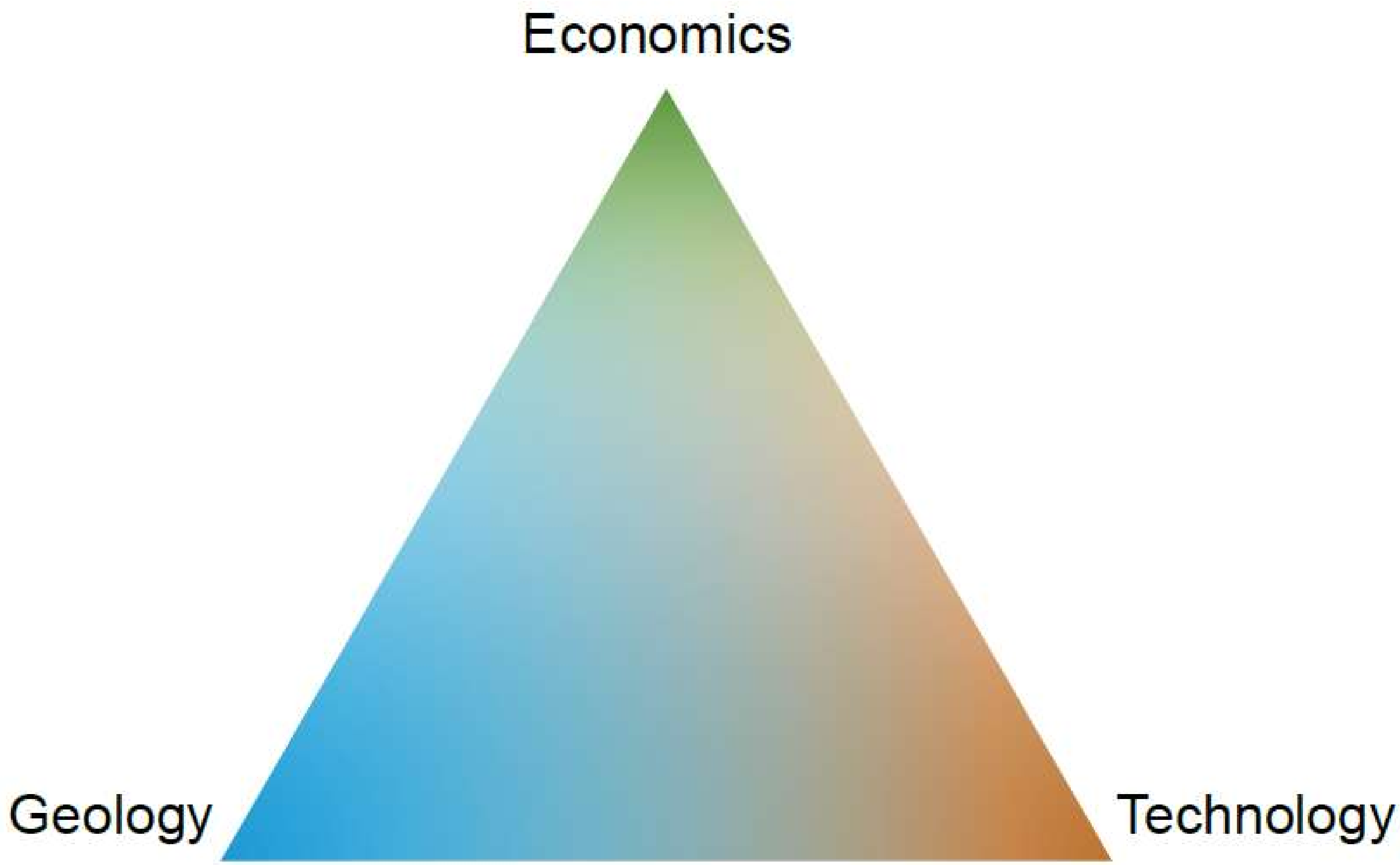
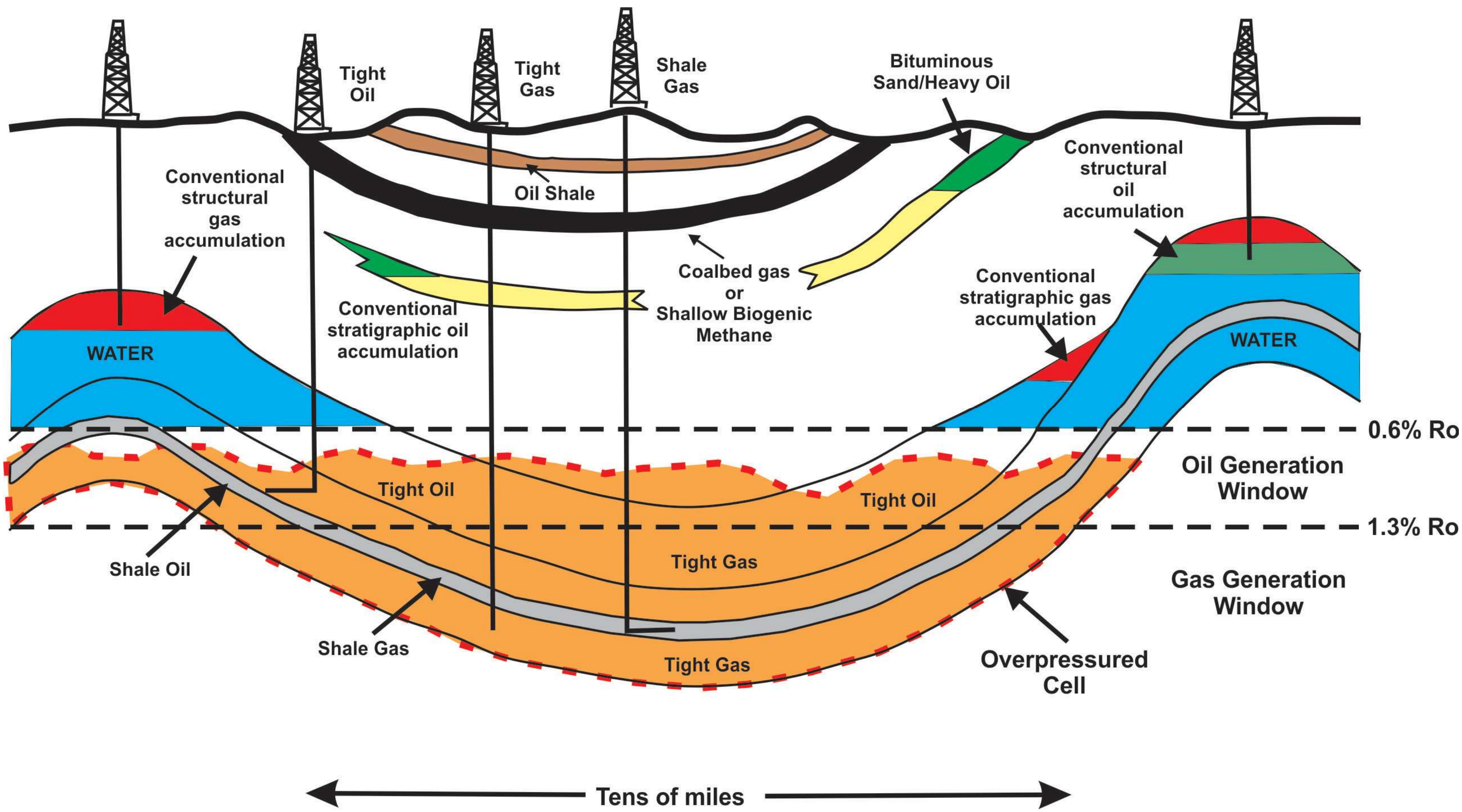
Denver Basin Overview

