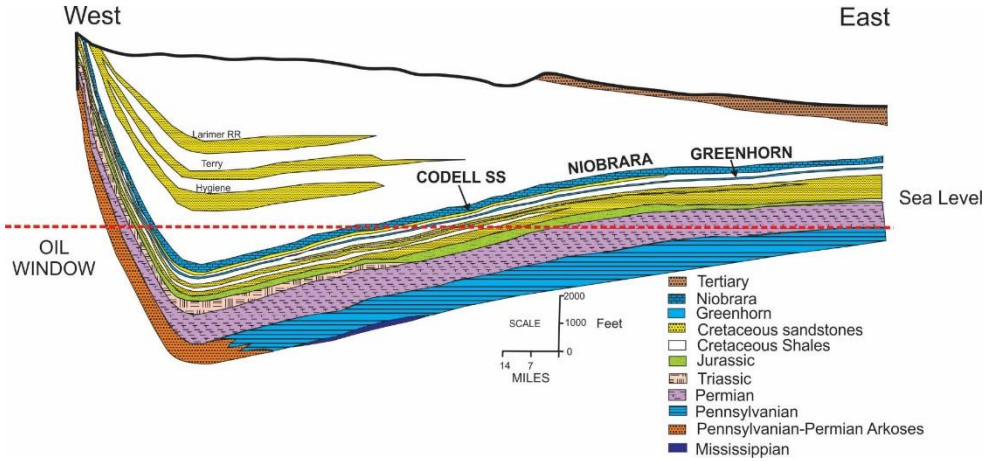
Greenhorn

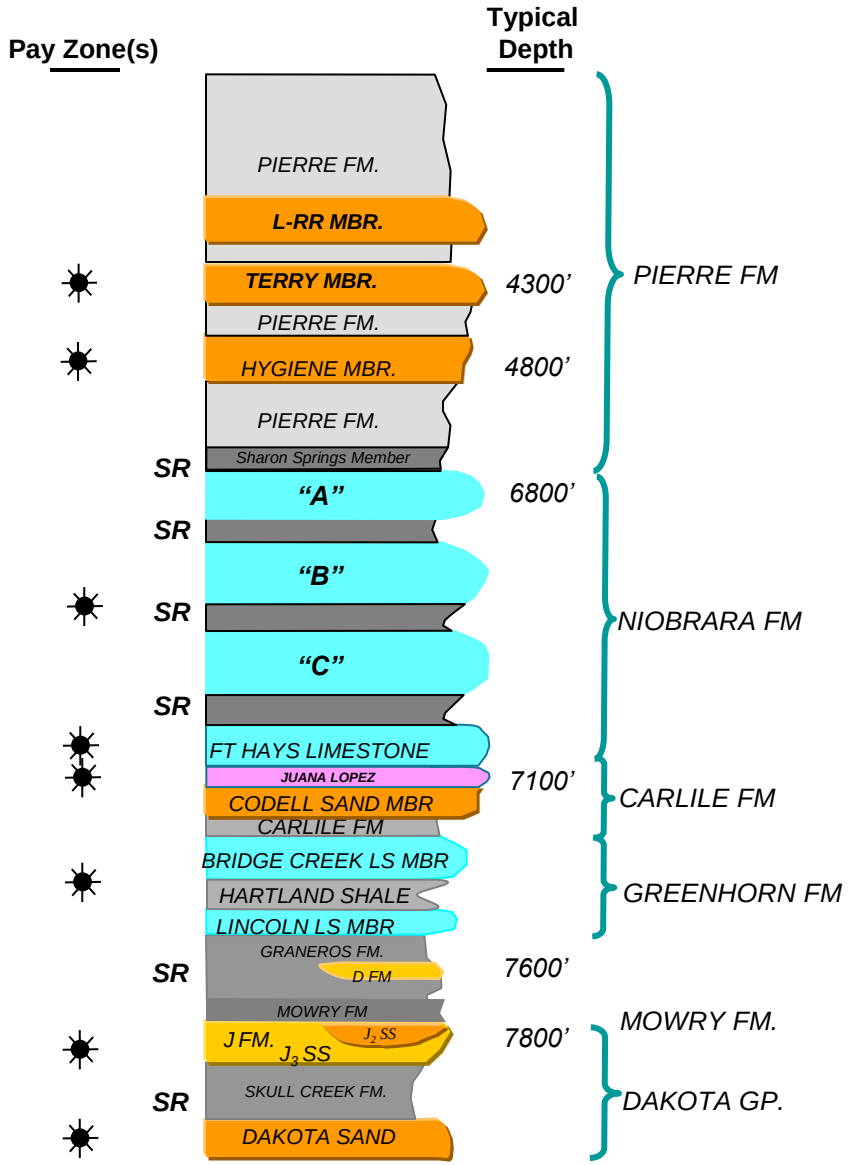
- Greenhorn was named by Gilbert (1896) for exposures near Greenhorn Station, 28 miles south of Pueblo
- Subdivided into Bridge Creek, Hartland, and Lincoln members
- ~ 95 ft thick in Kansas; 153 ft Rock Canyon anticline
- Carbonates predominantly of pelagic origin (i.e., coccoliths & forams)
- Water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



GRANEROS-GREENHORN
PETROLEUM SYSTEM
ROCK CANYON AREA
modified from Eicher and Diner, 1985

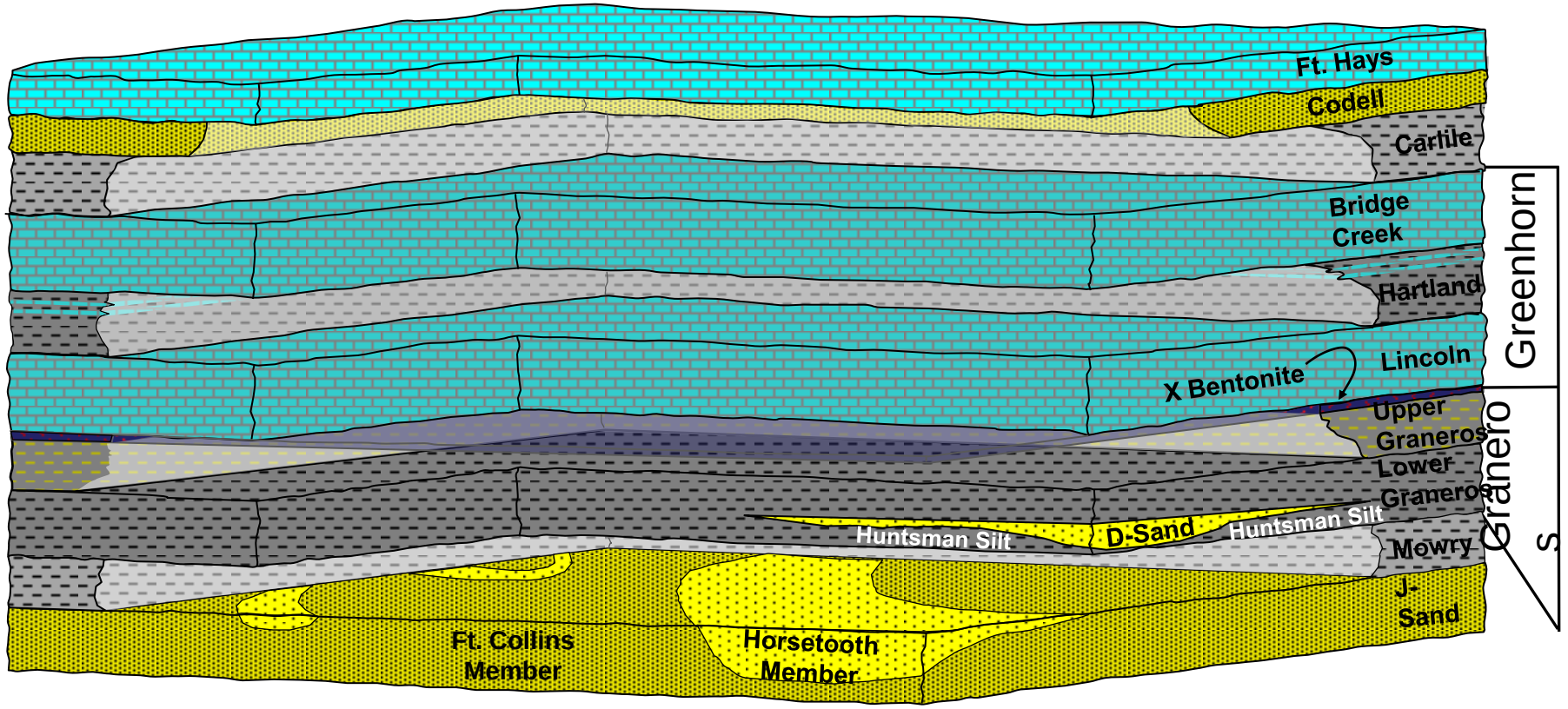

WYO
Hartville Uplift
Chadron-Cambridge Arch
NEBRASKA
Silo
Hereford
A
A'
Front Range
Wattenberg
COLO
Las Animas Arch
Apishapa Uplift
Sierra Grande Uplift
2000
1000
0
3000
4000
0 25 50 100 mi
SCALE
Denver Basin
Structure
Top Niobrara


West
East
Larimer RR
Terry
Hygiene
CODELL SS
NIOBRARA
GREENHORN
Sea Level
OIL
WINDOW
SCALE
2000
1000
0
Feet
14 7
MILES
Tertiary
Niobrara
Greenhorn
Cretaceous sandstones
Cretaceous Shales
Jurassic
Triassic
Permian
Pennsylvanian
Pennsylvanian-Permian Arkoses
Mississippian


Pay Zone(s)
Typical Depth
PIERRE FM.
L-RR MBR.
TERRY MBR.
4300'
PIERRE FM.
HYGIENE MBR.
4800'
PIERRE FM.
Sharon Springs Member
PIERRE FM
SR
"A"
6800'
SR
"B"
SR
NIOBRARA FM
"C"
SR
FT HAYS LIMESTONE
JUANA LOPEZ
7100'
CODELL SAND MBR
CARLILE FM
CARLILE FM
BRIDGE CREEK LS MBR
HARTLAND SHALE
GREENHORN FM
LINCOLN LS MBR
GRANEROS FM.
SR
7600'
D FM
MOWRY FM
MOWRY FM.
J FM.
J2 SS
J3 SS
7800'
SR
SKULL CREEK FM.
DAKOTA GP.
DAKOTA SAND

