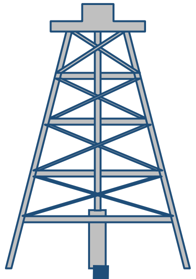
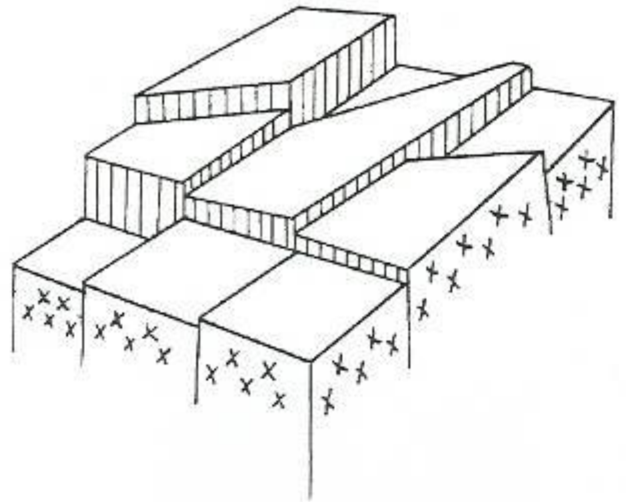
Niobrara Production from the Lowry-Bombing Range Area Denver Basin, a Deep-Basin, Paleostructural Trap

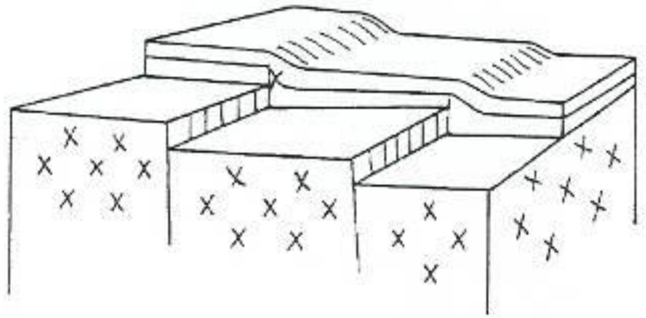


Stephen A. Sonnenberg
PI MUDTOC Consortium
Colorado School of Mines

Intrabasin Tectonic Control on Sedimentation

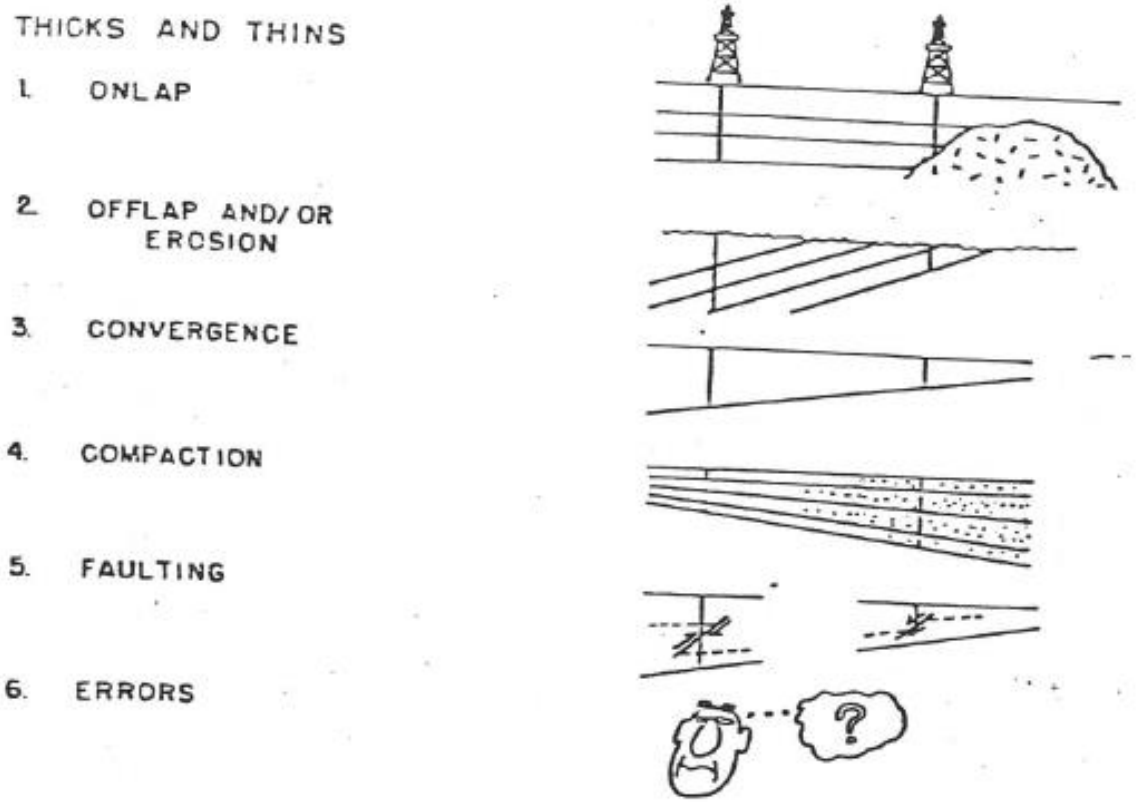


Basement: mosaic of fault blocks



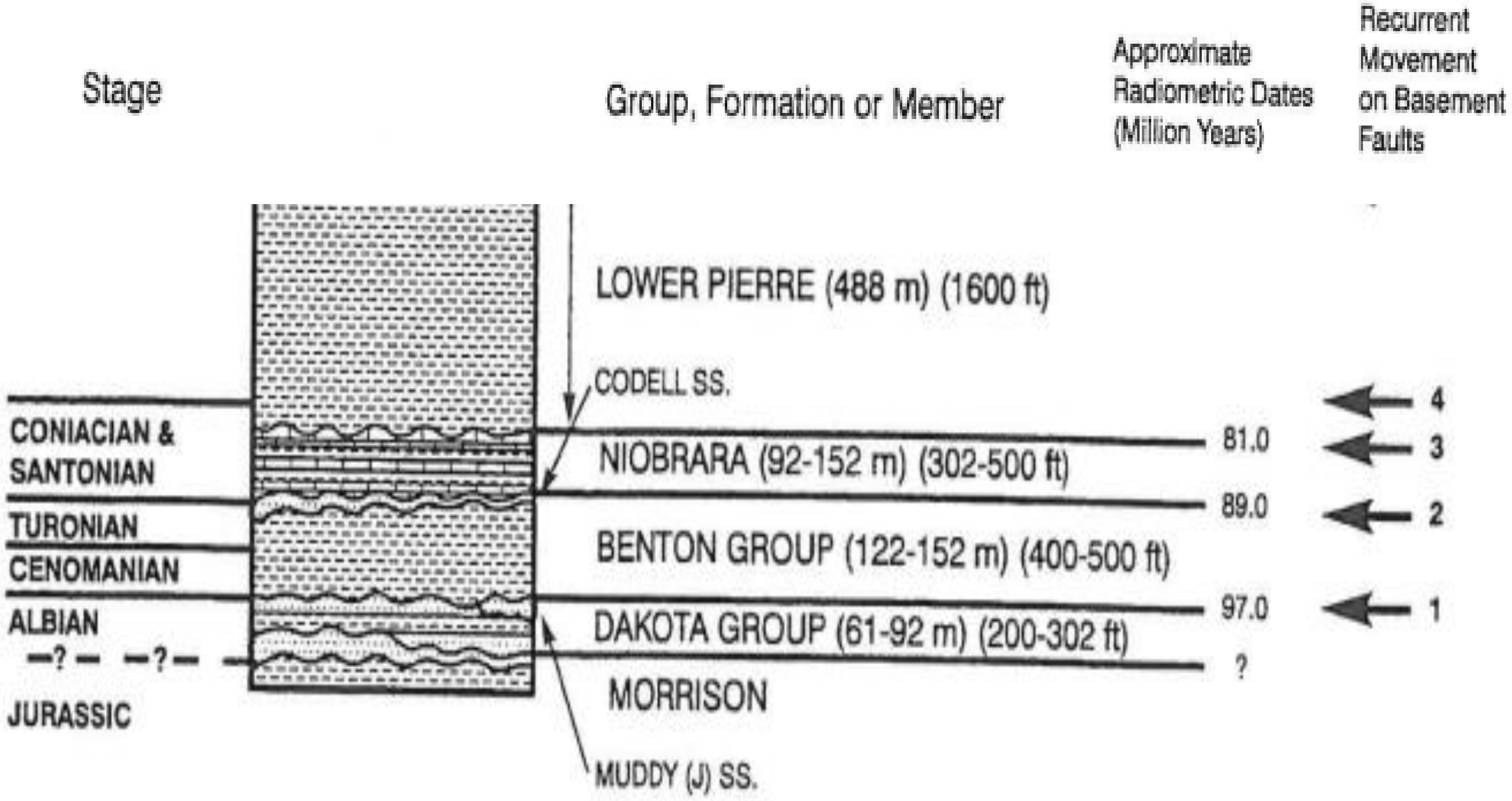
Recurrent movement on fault blocks

Thicks and Thins
& Paleostructure

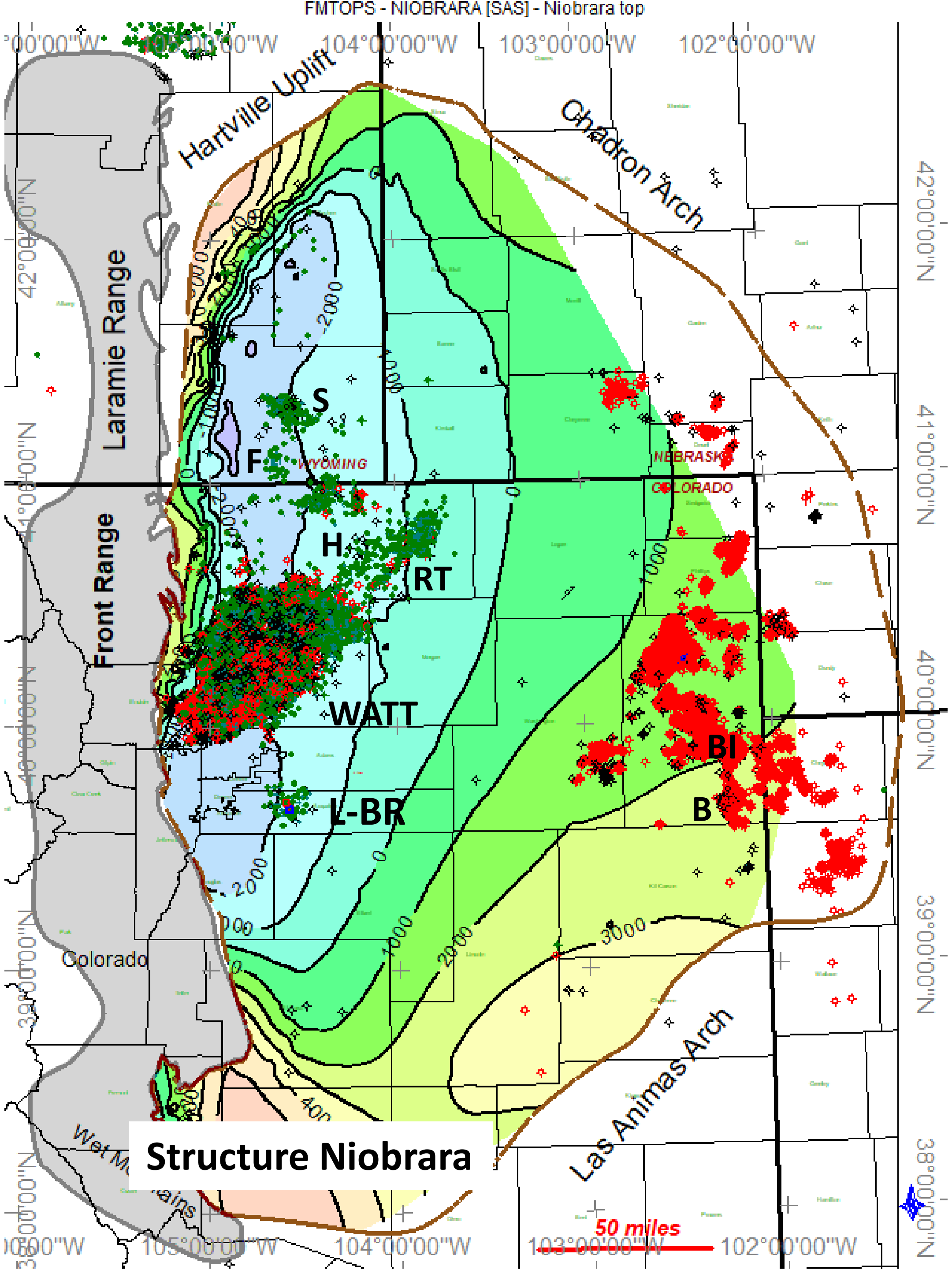


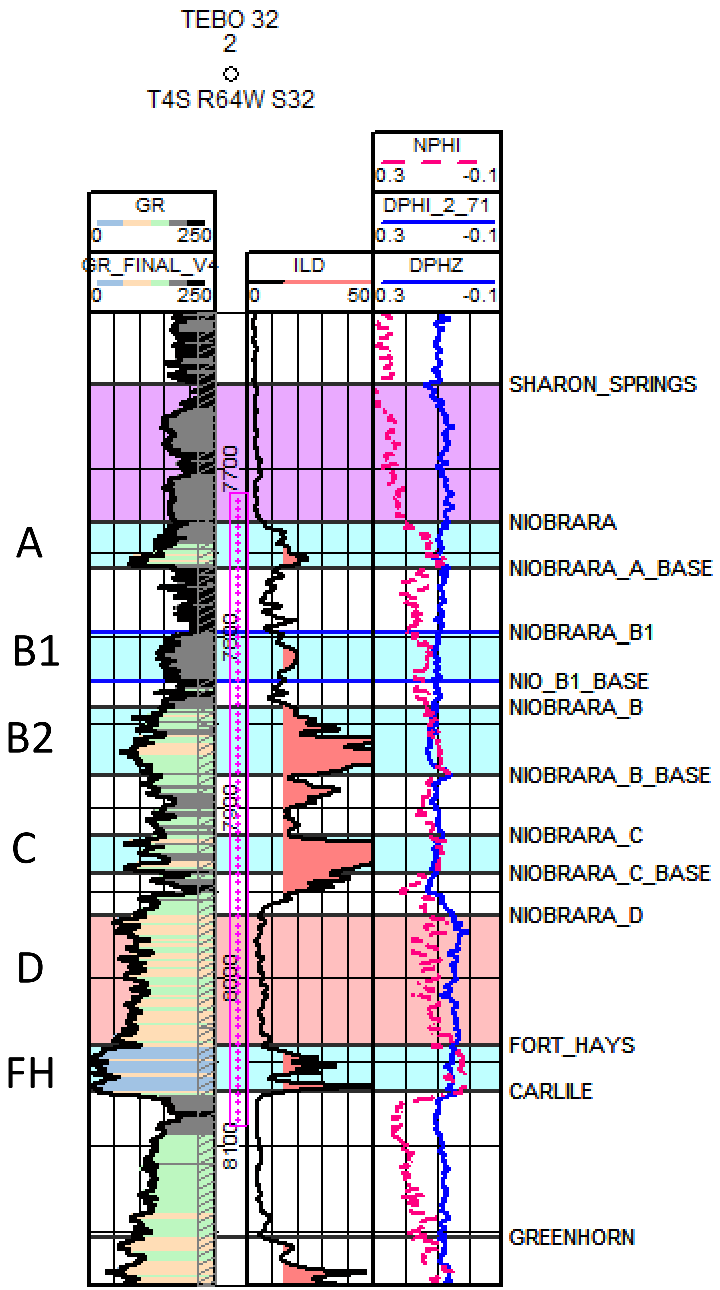
From Sonnenberg & Weimer, 1981

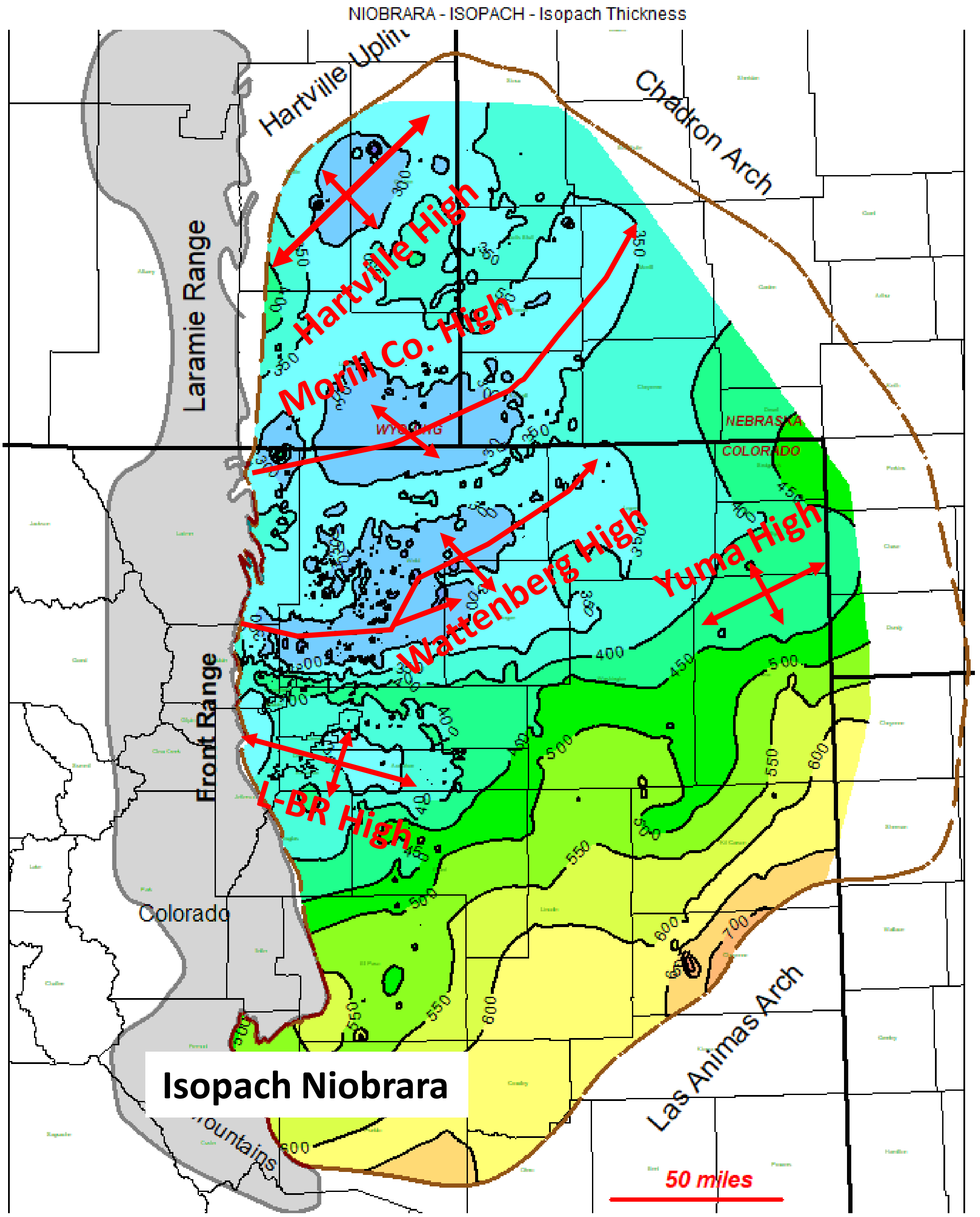
Recurrent Movement on Basement Fault Systems
"Intrabasin Tectonic Control on Sedimentation"