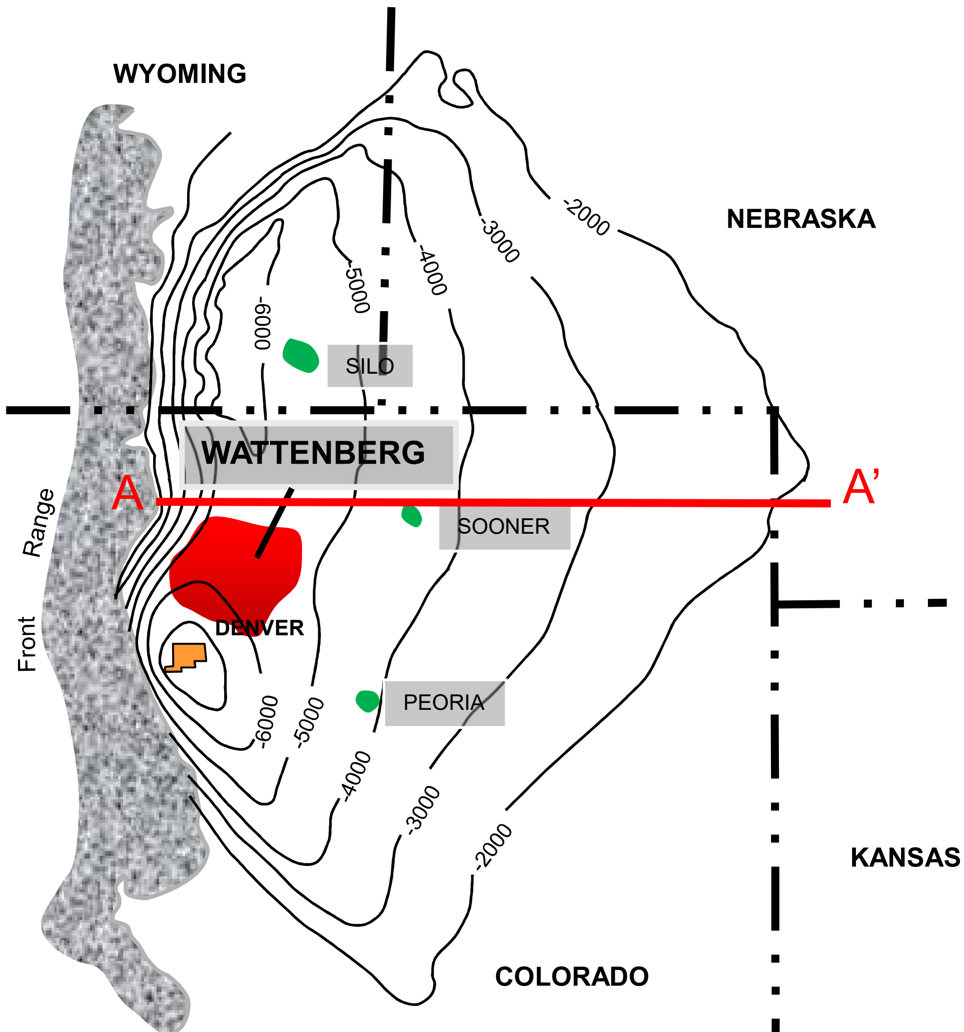
Dr. Steve Sonnenberg

Three Main Drivers of Oil and Natural Gas Production And Resource Estimates

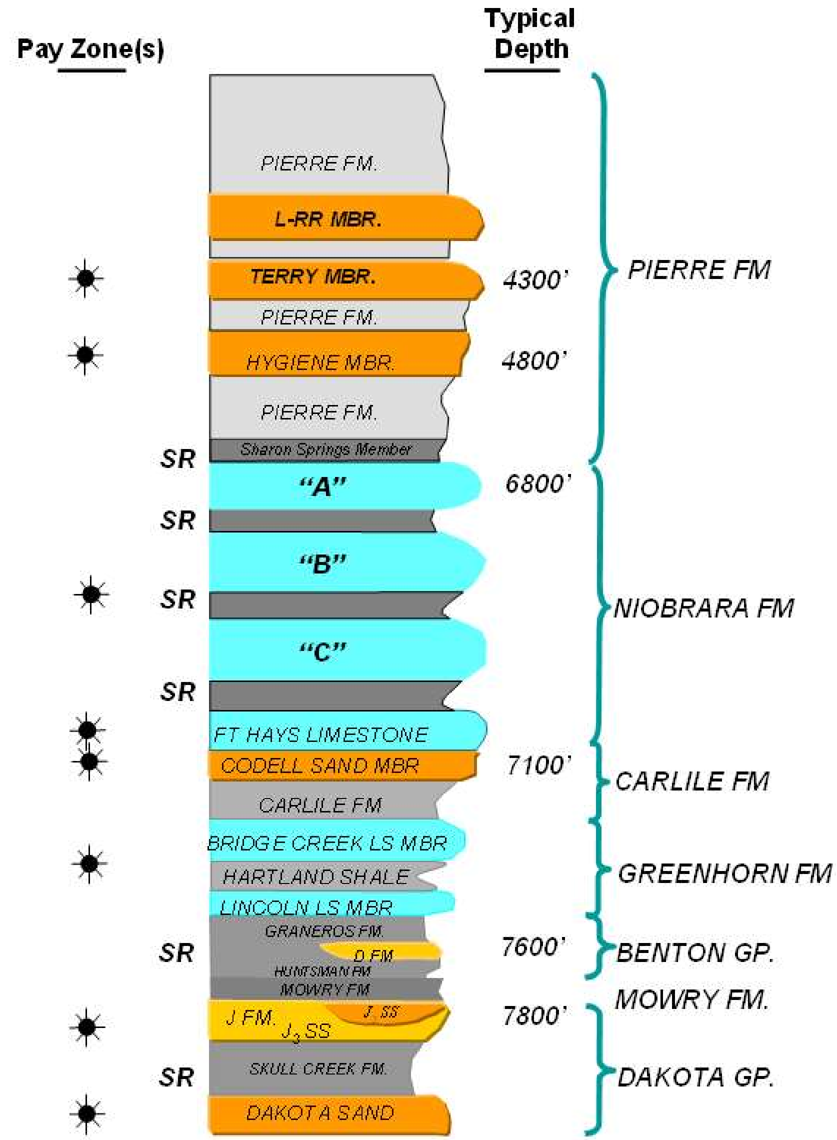


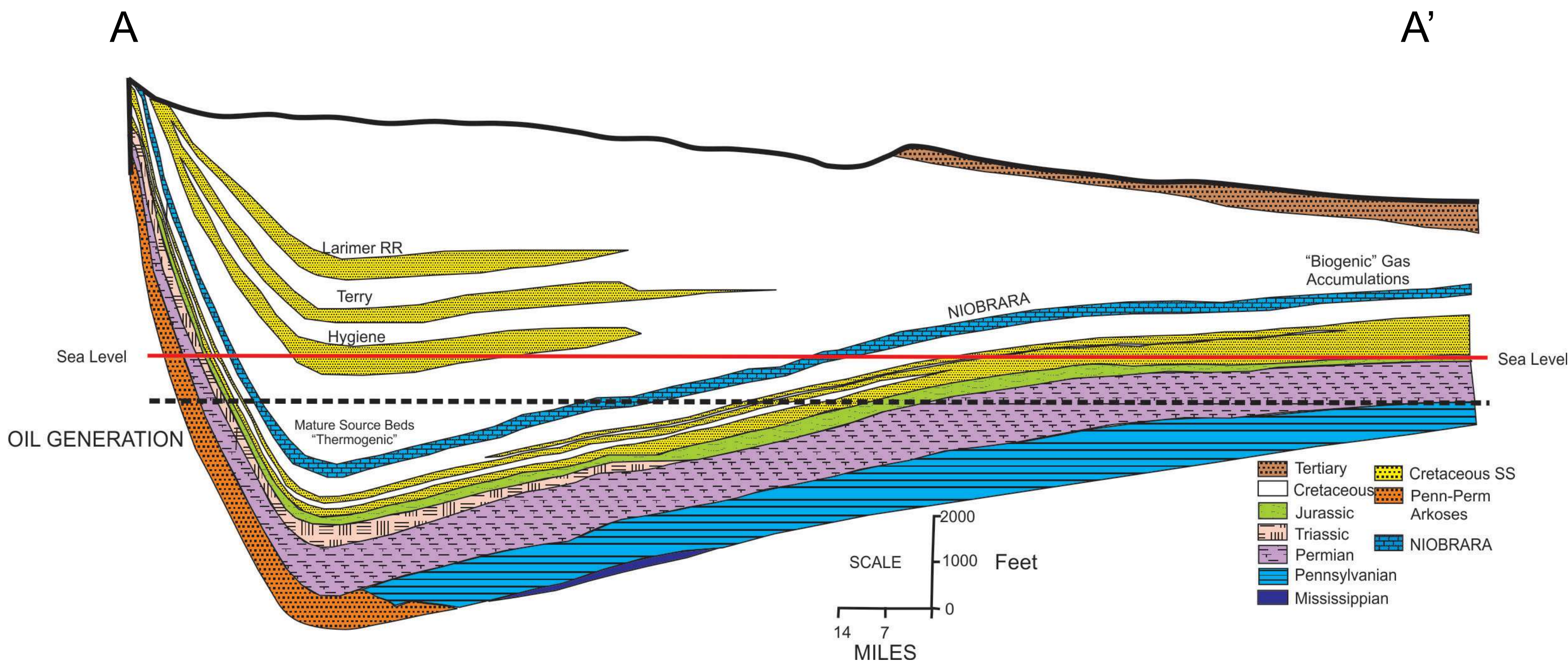
Conventional and Unconventional Traps



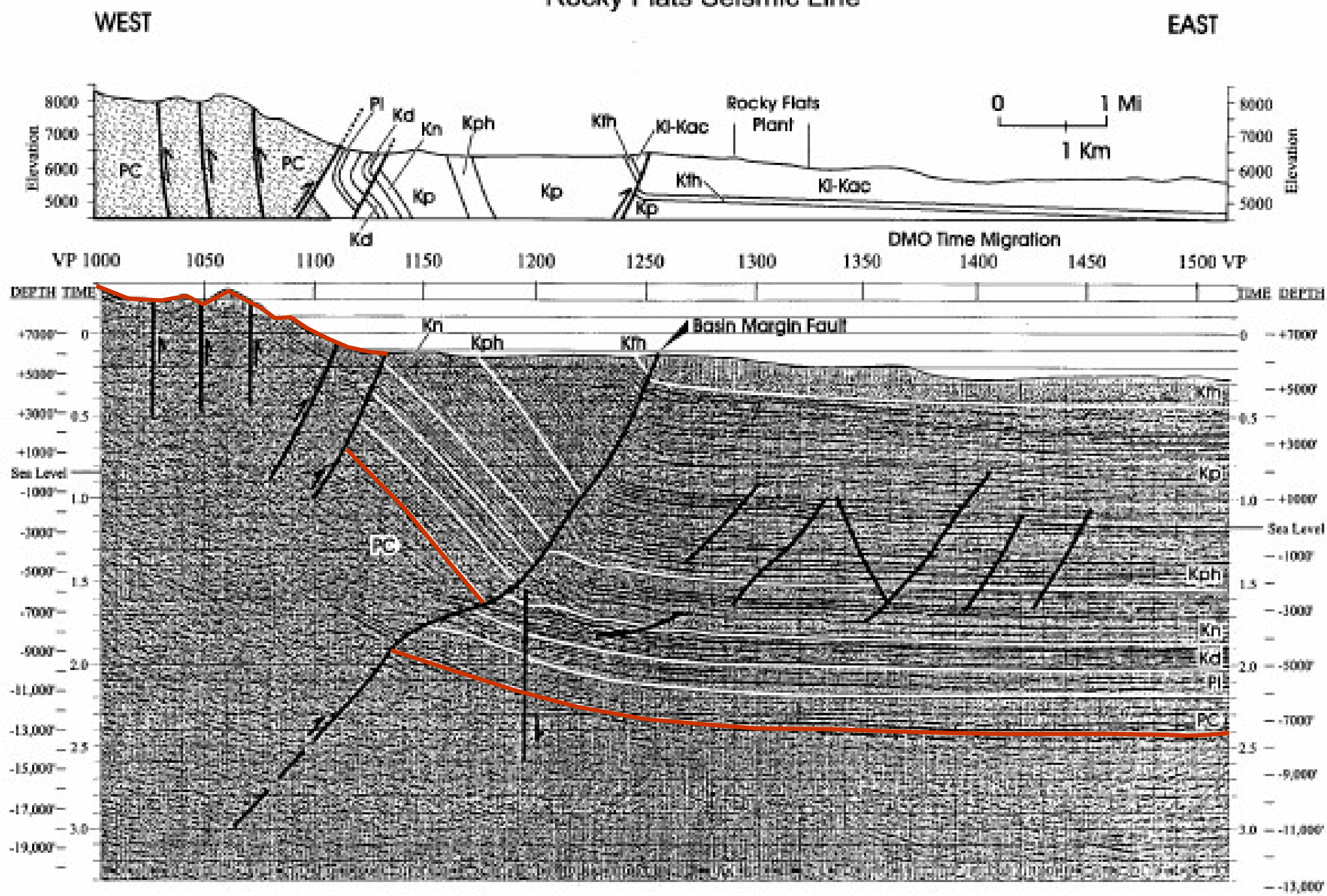


Structure Base Pennsylvanian
After Martin, 1965

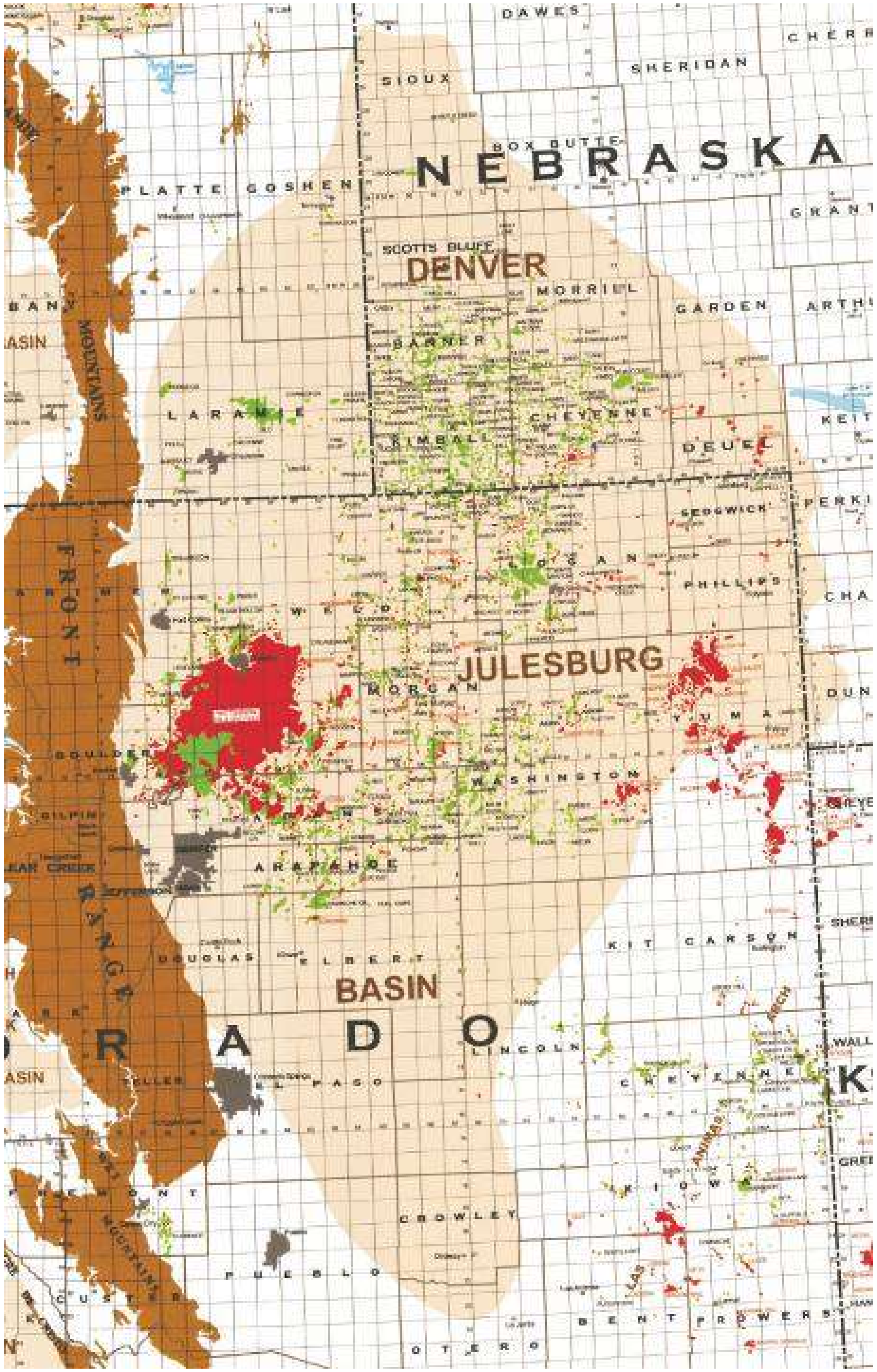



A
A'
Larimer RR
Terry
Hygiene
"Biogenic" Gas Accumulations
NIOBRARA
Sea Level
Sea Level
OIL GENERATION
Mature Source Beds "Thermogenic"
Tertiary
Cretaceous
Jurassic
Triassic
Permian
Pennsylvanian
Mississippian
Cretaceous SS
Penn-Perm Arkoses
NIOBRARA
SCALE
2000
1000
0
Feet
14
7
MILES

Rocky Flats Seismic Line



Weimer & Ray, 1997



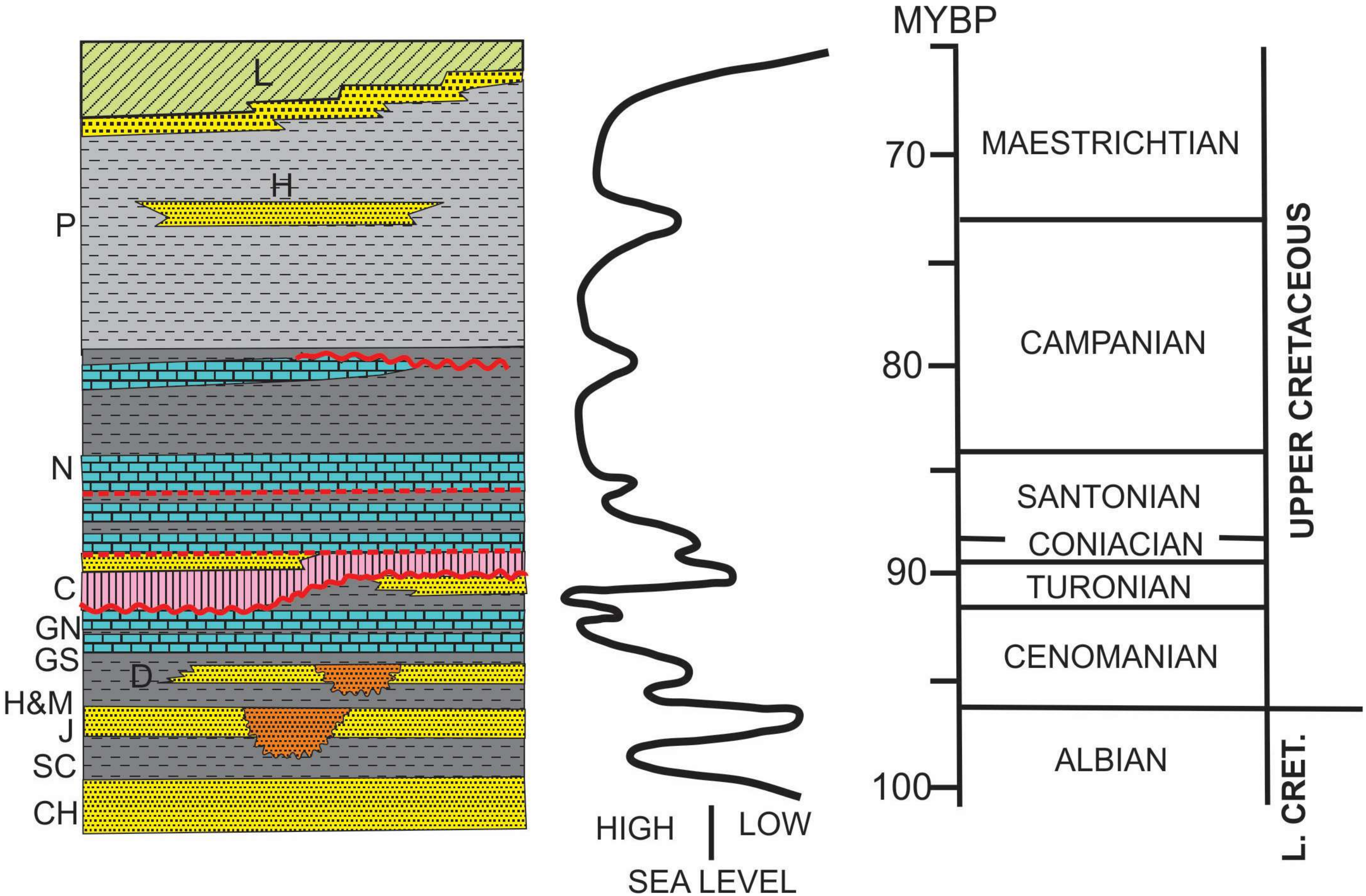
Denver Basin

- •Asymmetric Basin
- •60,000 mi^2
- •Up to 13,000 ft deep
- •Majority of Production from Cretaceous reservoirs

- •First oil-1862: Oil spring near Canon City; ~ 1 BOPD
- •First oil well-1876:
  - •Cassidy & Canfield drilled well to 1445 ft and hit oil
  - •Florence Canon City Field has produced > 15 million BO
  - •Fracture Pierre shale bottom of Canon City Embayment

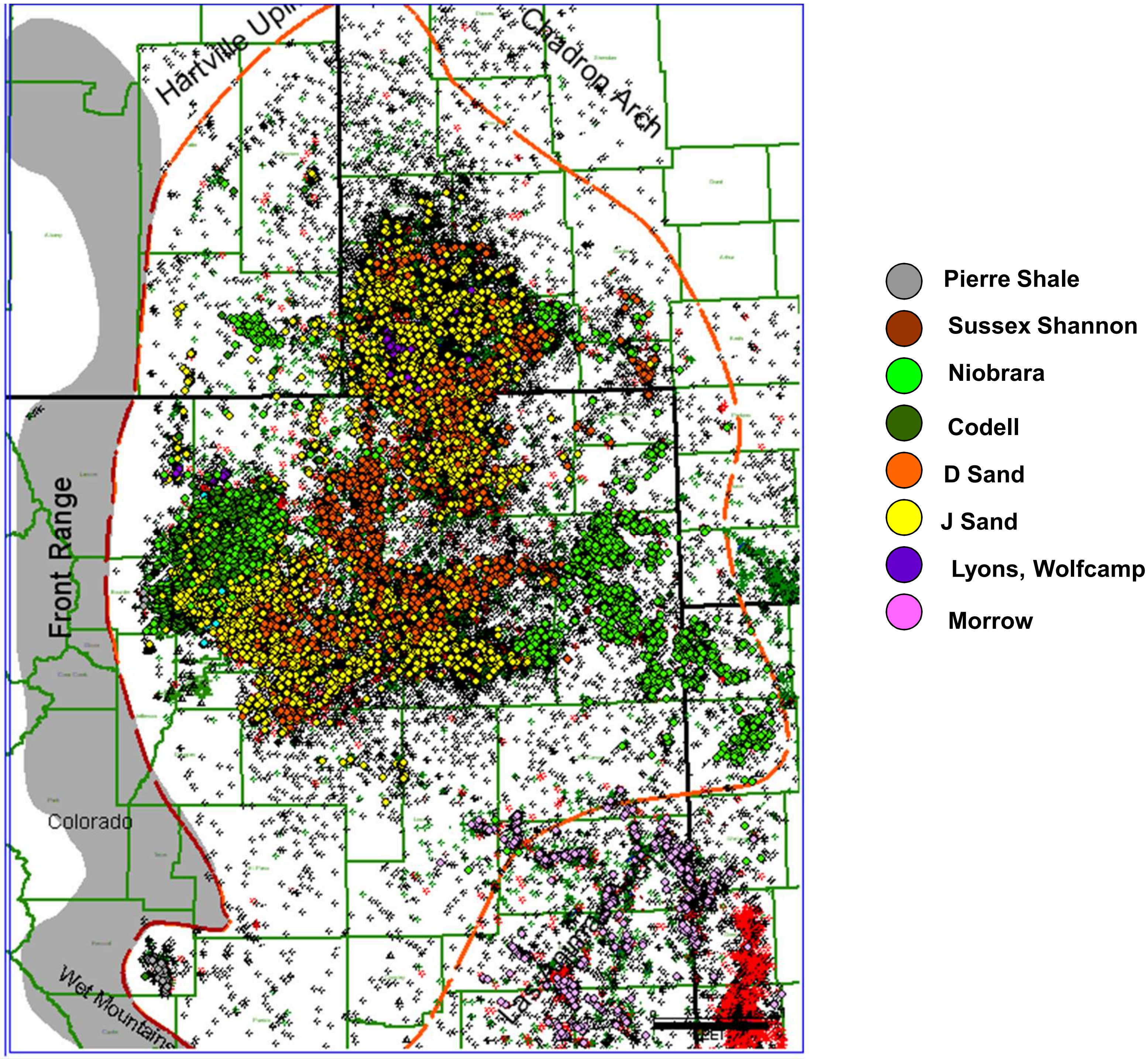
- •Boulder Oil Field:
  - •1901
  - •Fracture Pierre Shale