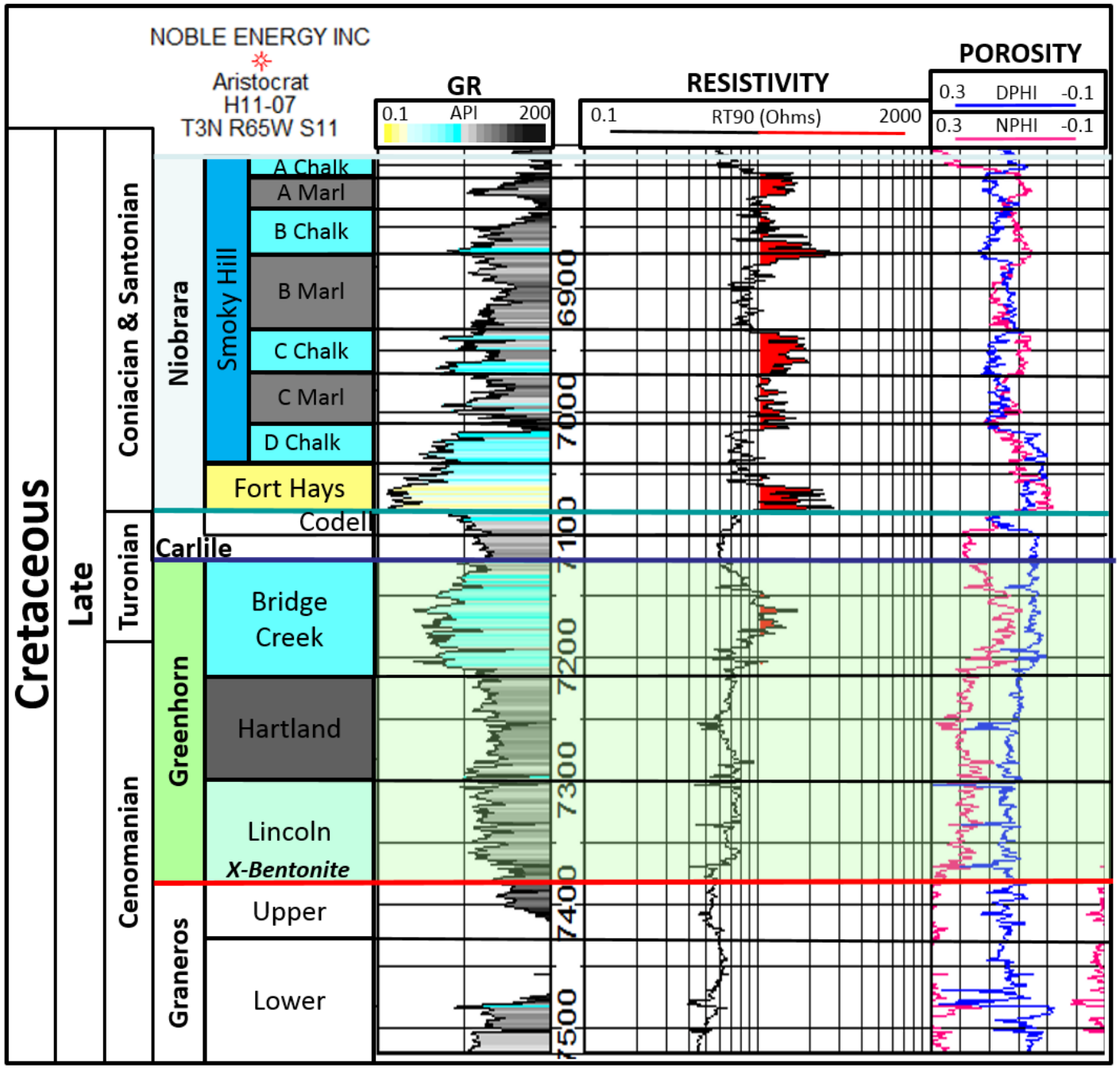
Greenhorn & Graneros Formations

- Late-Cretaceous shales, marls and chalks



Kaiser, 2012

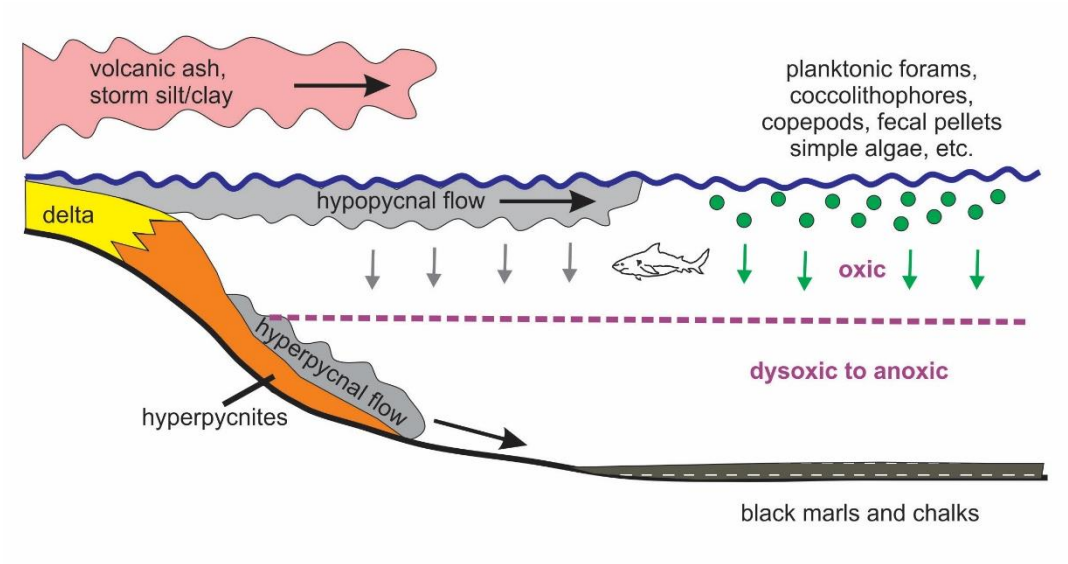
*lithologic units not to scale

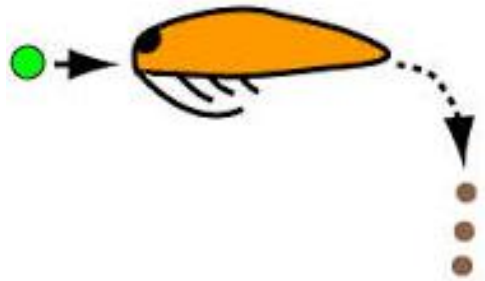


Type Log

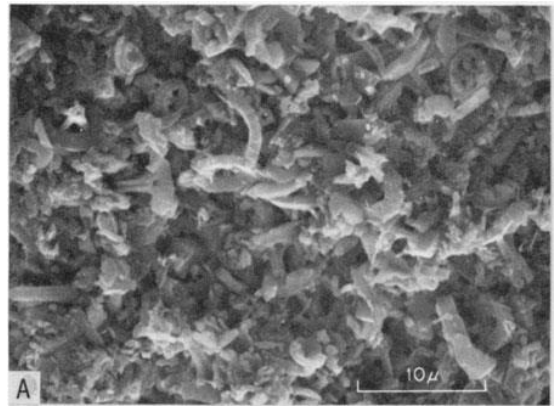
- Bridge Creek Member
  - Low GR, Elevated resistivity,
  - Elevated Neutron-Density porosity readings
  - Similar to Niobrara Chalks
- Hartland Shale
  - Relatively homogeneous
- Lincoln Member
  - lower resistivity and Neutron-Density separation
  - Indicates higher clay content
  - Thin interbeds

Durkee, 2016



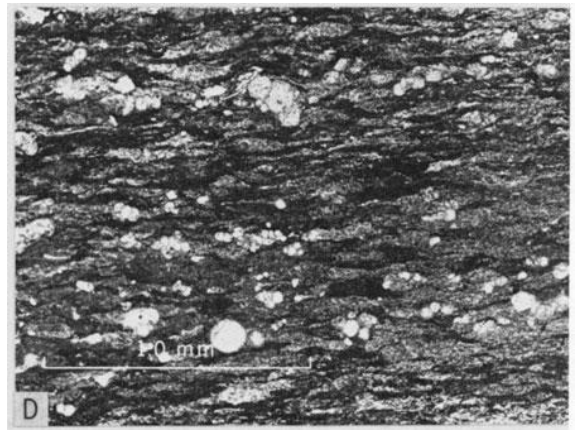


Lincoln Member (Hattin, 1979)



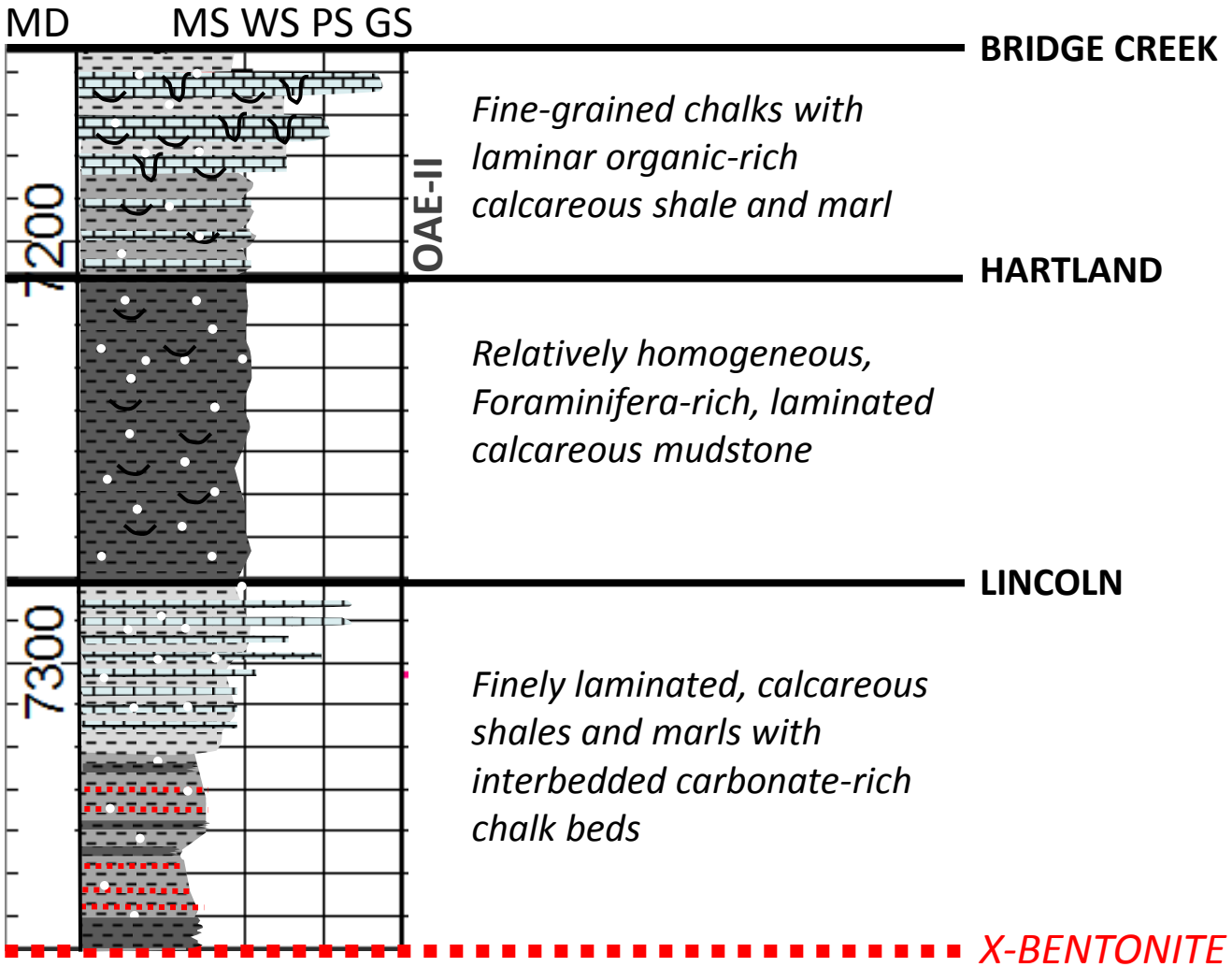
Abundant coccoliths

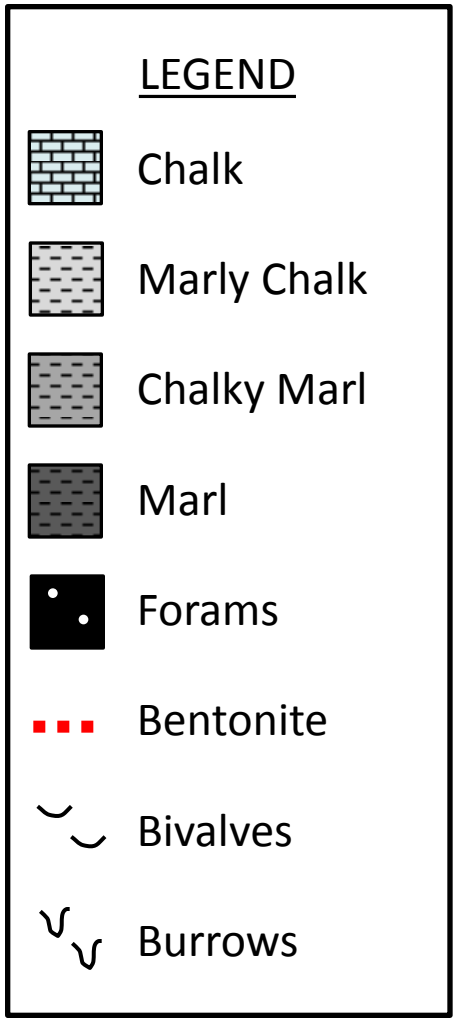
Lincoln Member (Hattin, 1979)



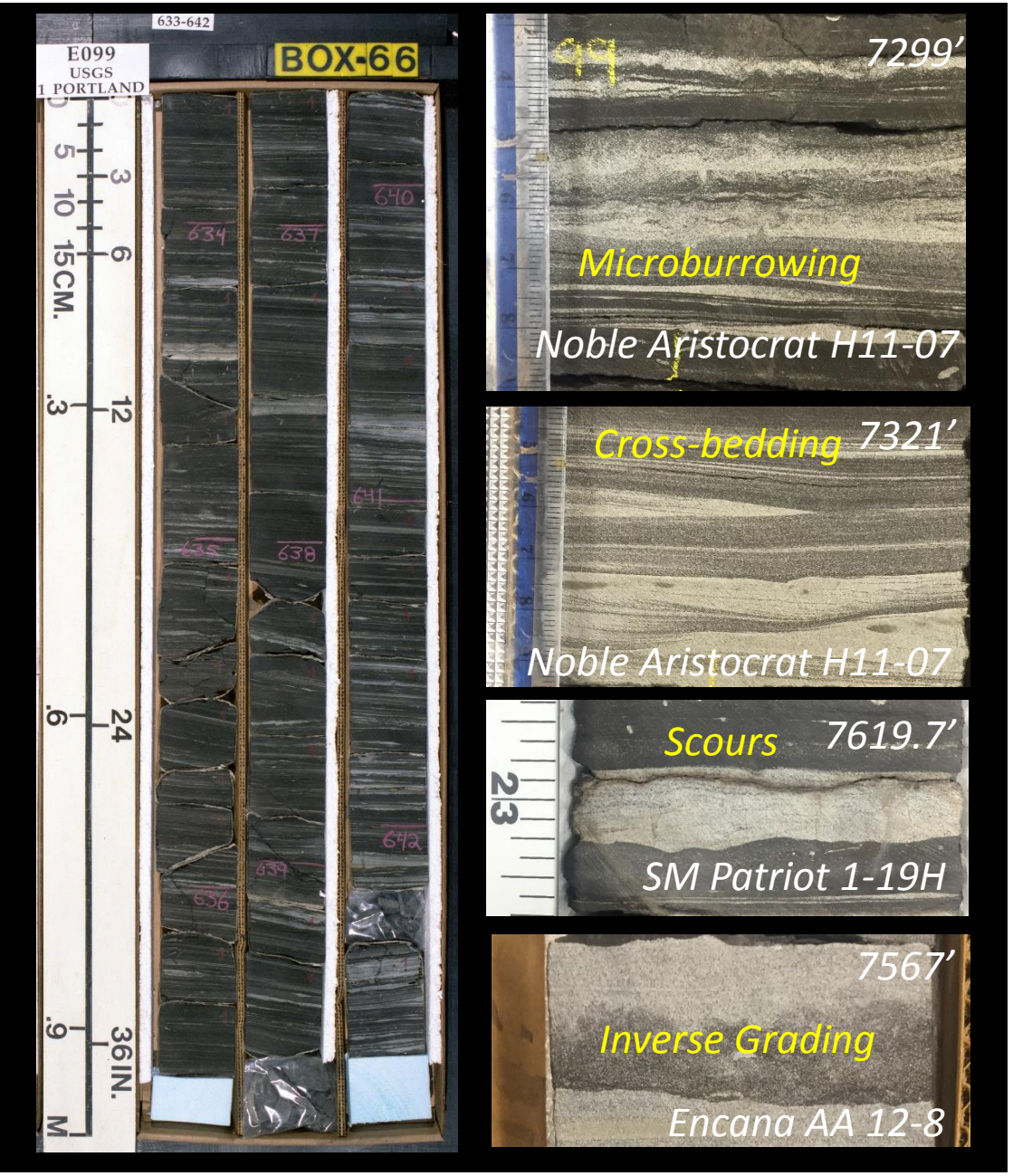
Compacted fecal pellets & forams

Generalized Stratigraphic Column





Lincoln Member



- 3 Facies:
  - Light-grey foraminifera-rich grainstone with little Qz/clay
    - Laminated, cryptic bioturbation, scour and fill
    - Offshore, deep water active currents
  - Interbedded calcareous mudstone and foraminifera-rich packstone/grainstone
    - Offshore quiet water conditions near the edge of clay transport
  - Dark-grey, calcareous, homogeneous mudstone with low fossil content
    - Offshore conditions in quiescent water
- 70-90 feet thick in Wattenberg