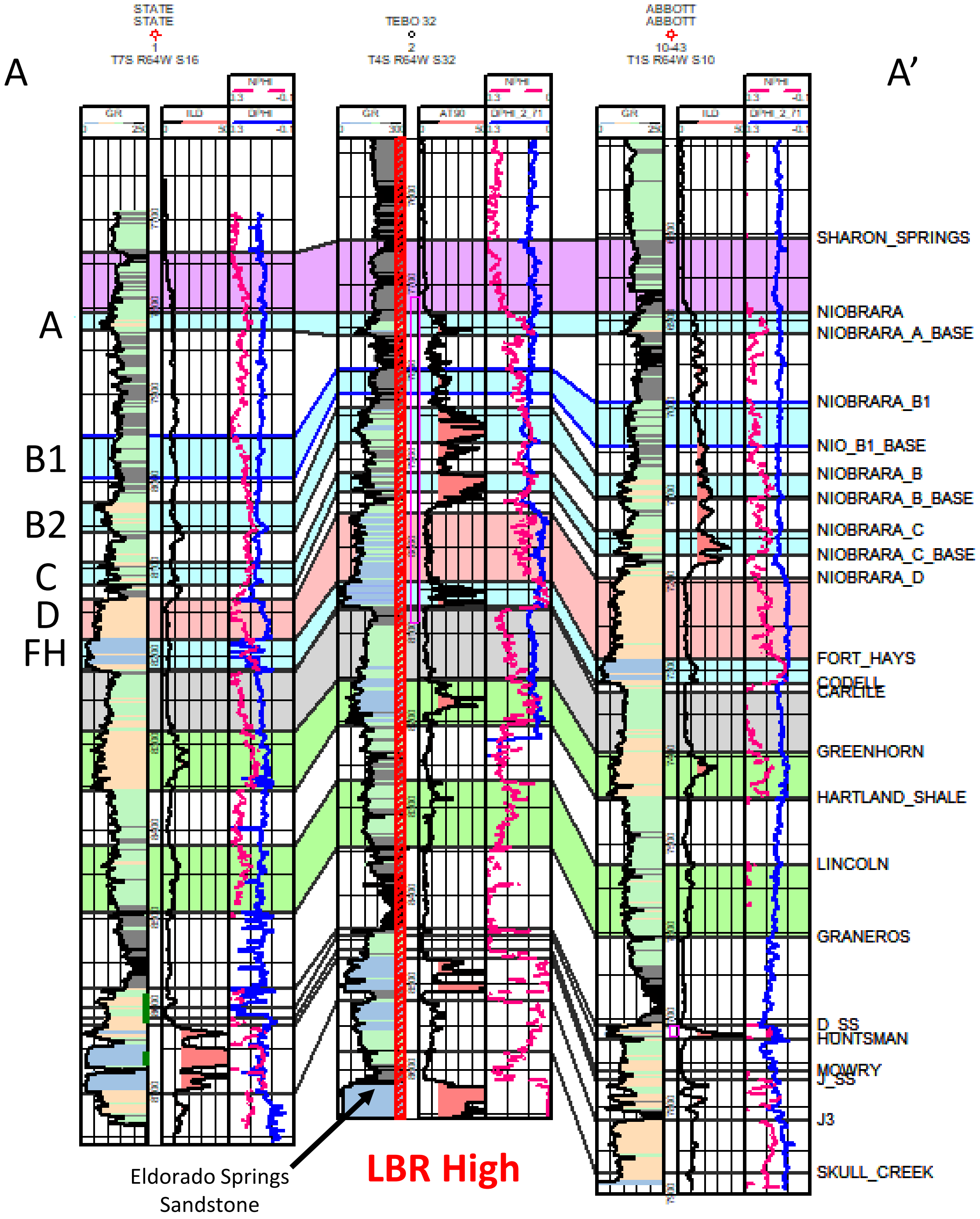
Modified from Weimer, 1996


FMTOPS - NIOBRARA [SAS] - Niobrara top
Hartville Uplift
Chadron Arch
Laramie Range
Front Range
Wet Mountains
Las Animas Arch
WYOMING
NEBRASKA
COLORADO
Colorado
S
F
H
RT
WATT
L-BR
BI
B
0
1000
2000
3000
4000
50 miles
104°00'00"W
103°00'00"W
102°00'00"W
105°00'00"W
42°00'00"N
41°00'00"N
40°00'00"N
39°00'00"N
38°00'00"N
Structure Niobrara

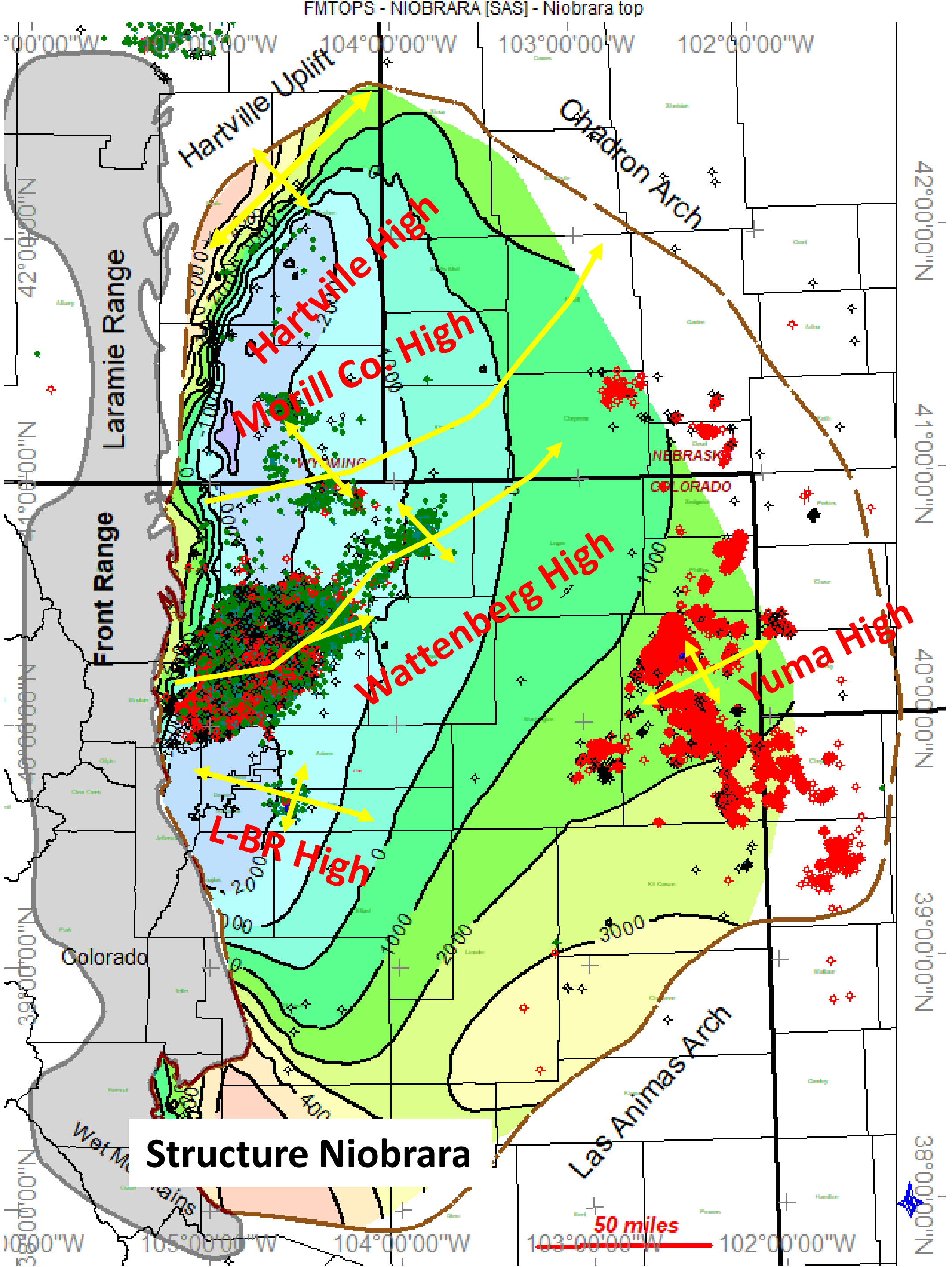

TEBO 32
2
T4S R64W S32
GR
0 250
GR_FINAL_V4
0 250
ILD
0 50
NPHI
0.3 -0.1
DPHI_2_71
0.3 -0.1
DPHZ
0.3 -0.1
7700
7800
7900
8000
8100
A
B1
B2
C
D
FH
SHARON_SPRINGS
NIOBRARA
NIOBRARA_A_BASE
NIOBRARA_B1
NIO_B1_BASE
NIOBRARA_B
NIOBRARA_B_BASE
NIOBRARA_C
NIOBRARA_C_BASE
NIOBRARA_D
FORT_HAYS
CARLILE
GREENHORN



NIOBRARA - ISOPACH - Isopach Thickness
Hartville Uplift
Chadron Arch
Laramie Range
Hartville High
Morill Co. High
WYOMING
NEBRASKA
COLORADO
Wattenberg High
Yuma High
Front Range
LBR High
Colorado
Las Animas Arch
Isopach Niobrara
Mountains
50 miles



A
A'
STATE STATE
T7S R64W S16
TEBO 32
T4S R64W S32
ABBOTT ABBOTT
10-43
T1S R64W S10
A
B1
B2
C
D
FH
SHARON_SPRINGS
NIOBRARA
NIOBRARA_A_BASE
NIOBRARA_B1
NIO_B1_BASE
NIOBRARA_B
NIOBRARA_B_BASE
NIOBRARA_C
NIOBRARA_C_BASE
NIOBRARA_D
FORT_HAYS
CODELL
CARLILE
GREENHORN
HARTLAND_SHALE
LINCOLN
GRANEROS
D_SS
HUNTSMAN
MOWRY
J_SS
J3
SKULL_CREEK
Eldorado Springs Sandstone
LBR High



Niobrara Production associated with paleostructural highs

High heat flow along fault systems or intrusive bodies

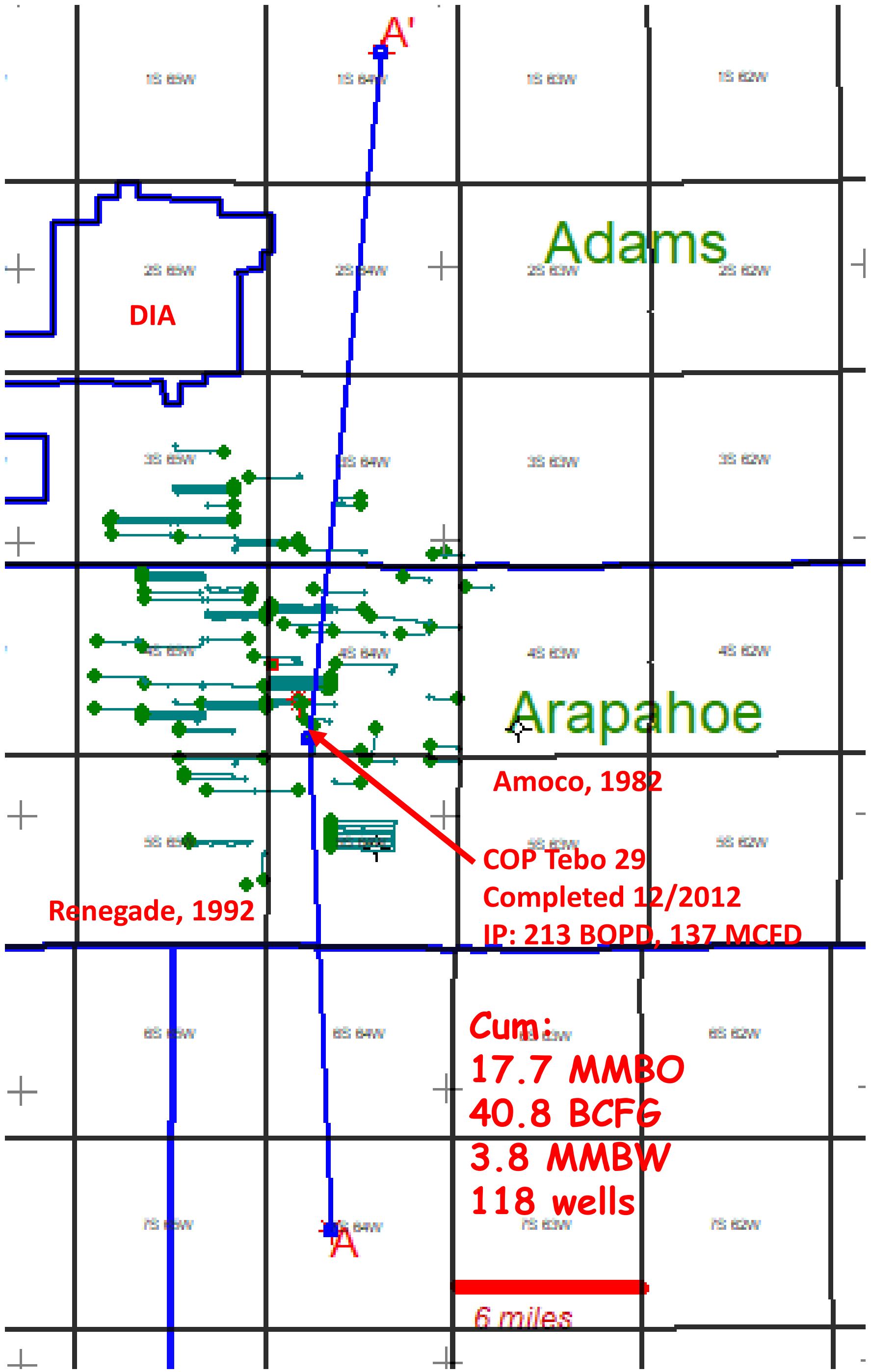
Higher heat conduction associated with Niobrara thins thus higher thermal maturity

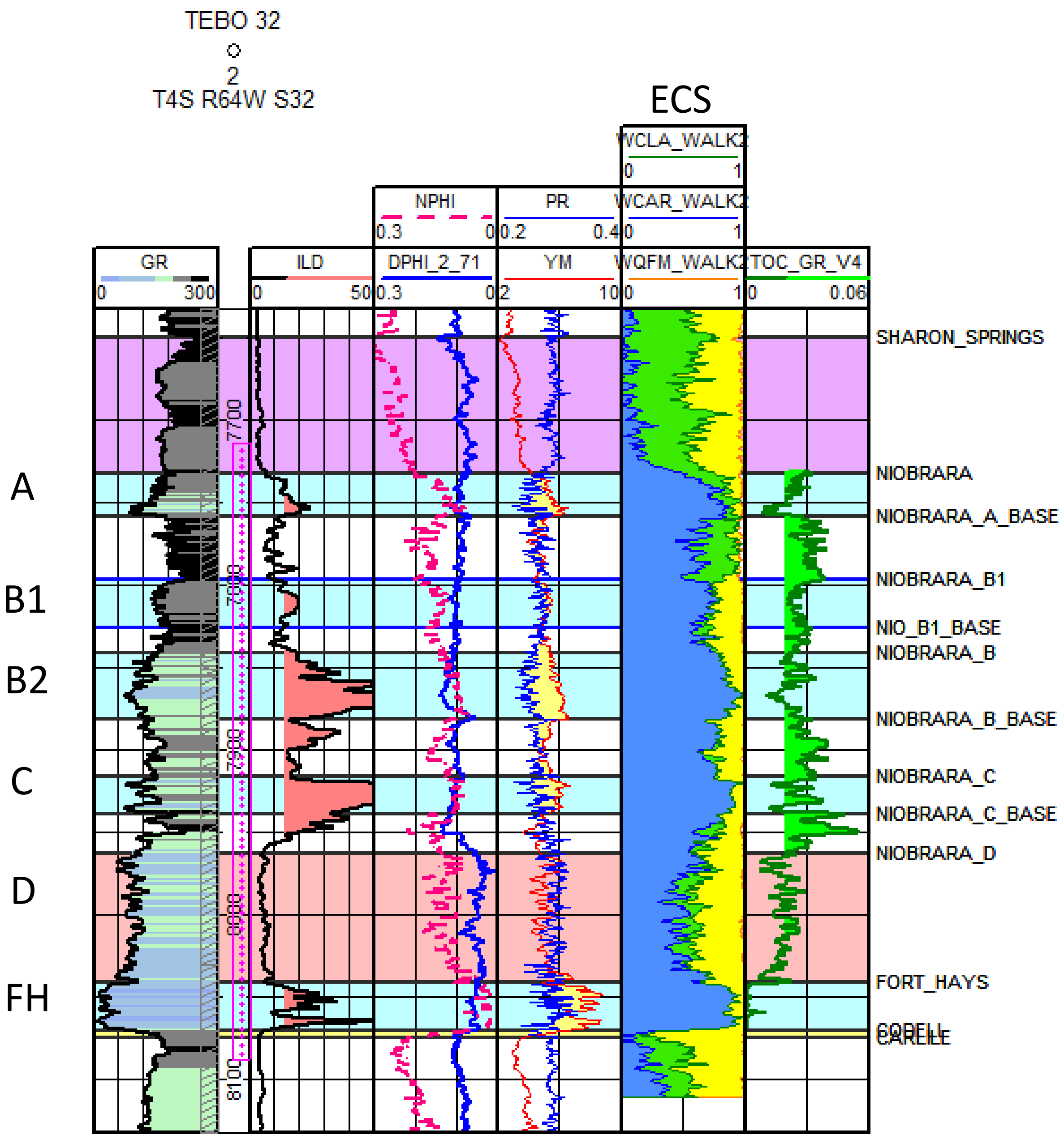
More heat insolation associated with Niobrara thicks thus lower thermal maturity

Lowry-Bombing Range Niobrara Field

- **Depth: 7732 -- 8071 ft (vertical)**
- **Thickness:**
  - Niobrara – 340 ft
  - A chalk – 27 ft
  - A marl – 38 ft
  - B1 chalk – 29 ft
  - B1 marl – 15 ft
  - **B2 chalk – 40 ft**
  - B2 marl – 35 ft
  - **C chalk – 23 ft**
  - C marl – 24 ft
  - D marl/chalk – 78 ft
  - Fort Hays – 30 ft
  - Codell – 1 ft
- **Porosity: Niobrara 10-13%**
- **Permeability: < 0.1 md**
- **GOR: 650 scf/bbl**
- **Gravity: 38 deg. API**
- **Tmax: 445°C**
- **Ro: 0.8-0.9%**
- **Pressure gradient: 0.6 psi/ft**

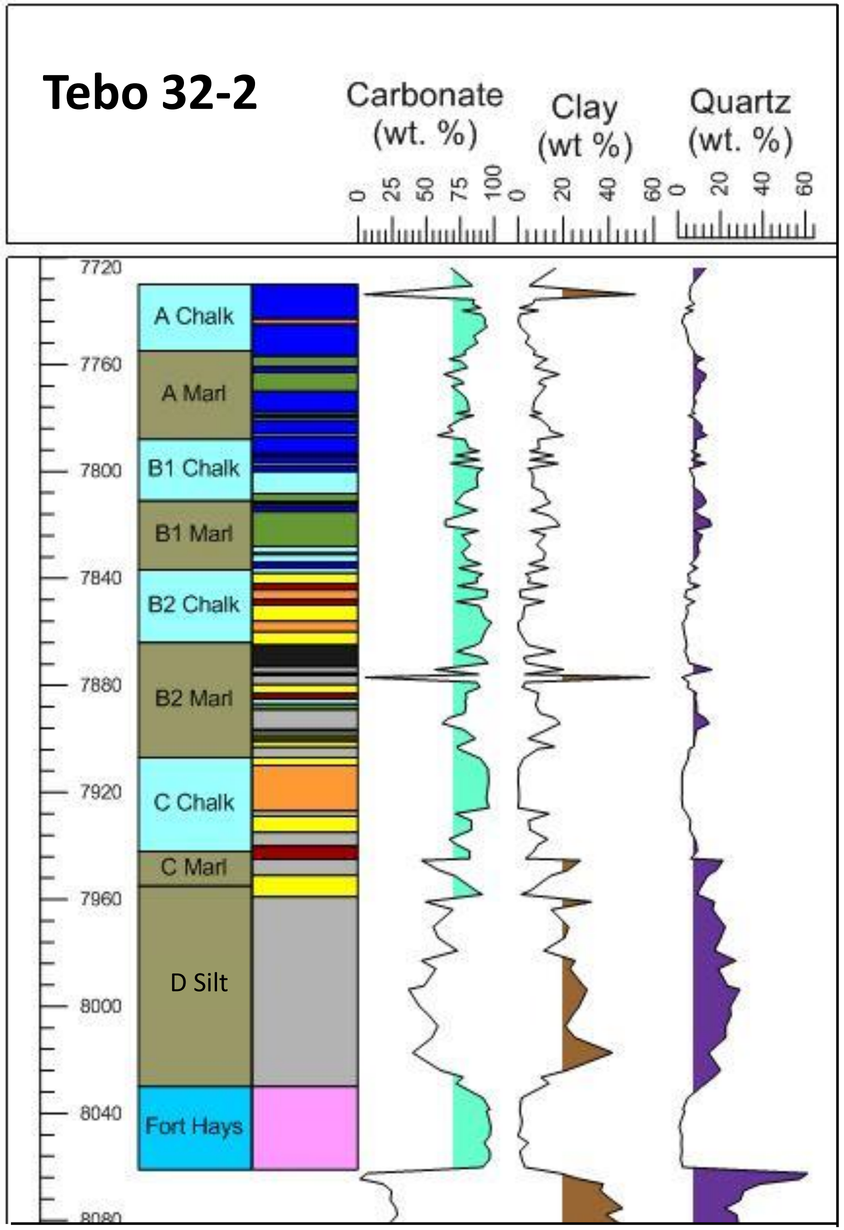
- ConocoPhillips leases 21,048 contiguous acres from CO Land Board $137 million, January 2012
- Also acquired acreage from Anadarko
- Horizontal discoveries in 2012
- Older uneconomic Niobrara vertical completions in the area (e.g., Renegade, 1992; Amoco, 1982)
- Crestone Peak (now Civitas) acquires L-BR 2019