- •1949-- Discovery in Nebraska: Ohio Oil Company 225 BOPD

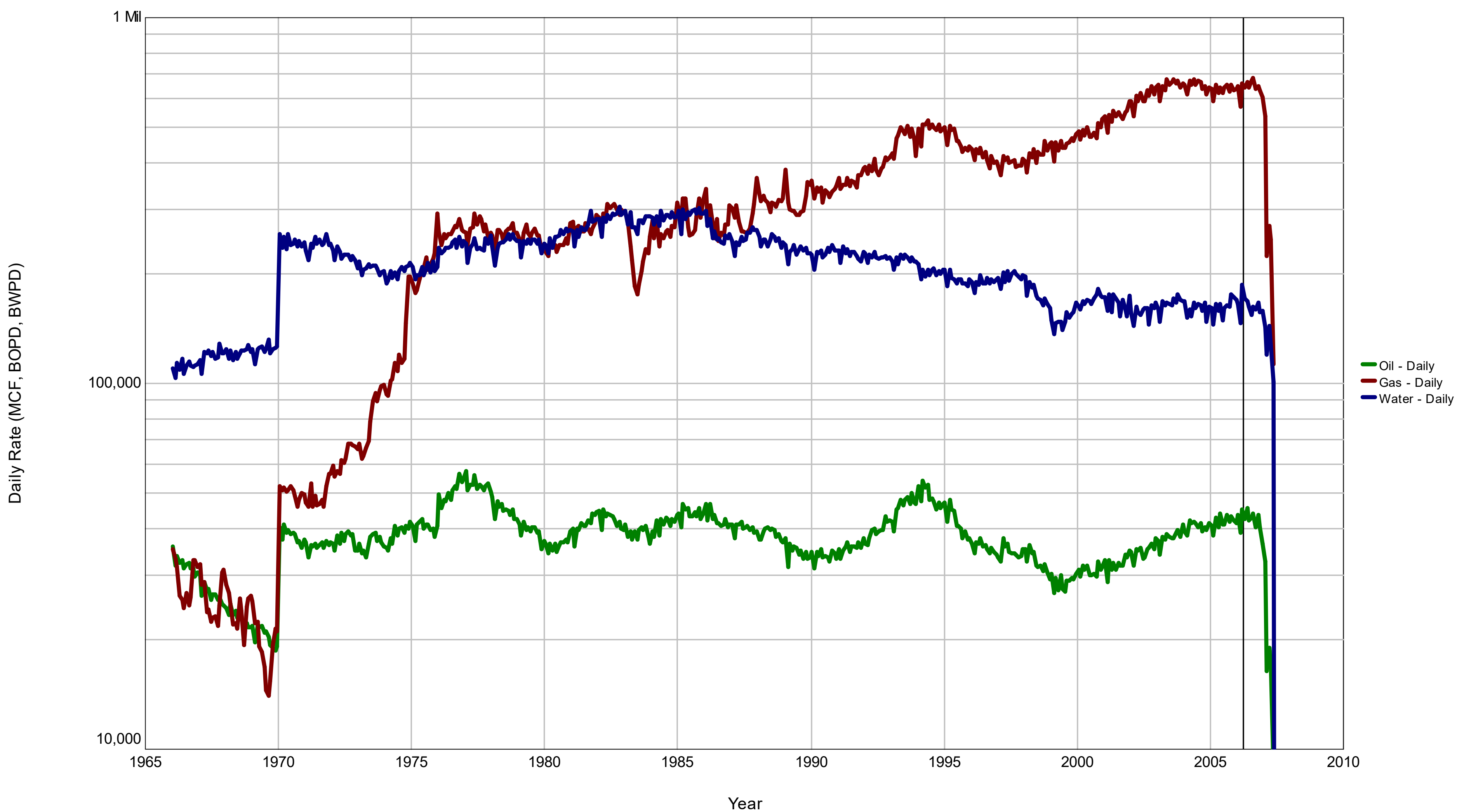


L
H
P
N
C
GN
GS
D
H&M
J
SC
CH
HIGH
LOW
SEA LEVEL
MYBP
70
80
90
100
MAESTRICHTIAN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
CENOMANIAN
ALBIAN
UPPER CRETACEOUS
L. CRET.

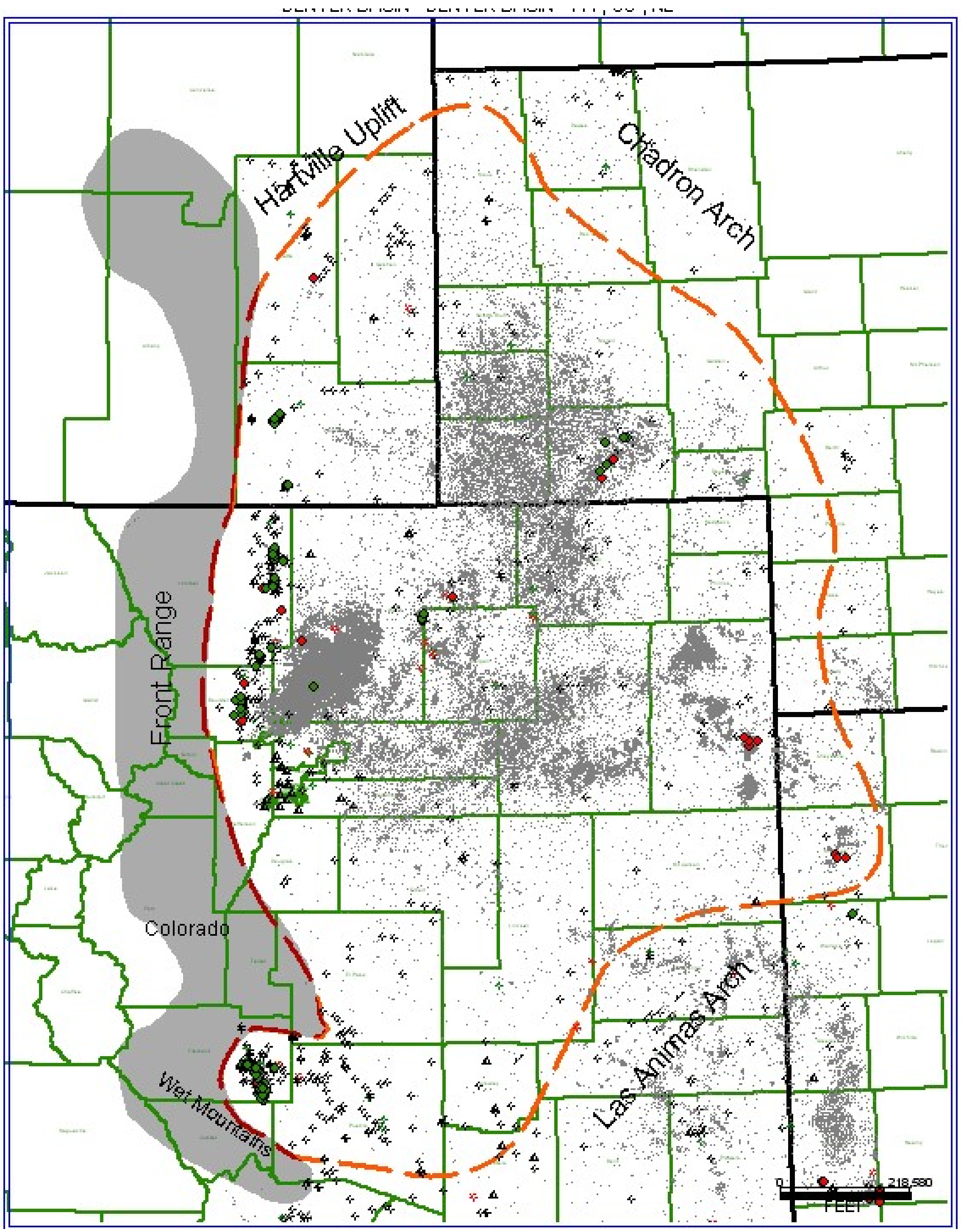

OIL CREEK
SITE OF THE FIRST OIL WELL IN THE WEST; SECOND PLACE IN THE UNITED STATES TO PRODUCE PETROLEUM FROM THE WELLS.
In 1862, just across the stream from this point, A. M. Cassidy drilled an oil well fifty feet deep. By February, 1863, production was one barrel a day. Later, several thousand gallons of petroleum were produced by primitive methods, and kerosene and lubricating oil were shipped by ox-team as far as Denver & Santa Fe.
Cassidy's success led to the finding of Colorado's first real oil field, about seven miles south of here. This field, known as the Florence Pool, was discovered in 1876 by Isaac Canfield. It subsequently was operated for about seventy years by Continental Oil Company and its predecessors. The field still produces a small amount of petroleum.


Chadron Arch
Front Range
Colorado
Wet Mountains
Pierre Shale
Sussex Shannon
Niobrara
Codell
D Sand
J Sand
Lyons, Wolfcamp
Morrow

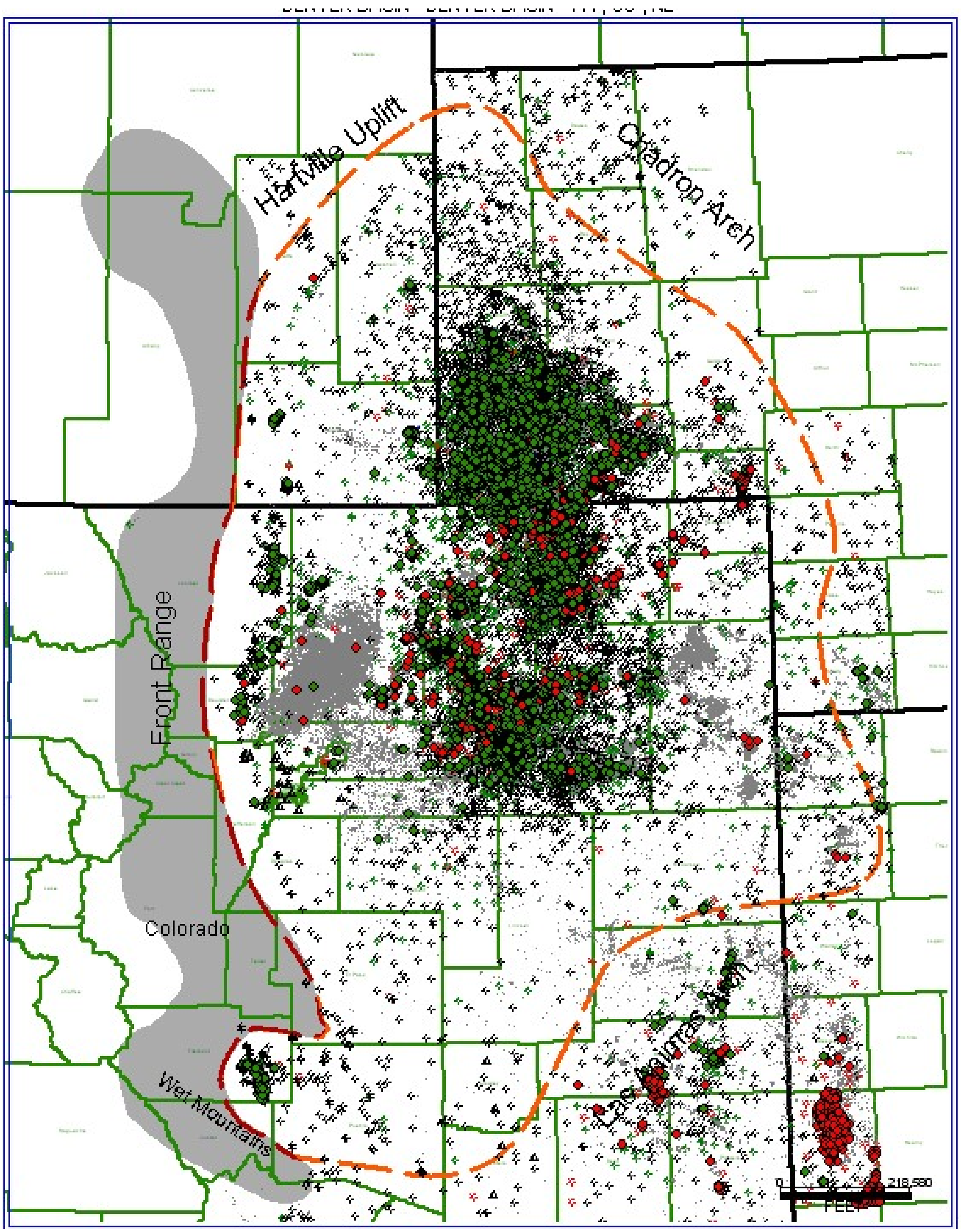
DJ Basin Historical Production



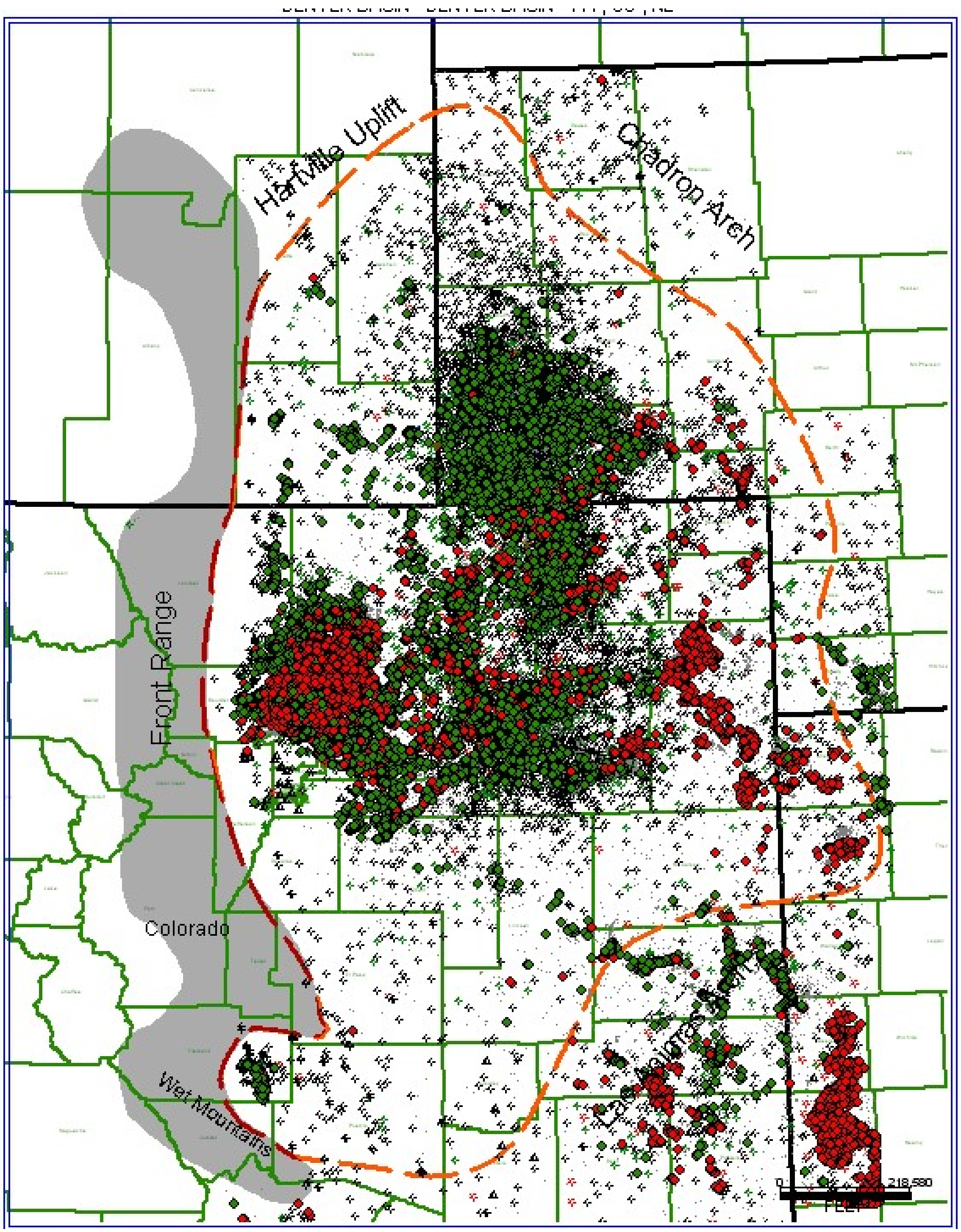
Current Production: > 600 MMCFGD; > 40,000 BOPD