Durkee, 2016

Lincoln Member

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

Hartland Shale

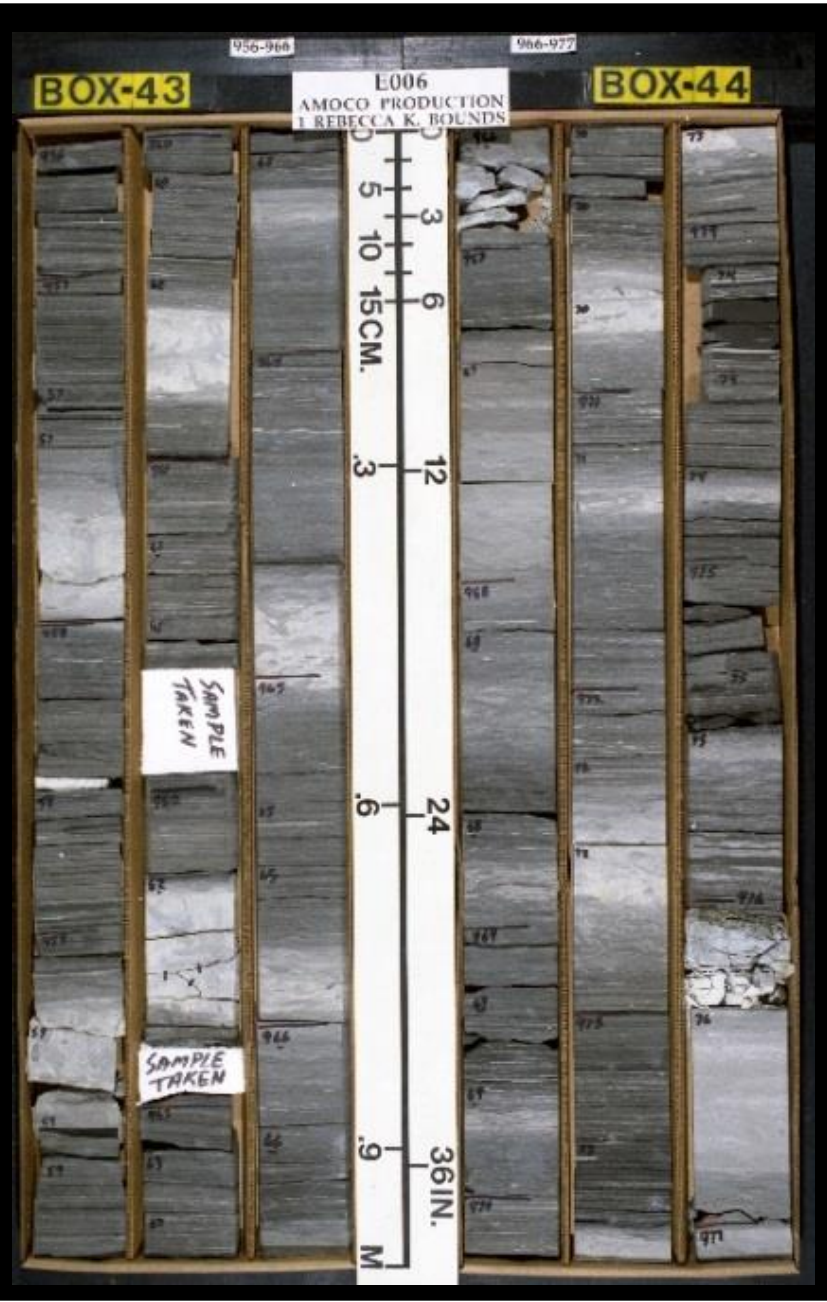
- 2 Facies:
  - Laminated foraminifera-rich mudstone
  - Fossiliferous mudstone
- Well-laminated
  - Abundant foraminifera, fossil fragments, and fecal pellets concentrated into laminae
  - Graded beds/ turbidites
- Foraminifera “white specks”
- Inoceramid Bivalves and oyster fragments
- Relatively low energy, pelagic sedimentation
- Remaining TOC values 2-4 wt. %
  - Type II marine Kerogen
  - Lowest near basin axis

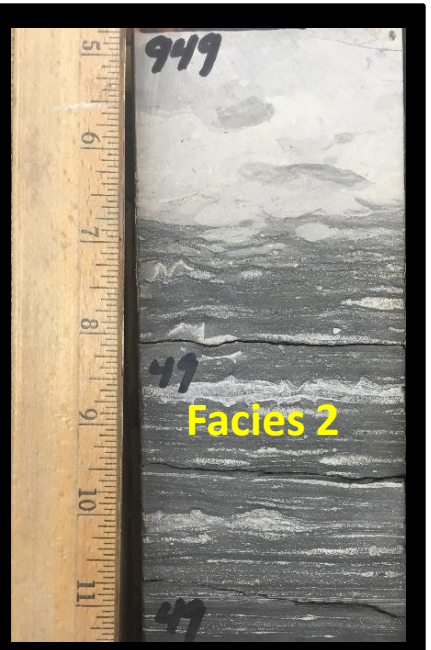
Durkee, 2016

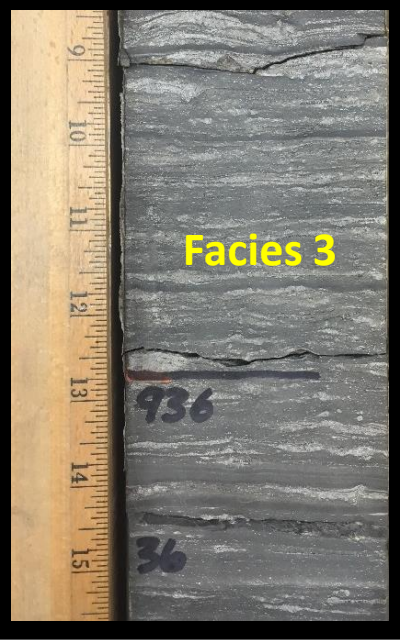
Hartland Shale

- 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)

Bridge Creek Limestone







- 4 main Facies:
  1) Bioturbated chalk intervals
     - *Planolites, Thalassinoides*
     - transgressive phases with less clay
  2) Fossiliferous Marly Chalk
     a. Bioturbated Marly Chalk
     b. Laminated Marly chalk
  3) Chalky Marl
  4) Marl
     a. Laminated foraminifera-rich marl
     b. Lenticular bedded ripple marl

- Chalks considered reservoirs, Calcareous marlstone facies considered sources
  – Chalk: TOC <1%
  – Marl: TOC 4-5 wt. %

- Less than 40 to over 90 ft thick

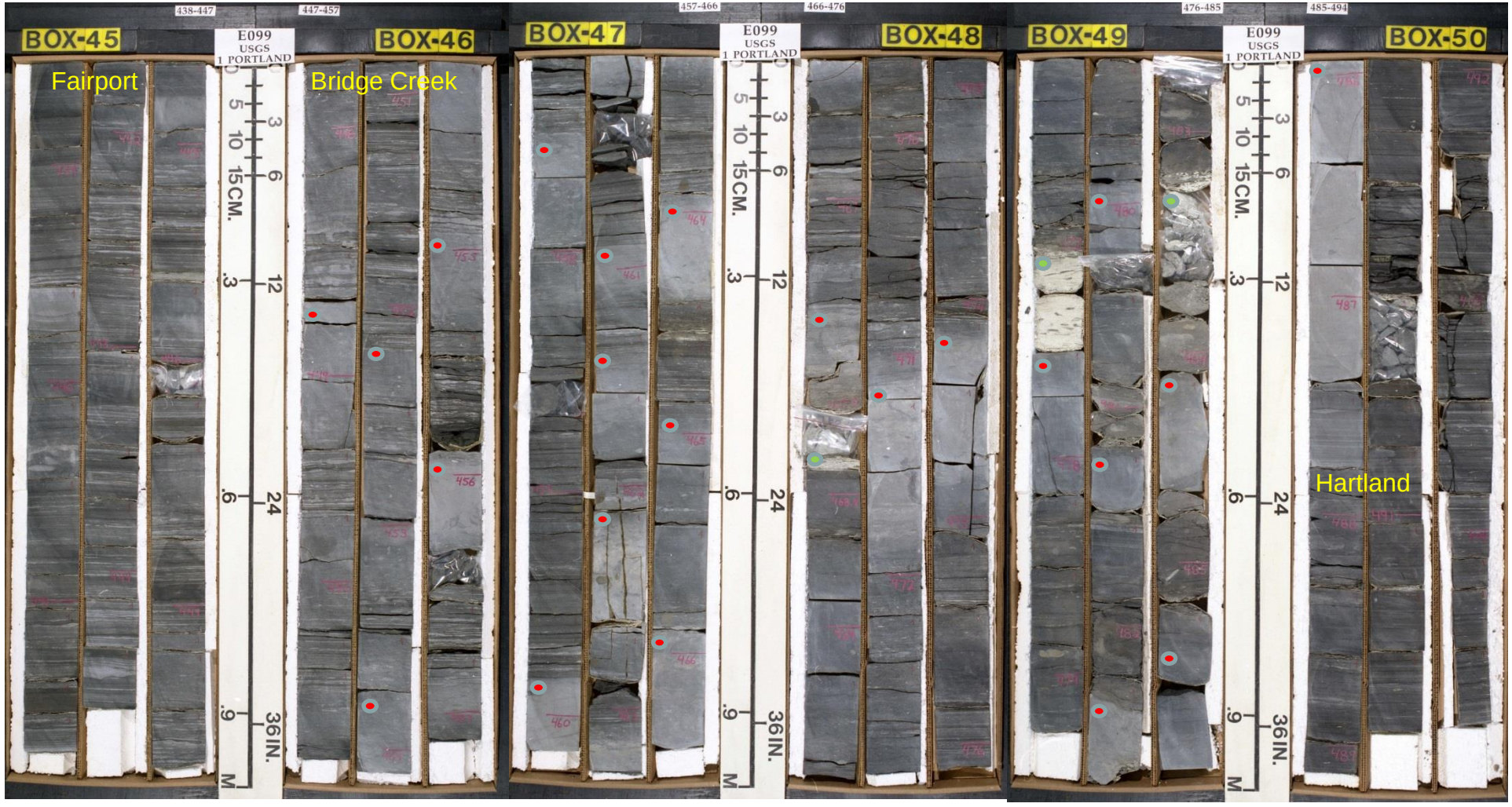
Durkee, 2016

Bridge Creek Limestone

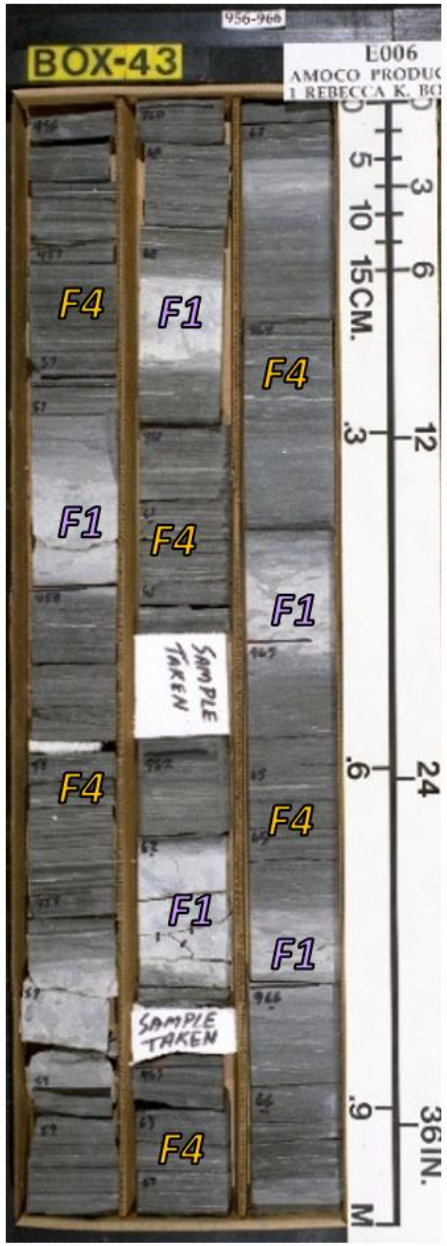
- Rhythmic limestone-shale cycles in response to Milankovitch orbital cycles 20,000 to 100,000 years Barron et al., 1985
- Encompasses Cenomanian-Turonian extinction event and a major Cretaceous oceanic anoxic event
- Named by Bass (1926) for a series of beds at top of Greenhorn limestone near Medway,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