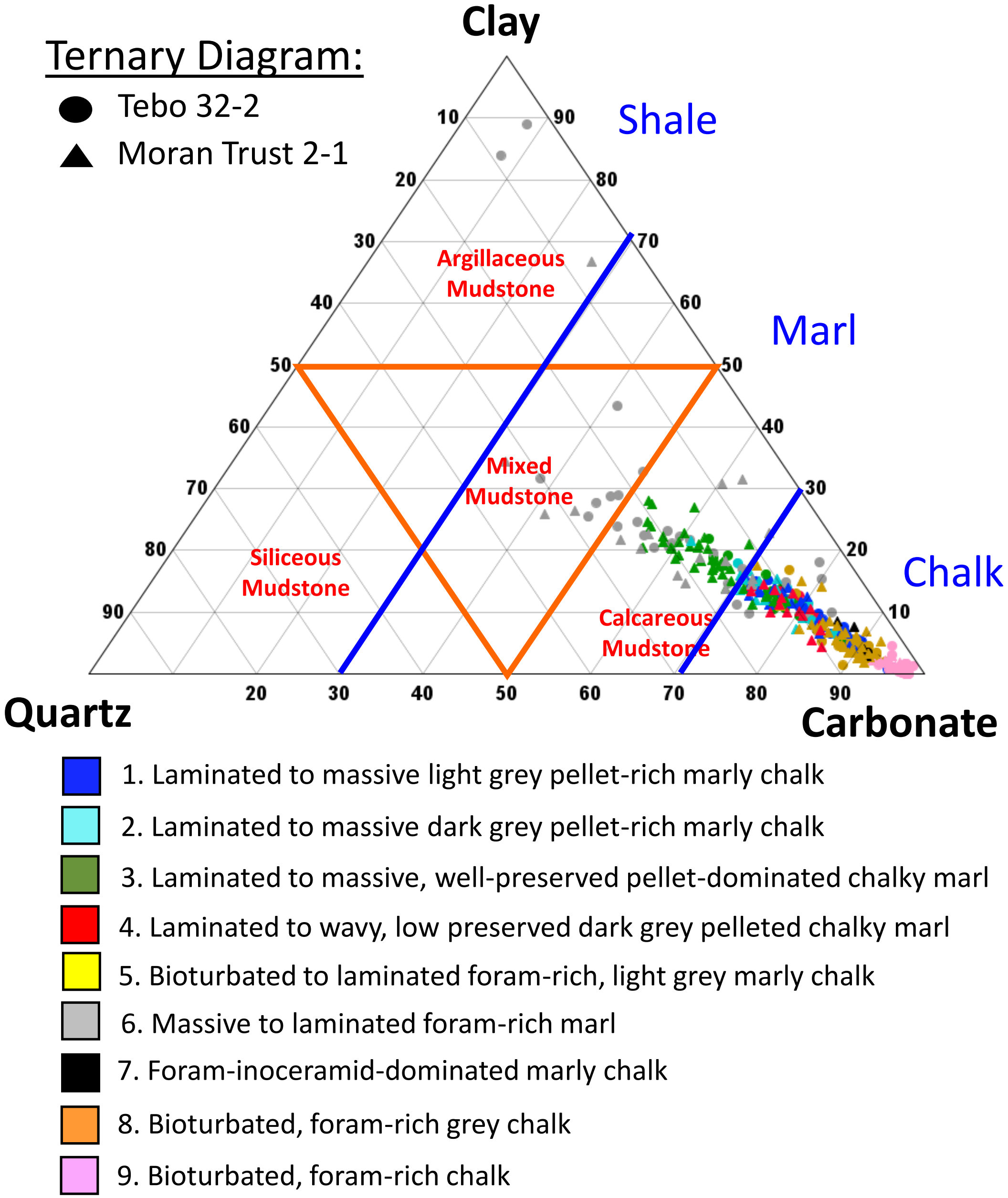




- High resistivities in B2 & C chalks
- 10% porosities in A, B, C chalks
- PR & YM cross over illustrates “brittle” zones
- Chalks high in carbonate content
- Marls less carbonate & more clay and QFM
- GR log TOC suggests higher TOC in marl beds

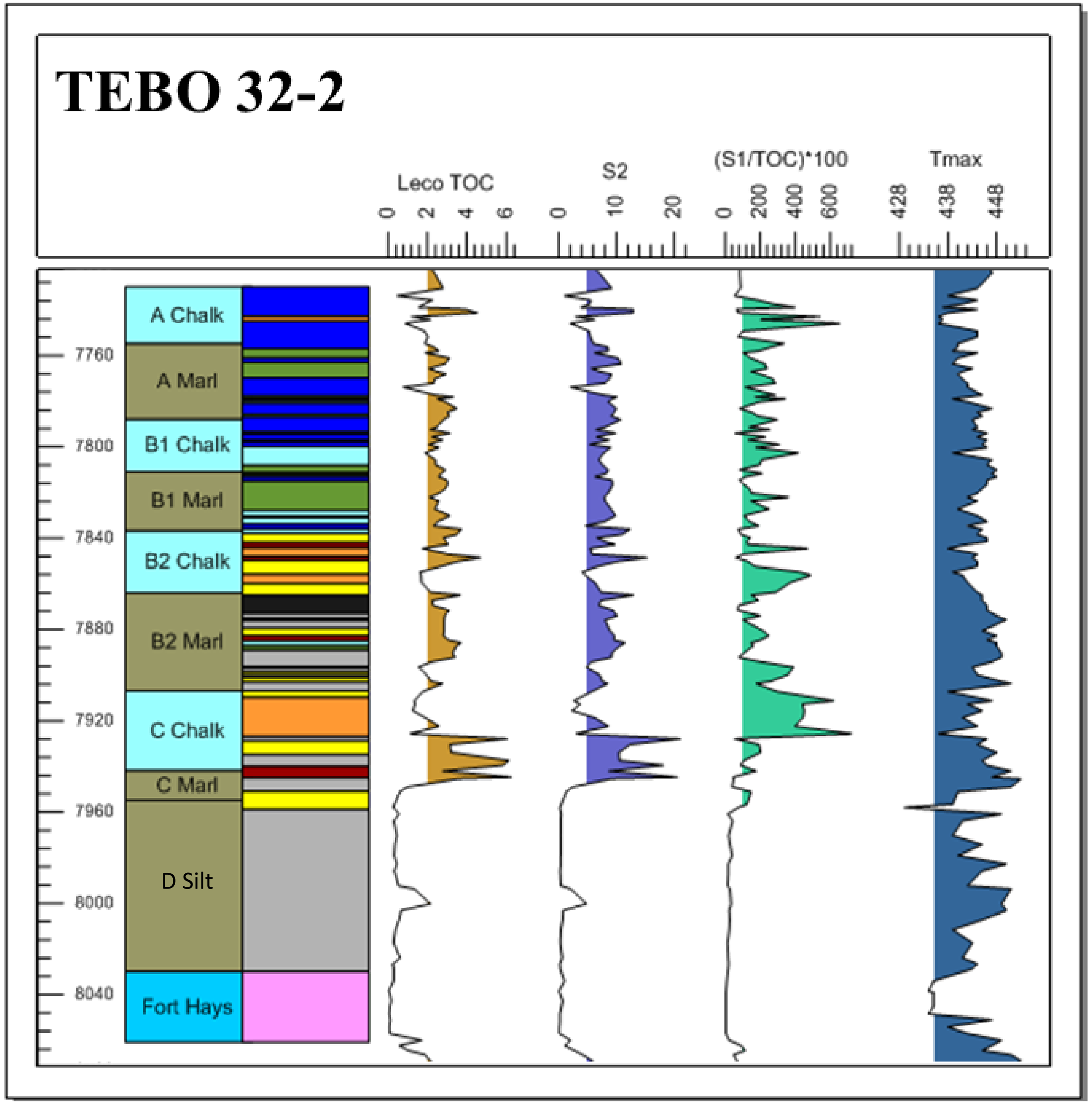
XRD Analysis





Bane, 2018

Source Quality and Maturity Evaluation



Bane, 2018

Organic Richness (TOC)

- Highest in the C Chalk and C Marl
- Range 0.5-6.3 wt. %

Hydrocarbon Potential (S2)

- > 5 mg/g rock considered "good to excellent"

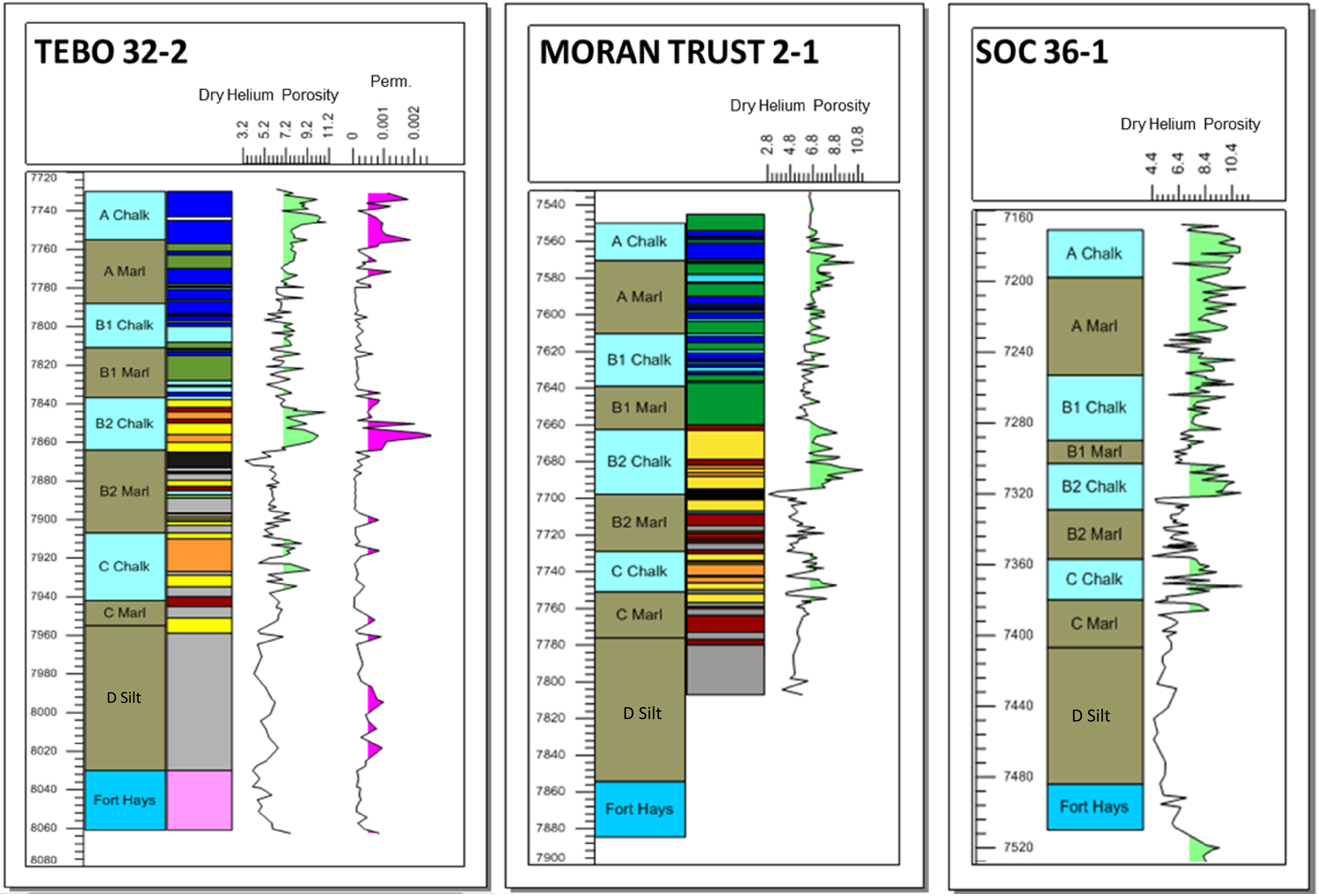
Normalized Oil Content (S1/TOC * 100)

- >100 mg HC/g rock indicates increasing producibility
- Highest in chalk benches

Thermal Maturity (Tmax)

- Majority of Niobrara stratigraphy is in the oil generation window (values > 435°C)

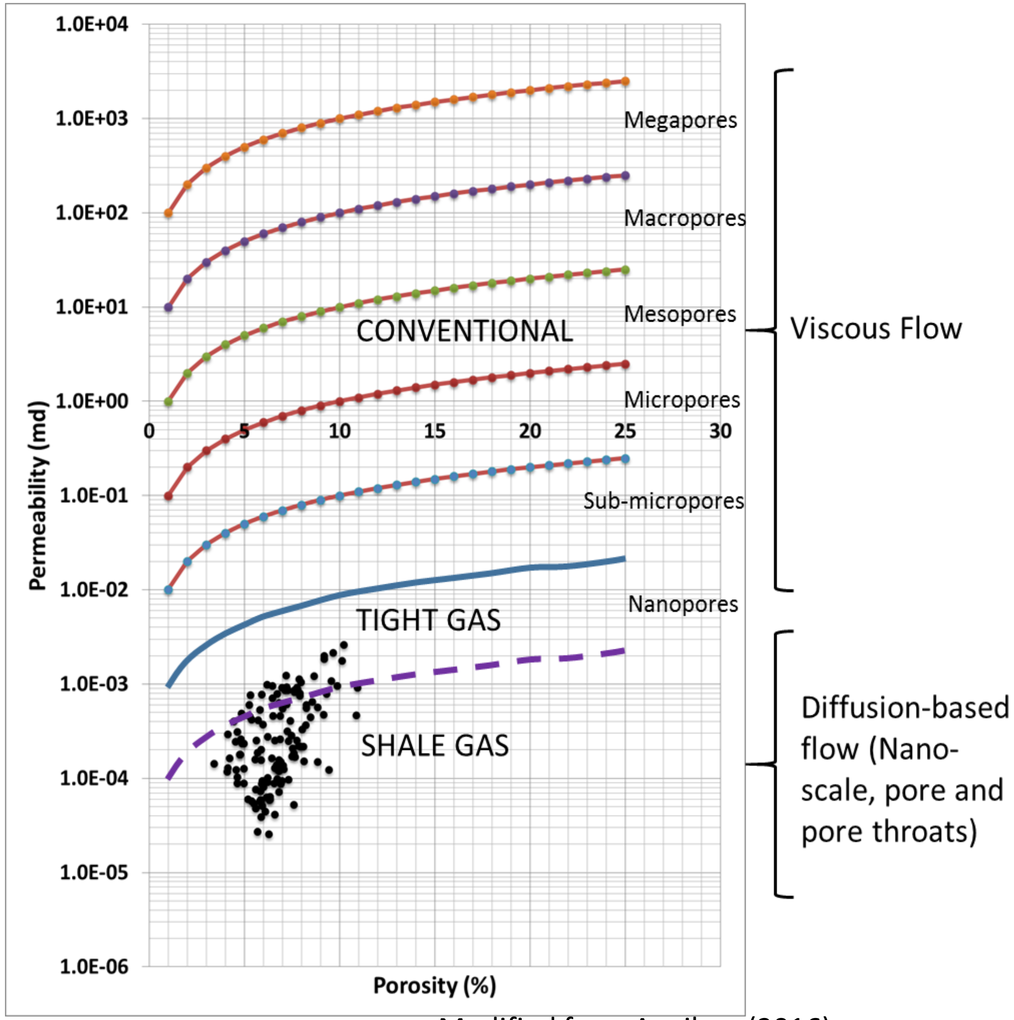
Permeability & Porosity Trends



Bane, 2018

Reservoir Quality

Permeability (mD) vs. Porosity (%)

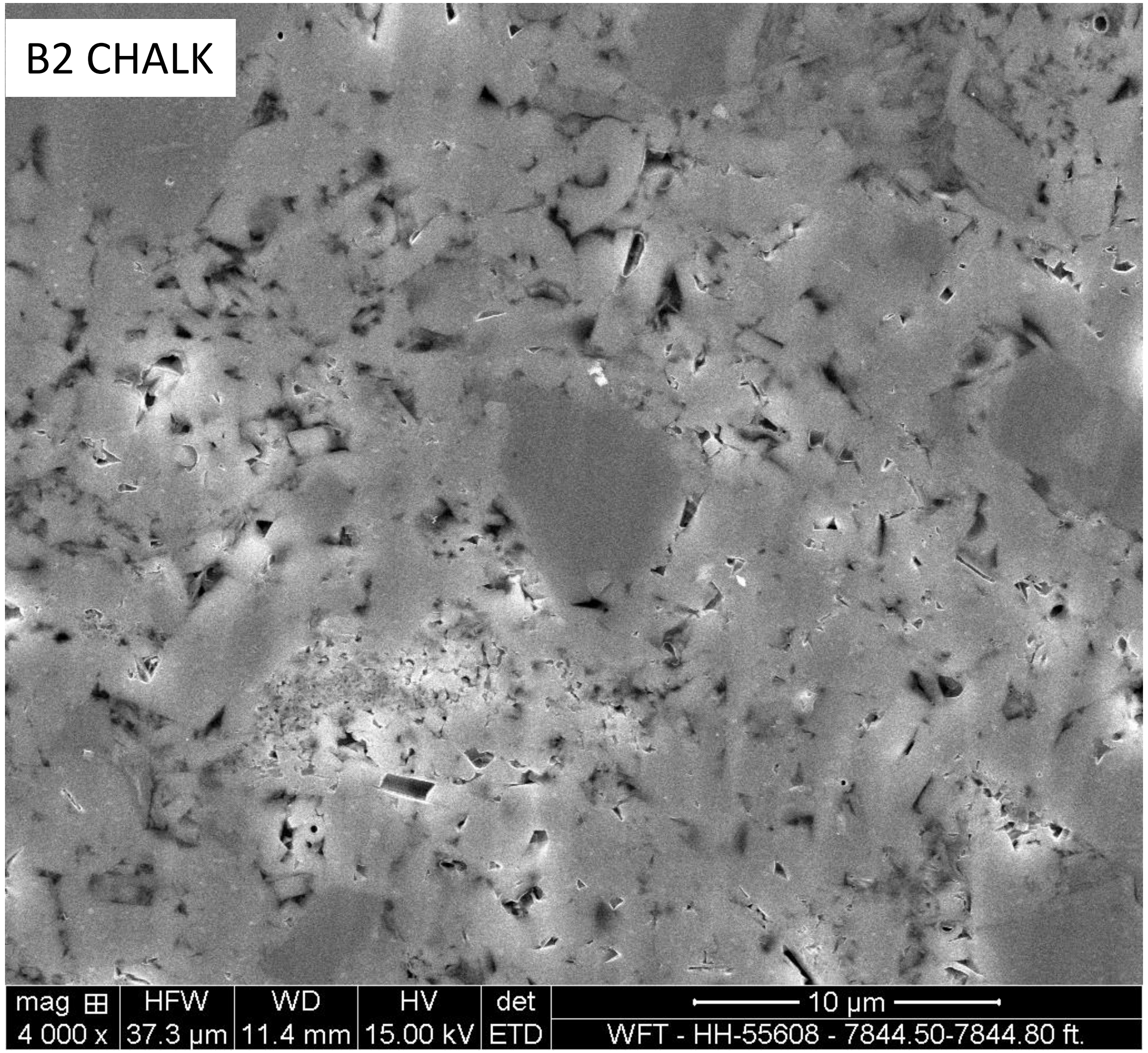


Modified from Aguilera (2016)