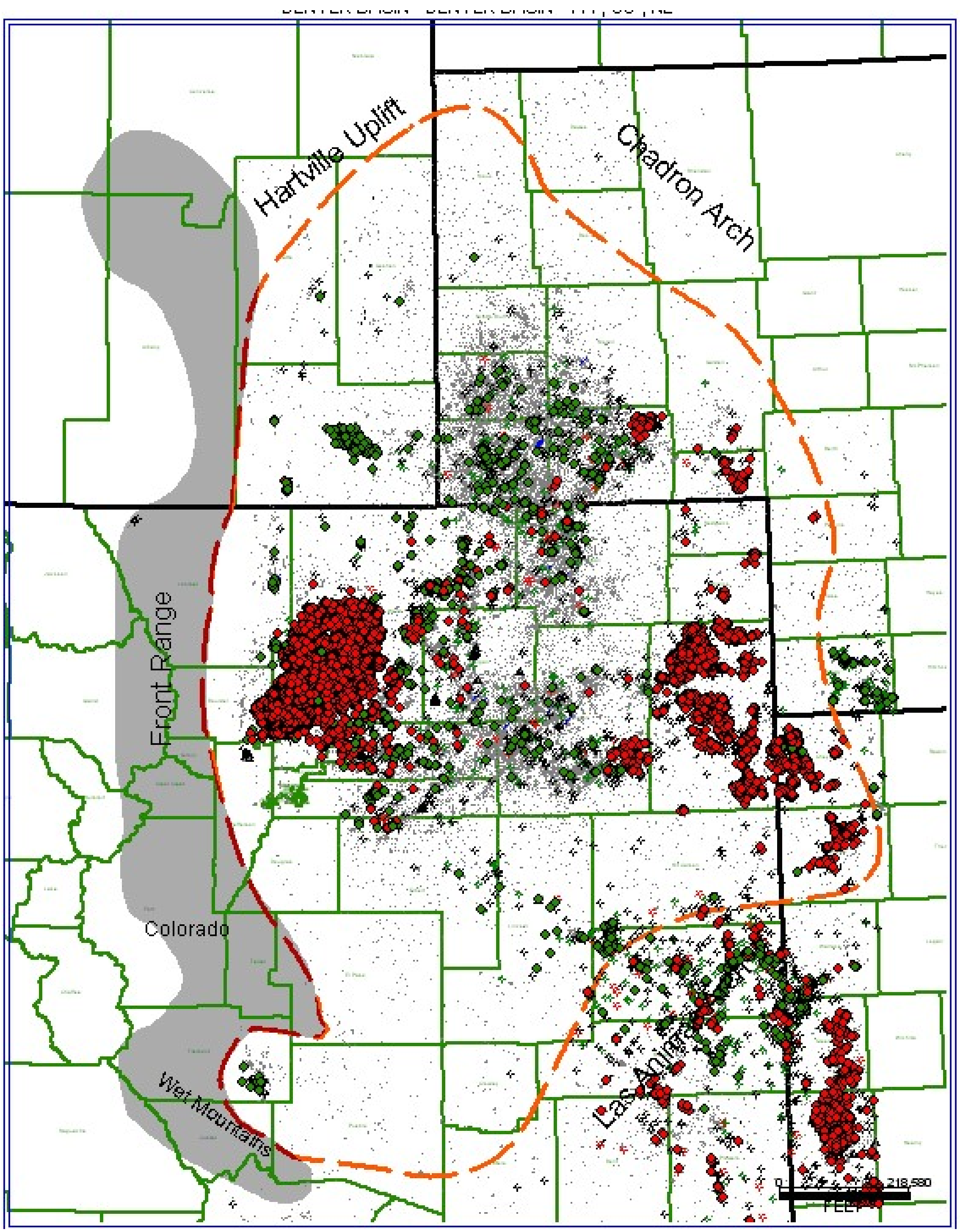
Wells 1850-1950



Wells 1850-1970

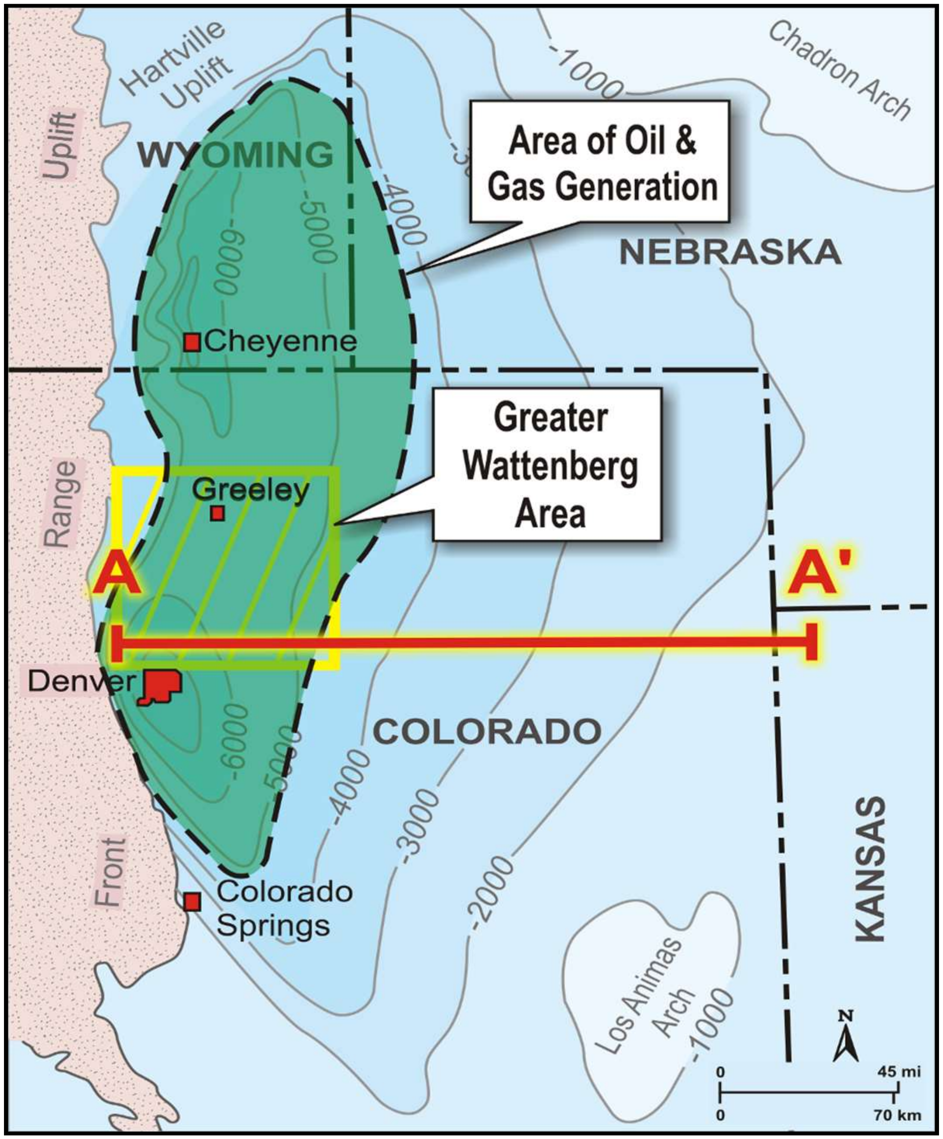


Wells 1850-1990



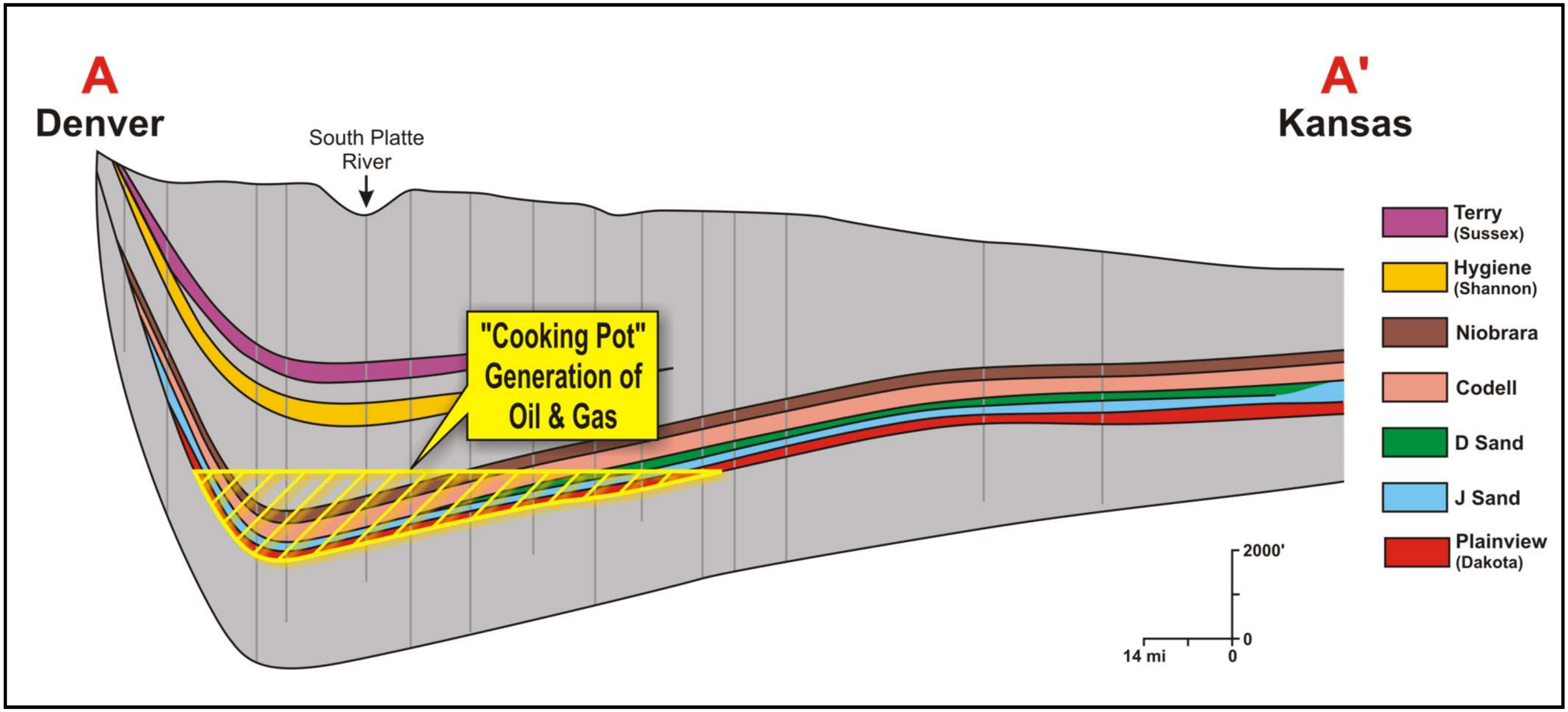
Wells 1990-2007

Deep Basin Petroleum Generation Structure Map (Top PC)

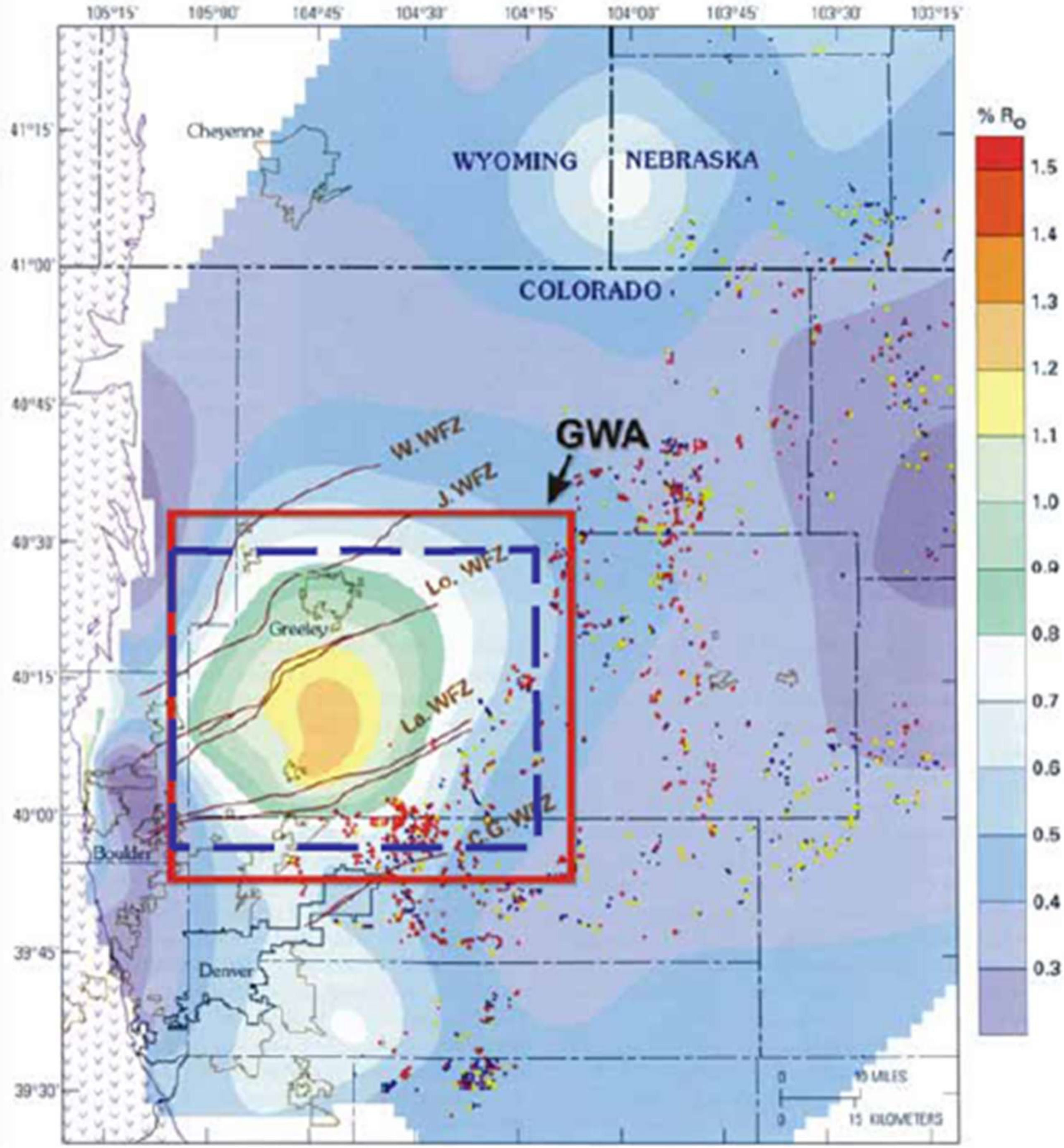


Weimer, 1996

Structural Cross Section of the Denver Basin



Weimer, 1996



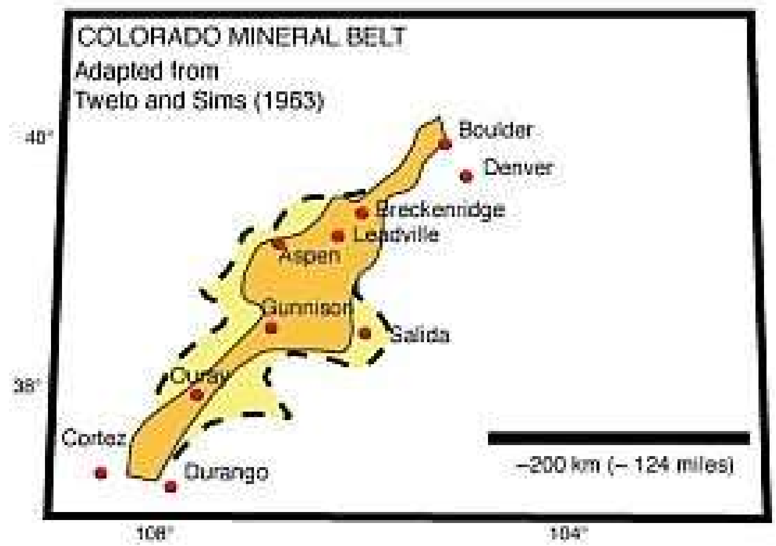
The Wattenberg Geothermal Anomaly

Vitrinite Reflectance Values, %Ro

Higley & Cox, 2005

Wattenberg Thermal Anomaly

- Related to igneous masses in basement (?)
- Located where CMB intersects Denver Basin
- Direct temperature measurements
- Ro values
- GORs



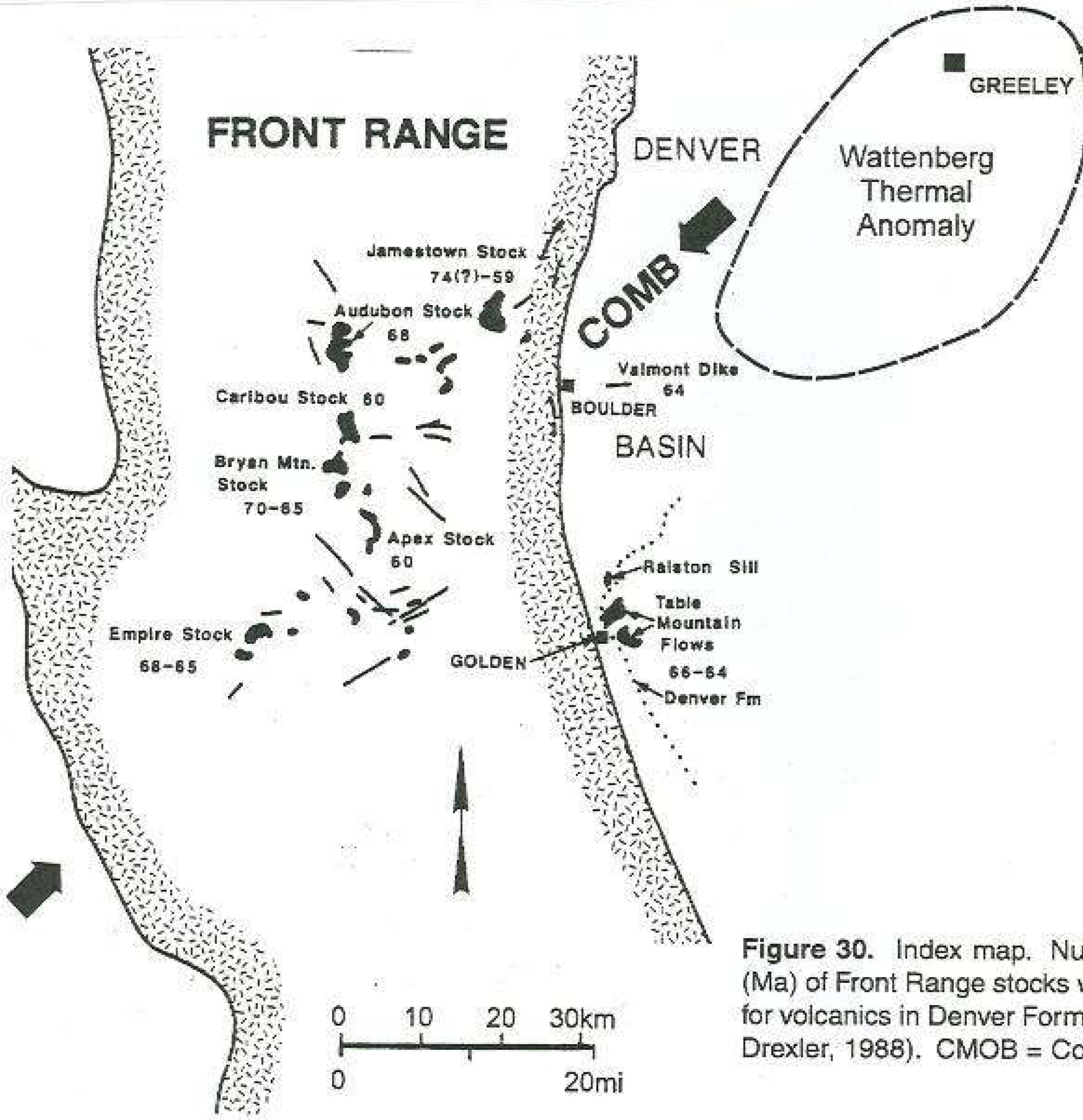


Figure 30. Index map. Numbers represent ages (Ma) of Front Range stocks which could be sources for volcanics in Denver Formation (from Larson and Drexler, 1988). CMOB = Colorado Mineral Belt.