USGS # 1
Portland

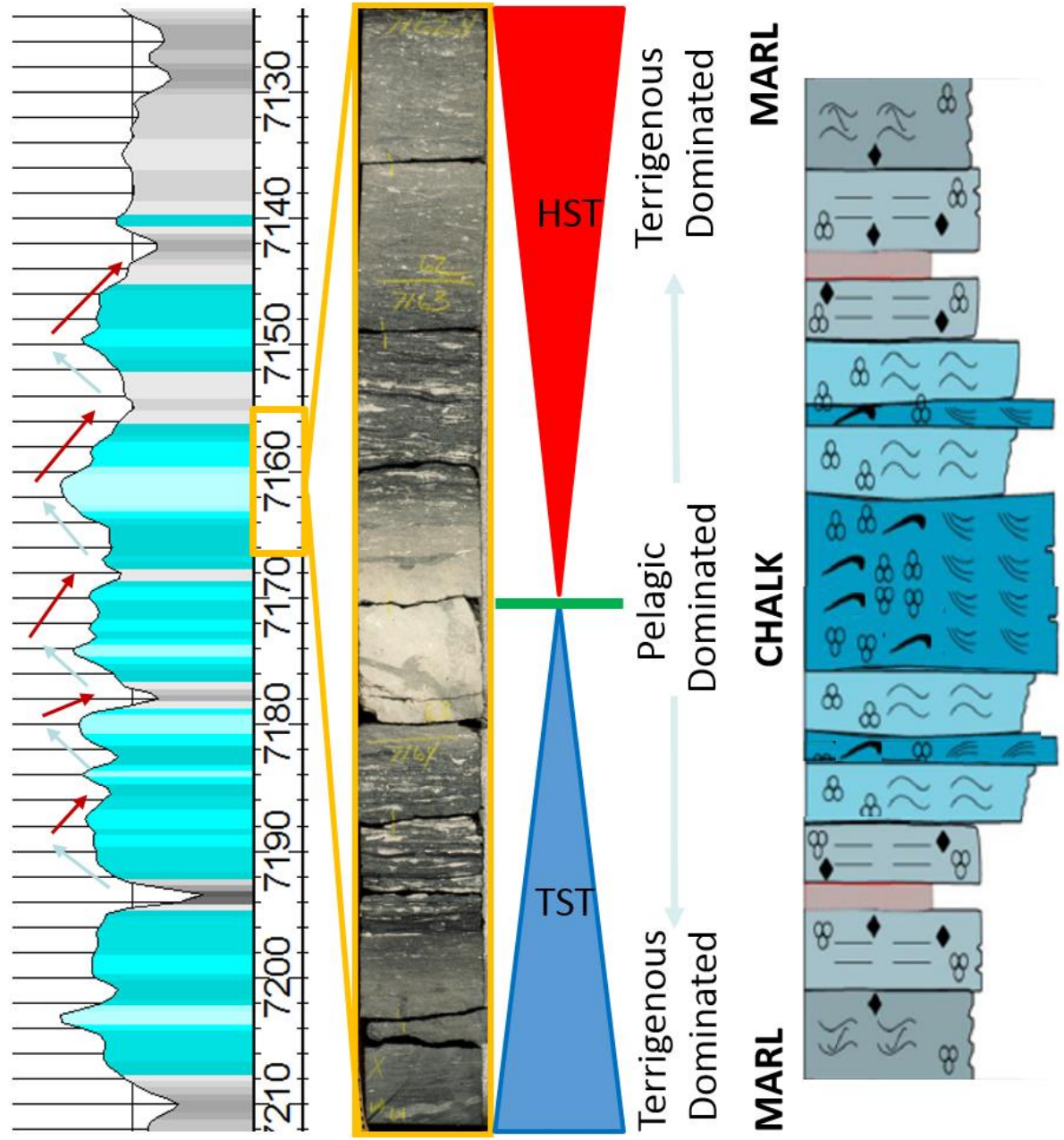
~ 23 cycles in the Bridge Creek



Bridge Creek Limestone Parasequence Model



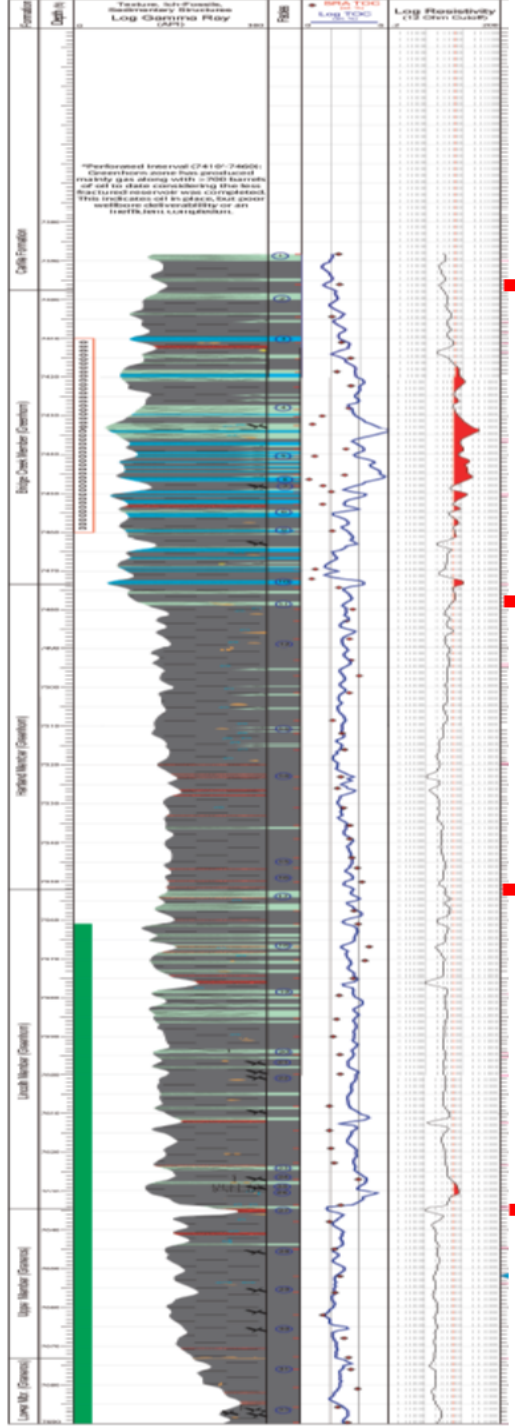
- Oscillations between mud-rich and carbonate-rich facies
- Earth Orbital variations:
  - Axial precession about 21 Ka
  - Axial obliquity 41 Ka
  - Orbital eccentricity 100 Ka and 413 Ka
- Greenhorn Cycles correspond to Milankovitch cycles
  - appear to be 41 Ka obliquity cycles
- Periods of stratified and mixed water columns explain benthic and redox cycles



The Graneros-Greenhorn Petroleum System

- Reservoirs: Bridge Creek LS., Lincoln LS.
- Source Beds: Graneros, Lincoln LS., Hartland Shale
- Seals: Carlile and Greenhorn shales
- Overburden: Tertiary beds, Laramie, Fox Hills, Pierre and Niobrara formations