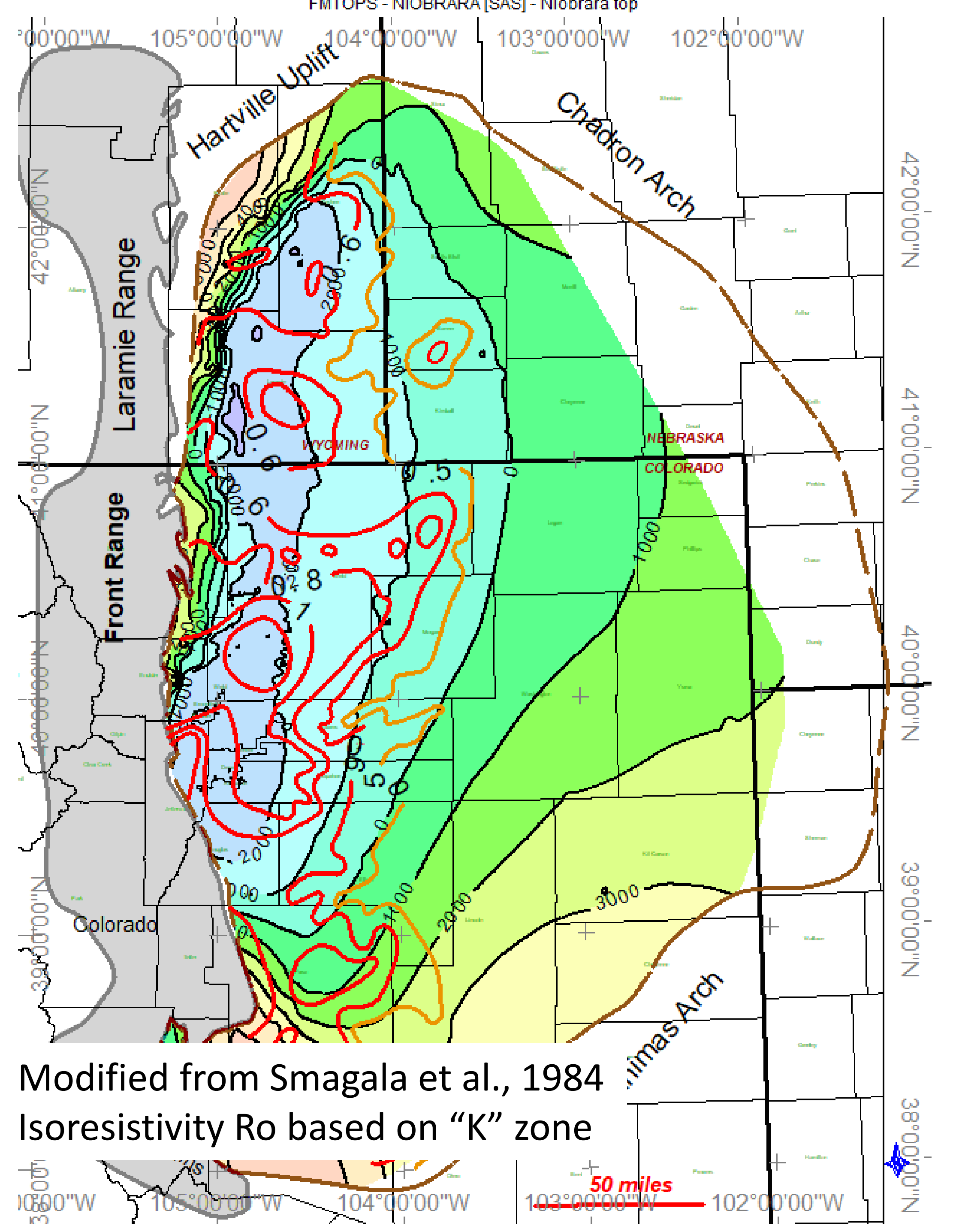
● = Data from Tebo 32-2

Secondary Electron Image

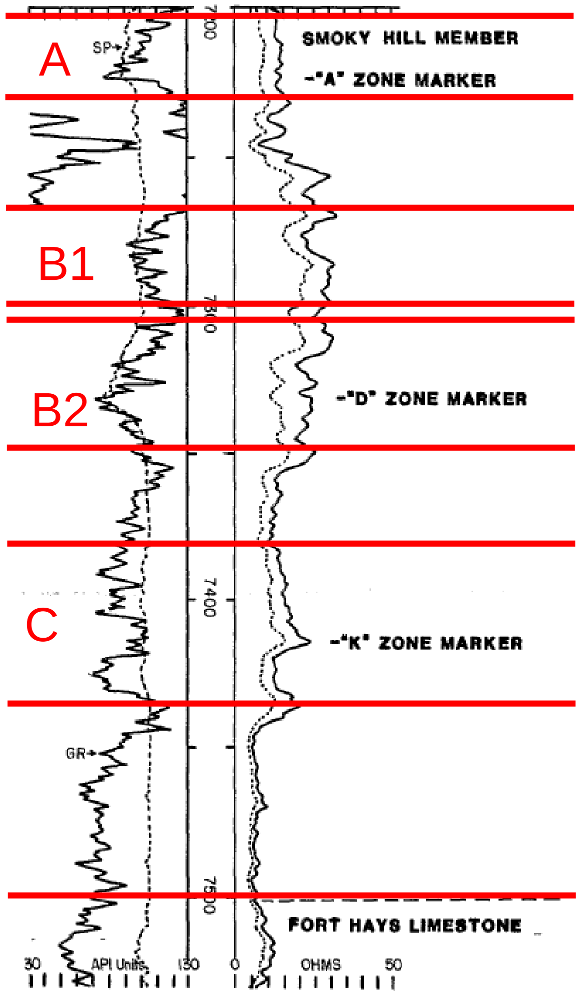
Chalky Porosity

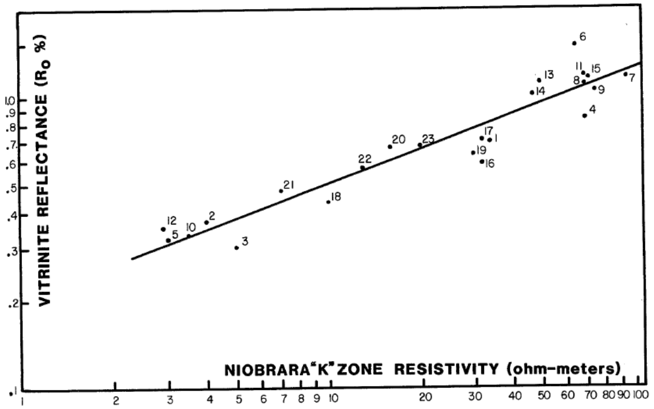


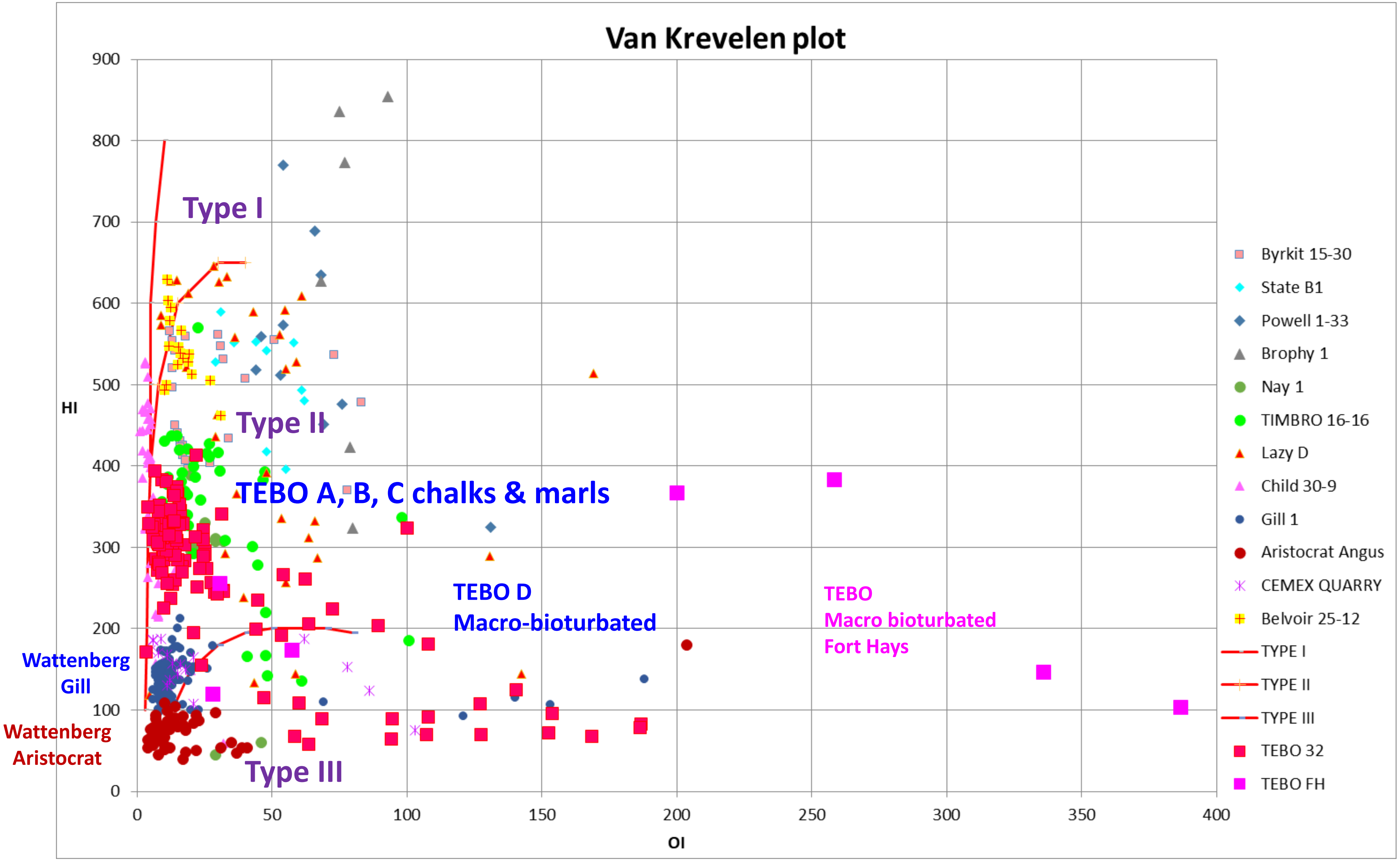
Tebo 7844.5: intergranular, intraparticle and intercrystalline porosity (coccoliths and overgrowths on coccoliths)

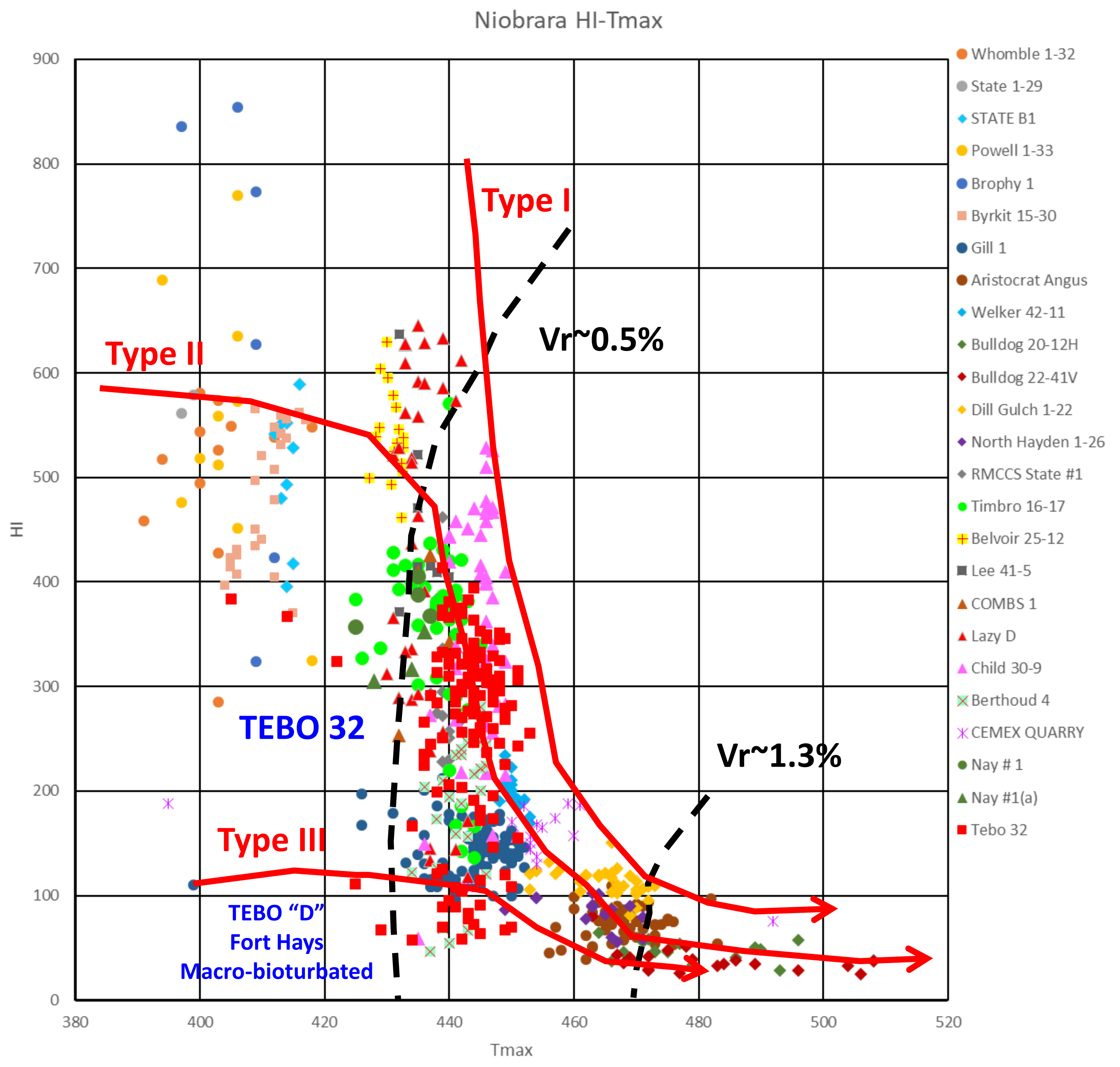


Modified from Smagala et al., 1984
Isoresistivity Ro based on "K" zone

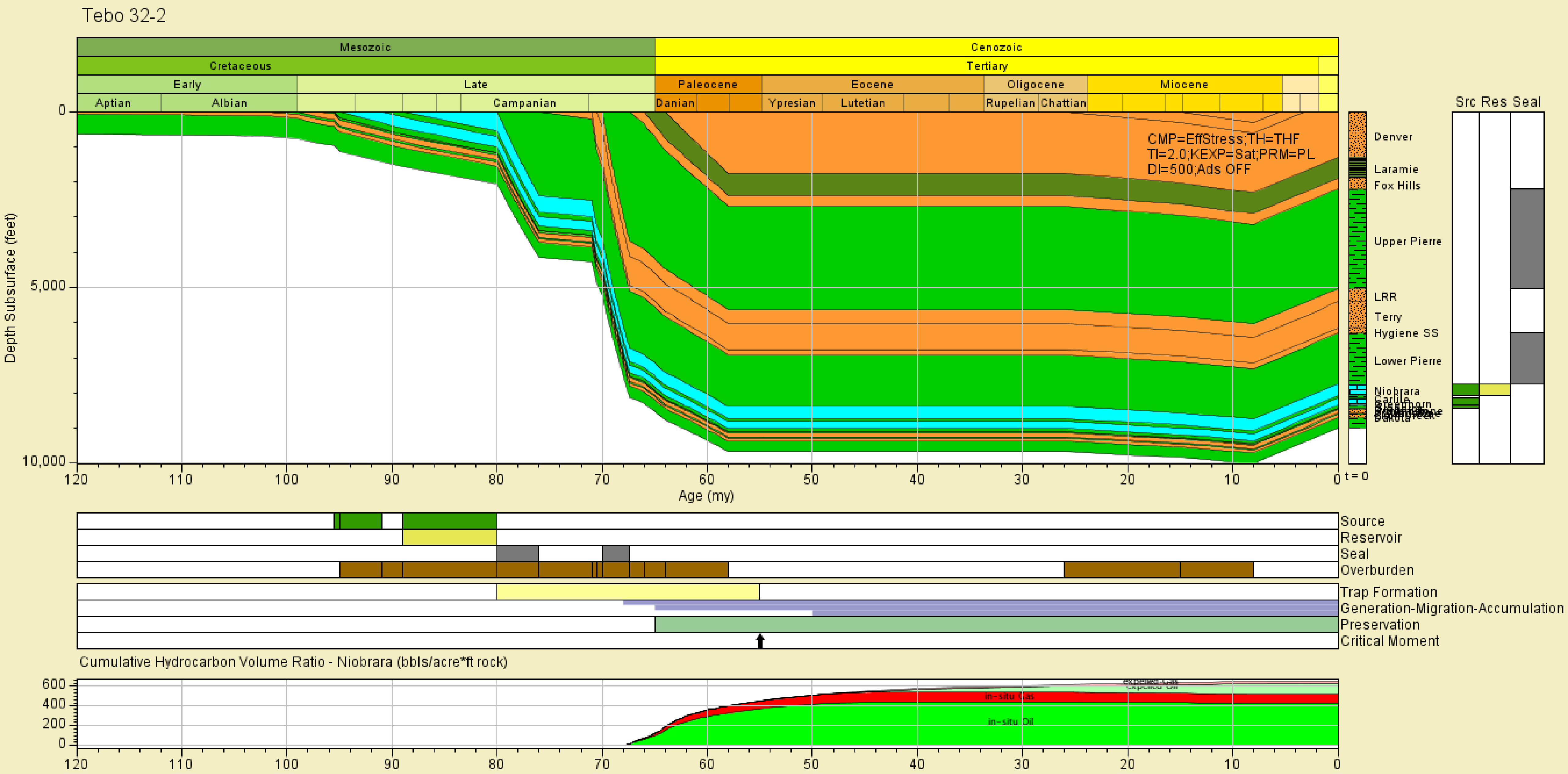




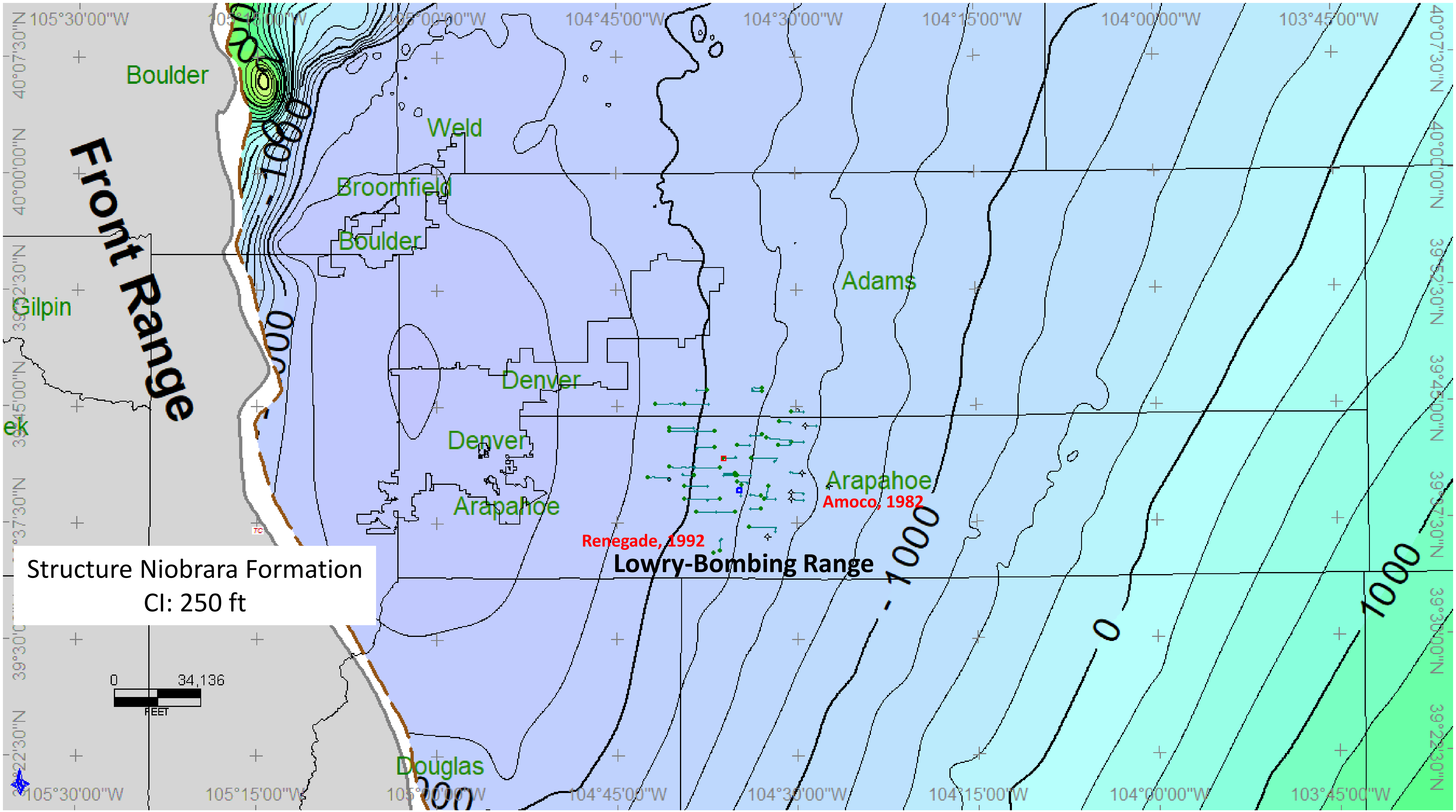

Van Krevelen plot
HI
OI
900
800
700
600
500
400
300
200
100
0
0
50
100
150
200
250
300
350
400
Type I
Type II
Type III
TEBO A, B, C chalks & marls
TEBO D
Macro-bioturbated
TEBO
Macro bioturbated
Fort Hays
Wattenberg
Gill
Wattenberg
Aristocrat
Byrkit 15-30
State B1
Powell 1-33
Brophy 1
Nay 1
TIMBRO 16-16
Lazy D
Child 30-9
Gill 1
Aristocrat Angus
CEMEX QUARRY
Belvoir 25-12
TYPE I
TYPE II
TYPE III
TEBO 32
TEBO FH