Weimer, 1995

Wattenberg Thermal Anomaly

- Related to igneous masses in basement
- Located where CMD intersects Denver basin
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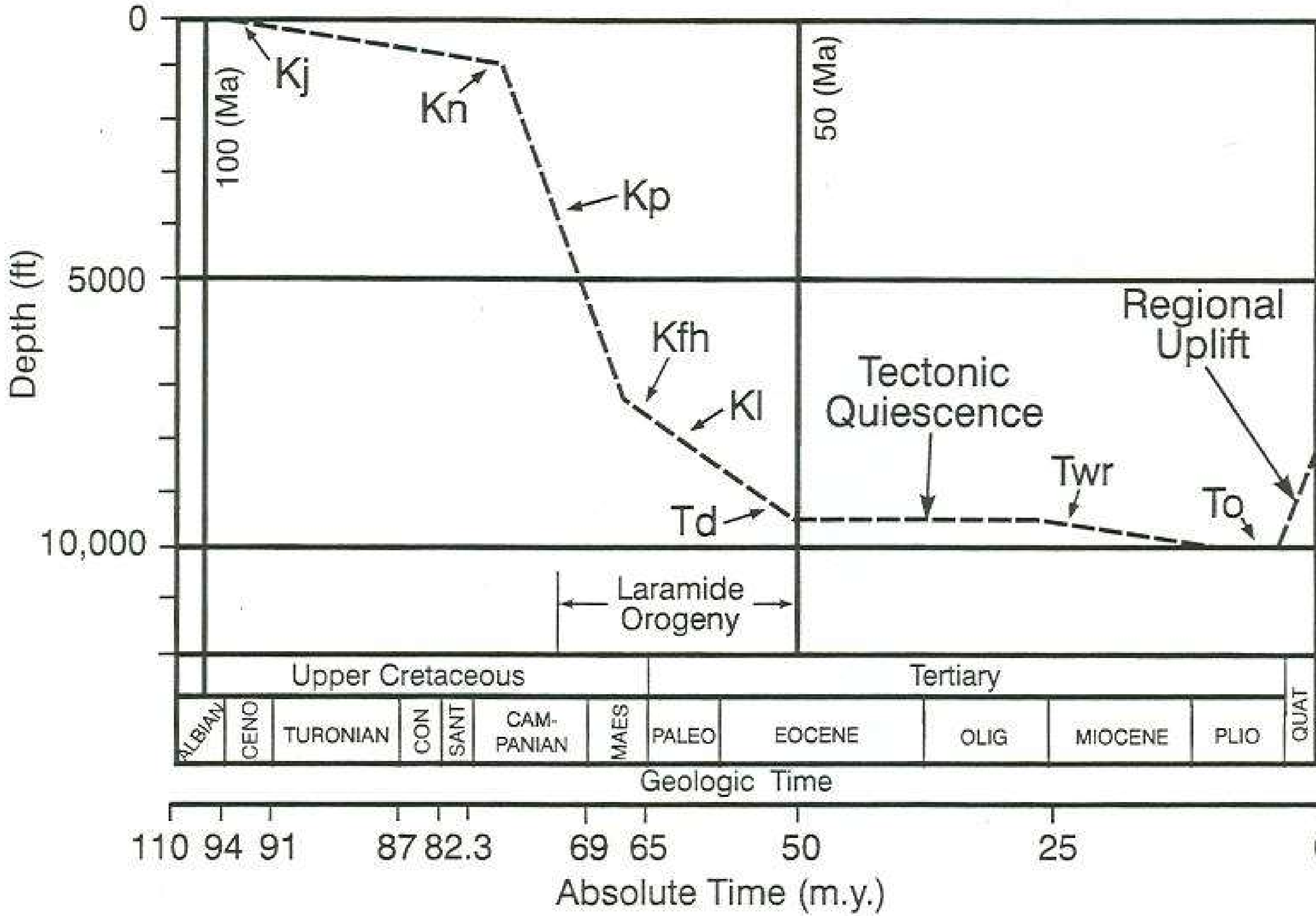
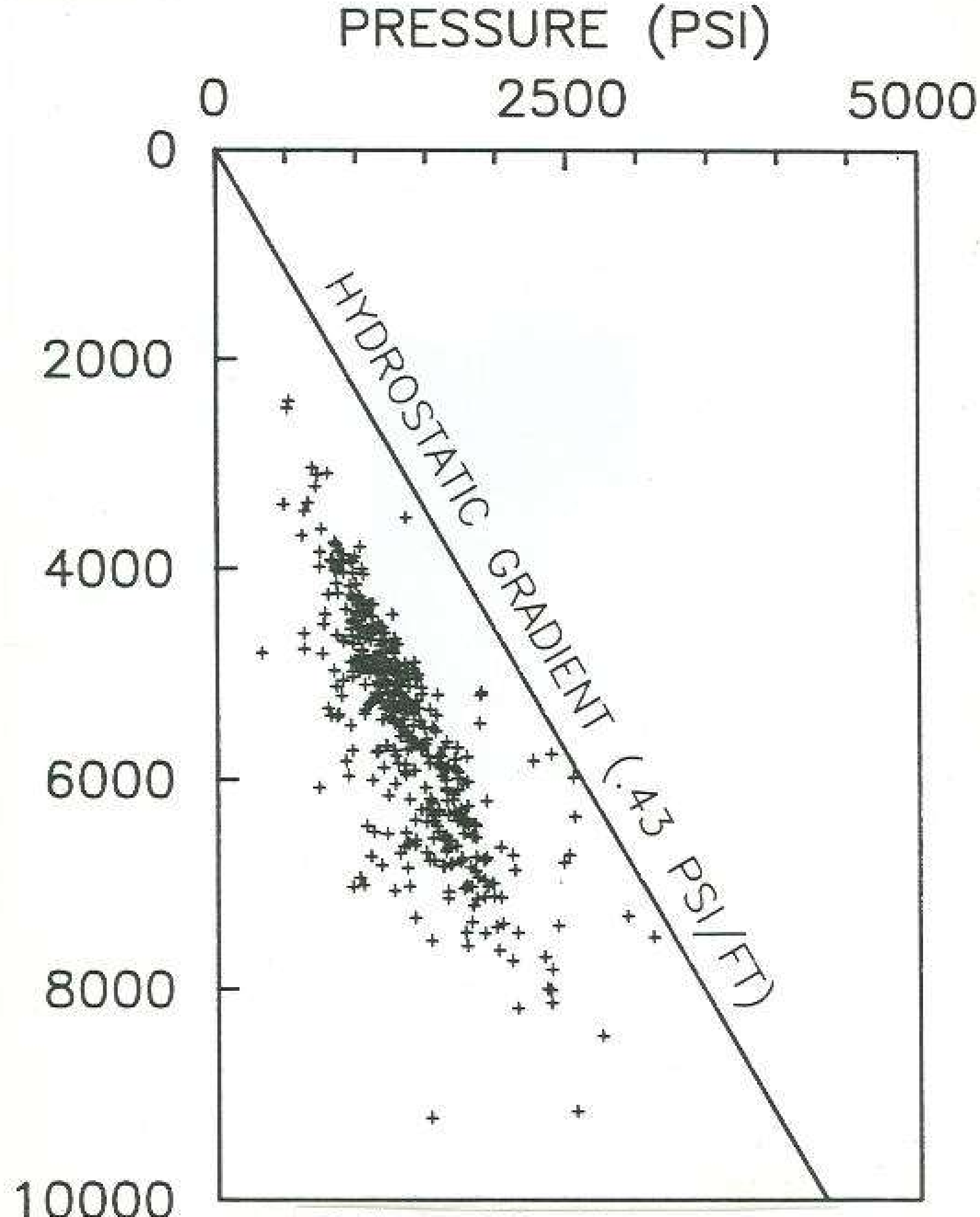
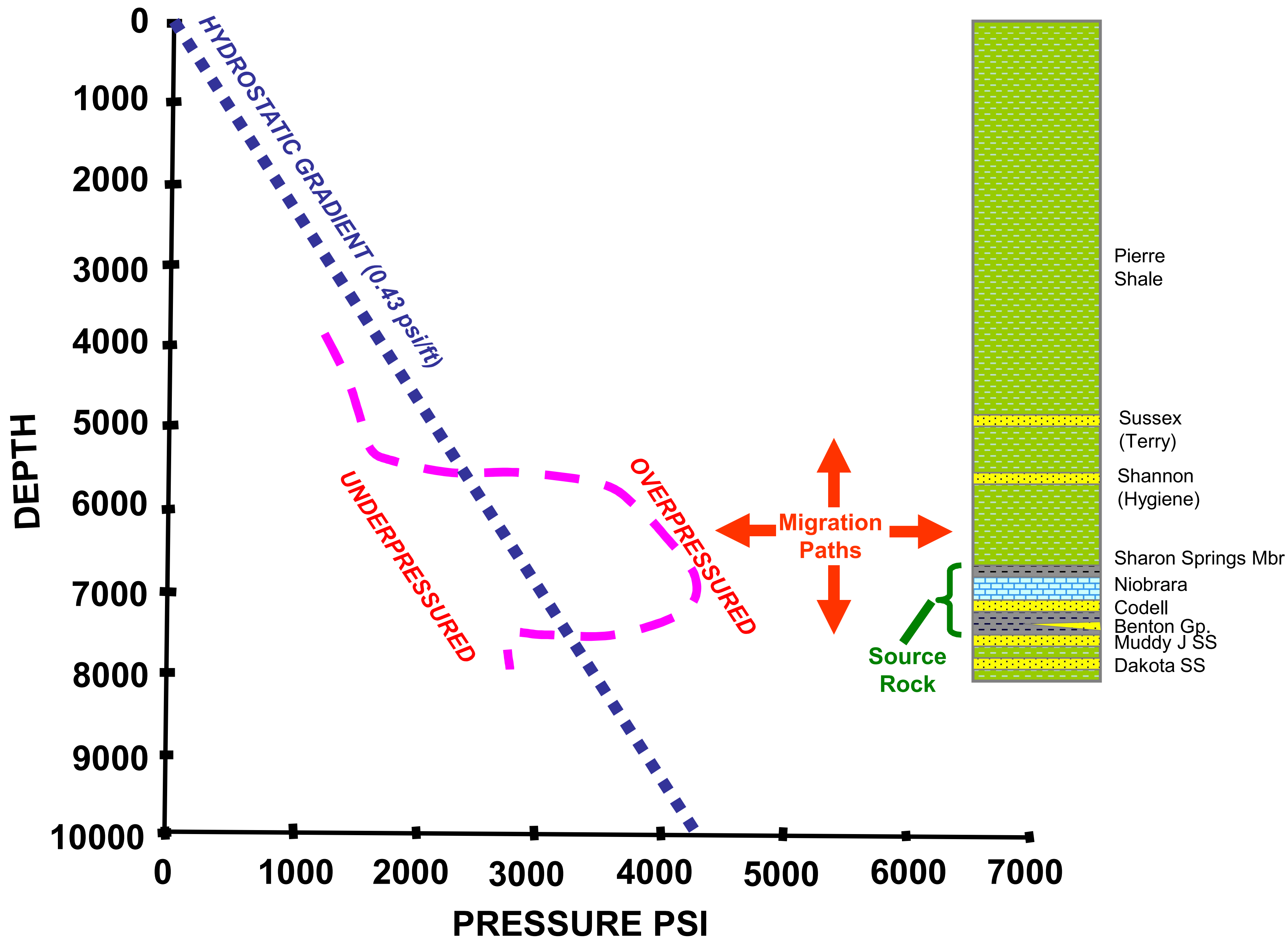


Subsidence profile Muddy (J) Sandstone

Weimer, 1995

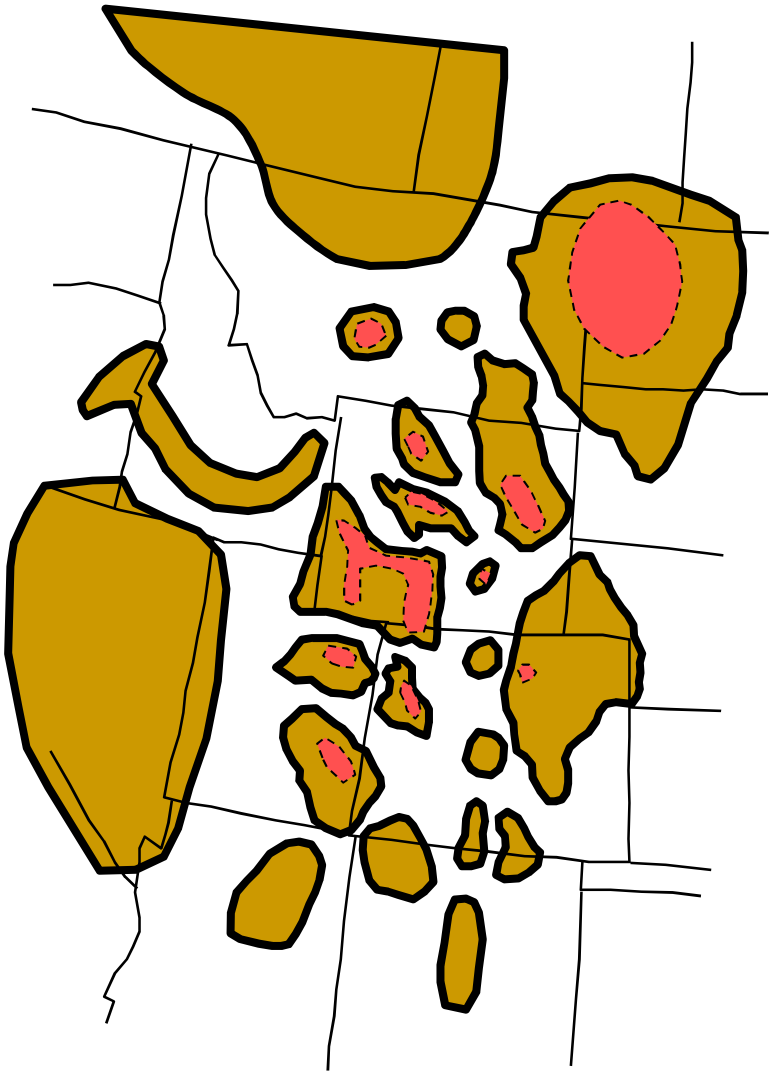


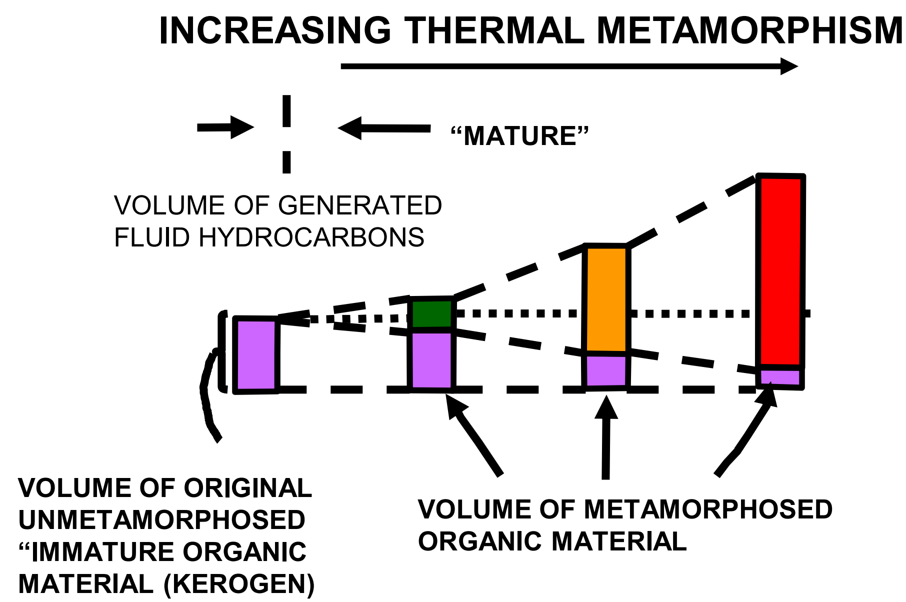
Belitz and Bredehoeft, 1988


DEPTH
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
HYDROSTATIC GRADIENT (0.43 psi/ft)
UNDERPRESSURED
OVERPRESSURED
Migration
Paths
Source
Rock
0
1000
2000
3000
4000
5000
6000
7000
PRESSURE PSI
Pierre
Shale
Sussex
(Terry)
Shannon
(Hygiene)
Sharon Springs Mbr
Niobrara
Codell
Benton Gp.
Muddy J SS
Dakota SS