The Graneros-Greenhorn Petroleum System



Hartland Mbr. Carlile

Greenhorn Formation

Bridge Creek
$CaCO_3$: 40-85 %
TOC: 0.5 – 3.4 wt. %

Hartland Shale Member
$CaCO_3$: 20-80 %
TOC: 0.7 – 4.1 wt. %

Lincoln LS. Member
$CaCO_3$: 20-80 %
TOC: 2.2 – 4.7 wt. %

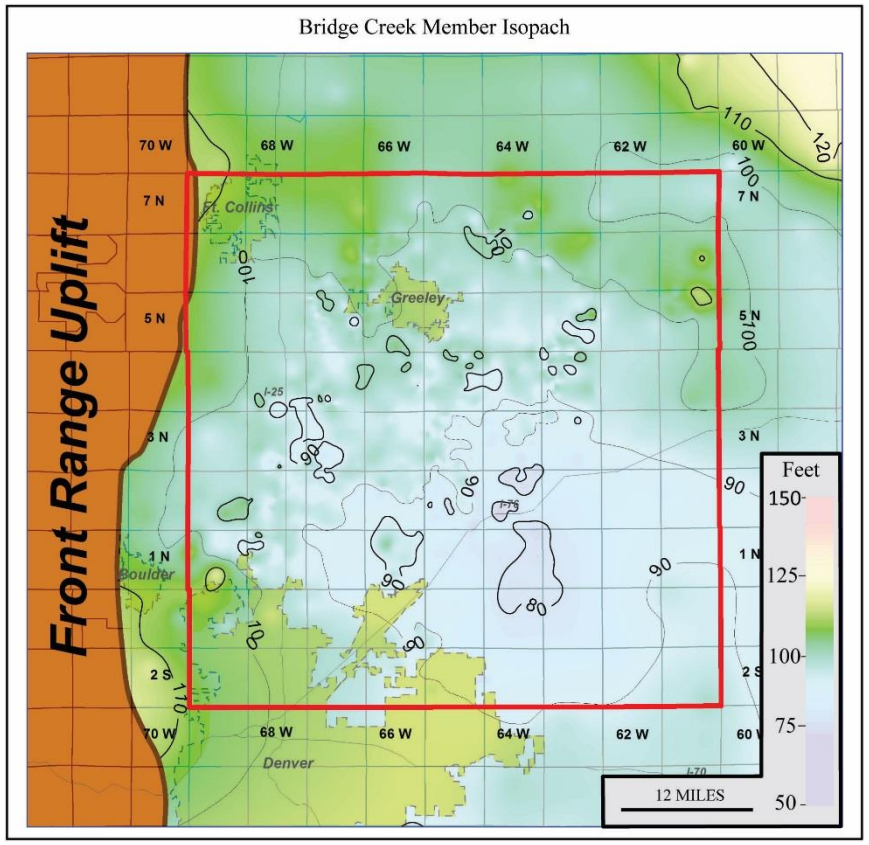
50 ft

Graneros Formation
TOC: 1.6 – 4.03 wt. %

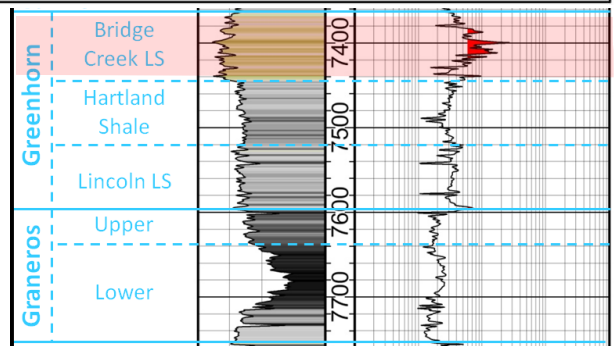
Kaiser, 2012

Reservoir Rock Thicknesses

Bridge Creek Member Isopach

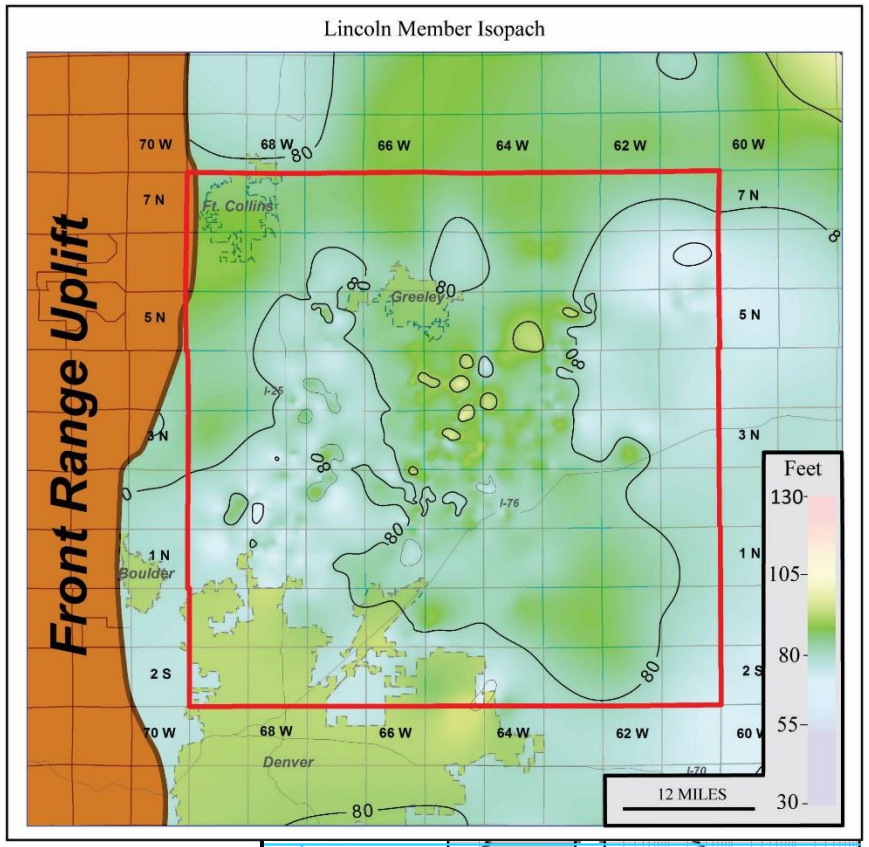


≈80-110 ft. thick

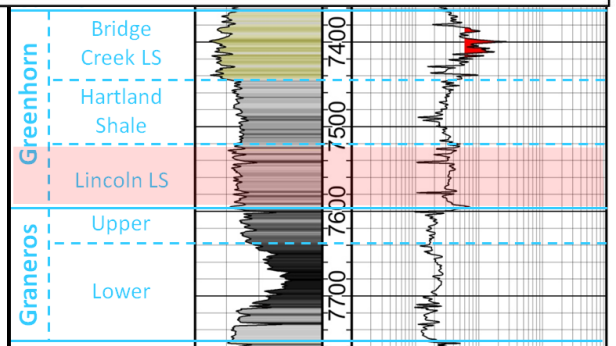


Kaiser, 2012

Lincoln Member Isopach

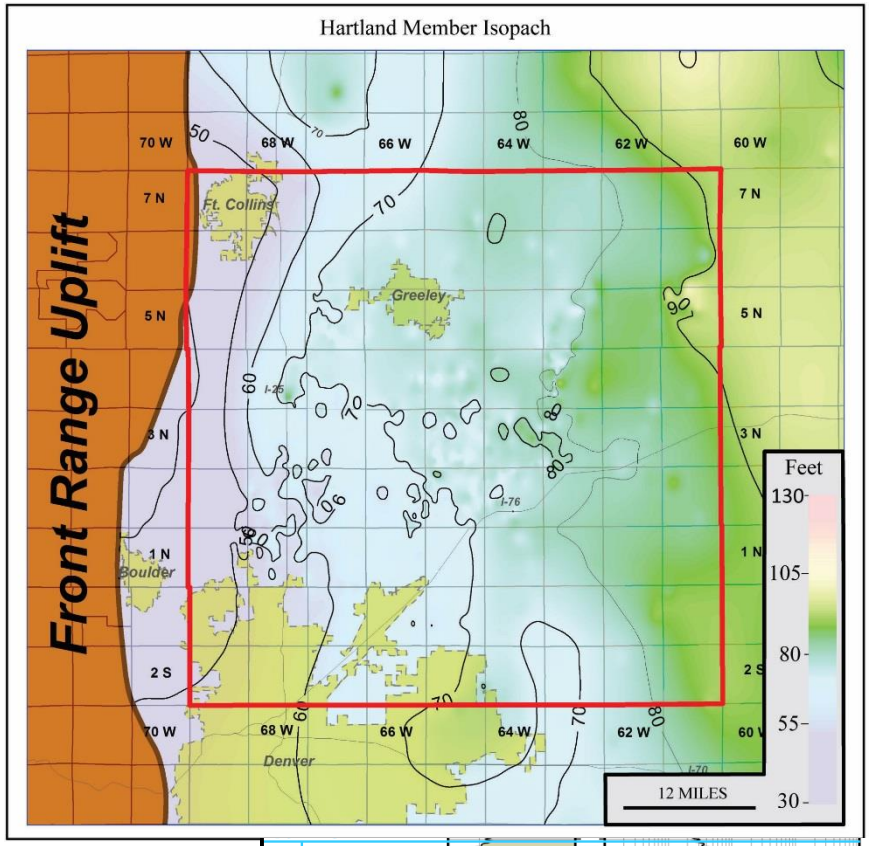


≈70-90 ft. thick

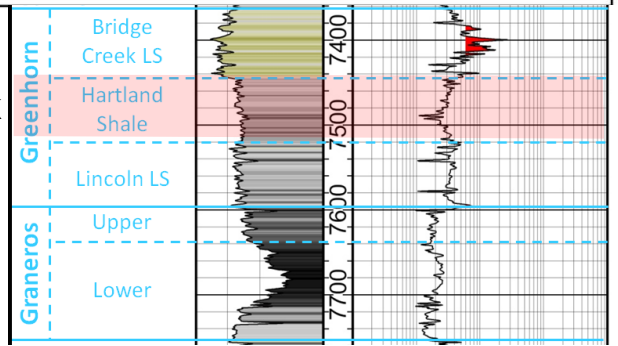


Source Rock Thicknesses

Hartland Member Isopach

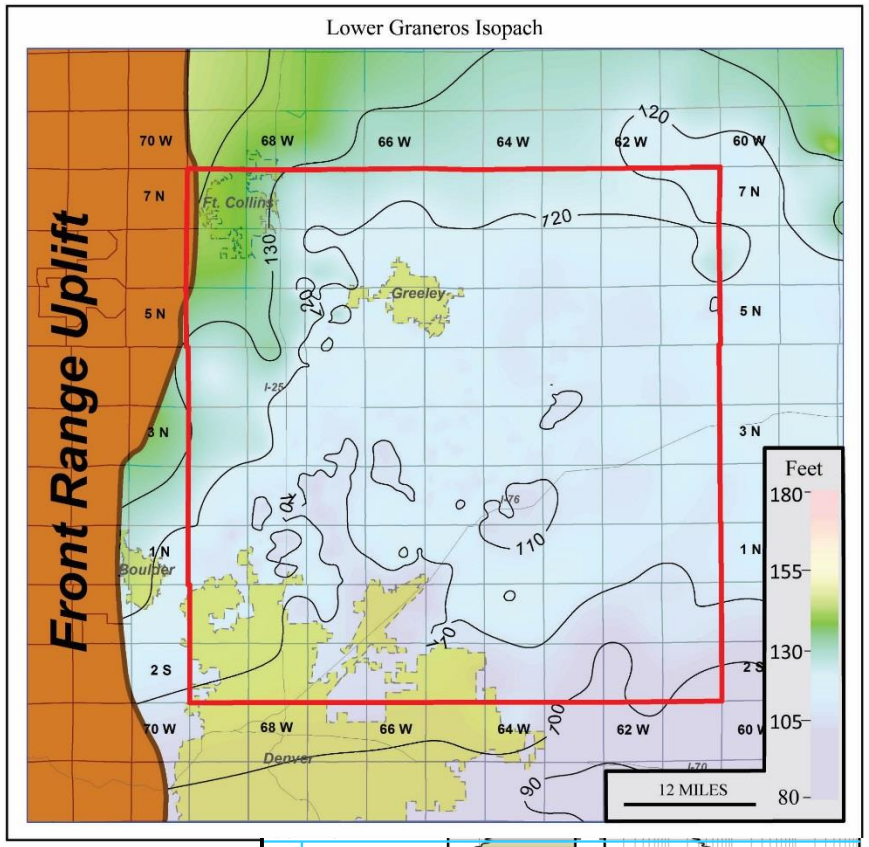


≈40-90 ft. thick

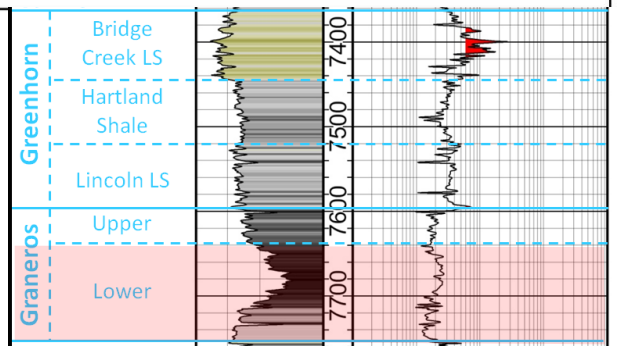


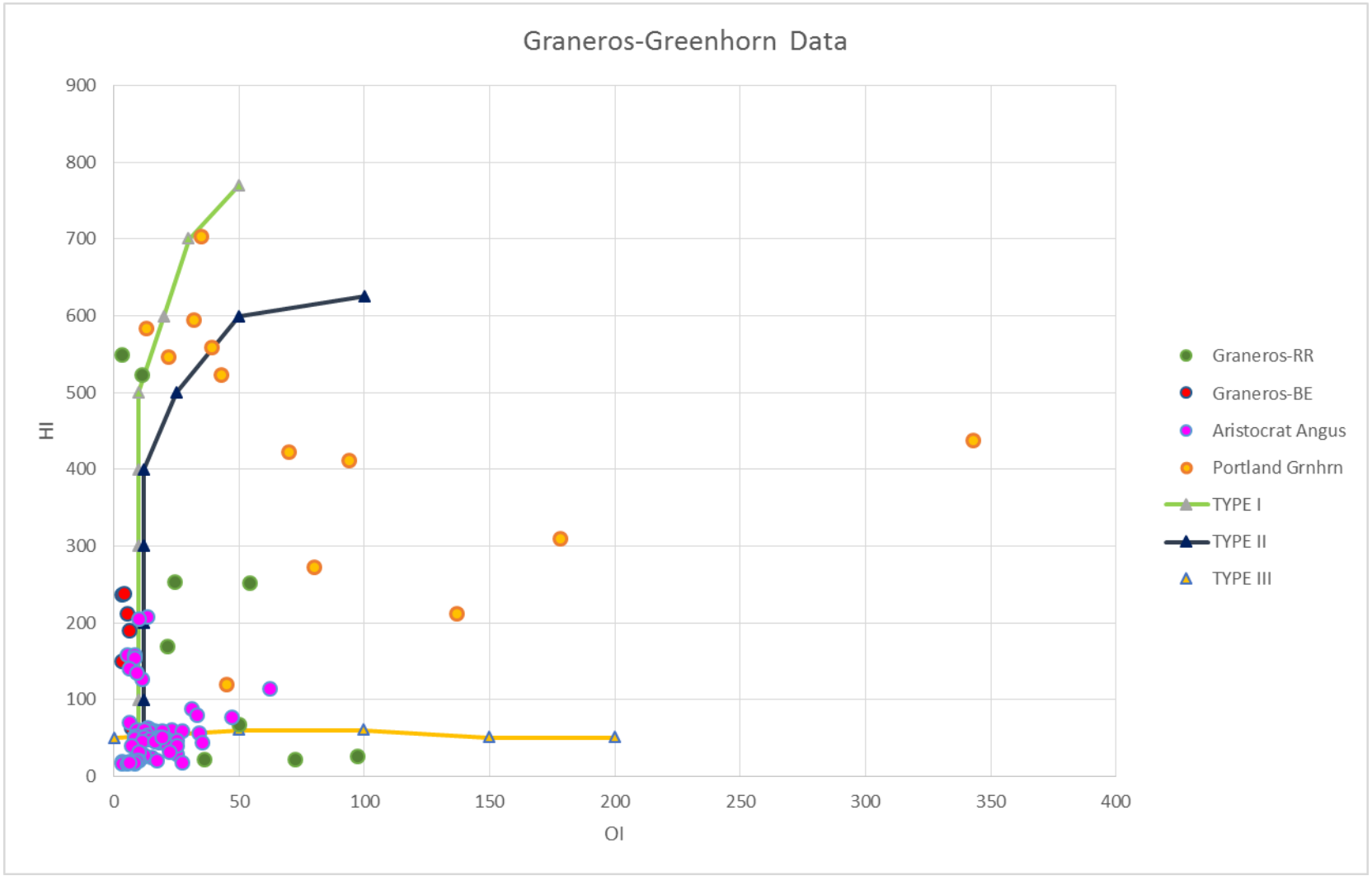
Kaiser, 2012

Lower Graneros Isopach



≈100-130 ft. thick





Aristocrat Angus file

XRF DATA

Detrital indicators
Al, Ti, K

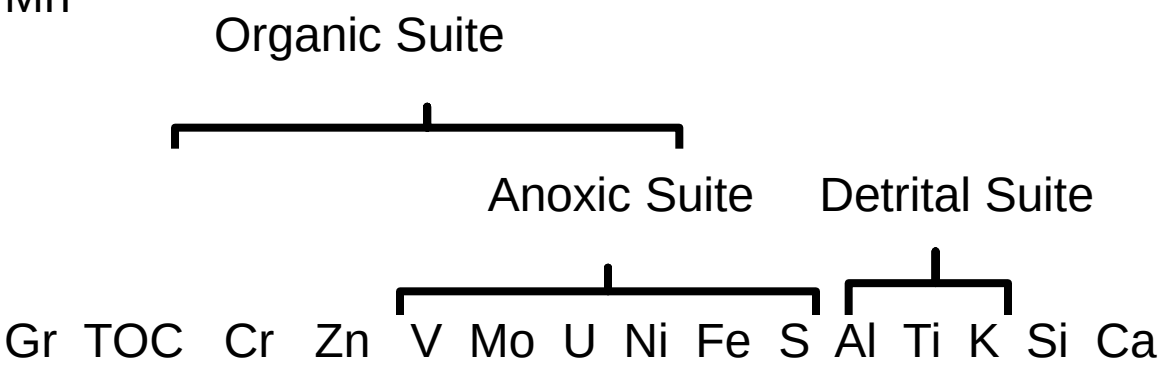
Ca, Si

Organic Elements
Cr, Zn, Mo, V, Ni, U

Anoxic Suite (Redox)
Mo, U, Ni
Fe, S (pyrite)