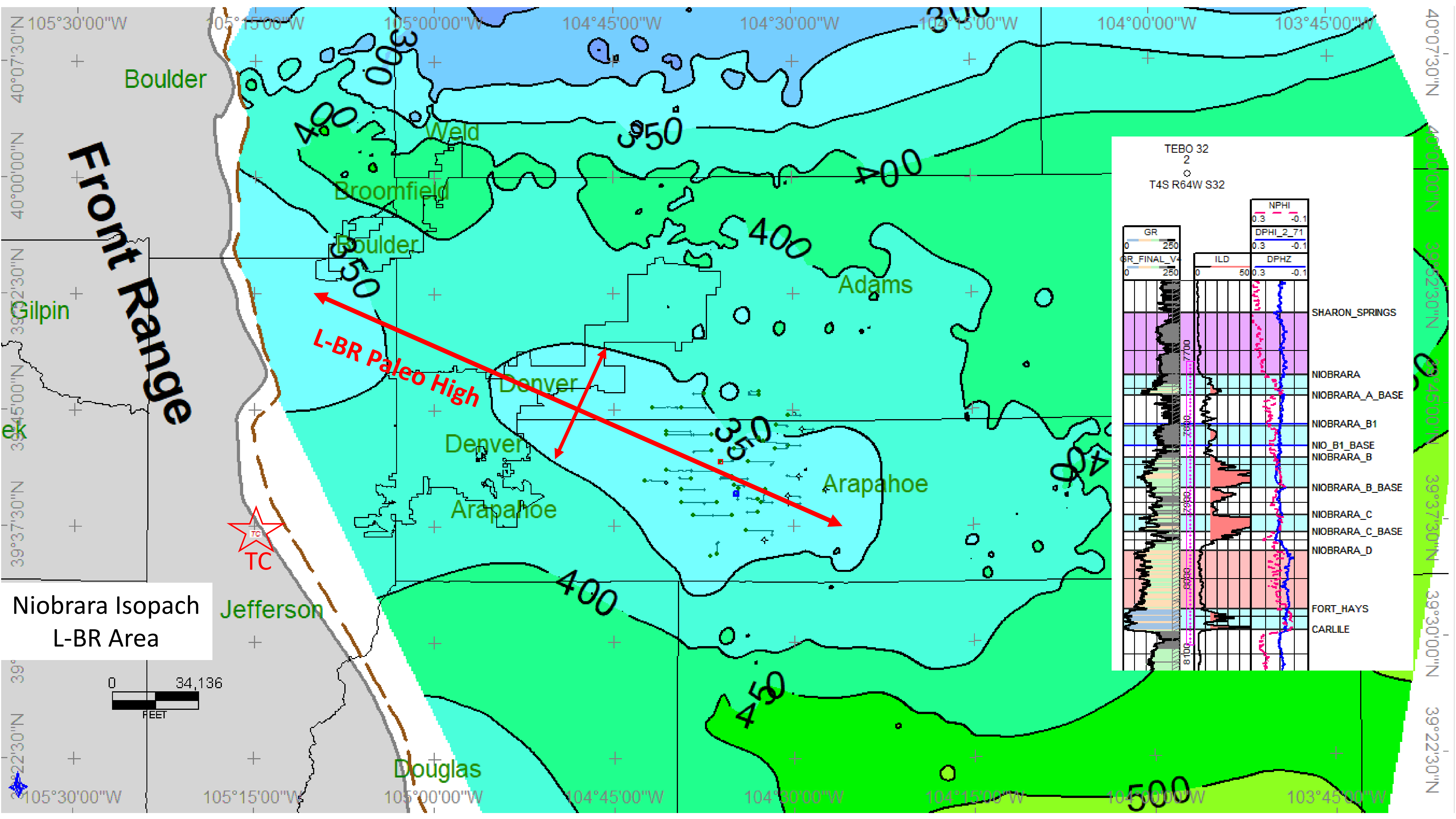
Niobrara HI-Tmax
900
800
700
600
500
400
300
200
100
0
HI
380
400
420
440
460
480
500
520
Tmax
Type I
Type II
Type III
Vr~0.5%
Vr~1.3%
TEBO 32
TEBO "D"
Fort Hays
Macro-bioturbated
Whomble 1-32
State 1-29
STATE B1
Powell 1-33
Brophy 1
Byrkit 15-30
Gill 1
Aristocrat Angus
Welker 42-11
Bulldog 20-12H
Bulldog 22-41V
Dill Gulch 1-22
North Hayden 1-26
RMCCS State #1
Timbro 16-17
Belvoir 25-12
Lee 41-5
COMBS 1
Lazy D
Child 30-9
Berthoud 4
CEMEX QUARRY
Nay # 1
Nay #1(a)
Tebo 32

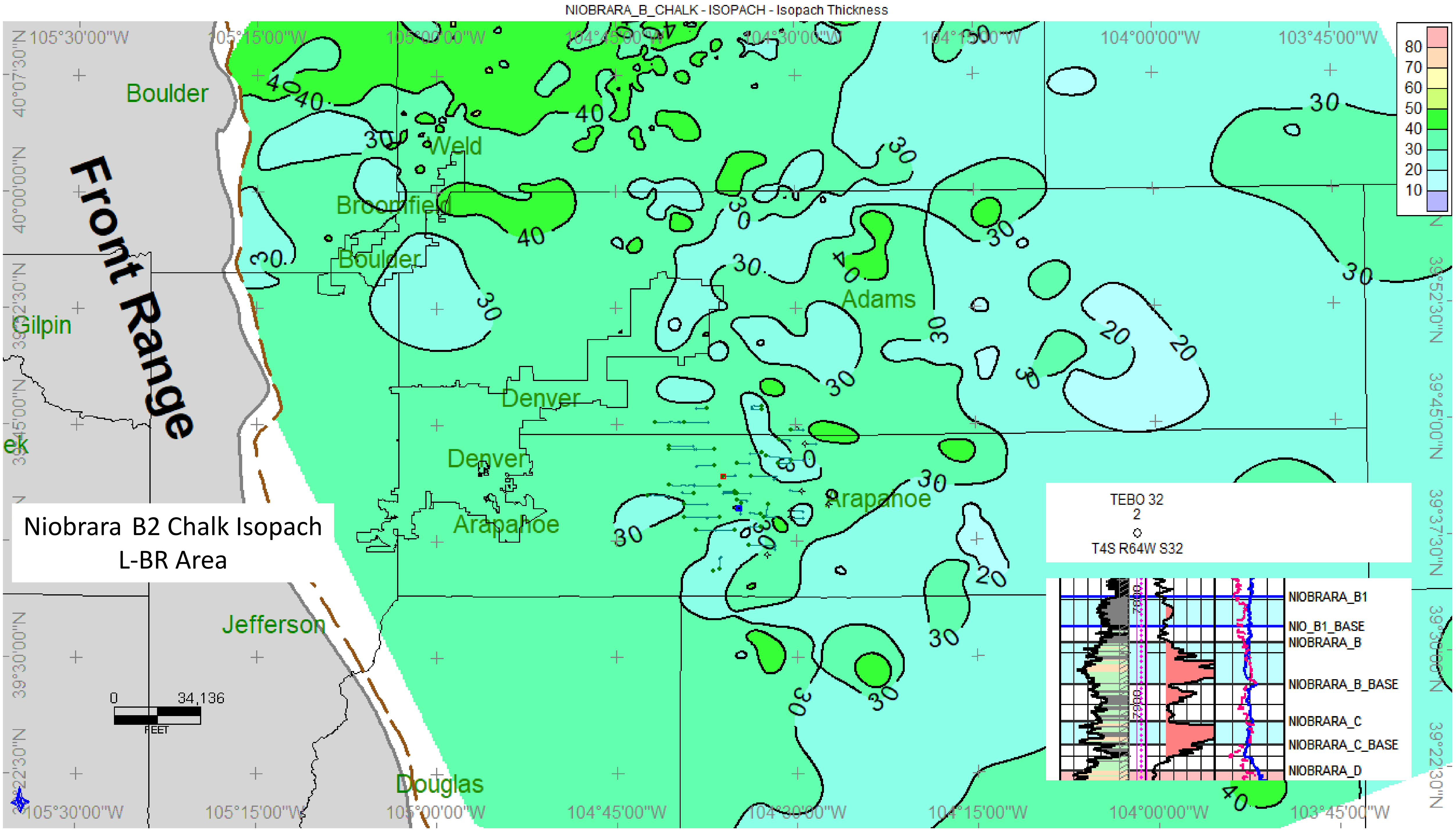


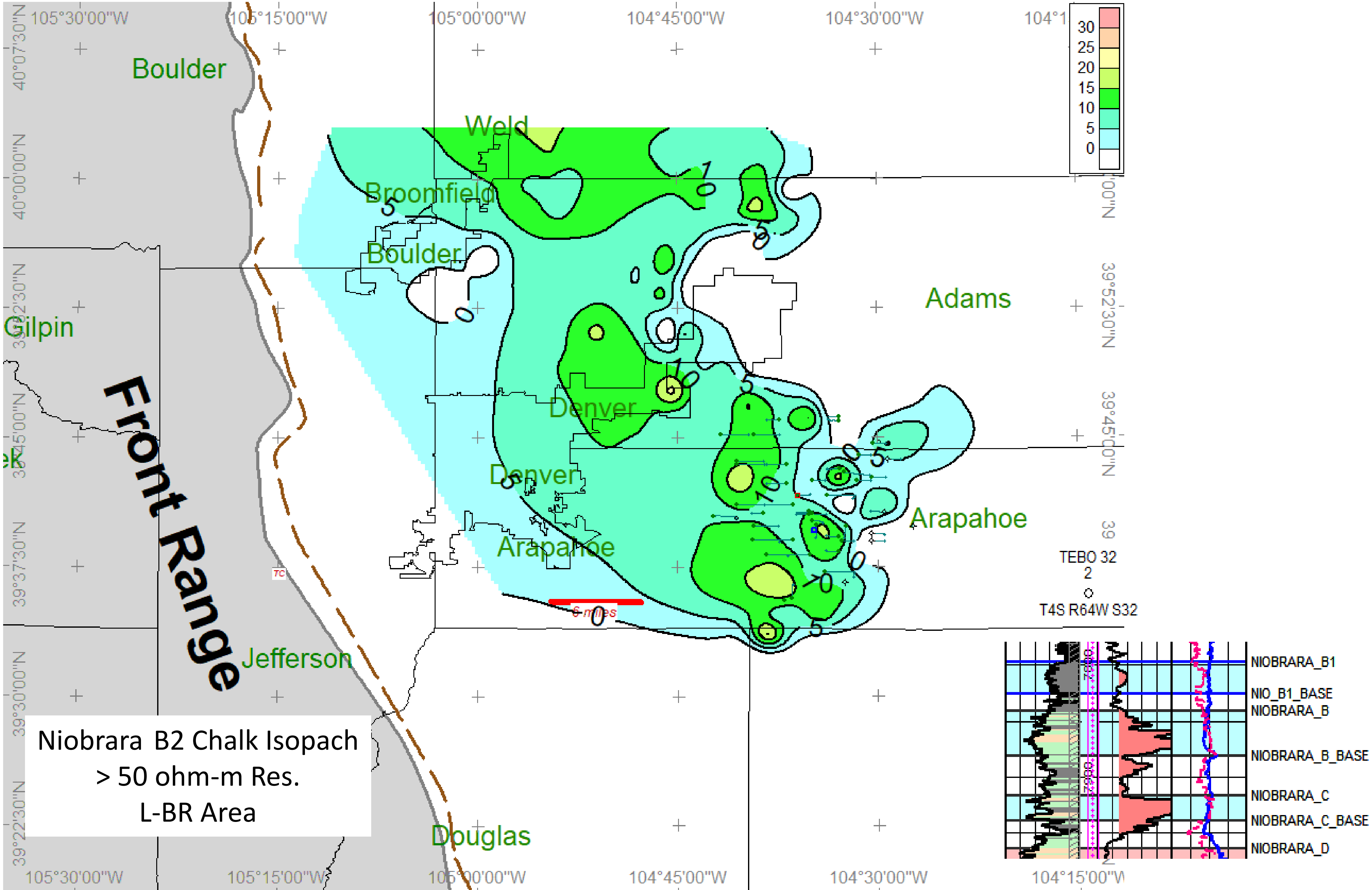
Tebo 32-2
Mesozoic
Cenozoic
Cretaceous
Tertiary
Early
Late
Paleocene
Eocene
Oligocene
Miocene
Aptian
Albian
Campanian
Danian
Ypresian
Lutetian
Rupelian
Chattian
CMP=EffStress;TH=THF
TI=2.0;KEXP=Sat;PRM=PL
DI=500;Ads OFF
Depth Subsurface (feet)
Age (my)
Denver
Laramie
Fox Hills
Upper Pierre
LRR
Terry
Hygiene SS
Lower Pierre
Niobrara
Src Res Seal
t = 0
Source
Reservoir
Seal
Overburden
Trap Formation
Generation-Migration-Accumulation
Preservation
Critical Moment
Cumulative Hydrocarbon Volume Ratio - Niobrara (bbls/acre*ft rock)
in-situ Gas
in-situ Oil



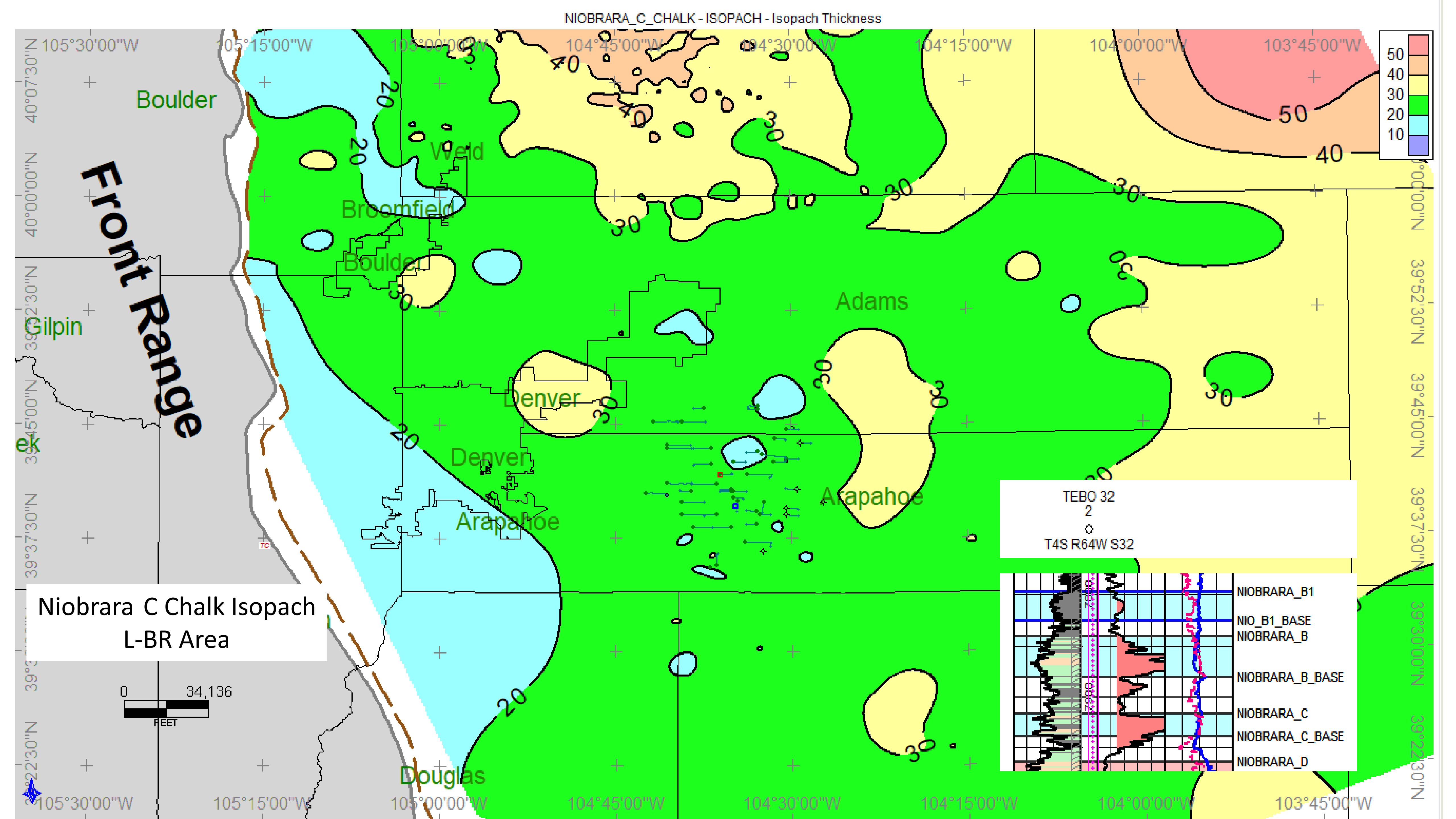
FMTOPS - NIOBRARA [SAS] - Niobrara top
105°30'00"W
105°00'00"W
104°45'00"W
104°30'00"W
104°15'00"W
104°00'00"W
103°45'00"W
105°15'00"W
40°07'30"N
40°00'00"N
39°52'30"N
39°45'00"N
39°37'30"N
39°30'00"N
39°22'30"N
Boulder
Weld
Broomfield
Boulder
Front Range
Gilpin
Adams
Denver
Denver
Arapahoe
Arapahoe
Amoco, 1982
Renegade, 1992
Lowry-Bombing Range
Douglas
-1000
0
1000
Structure Niobrara Formation
CI: 250 ft
0
34,136
FEET

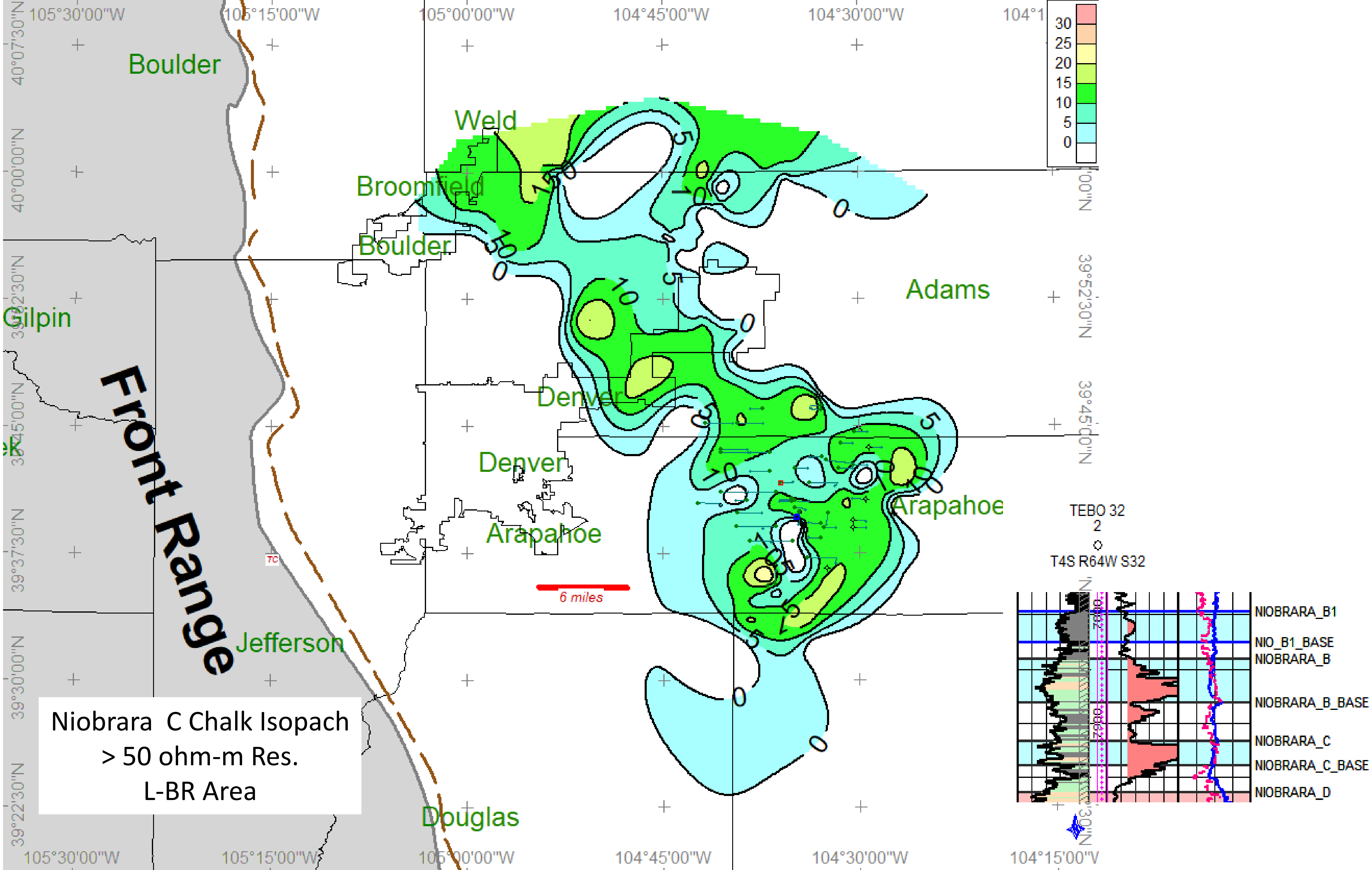

Niobrara Isopach
L-BR Area
Front Range
L-BR Paleo High
TC
Boulder
Weld
Broomfield
Gilpin
Denver
Adams
Arapahoe
Jefferson
Douglas
300
350
400
450
500
0
34,136
FEET
105°30'00"W
105°15'00"W
105°00'00"W
104°45'00"W
104°30'00"W
104°15'00"W
104°00'00"W
103°45'00"W
40°07'30"N
40°00'00"N
39°52'30"N
39°45'00"N
39°37'30"N
39°30'00"N
39°22'30"N
TEBO 32
2
T4S R64W S32
GR
GR_FINAL_V4
ILD
NPHI
DPHI_2_71
DPHZ
SHARON_SPRINGS
NIOBRARA
NIOBRARA_A_BASE
NIOBRARA_B1
NIO_B1_BASE
NIOBRARA_B
NIOBRARA_B_BASE
NIOBRARA_C
NIOBRARA_C_BASE
NIOBRARA_D
FORT_HAYS
CARLILE
7700
7800
7900
8000
8100