Weimer, 1995

Overpressuring in Rockies Basins



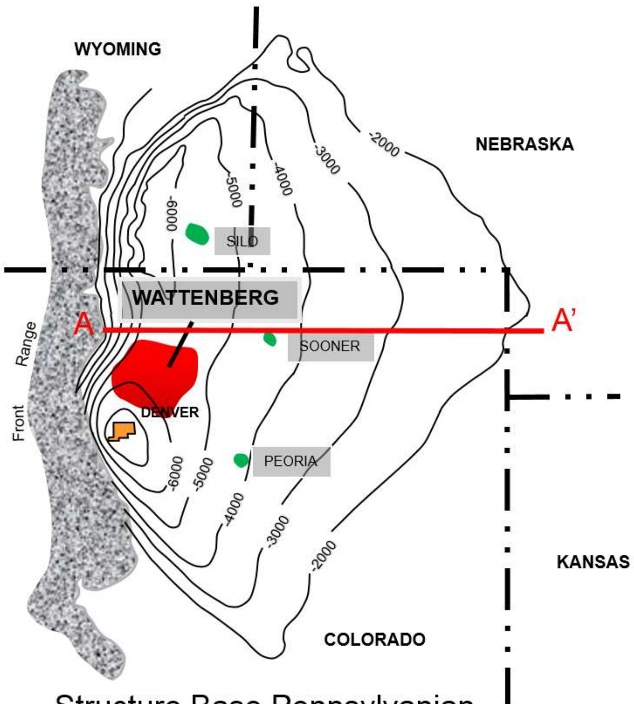


ASSUMES GENERATED HYDROCARBONS ARE RETAINED IN SYSTEM & CONVERT TO STABLE SPECIES

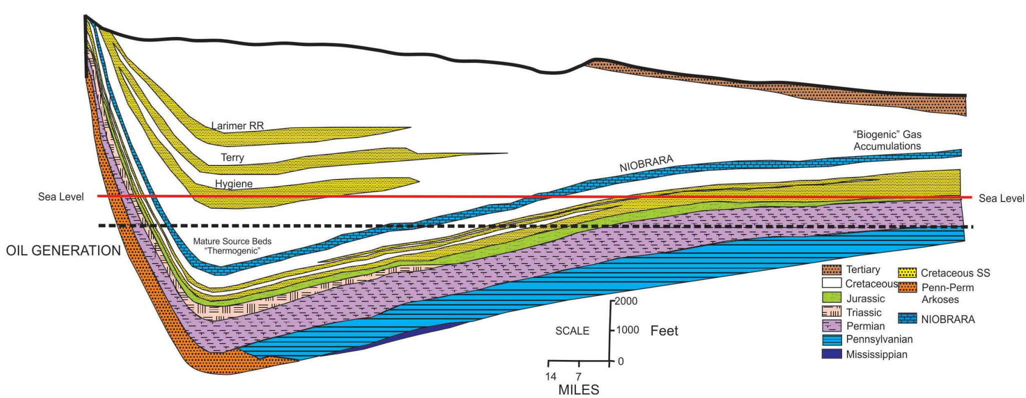
SAS, 04

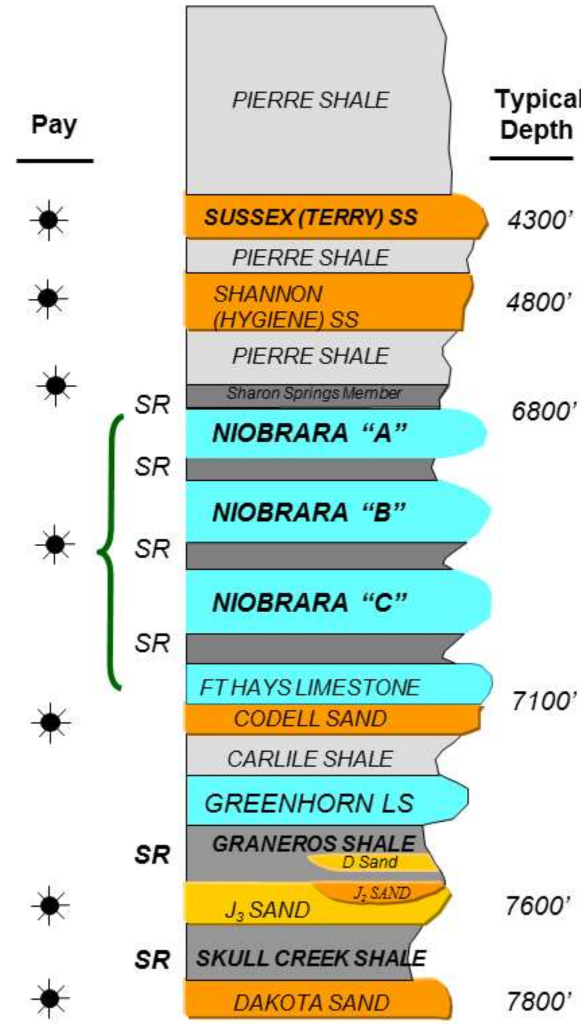
Modified from Spencer, 1987 and Meissner, 1980