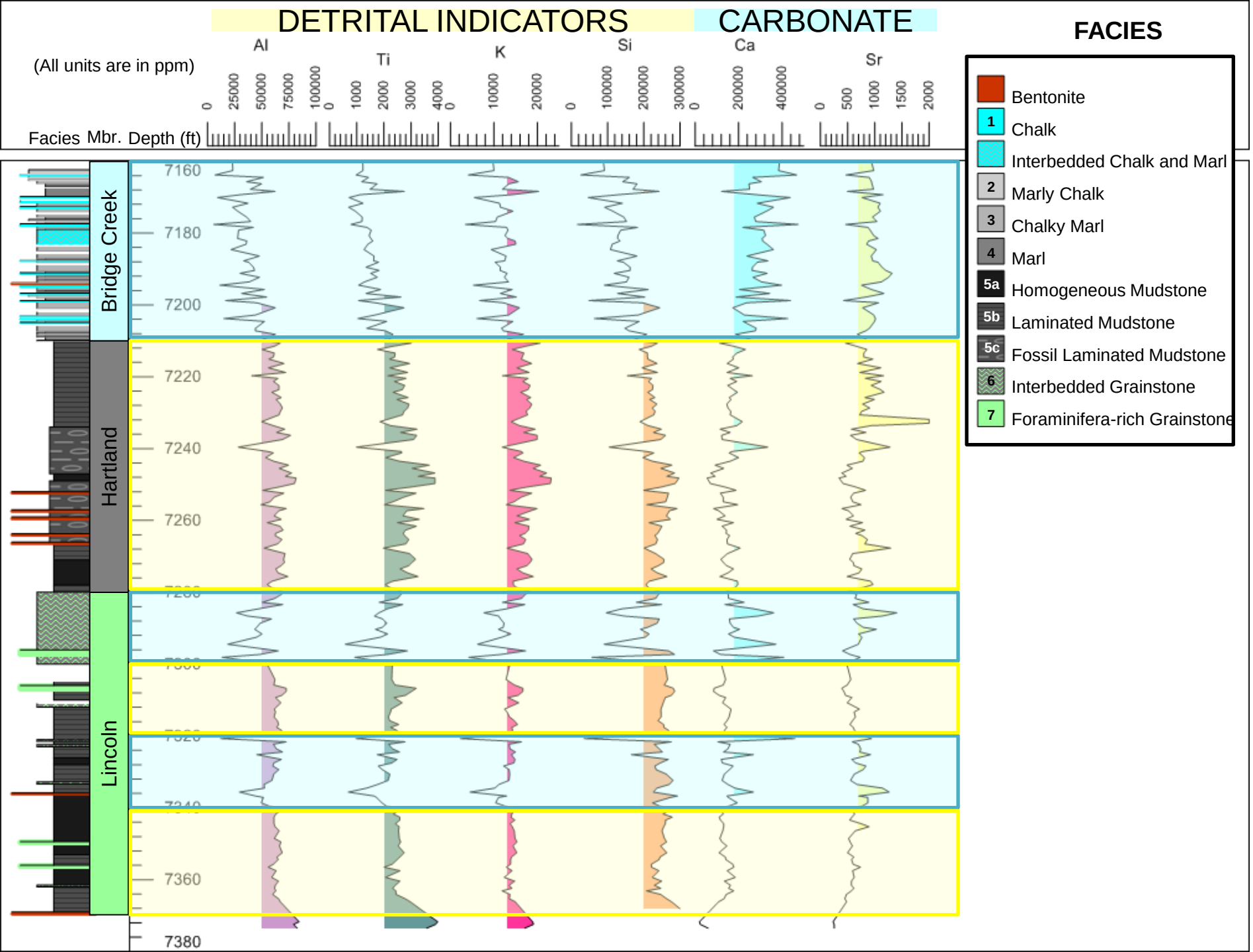
Oxic Suite
Mn

Figure 1-14: Thermo Scientific Niton XRF analyzer (Niton XL3t GOLDD+) (Thermo Fisher Scientific, 2010).



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.

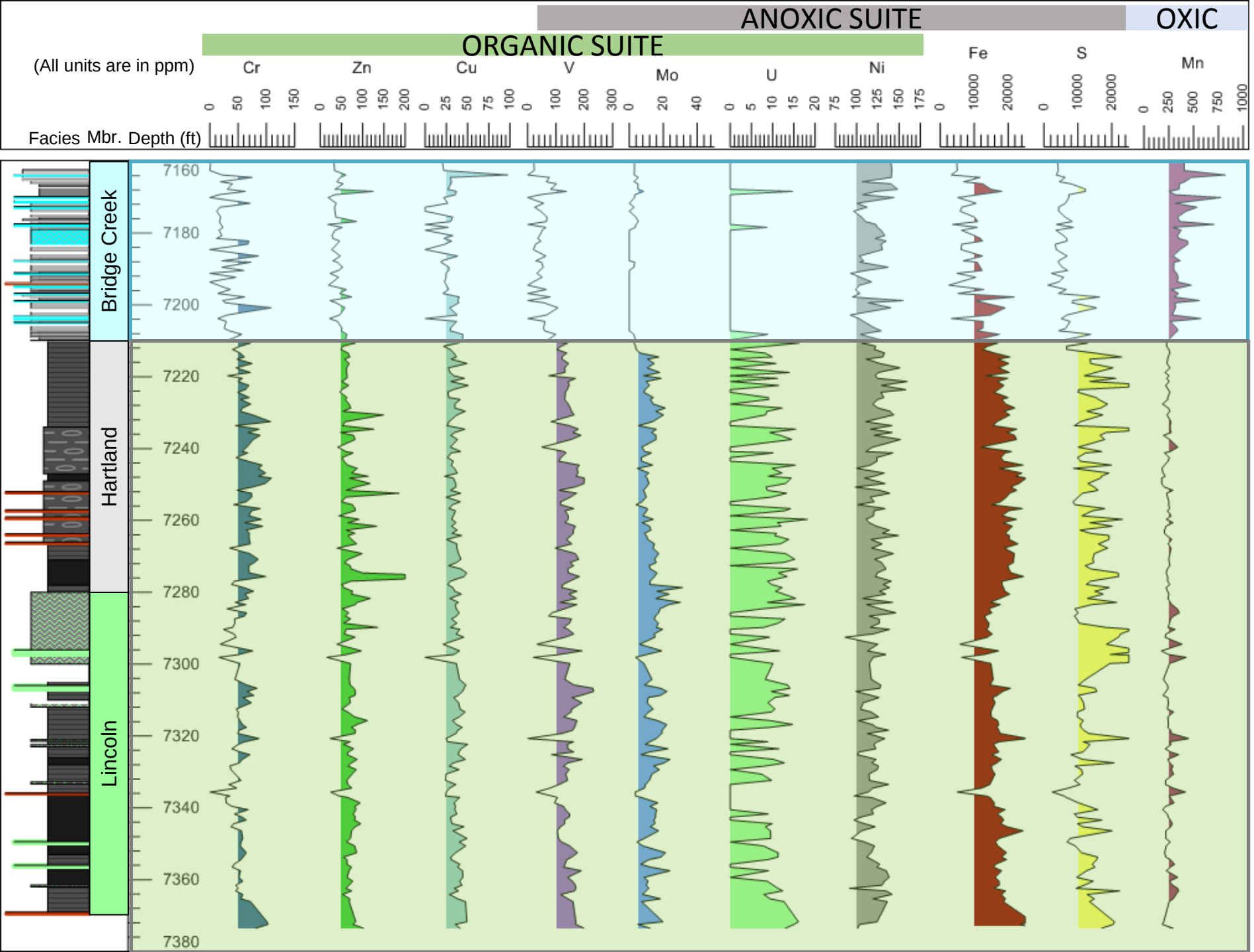


XRF

- **Detrital indicators:**
  - Associated with terrigenous materials
- **Carbonate indicators:**
  - Associated with carbonate production

Durkee, 2016

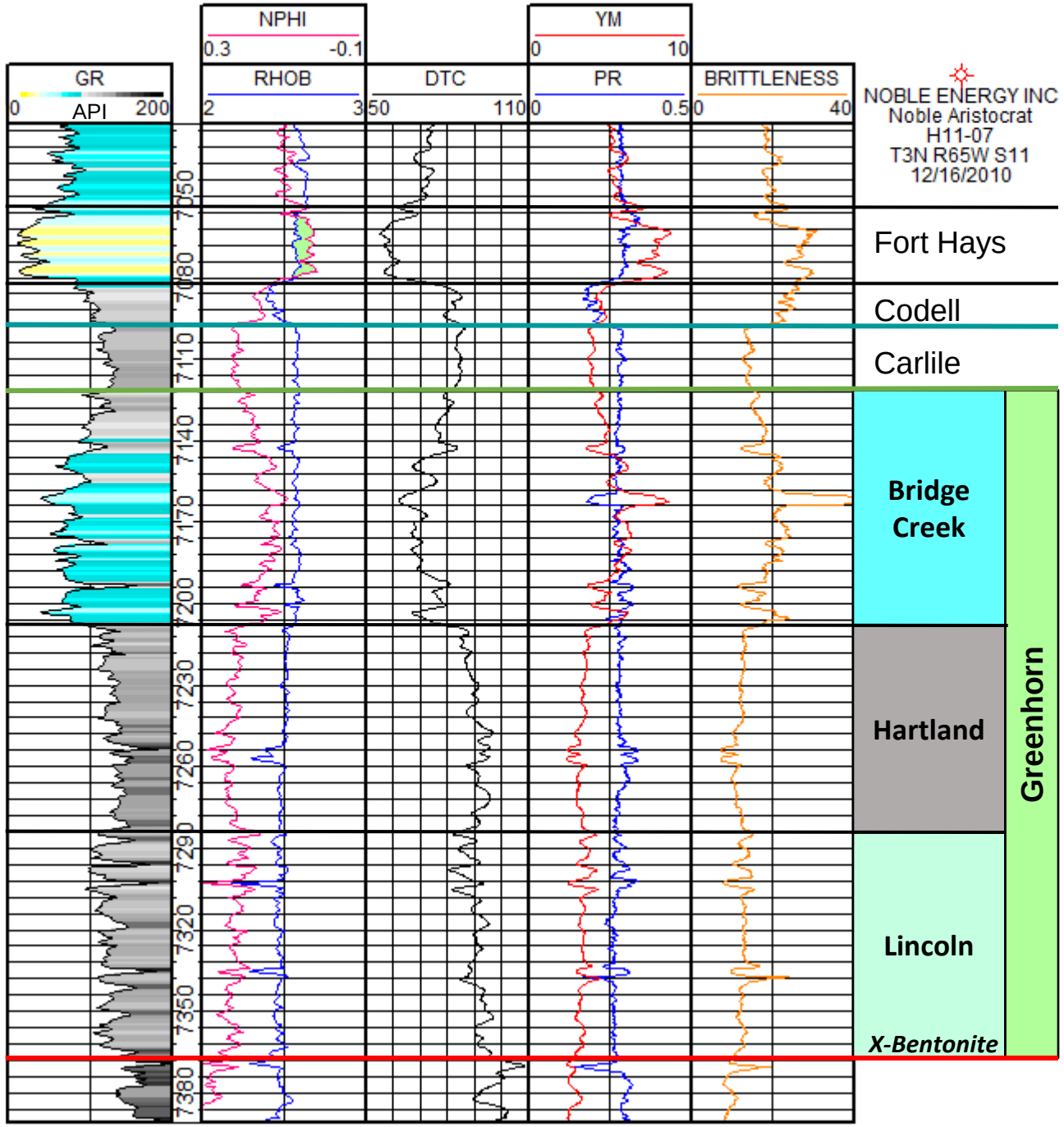
XRF



- **Organic suite:**
  - Redox conditions, organic matter
- **Anoxic Suite:**
  - Anoxic conditions associated with redox reactions
- **Oxic Suite:**
  - Oxic to Suboxic conditions

Durkee, 2016

Calculated Geomechanics



Elastic moduli and brittleness:

$$PR = \frac{\frac{1}{2}\left(\frac{DTS}{DTC}\right)^2 - 1}{\left(\frac{DTS}{DTC}\right)^2 - 1}$$

$$YM = 1000 * \rho \left(\frac{\left(\frac{1}{DTS}\right)^2 \left(3\left(\frac{1}{DTC}\right)^2 - 4\left(\frac{1}{DTS}\right)^2\right)}{\left(\frac{1}{DTC}\right)^2 - \frac{1}{DTS}} \right)$$