NIOBRARA_B_CHALK - ISOPACH - Isopach Thickness
Niobrara B2 Chalk Isopach
L-BR Area
Front Range
Boulder
Weld
Broomfield
Gilpin
Denver
Adams
Arapahoe
Jefferson
Douglas
105°30'00"W
105°15'00"W
105°00'00"W
104°45'00"W
104°30'00"W
104°15'00"W
104°00'00"W
103°45'00"W
40°07'30"N
40°00'00"N
39°52'30"N
39°45'00"N
39°37'30"N
39°30'00"N
39°22'30"N
80
70
60
50
40
30
20
10
0
34,136
FEET
TEBO 32
2
T4S R64W S32
NIOBRARA_B1
NIO_B1_BASE
NIOBRARA_B
NIOBRARA_B_BASE
NIOBRARA_C
NIOBRARA_C_BASE
NIOBRARA_D



Niobrara B2 Chalk Isopach
> 50 ohm-m Res.
L-BR Area

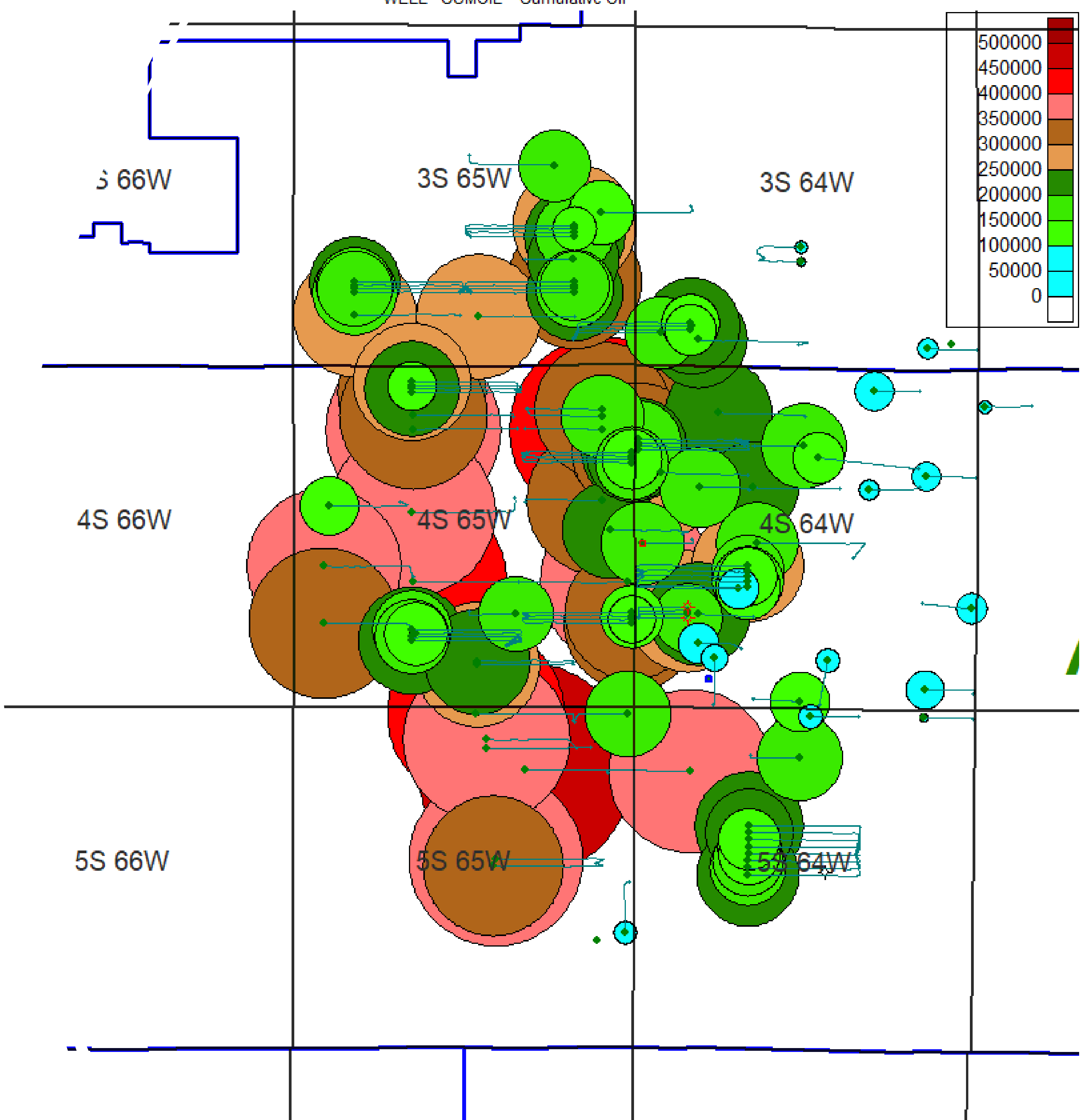

NIOBRARA_C_CHALK - ISOPACH - Isopach Thickness
Niobrara C Chalk Isopach
L-BR Area
Front Range
Boulder
Weld
Broomfield
Boulder
Gilpin
Adams
Denver
Denver
Arapahoe
Arapahoe
Douglas
105°30'00"W
105°15'00"W
105°00'00"W
104°45'00"W
104°30'00"W
104°15'00"W
104°00'00"W
103°45'00"W
40°07'30"N
40°00'00"N
39°52'30"N
39°45'00"N
39°37'30"N
39°30'00"N
39°22'30"N
50
40
30
20
10
0
34,136
FEET
TEBO 32
2
T4S R64W S32
NIOBRARA_B1
NIO_B1_BASE
NIOBRARA_B
NIOBRARA_B_BASE
NIOBRARA_C
NIOBRARA_C_BASE
NIOBRARA_D

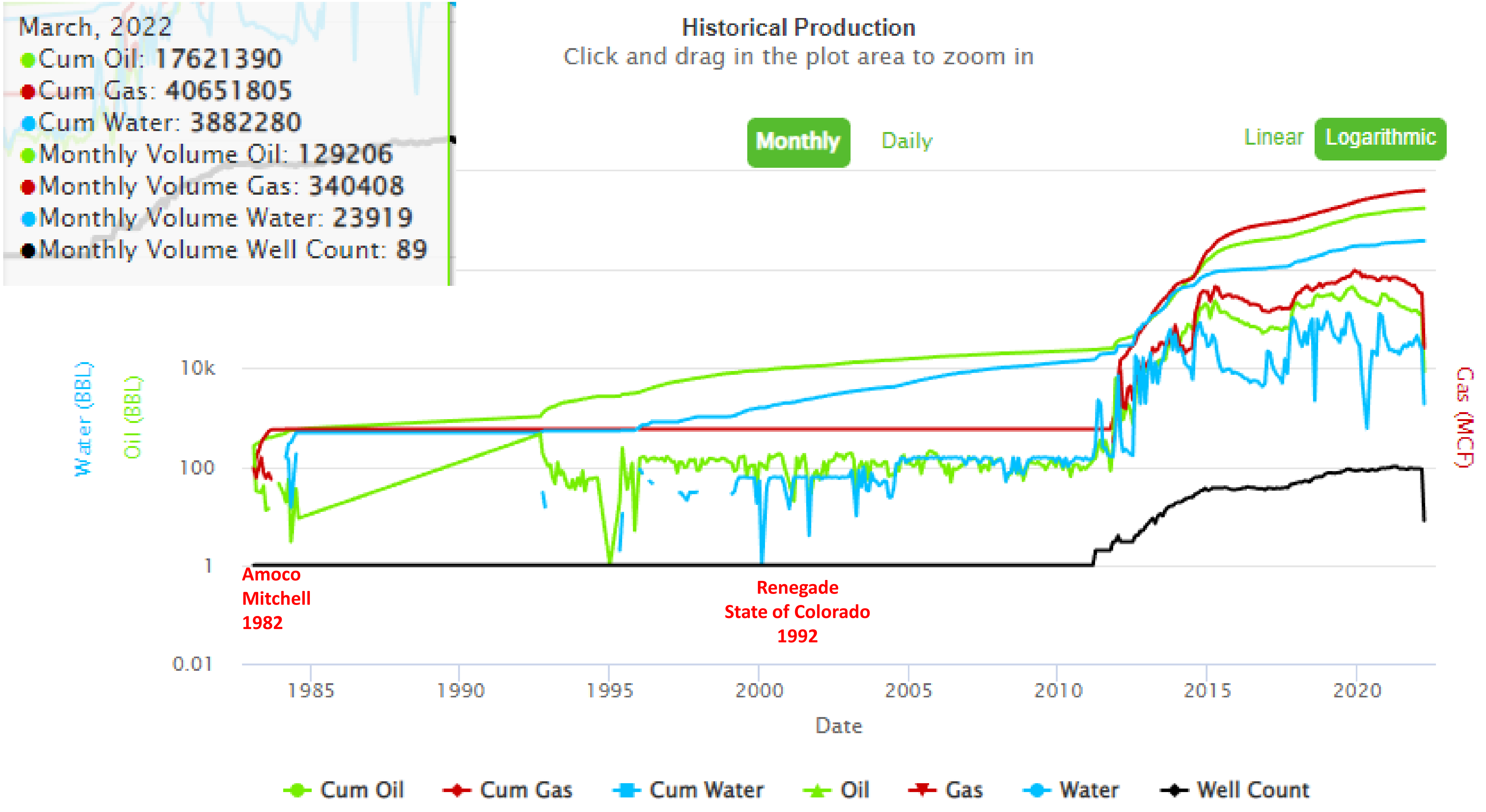


Niobrara C Chalk Isopach
> 50 ohm-m Res.
L-BR Area

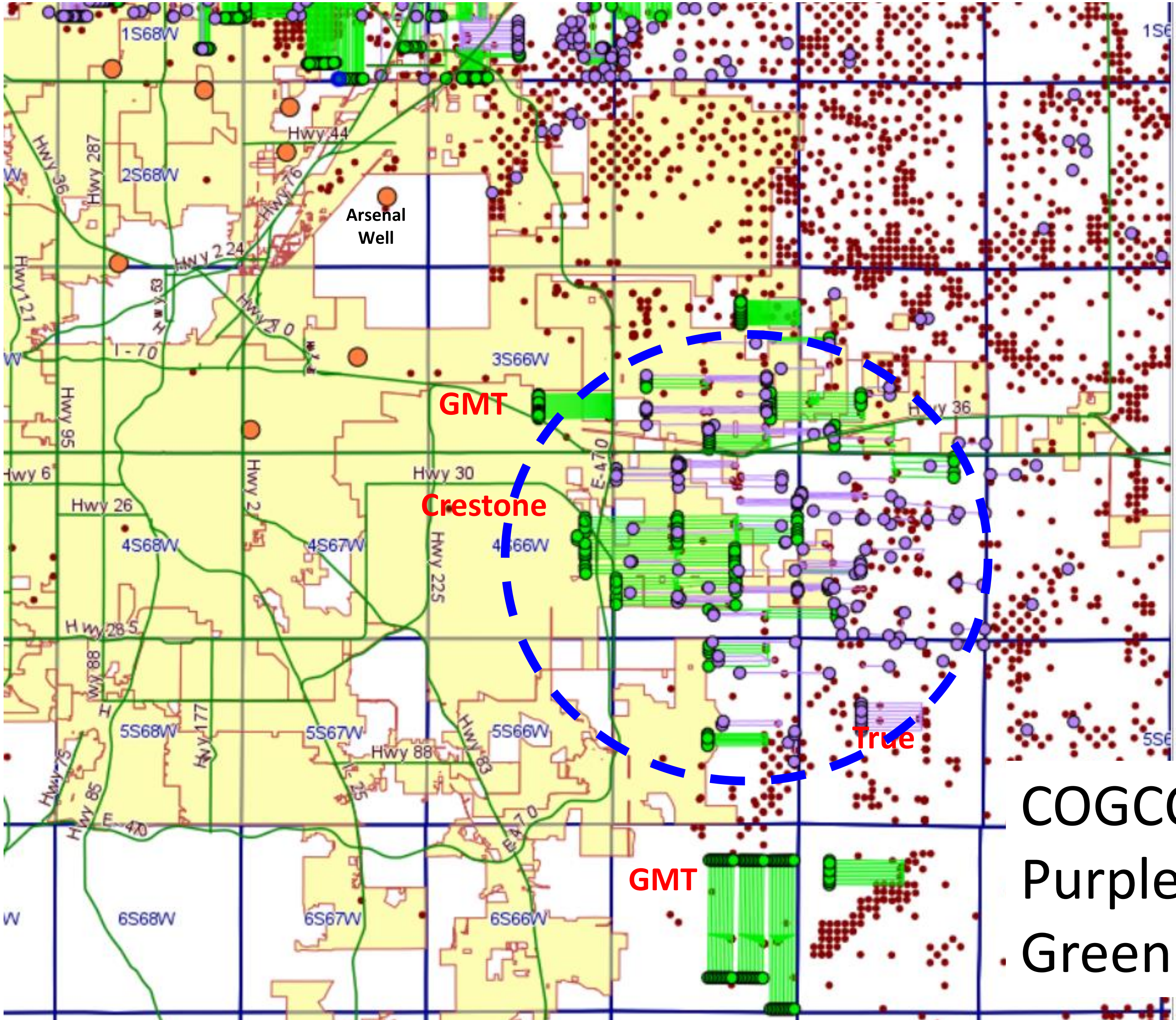
Oil EURs Lowry-Bombing Range

- EUR Factors
  - RQ: Lithology, K, Phi, H
  - Staying in target zone
  - Fractures
  - Maturity
  - Pressure
  - Well orientation & lateral length
  - Drainage area & well spacing
  - Fracture stimulation & stages