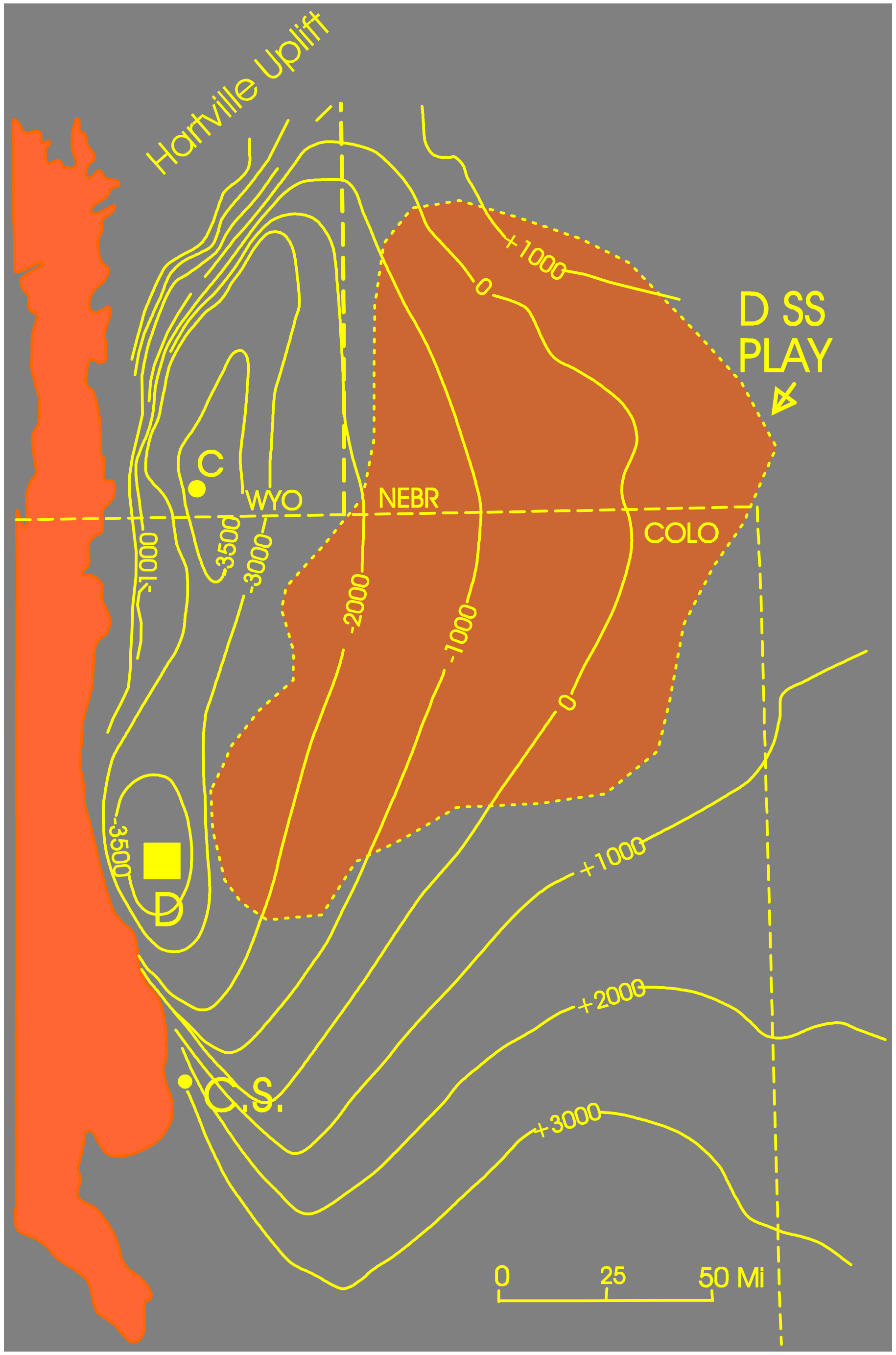
The D Sandstone



Structure Base Pennsylvanian
After Martin, 1965

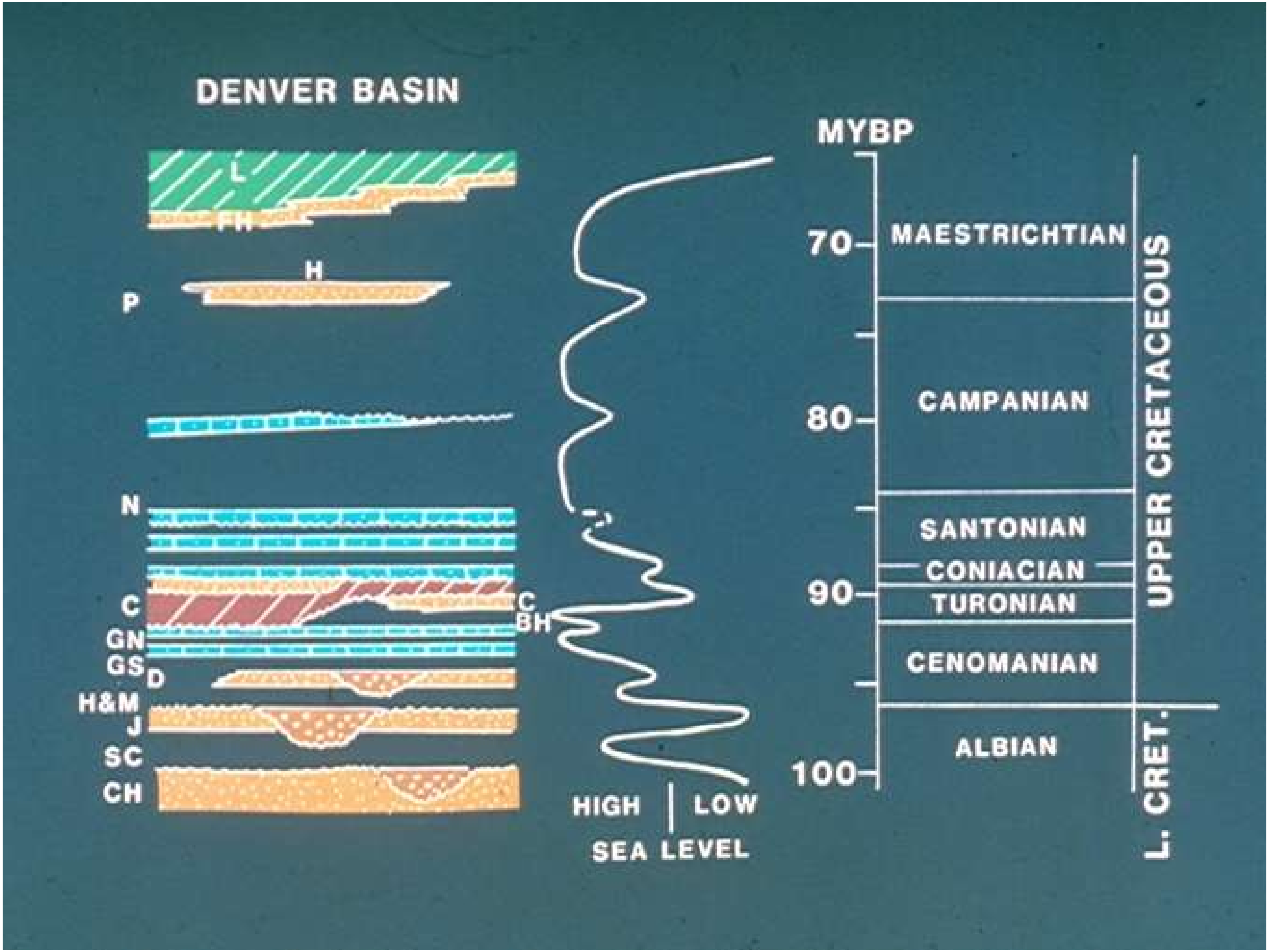


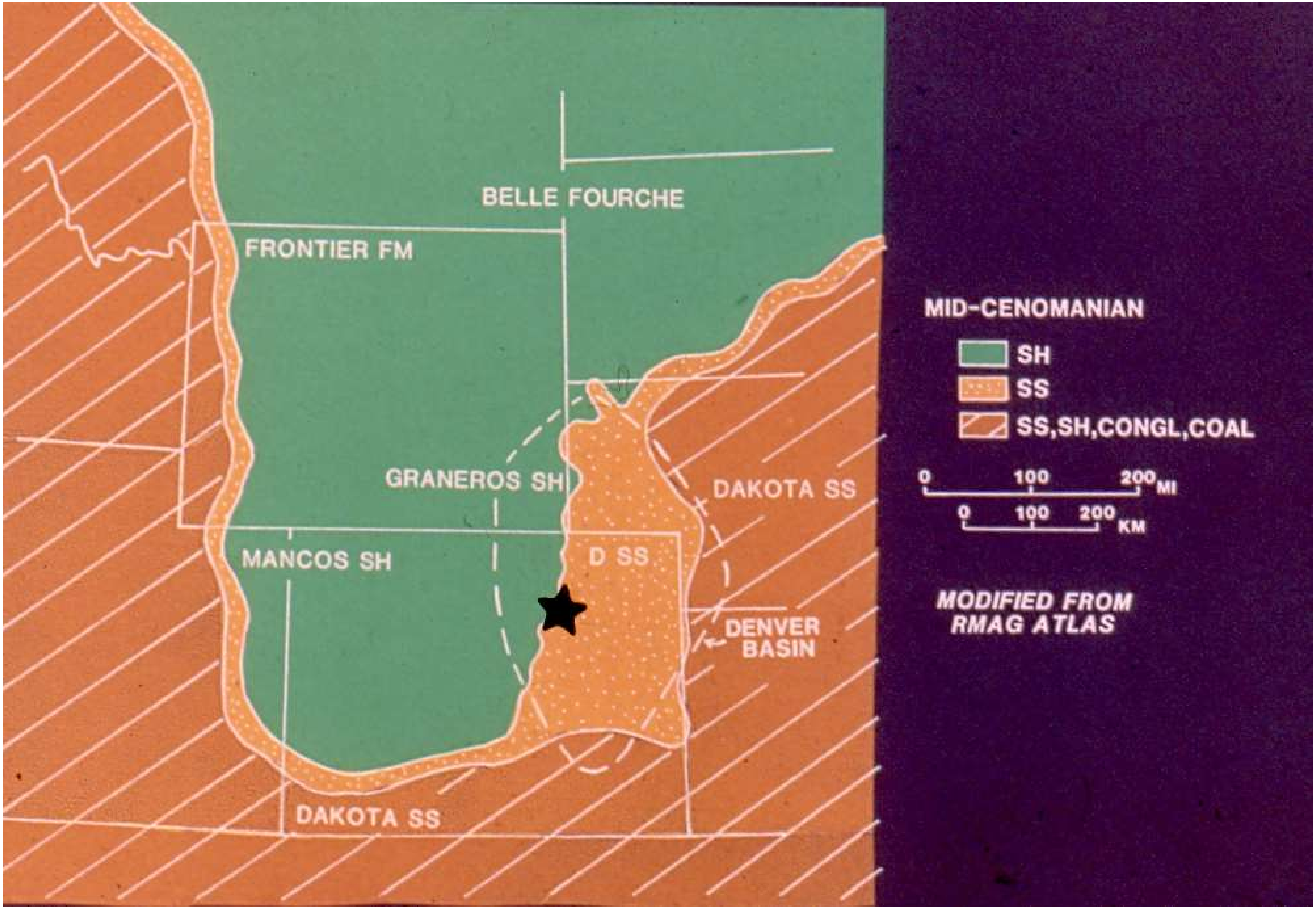


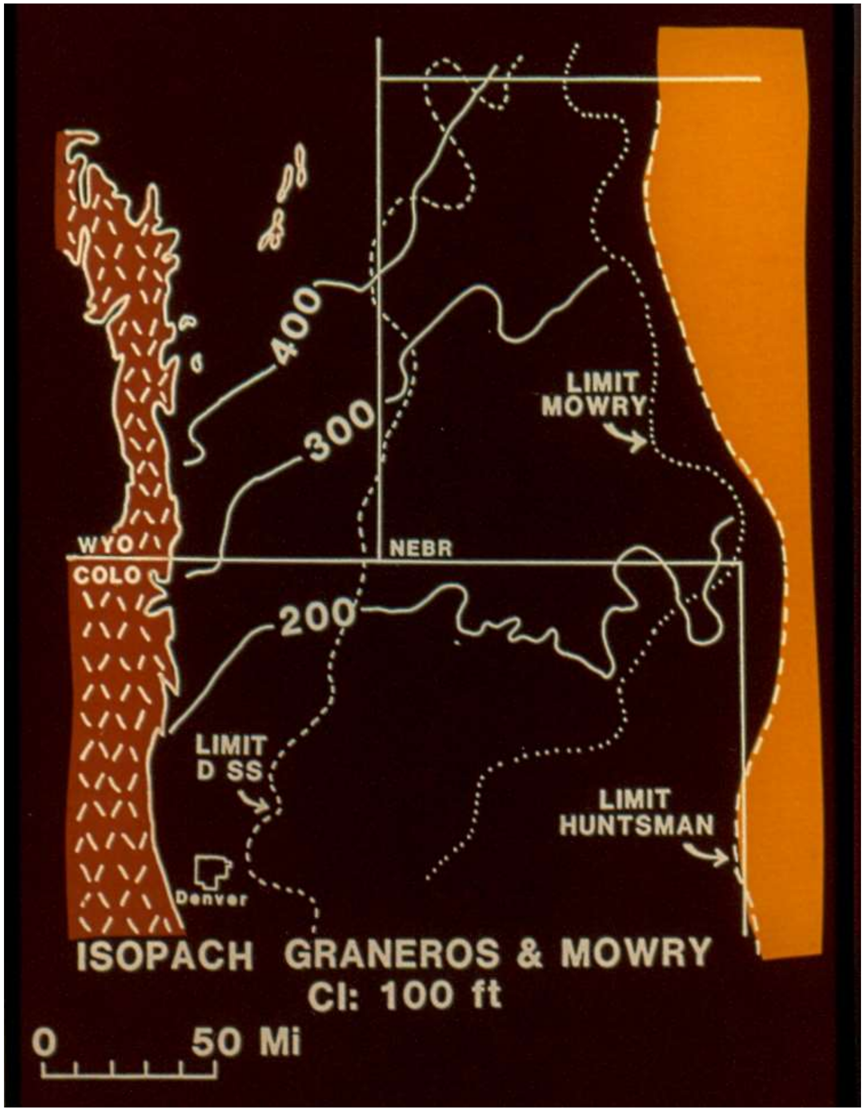


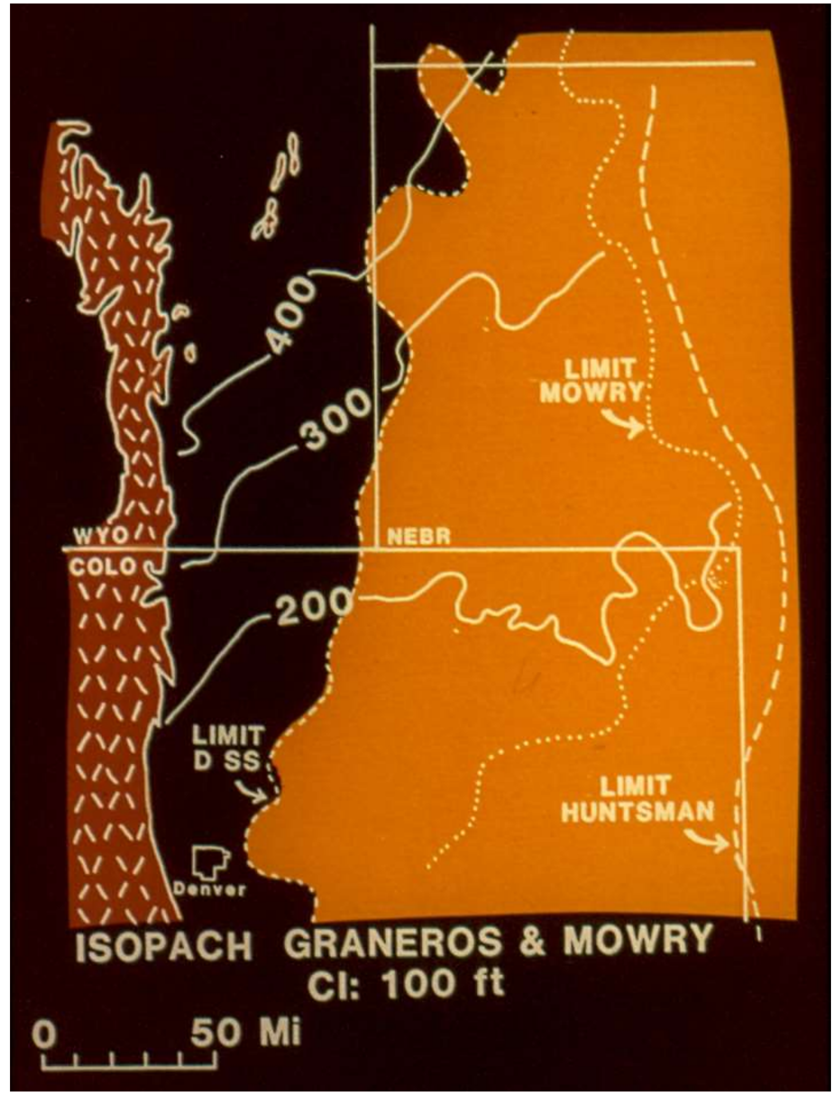
D SS PLAY

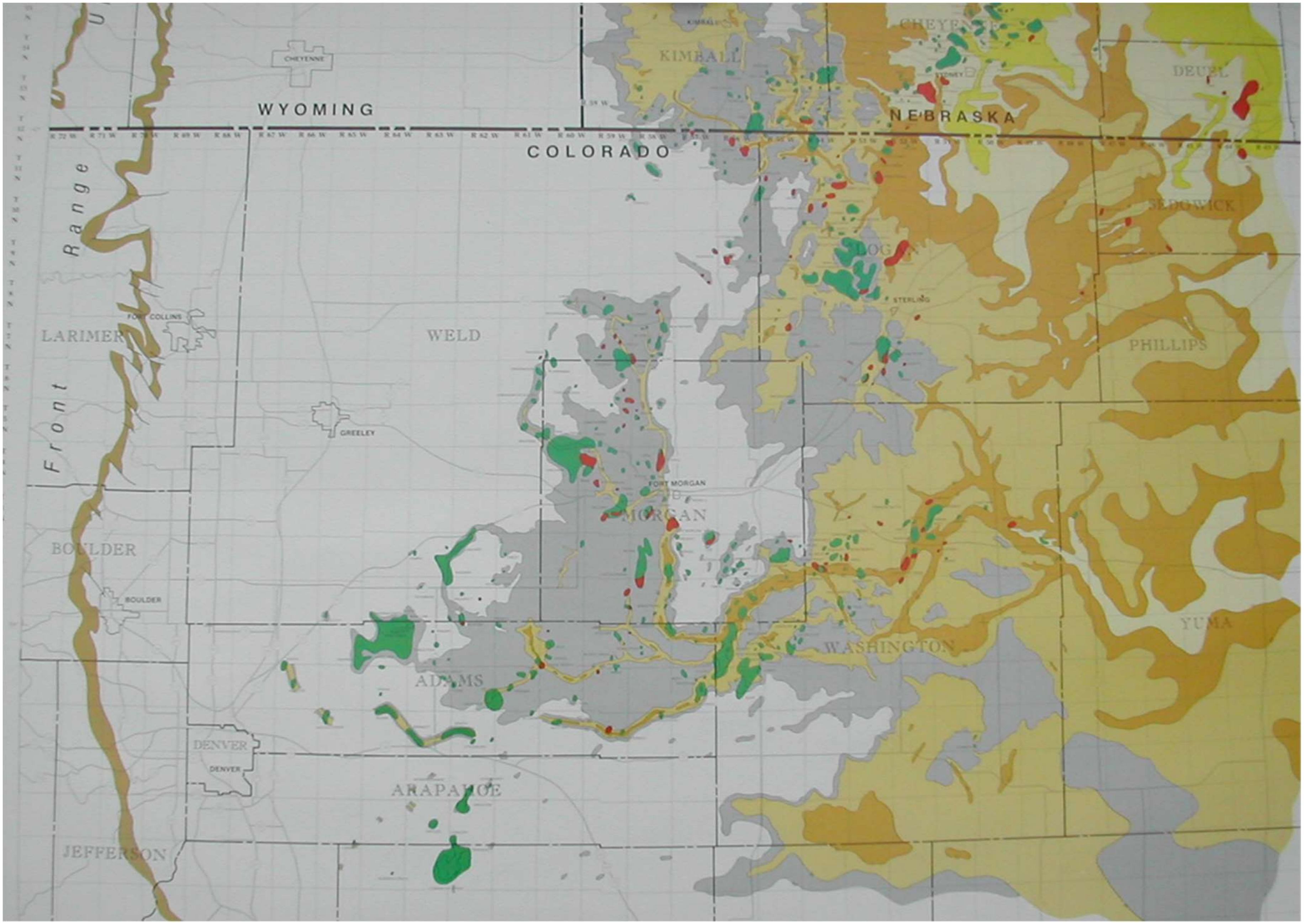
- Good reserves
- Shallow depth
- Low drilling costs
- Multiple pay areas
- Secondary recoveries


DENVER BASIN
L
FH
H
P
N
C
C
BH
GN
GS
D
H&M
J
SC
CH
HIGH
LOW
SEA LEVEL
MYBP
70
80
90
100
MAESTRICHTIAN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
CENOMANIAN
ALBIAN
UPPER CRETACEOUS
L. CRET.

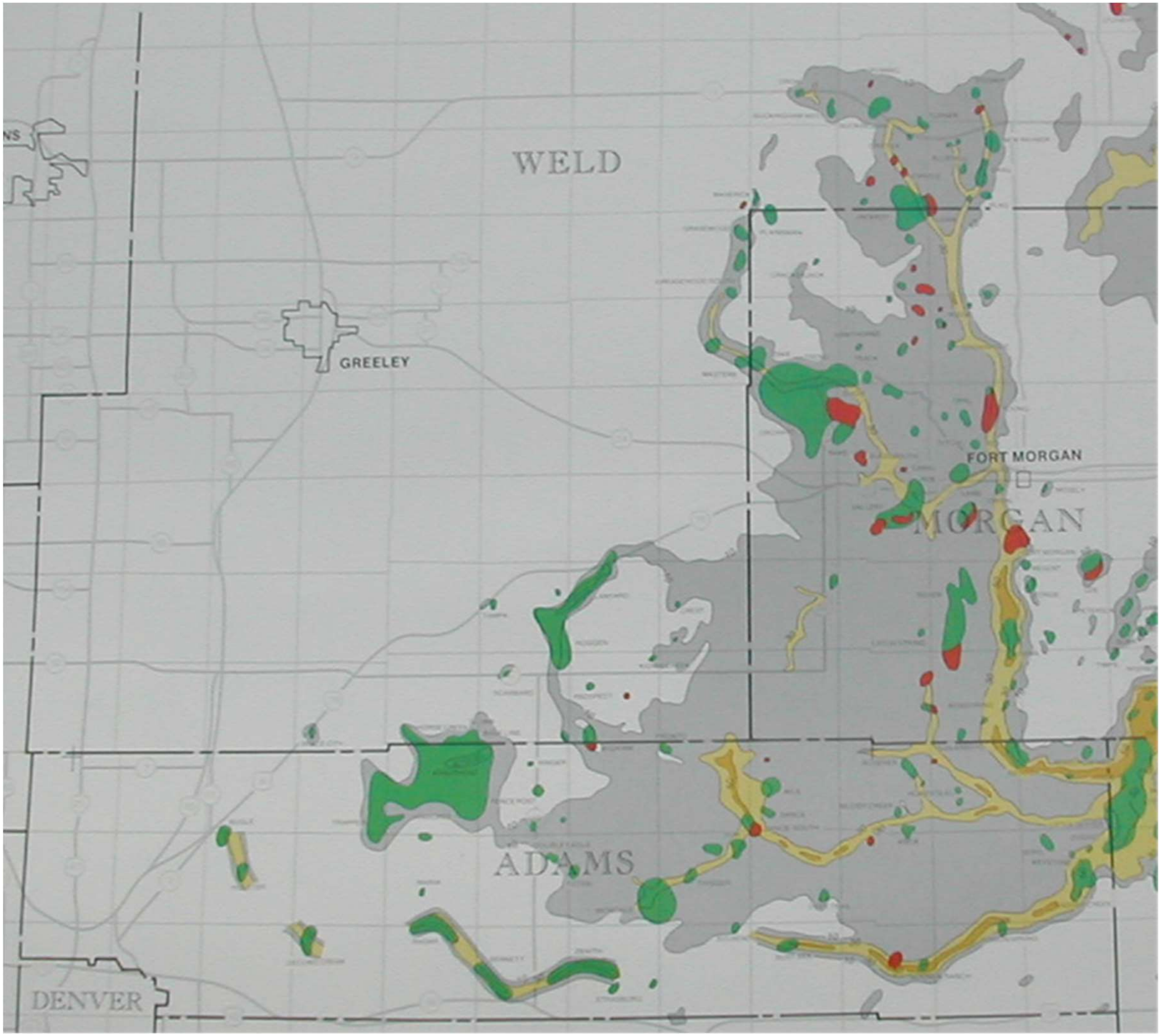

BELLE FOURCHE
FRONTIER FM
MID-CENOMANIAN
SH
SS
SS,SH,CONGL,COAL
0 100 200 MI
0 100 200 KM
GRANEROS SH
DAKOTA SS
MANCOS SH
D SS
DENVER BASIN
MODIFIED FROM RMAG ATLAS
DAKOTA SS


400
300
200
LIMIT MOWRY
WYO
COLO
NEBR
LIMIT D SS
LIMIT HUNTSMAN
Denver
ISOPACH GRANEROS & MOWRY
CI: 100 ft
0 50 Mi


400
300
200
LIMIT MOWRY
WYO
COLO
NEBR
LIMIT D SS
LIMIT HUNTSMAN
Denver
ISOPACH GRANEROS & MOWRY
CI: 100 ft
0 50 Mi

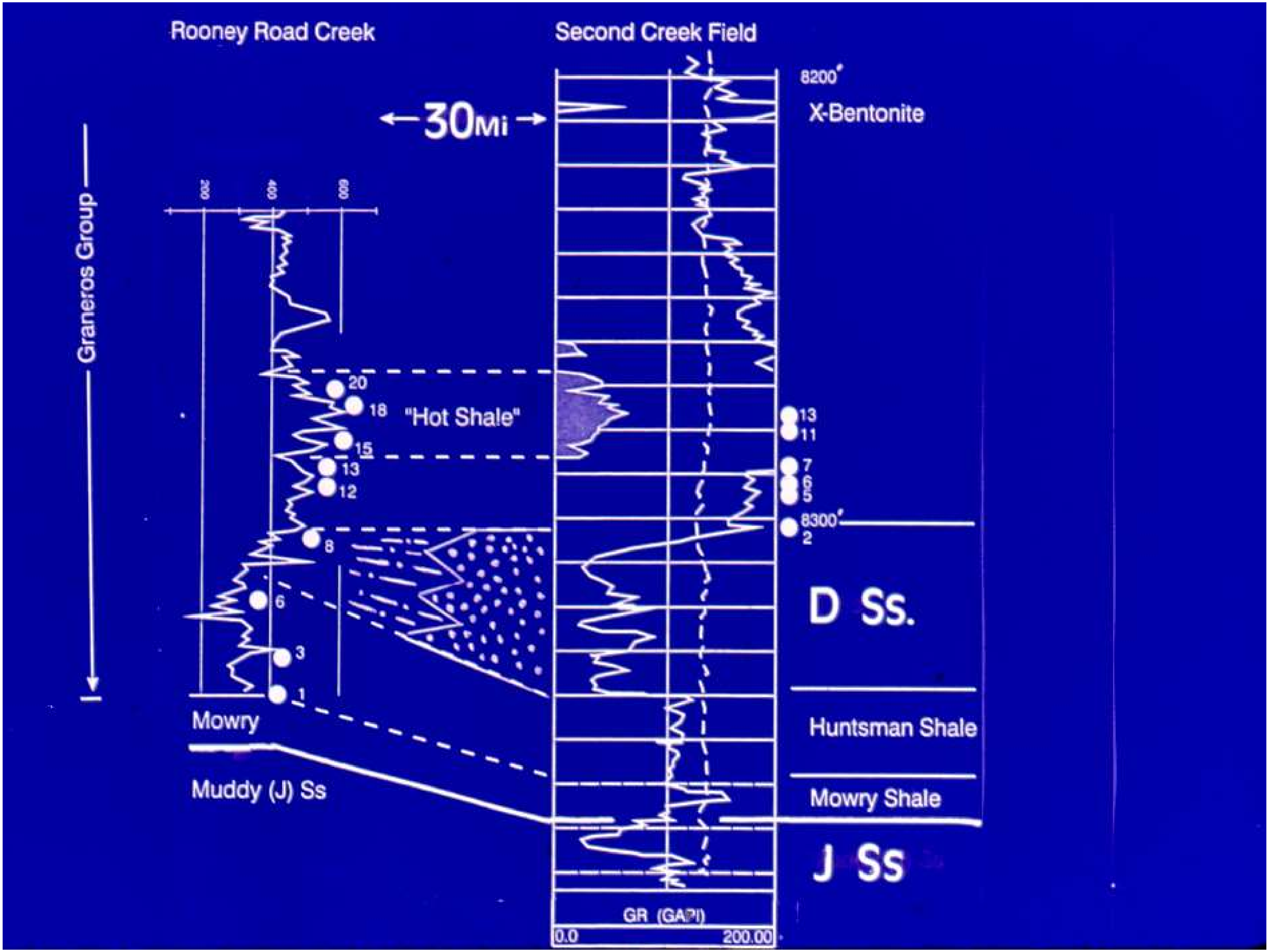


WYOMING
NEBRASKA
COLORADO
CHEYENNE
KIMBALL
DEUEL
SEDGWICK
LOGAN
STERLING
PHILLIPS
LARIMER
FORT COLLINS
WELD
GREELEY
Front Range
FORT MORGAN
MORGAN
BOULDER
ADAMS
WASHINGTON
YUMA
DENVER
ARAPAHOE
JEFFERSON