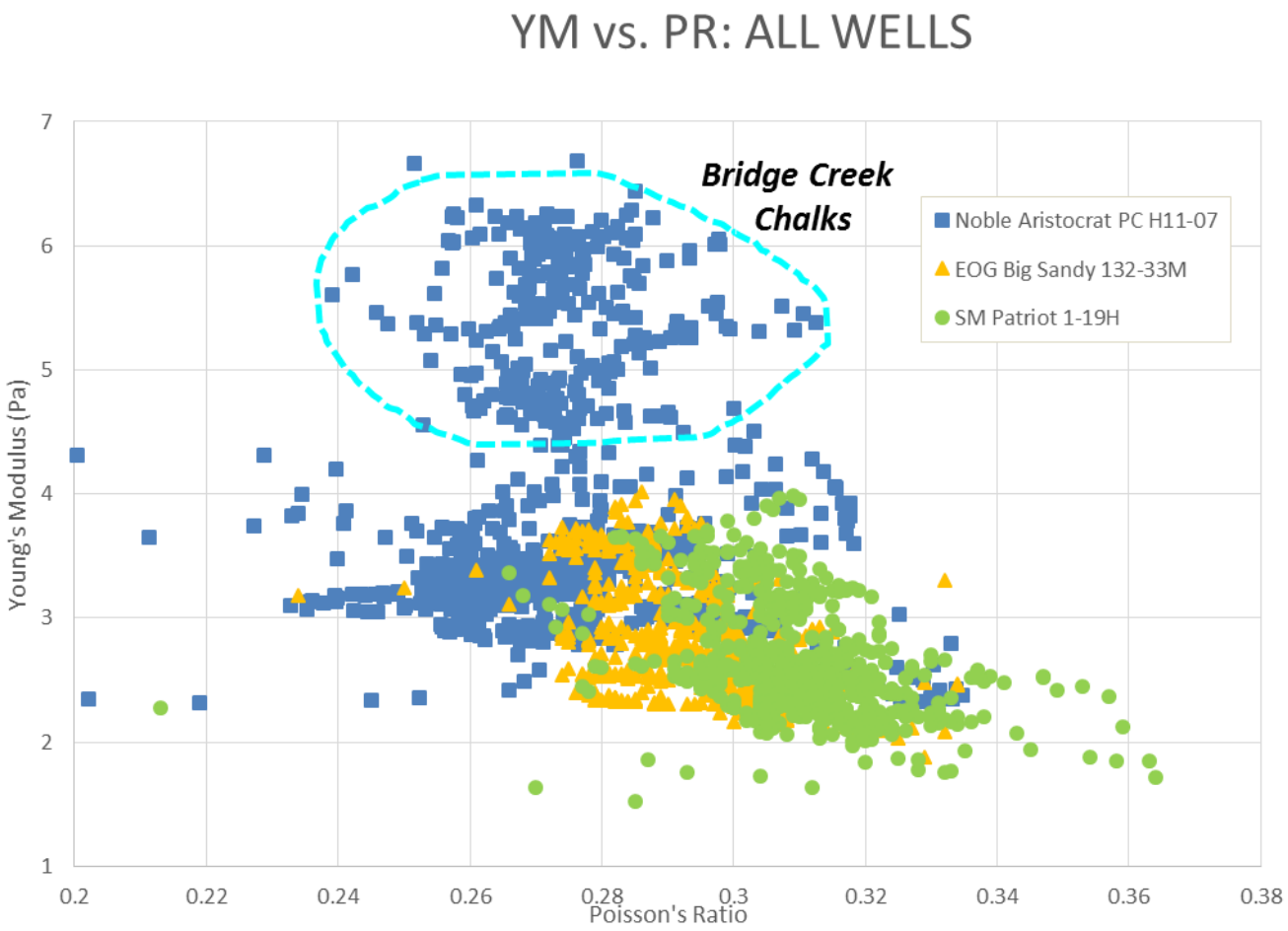
$$BI = \frac{YM}{PR}$$

Durkee, 2016

Elastic Moduli

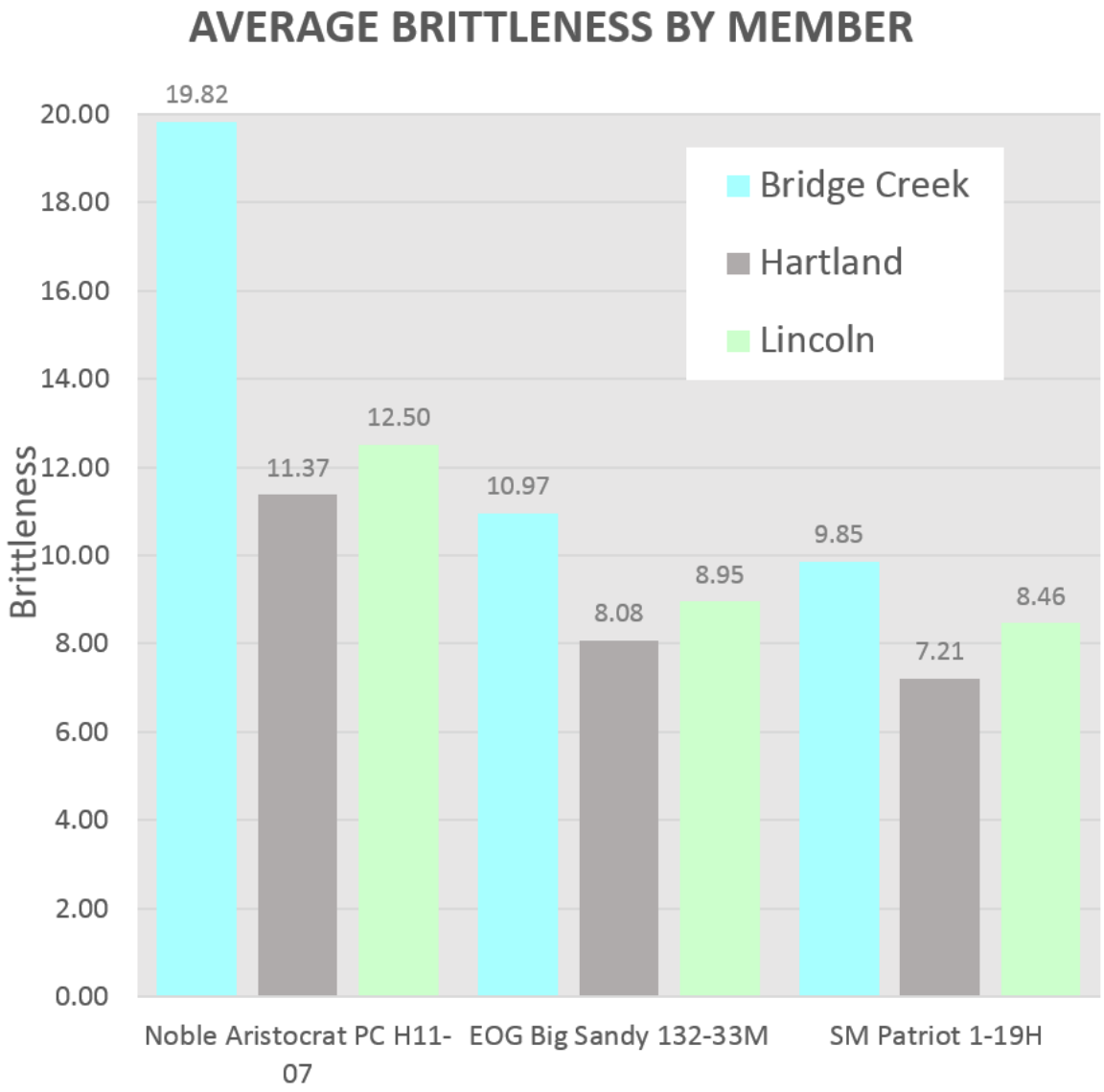
Average Geomechanical properties for each member in each of the study wells

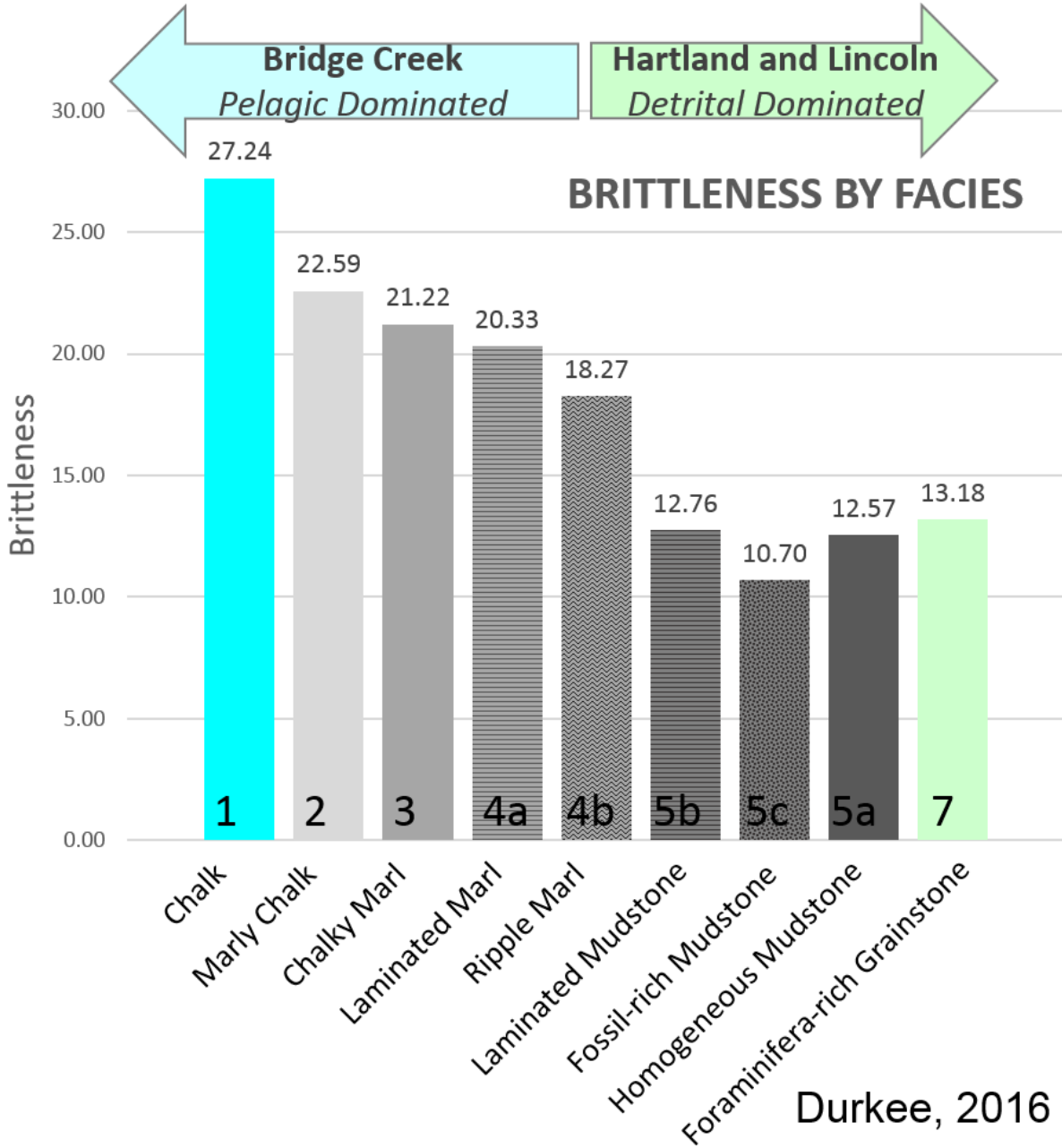
	PR	YM	Brittleness
Noble Aristocrat PC H11-07			
Bridge Creek	0.28	5.38	19.82
Hartland	0.28	3.20	11.37
Lincoln	0.26	3.29	12.50
EOG Big Sandy 132-33M			
Bridge Creek	0.29	3.18	10.97
Hartland	0.30	2.44	8.08
Lincoln	0.29	2.57	8.95
SM Patriot 1-19H			
Bridge Creek	0.31	3.02	9.85
Hartland	0.32	2.28	7.21
Lincoln	0.30	2.46	8.46



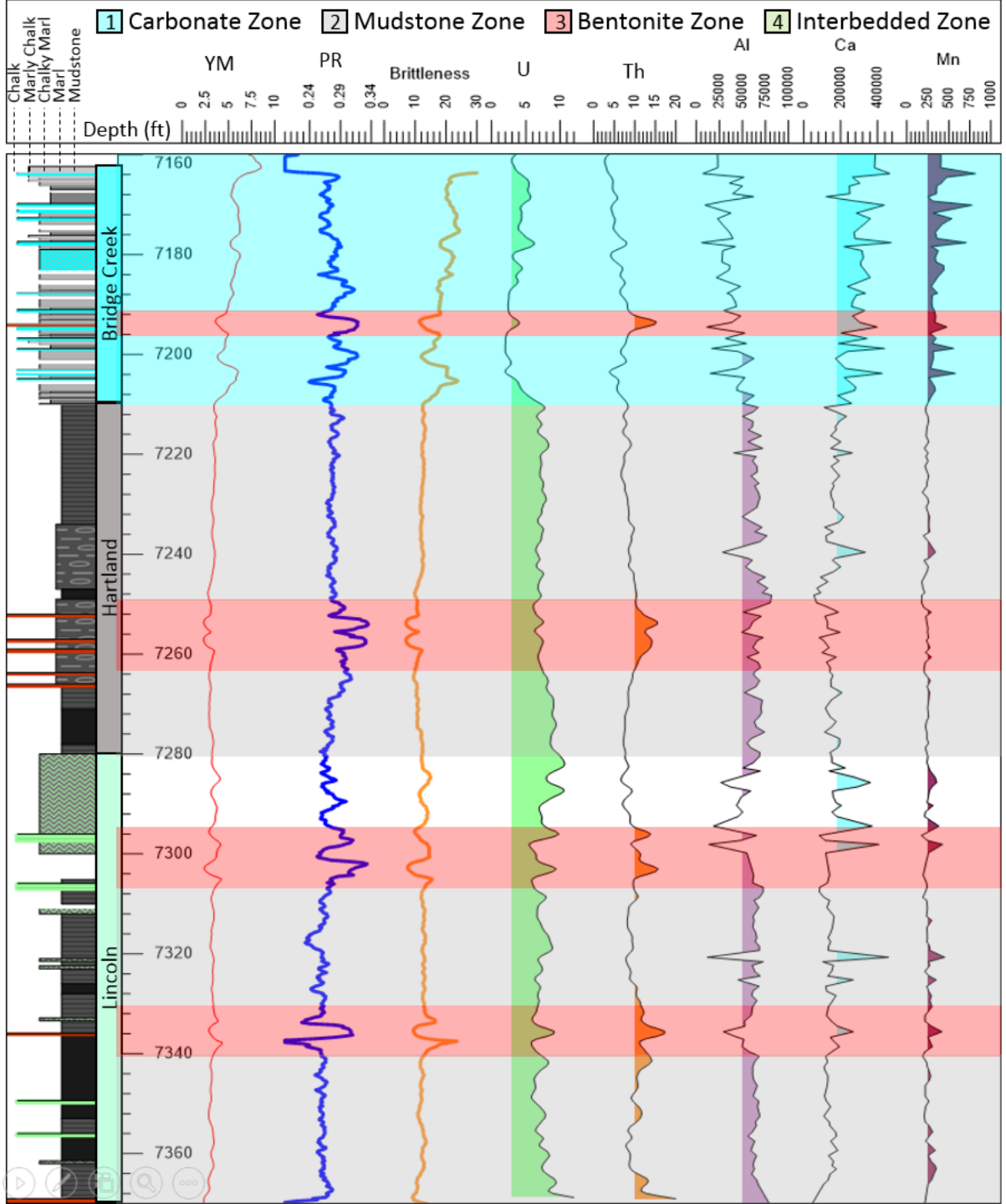
Durkee, 2016

Brittleness





Durkee, 2016



Mechanical Stratigraphy

- Zone 1: Carbonate Zone
  - Alternating chalks and marls (Facies 1-4)
  - Fluctuating YM, PR, and BI
  - Low clay
  - Brittleness: >15
- Zone 2: Mudstone Zone
  - Mudstone facies (Facies 5 a, b and c)
  - YM, PR, BI homogeneous
  - Increased TOC and Clay
  - Brittleness: 10-12
- Zone 3. Bentonite Zone
  - Bentonite (Facies 8)
  - Increased PR, Lowest YM and BI
  - Brittleness: <10