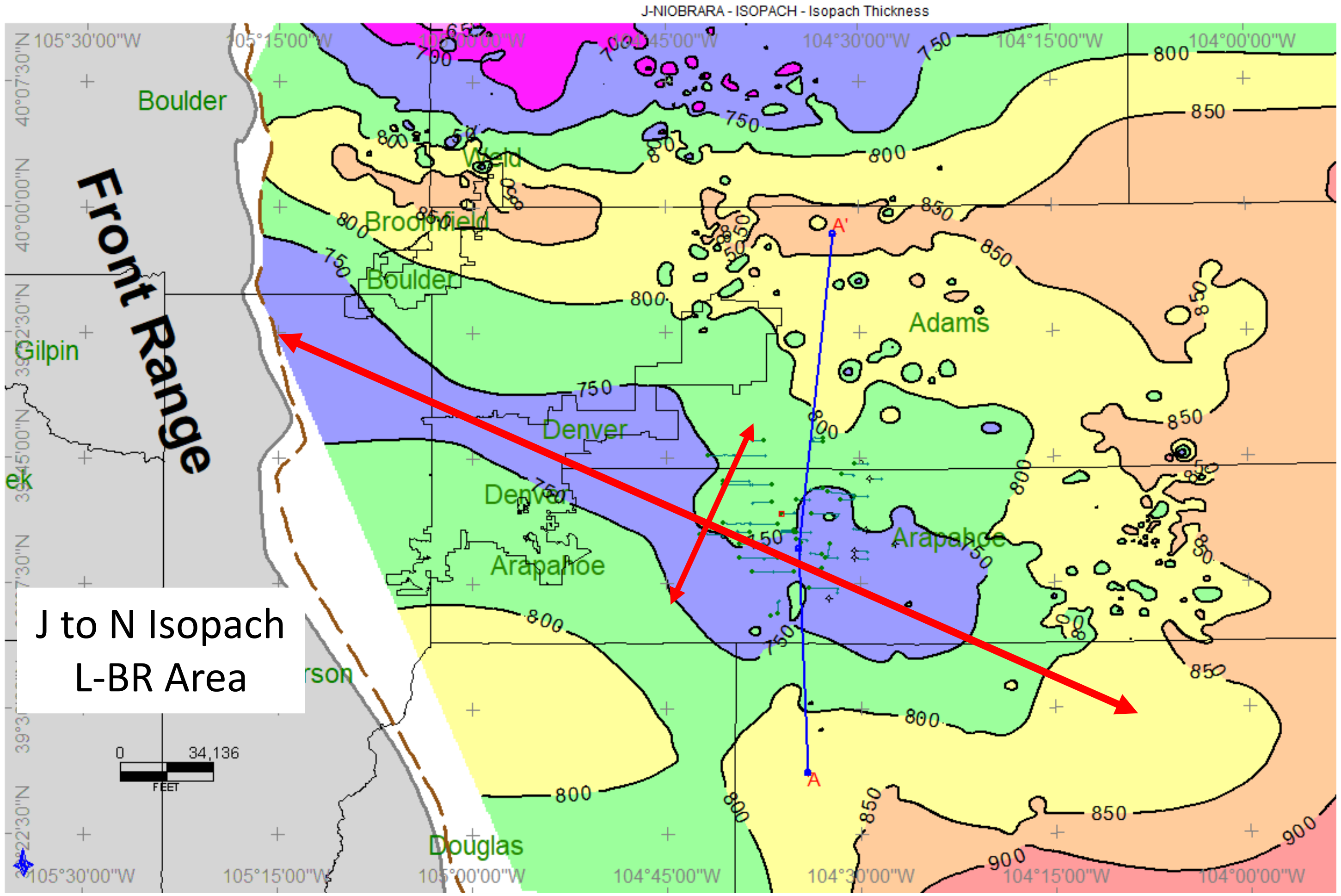


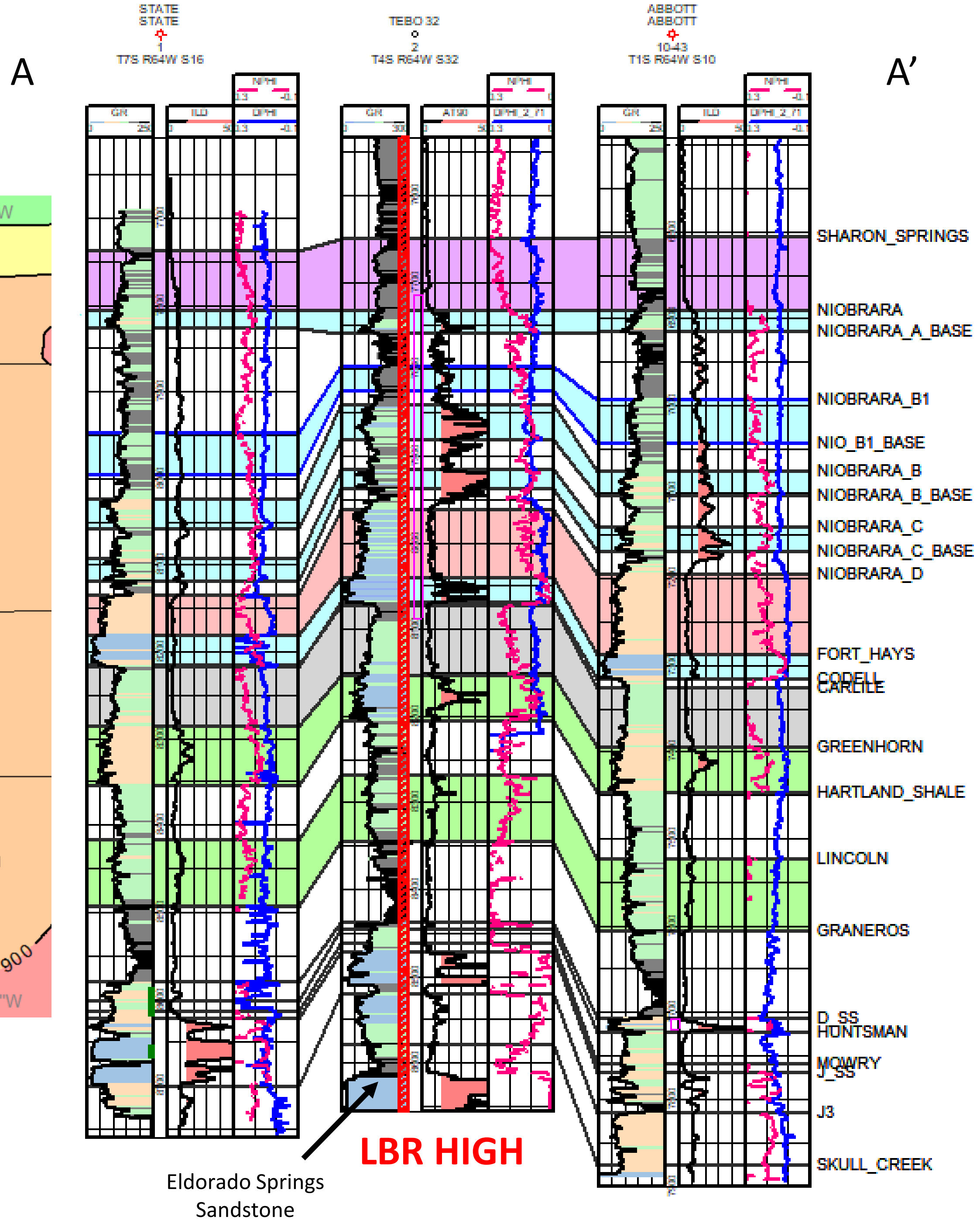


Enverus, 2022

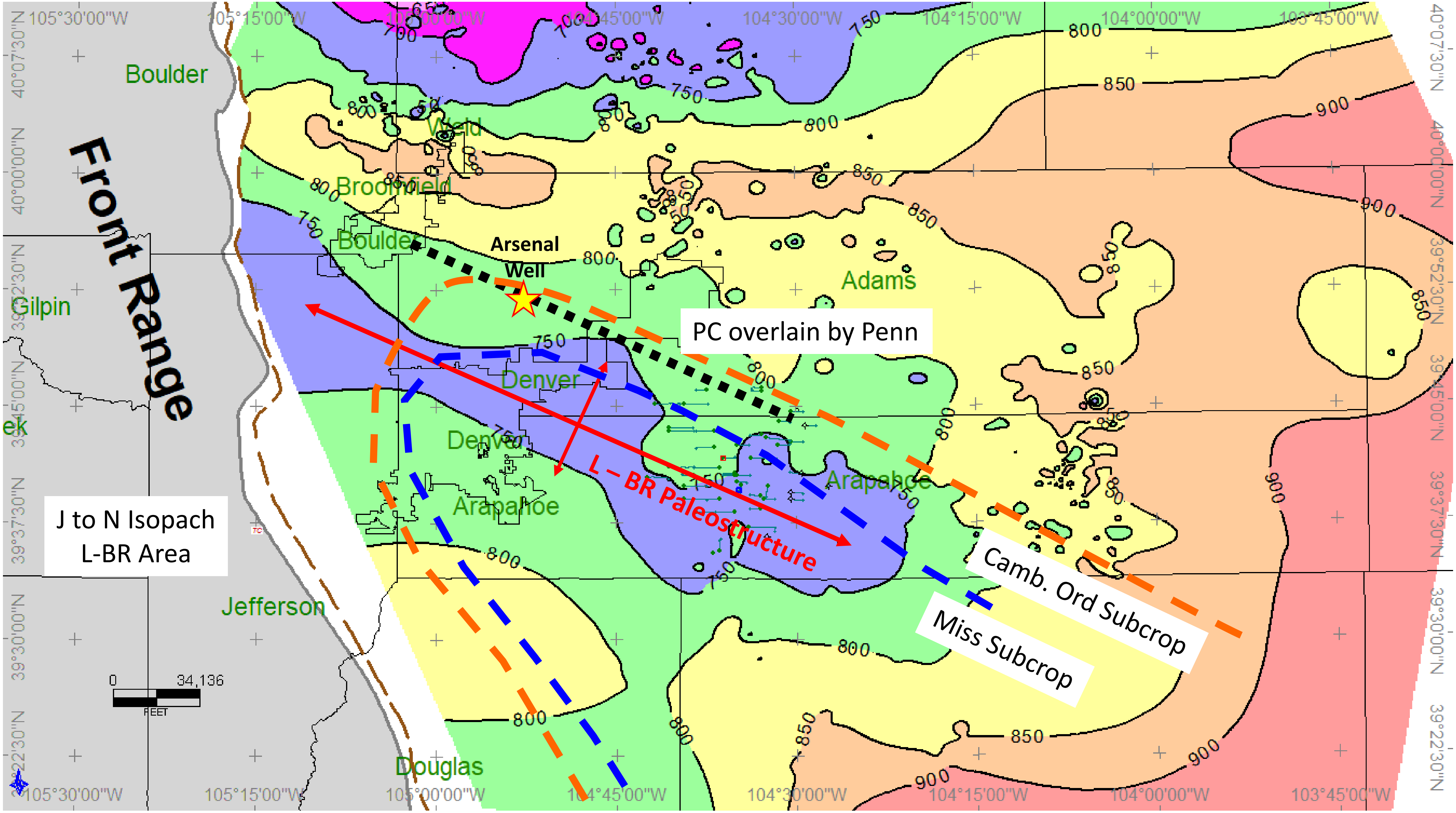


COGCC website
Purple: drilled
Green: permitted


J-NIOBRARA - ISOPACH - Isopach Thickness
105°30'00"W
105°15'00"W
105°00'00"W
104°45'00"W
104°30'00"W
104°15'00"W
104°00'00"W
Boulder
Weld
Broomfield
Boulder
Adams
Gilpin
Front Range
Denver
Denver
Arapahoe
Arapahoe
Douglas
A'
A
750
800
850
900
J to N Isopach
L-BR Area
0
34,136
FEET


A
A'
STATE
STATE
T7S R64W S16
TEBO 32
2
T4S R64W S32
ABBOTT
ABBOTT
10-43
T1S R64W S10
GR
ILD
NPHI
DPHI
AT90
SHARON_SPRINGS
NIOBRARA
NIOBRARA_A_BASE
NIOBRARA_B1
NIO_B1_BASE
NIOBRARA_B
NIOBRARA_B_BASE
NIOBRARA_C
NIOBRARA_C_BASE
NIOBRARA_D
FORT_HAYS
CODELL
CARLILE
GREENHORN
HARTLAND_SHALE
LINCOLN
GRANEROS
D_SS
HUNTSMAN
MOWRY
J_SS
J3
SKULL_CREEK
LBR HIGH
Eldorado Springs
Sandstone

J-NIOBRARA - ISOPACH - Isopach Thickness



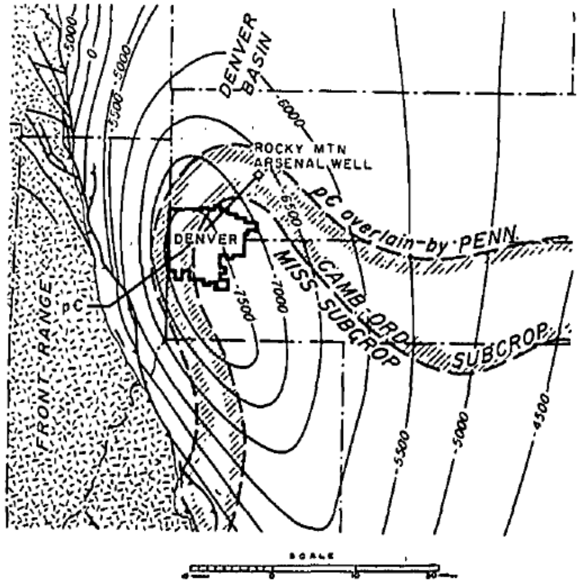
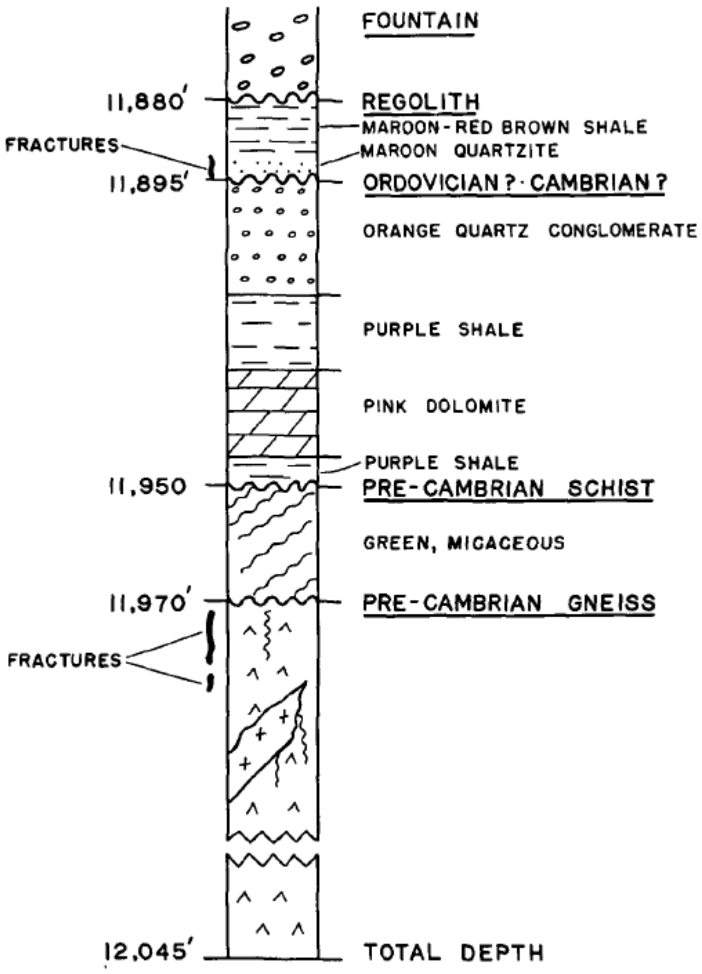


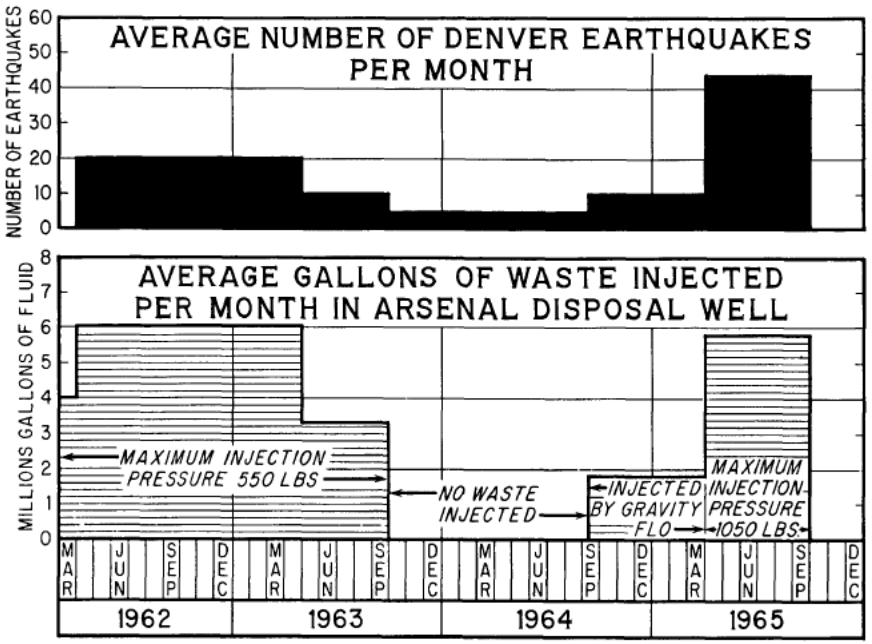
Figure 1. Structural map of a portion of the Denver-Julesburg Basin (after Anderman and Ackman, 1963), showing the location of the Rocky Mountain Arsenal well.

The Denver Earthquakes:

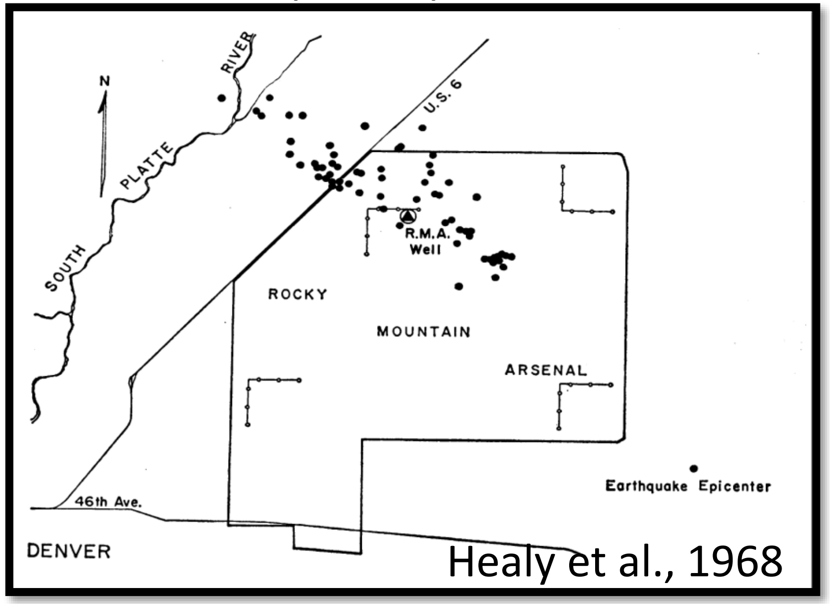
- *Disposal of waste fluid*
- *Arsenal well drilled in 1961*
- *Injection of contaminated wastewater began in 1962*
- *3.6 million bbls fluid injected*
- *710 earthquakes 1962-1965*
- *David Evans in 1965 showed a relationship between volumes of fluid injection and frequency of earthquakes*
- *Fluid injection increased pore pressure and reduced* frictional resistance to faulting
- *Magnitude 0.7-4.3*