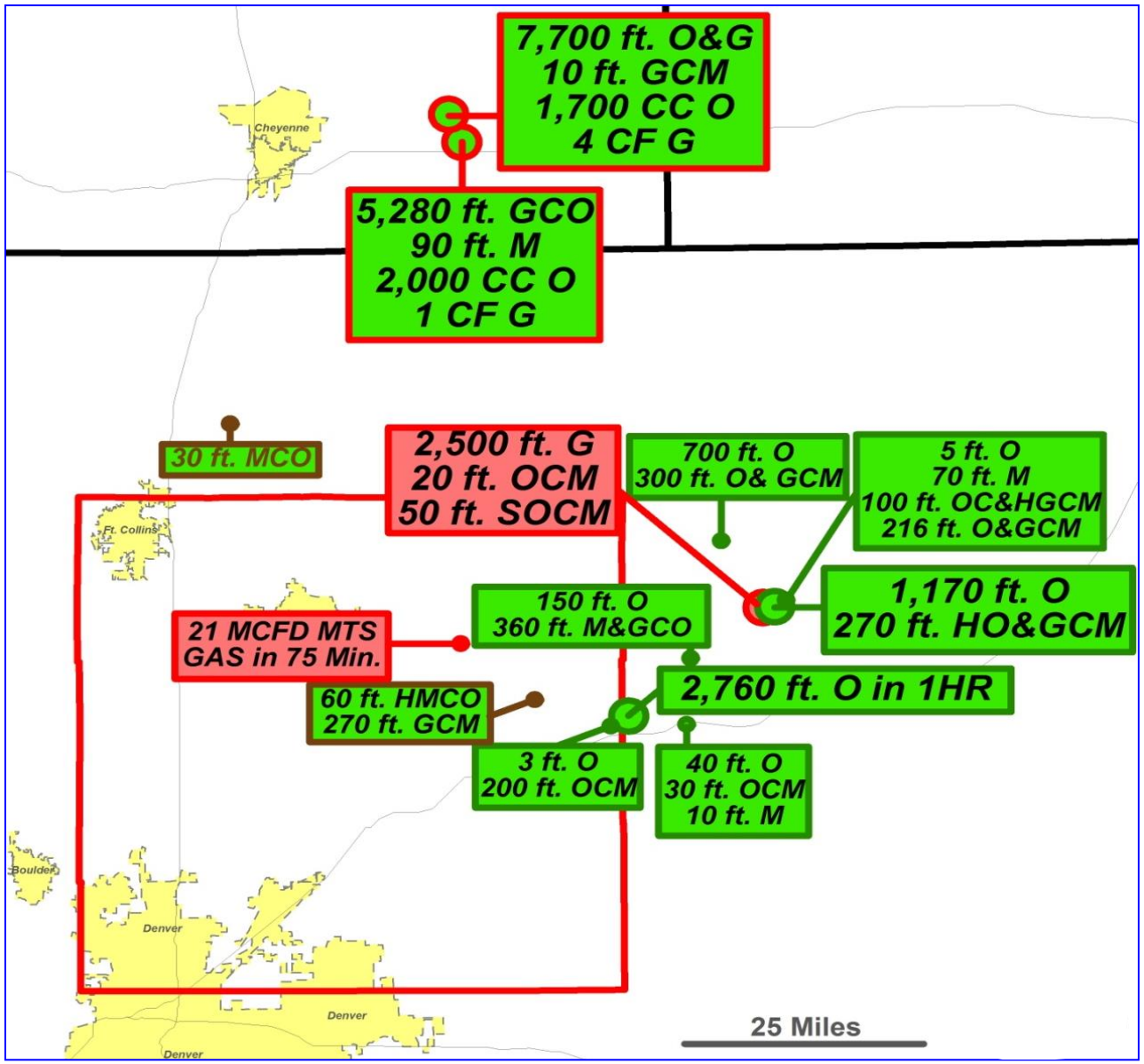
FACIES

- Bentonite
- 1 Chalk
- Interbedded Chalk and Marl
- 2 Marly Chalk
- 3 Chalky Marl
- 4 Marl
- 5a Homogeneous Mudstone
- 5b Laminated Mudstone
- 5c Fossil Laminated Mudstone
- 6 Interbedded Grainstone
- 7 Foraminifera-rich Grainstone

Durkee, 2016

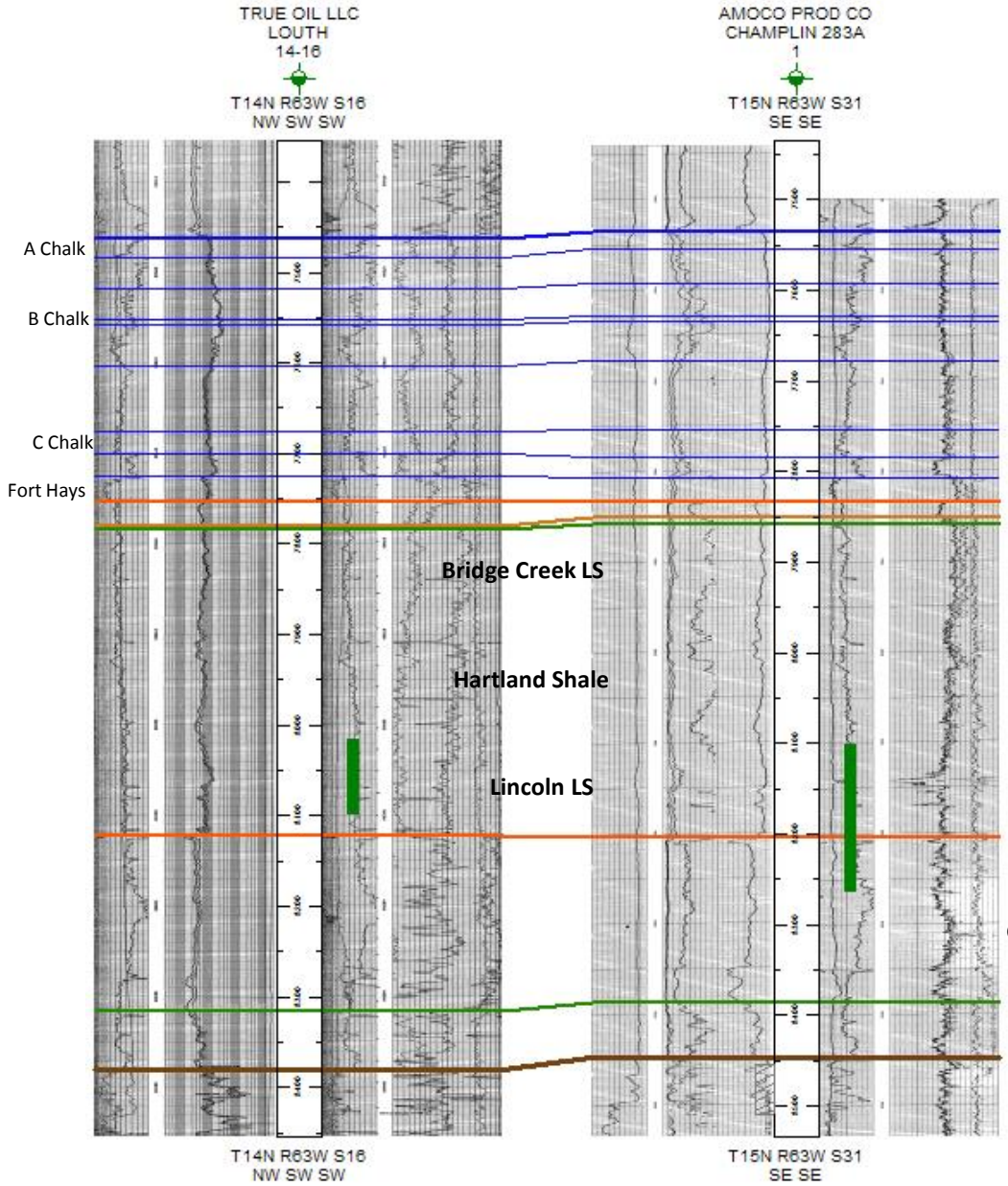
Lincoln DST Recoveries

- DST's
  - Largest in southeast Wyoming
    - >7,000 ft. Oil
- Multiple wells >1,000 ft. oil recovered
  - In areas with low resistivity
    - <10 Ohms



Kaiser, 2012

Other Shows of Interest

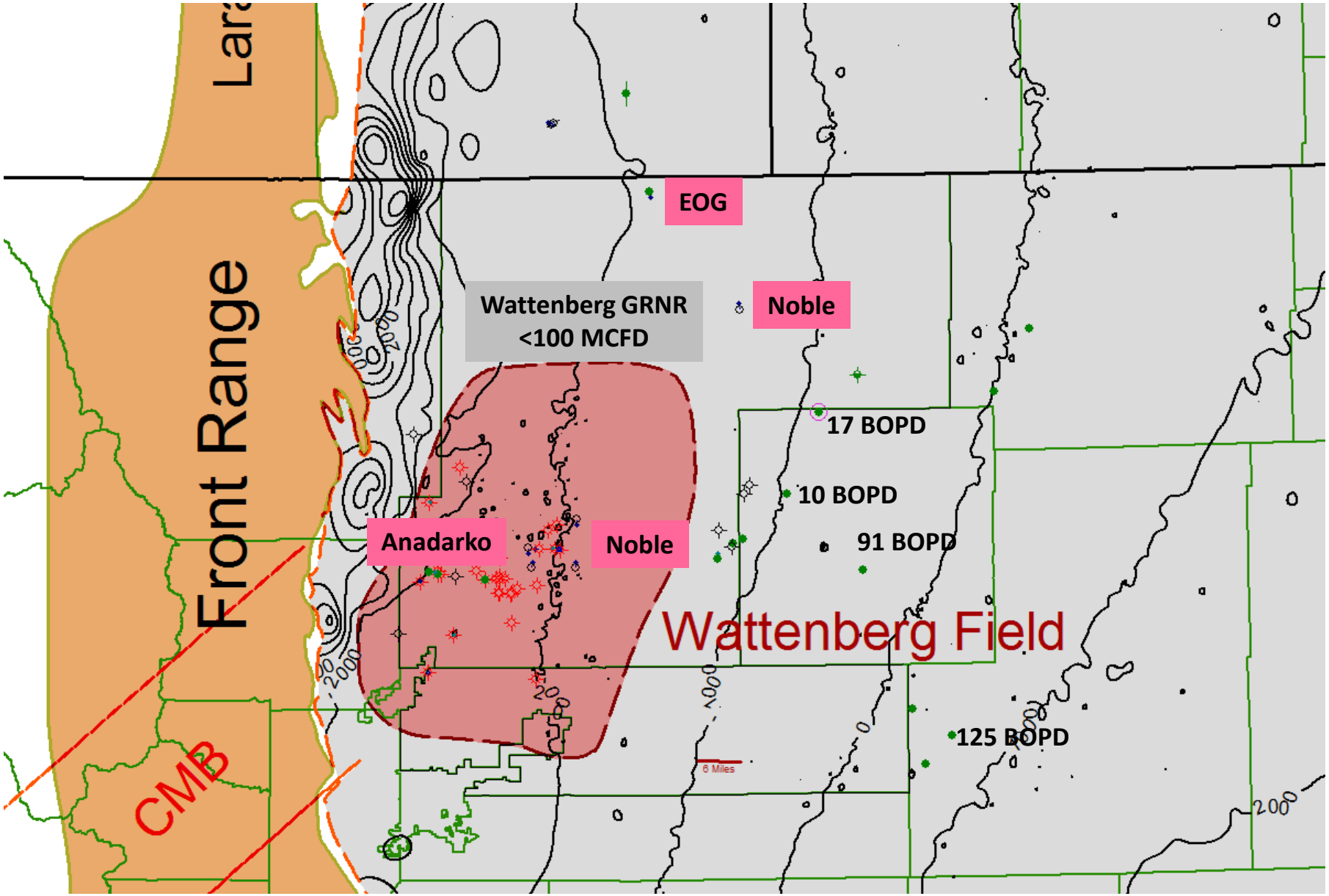


Rec. 5280 GCO

Greenhorn

Rec. 7700 O&G

Greenhorn Producers
(some mislabeled wells)



Summary

- Continuous-type hydrocarbon accumulation in Greenhorn
- Abundant shows (Type I) and/or production
- Areally pervasive
- Sapropelic source beds
- TOC> 2.5 wt. %
- Thickness > 50 ft
- Abnormally pressured
- Lacks water and a downdip water contact
- Low ϕ (<10%) & k (<0.1 md)
- Bridge Creek is recommended target in GWA
- Tectonically quiet