Evans, 1966

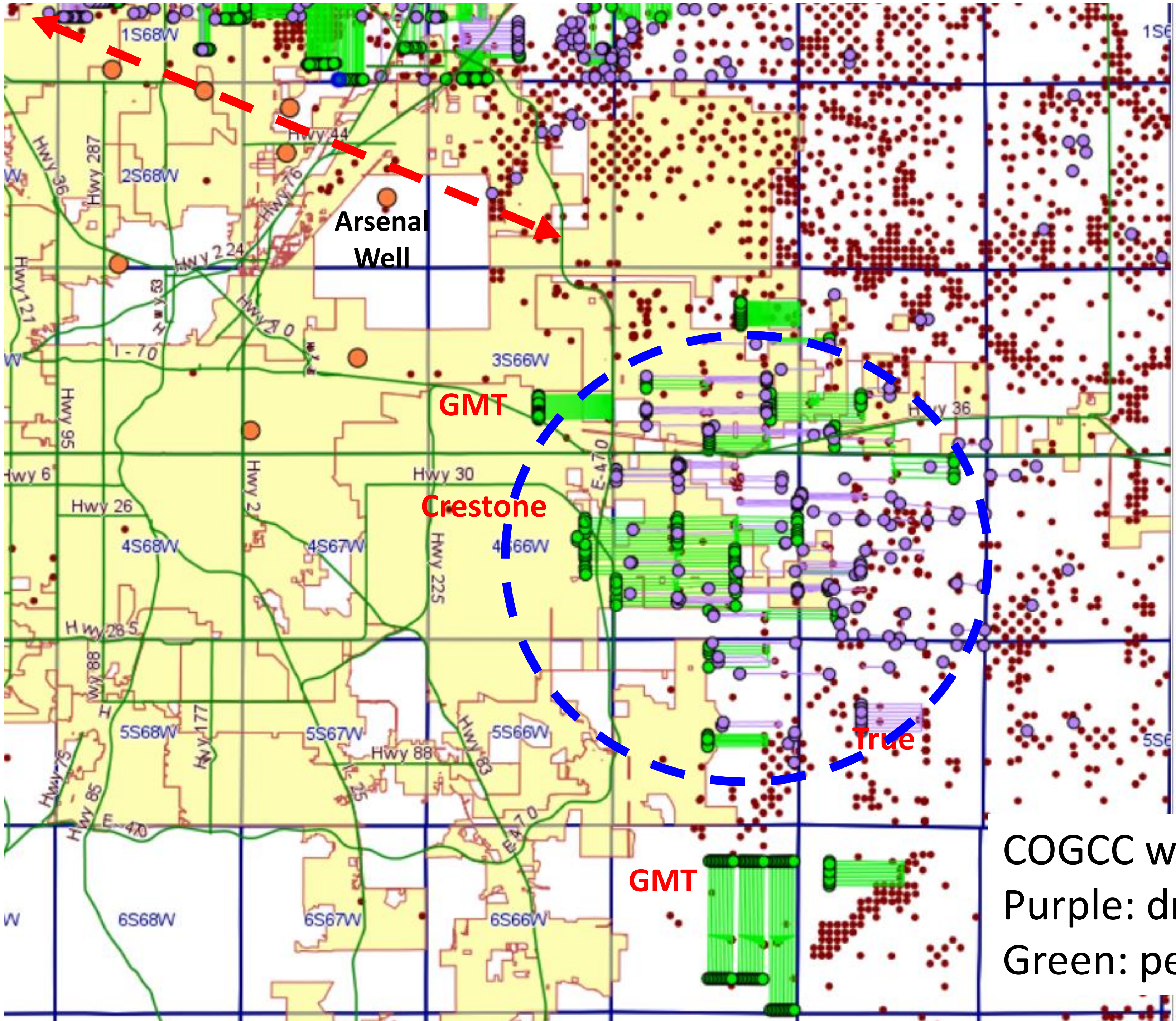


Earthquake Epicenters

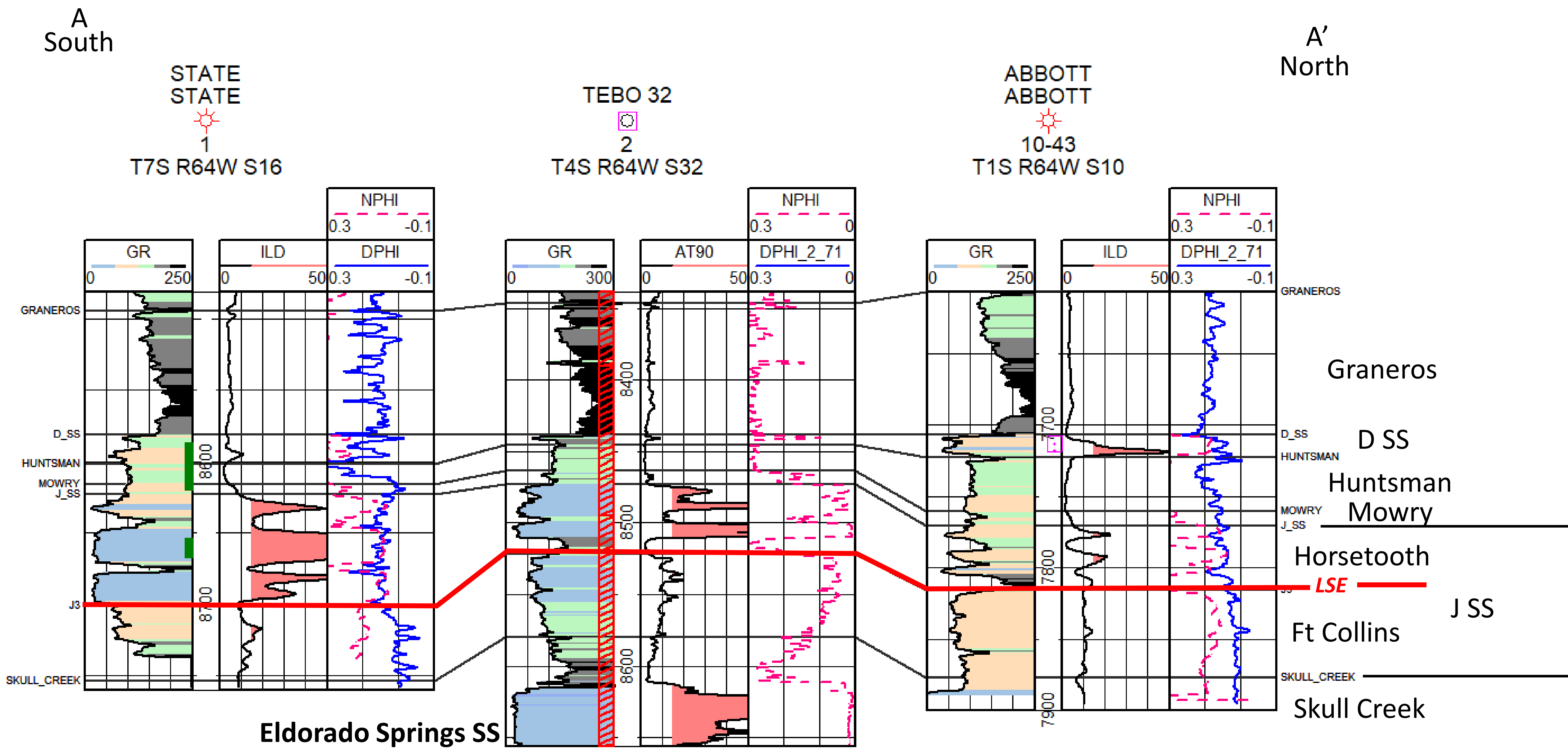


Healy et al., 1968

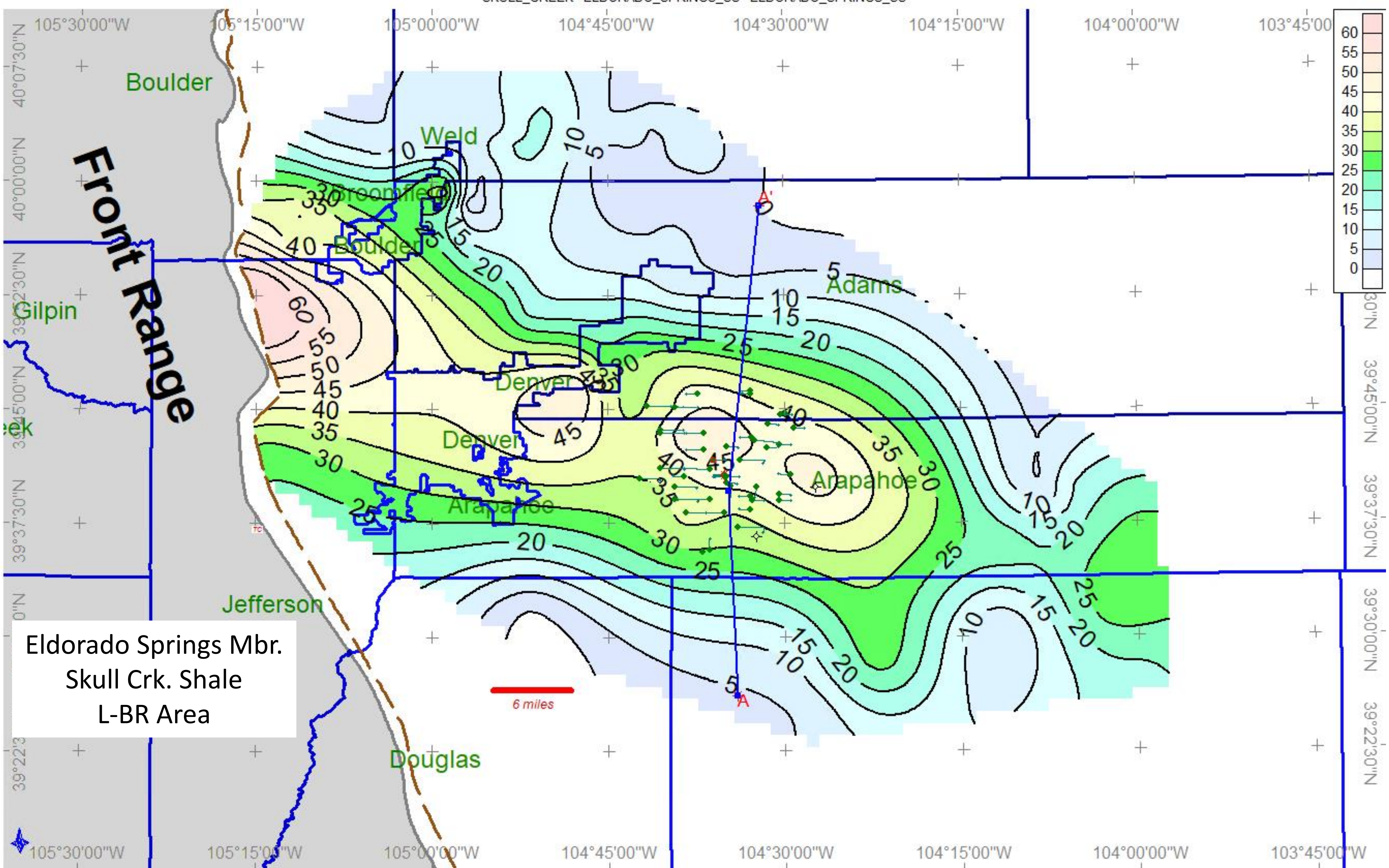
Earthquakes since 1973



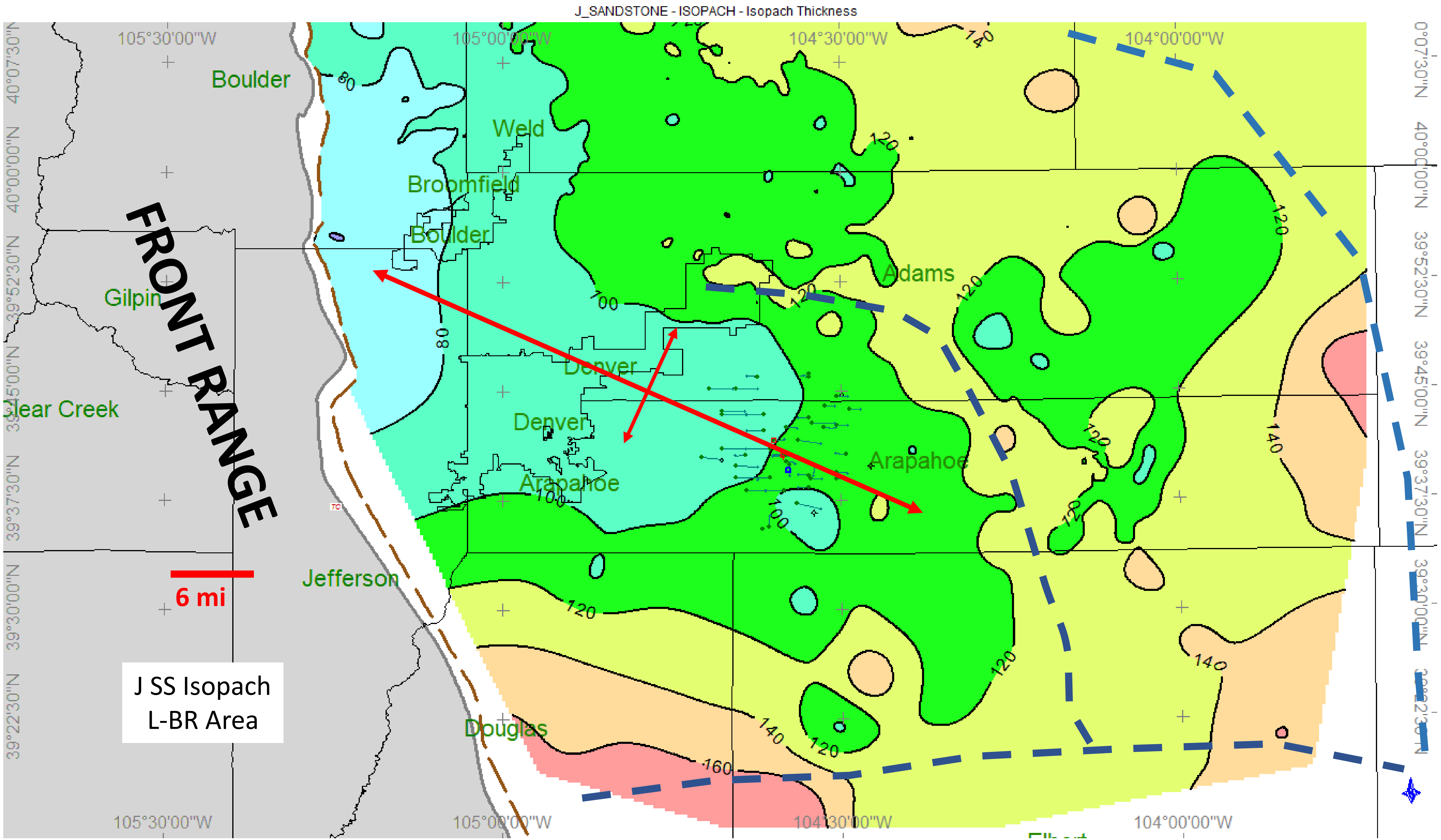
COGCC website
Purple: drilled
Green: permitted

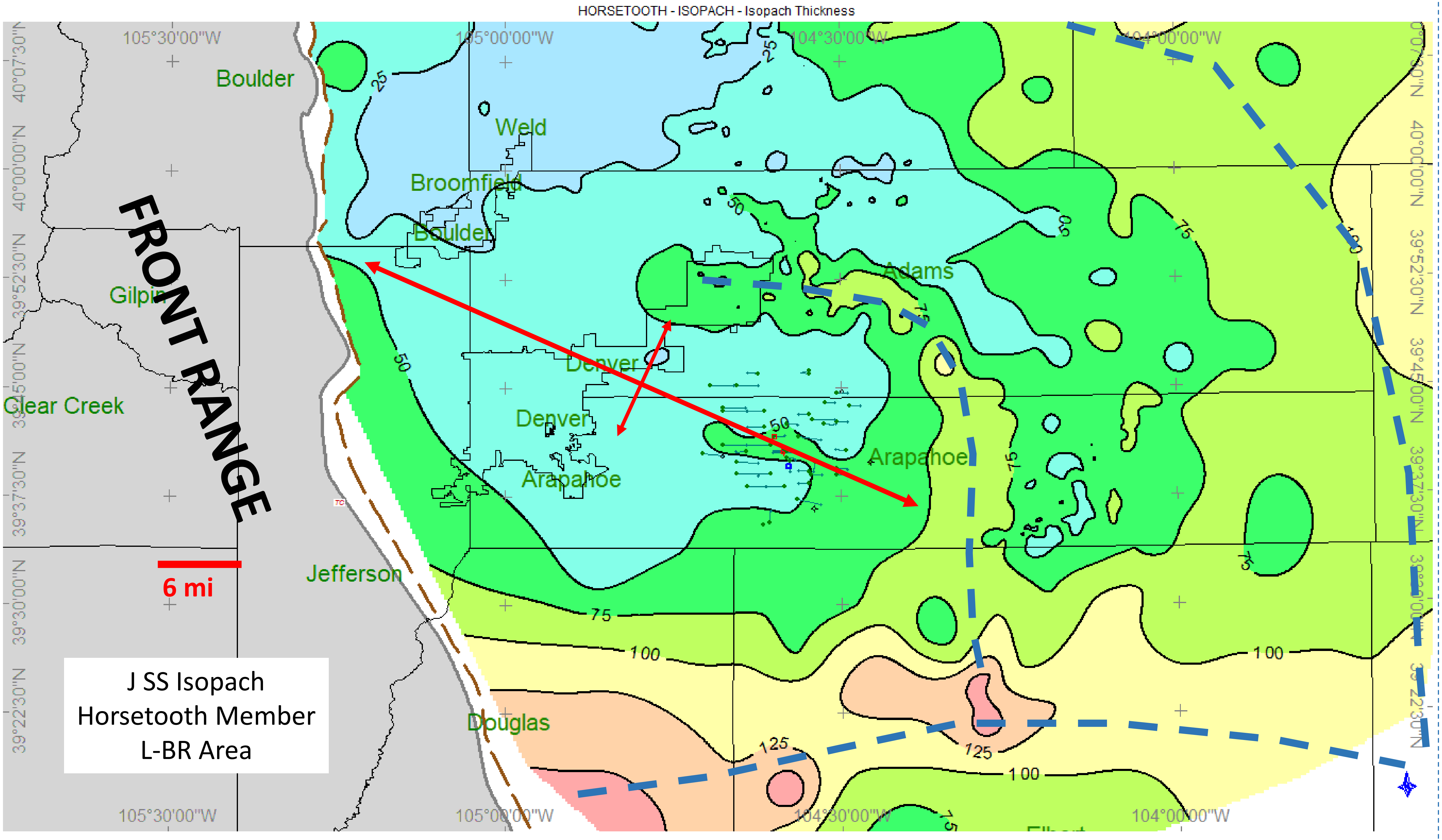


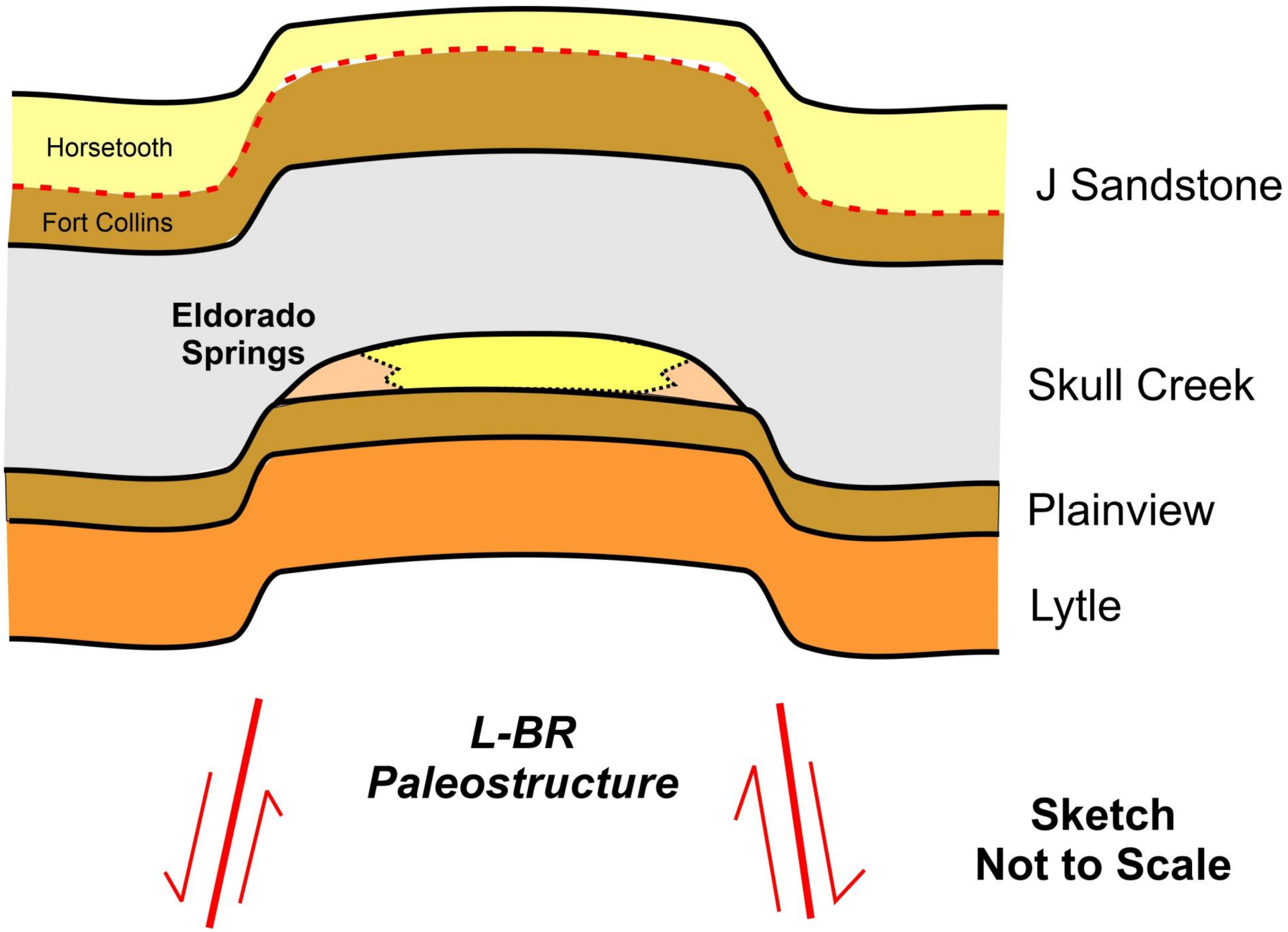
A
South
A'
North
STATE
STATE
1
T7S R64W S16
TEBO 32
2
T4S R64W S32
ABBOTT
ABBOTT
10-43
T1S R64W S10
GR
ILD
AT90
NPHI
DPHI
DPHI_2_71
GRANEROS
D_SS
HUNTSMAN
MOWRY
J_SS
J3
SKULL_CREEK
8400
8500
8600
8700
7700
7800
7900
Graneros
D SS
Huntsman
Mowry
Horsetooth
LSE
J SS
Ft Collins
Skull Creek
Eldorado Springs SS



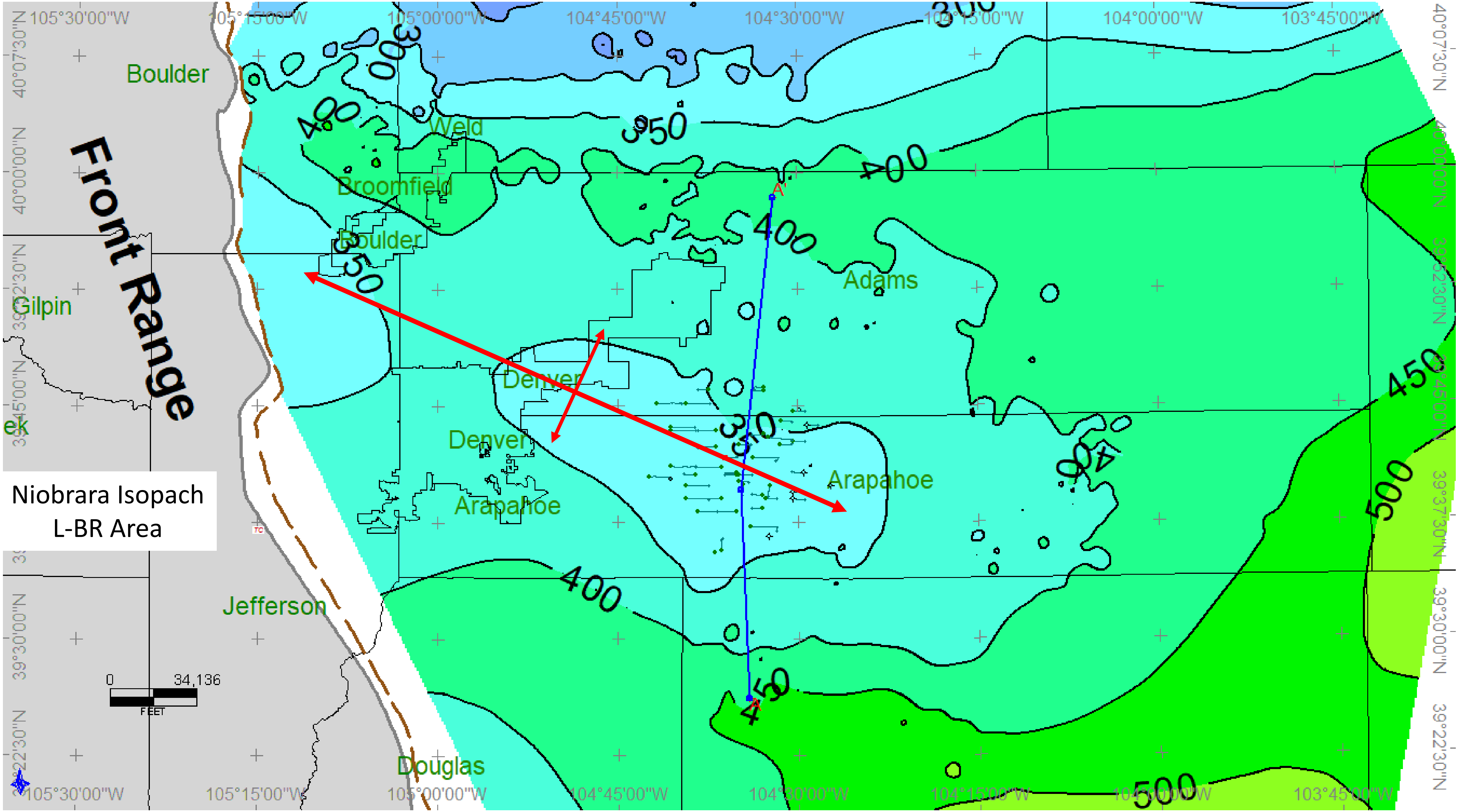
Eldorado Springs Mbr.
Skull Crk. Shale
L-BR Area


J_SANDSTONE - ISOPACH - Isopach Thickness
FRONT RANGE
6 mi
J SS Isopach
L-BR Area
Boulder
Weld
Broomfield
Boulder
Gilpin
Clear Creek
Denver
Denver
Adams
Arapahoe
Arapahoe
Jefferson
Douglas
80
100
120
140
160
105°30'00"W
105°00'00"W
104°30'00"W
104°00'00"W
40°07'30"N
40°00'00"N
39°52'30"N
39°45'00"N
39°37'30"N
39°30'00"N
39°22'30"N


HORSETOOTH - ISOPACH - Isopach Thickness
FRONT RANGE
Boulder
Weld
Broomfield
Boulder
Adams
Gilpin
Denver
Denver
Clear Creek
Arapahoe
Arapahoe
Jefferson
Douglas
6 mi
J SS Isopach
Horsetooth Member
L-BR Area
105°30'00"W
105°00'00"W
104°30'00"W
104°00'00"W
40°07'30"N
40°00'00"N
39°52'30"N
39°45'00"N
39°37'30"N
39°30'00"N
39°22'30"N
25
50
75
100
125


Horsetooth
Fort Collins
J Sandstone
Eldorado Springs
Skull Creek
Plainview
Lytle
L-BR Paleostructure
Sketch Not to Scale

NIOBRARA - ISOPACH - Isopach Thickness



Summary

- L-BR Paleostructure
  - Most unconventional Niobrara production located on paleostructures
  - Thinning in Niobrara, J SS
  - Lower Paleozoic thickness patterns
- L-BR is thermal anomaly (Tmax & Ro)
- Niobrara B and C resistivity anomalies (= accumulation)
- Horizontal targets: A, B2, C chalk intervals
  - Highest P&P: A & B2 chalks
  - Chalky (coccolith) porosity: interparticle, intraparticle, intercrystalline
- Niobrara source beds: A, B, C marls (Type II)

Other Potential

- CCS Lyons, Entrada
- Geothermal Lyons, Entrada

Special Thanks

- ConocoPhillips: cores and data
- MUDTOC Niobrara students