WELD
GREELEY
FORT MORGAN
MORGAN
ADAMS
DENVER

Graneros-D(!) Petroleum System

- Reservoirs: D Sandstone
- Source Beds: Graneros
- Seals: Graneros, Huntsman, tight D laterally
- Carrier Beds: D, fracture systems
- Migration: downward into D



Rooney Road Creek
Second Creek Field
30Mi
8200'
X-Bentonite
Graneros Group
200
400
600
20
18
"Hot Shale"
15
13
12
8
6
3
1
13
11
7
6
5
8300'
2
D Ss.
Huntsman Shale
Mowry Shale
J Ss
Mowry
Muddy (J) Ss
GR (GAPI)
0.0
200.00

Table 1. Rooney Road, Graneros Shale Section; organic geochemistry analyses (from Pietraszek-Mattner, 1995).

Sample	Location (ft.)	Tmax Deg C	TOC wt%	S1 mg/g	S2 mg/g	S3 mg/g	HI	OI	Reactive Carbon	Transformation Ratio	Facies
AMC 20	70	426	4.61	0.3	24.13	0.5	523	11	53	0.01	
AMC 18	68	428	5.26	0.41	28.92	0.14	550	3	55.8	0.01	C
AMC 15	61	419	4.62	0.2	11.75	1.13	254	24	25.9	0.02	
AMC 13	53	429	3.36	0.12	8.46	1.82	252	54	25.5	0.01	
AMC 12	50	428	2.81	0.08	6.29	1.02	22	36	22.7	0.01	B
AMC 8	39	423	2.84	0.11	4.82	0.61	170	21	17.4	0.02	
AMC 6	24	429	1.53	0.05	0.35	1.1	23	72	2.6	0.13	
AMC 3	9	424	0.95	0.05	0.25	0.92	26	97	3.2	0.17	A
AMC 1	0	428	2.13	0.08	1.44	1.07	68	50	7.1	0.05	

From Pietraszek-Mattner, 1995.

TOC = Total Organic (wt%); S1 = Free Hydrocarbons (mg/g); S2 = Pyrolyzable Hydrocarbons (mg/g);
S3 = CO2 released during pyrolysis (mg/g); HI = Hydrogen index = [(S2/%TOC) x 100]; OI = Oxygen Index = [(S3/%TOC) x 100];
Reactive Carbon = [10 x (S1+S2)/%TOC]; Transformation Ratio = S1/(S1+S2)

Table 2. Bass Box Elder Farm 6-32 Graneros core (SW SE Sec. 6, T. 3 S., R. 65 W.; organic geochemistry analyses (from Pietraszek-Mattner, 1995).

Sample	Core Depth	Log Depth	Tmax Deg. C	TOC wt%	S1 mg/g	S2 mg/g	S3 mg/g	HI	OI	Reactive Carbon	Transformation Ratio	Facies
BEF 13	8285	8277	445	4.42	2.7	10.46	0.15	237	3	29.8	0.21	C
BEF 11	8288	8280	441	3.77	2.44	8.99	0.15	238	4	30.3	0.21	
BEF 7	8296	8288	447	2.93	1.74	5.61	0.19	191	6	25.1	0.24	
BEF 6	8299.5	8291.5	447	3.13	1.94	6.68	0.15	213	5	27.5	0.23	B
BEF 5	8302	8294	448	2.05	1.06	3.08	0.06	150	3	20.2	0.26	
BEF 2	8309.5	8301.5	451	1.28	0.3	1.82	0.09	64	7	8.8	0.14	A

From Pietraszek-Mattner, 1995.

TOC = Total Organic (wt%); S1 = Free Hydrocarbons (mg/g); S2 = Pyrolyzable Hydrocarbons (mg/g);
S3 = CO2 released during pyrolysis (mg/g); HI = Hydrogen index = [(S2/%TOC) x 100]; OI = Oxygen Index = [(S3/%TOC) x 100];
Reactive Carbon = [10 x (S1+S2)/%TOC]; Transformation Ratio = S1/(S1+S2)

Weimer, 1995

Tectonics & Sedimentation

- Fault movement controlled location of valleys
  - 90^{o} turns in valley
  - anomalous thickness of D-Huntsman
  - 2-D & 3-D seismic
- Structural Inversion

Seals and Traps

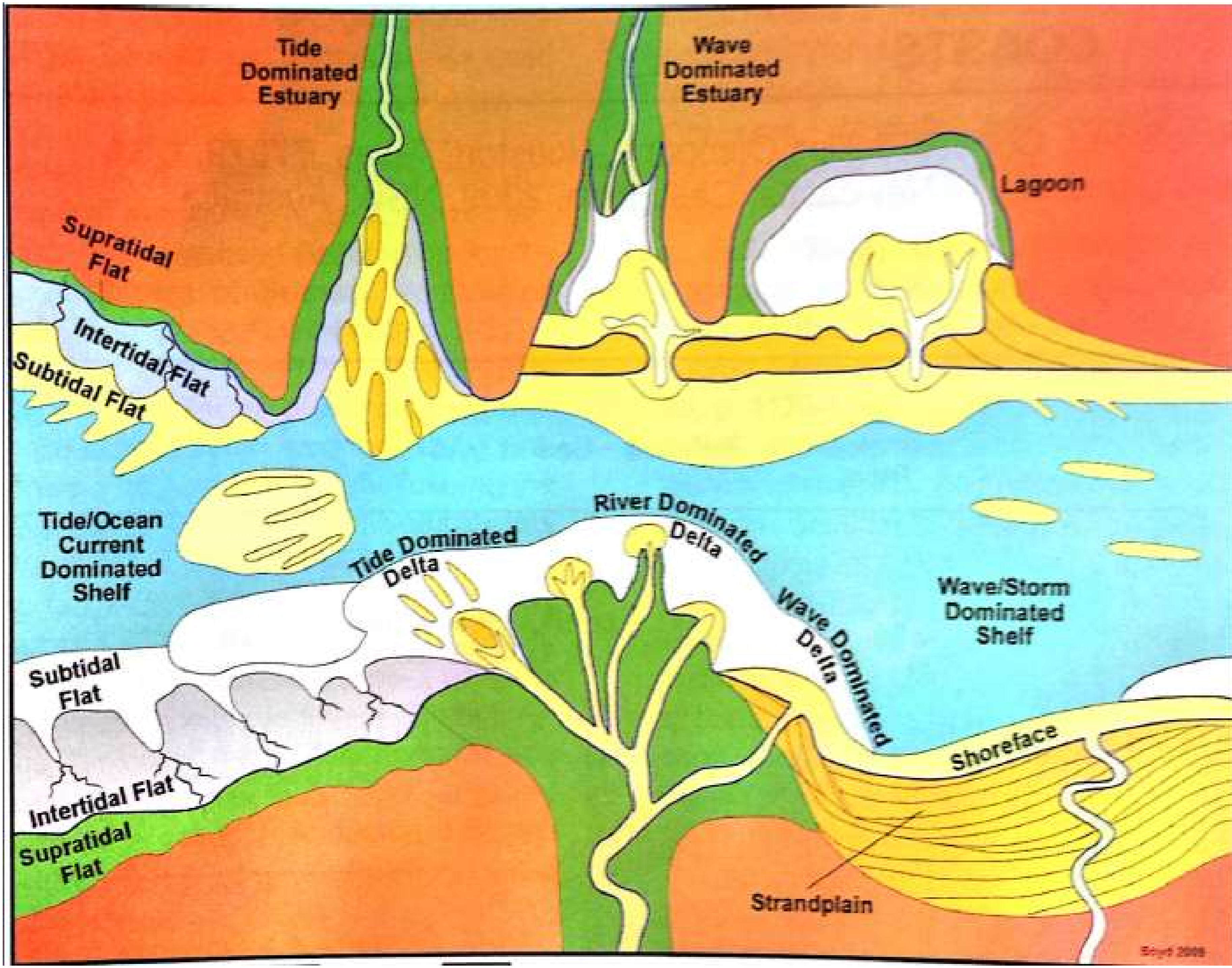
- Facies changes (capillarity)
- Faults
- Clay plugs within channel sandstones
- Diagenesis
- Unconformities
- Anticlines, noses, etc.
- Combination

D Sweet Spots

- EOD
  - Valley fills, distributary channels, transgressive marine ss
- Fracturing
  - Related to folding, faulting, regional stress field

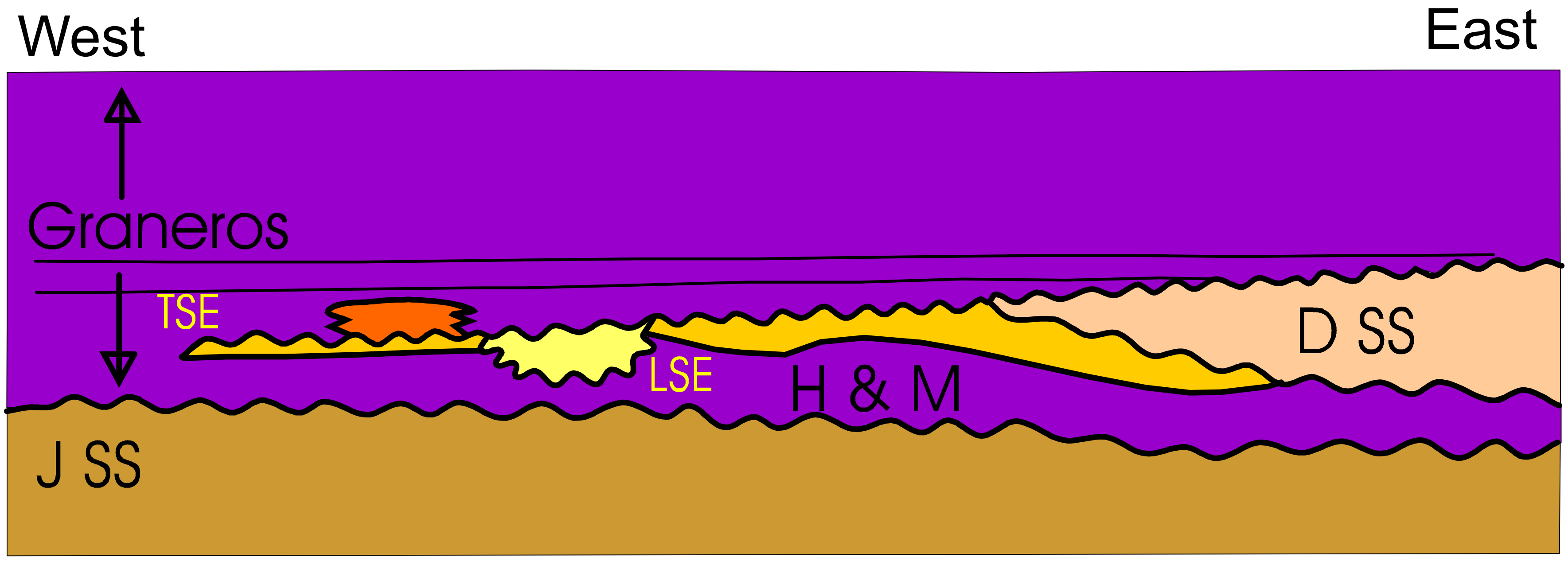
D Production

- Valley fills
- Low-stand deltaic
- Transgressive Marine
- Regional regressive



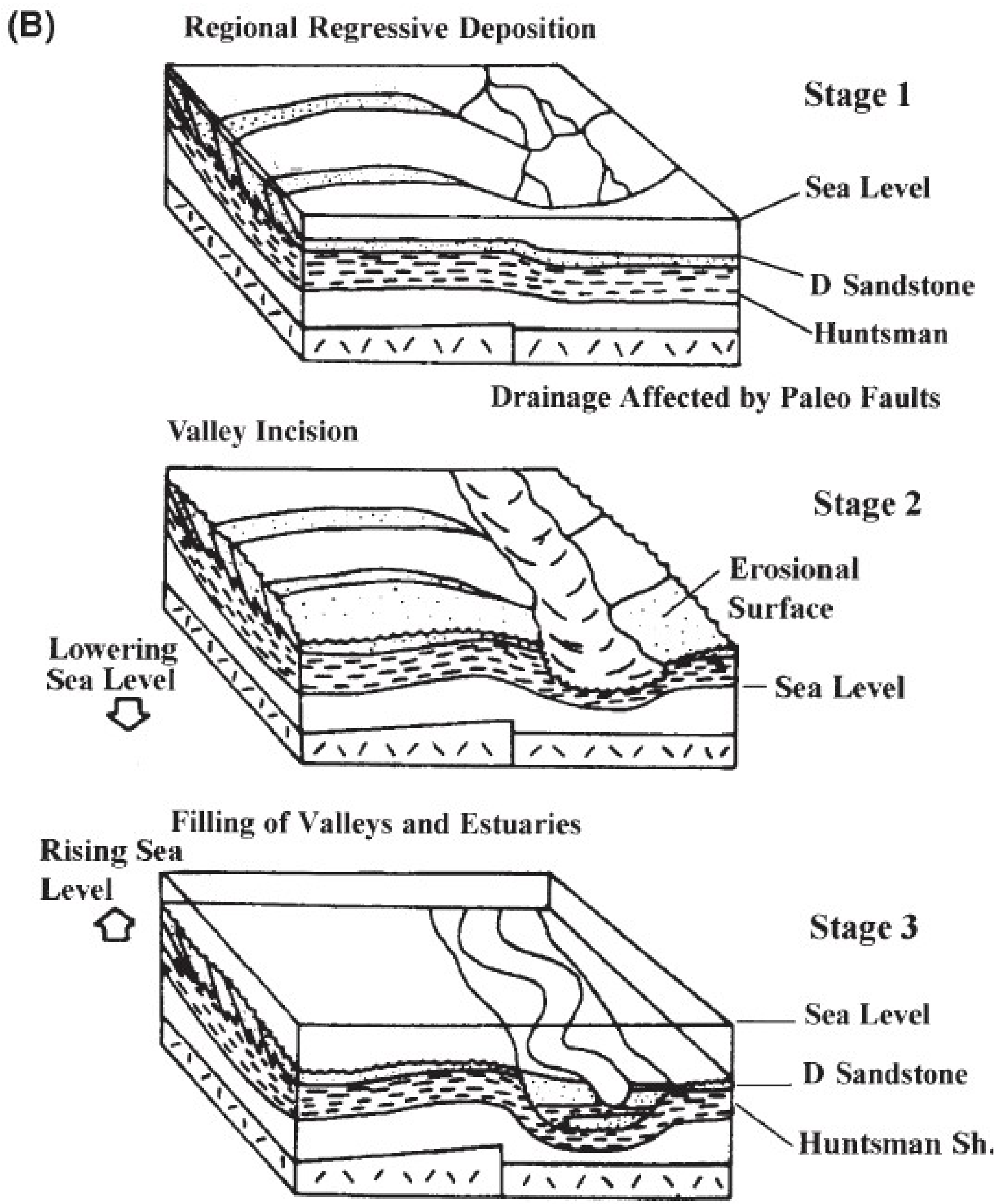
Tide Dominated Estuary
Wave Dominated Estuary
Lagoon
Supratidal Flat
Intertidal Flat
Subtidal Flat
Tide/Ocean Current Dominated Shelf
River Dominated Delta
Tide Dominated Delta
Wave Dominated Delta
Wave/Storm Dominated Shelf
Subtidal Flat
Intertidal Flat
Supratidal Flat
Shoreface
Strandplain

D Sandstone Sequence Stratigraphy

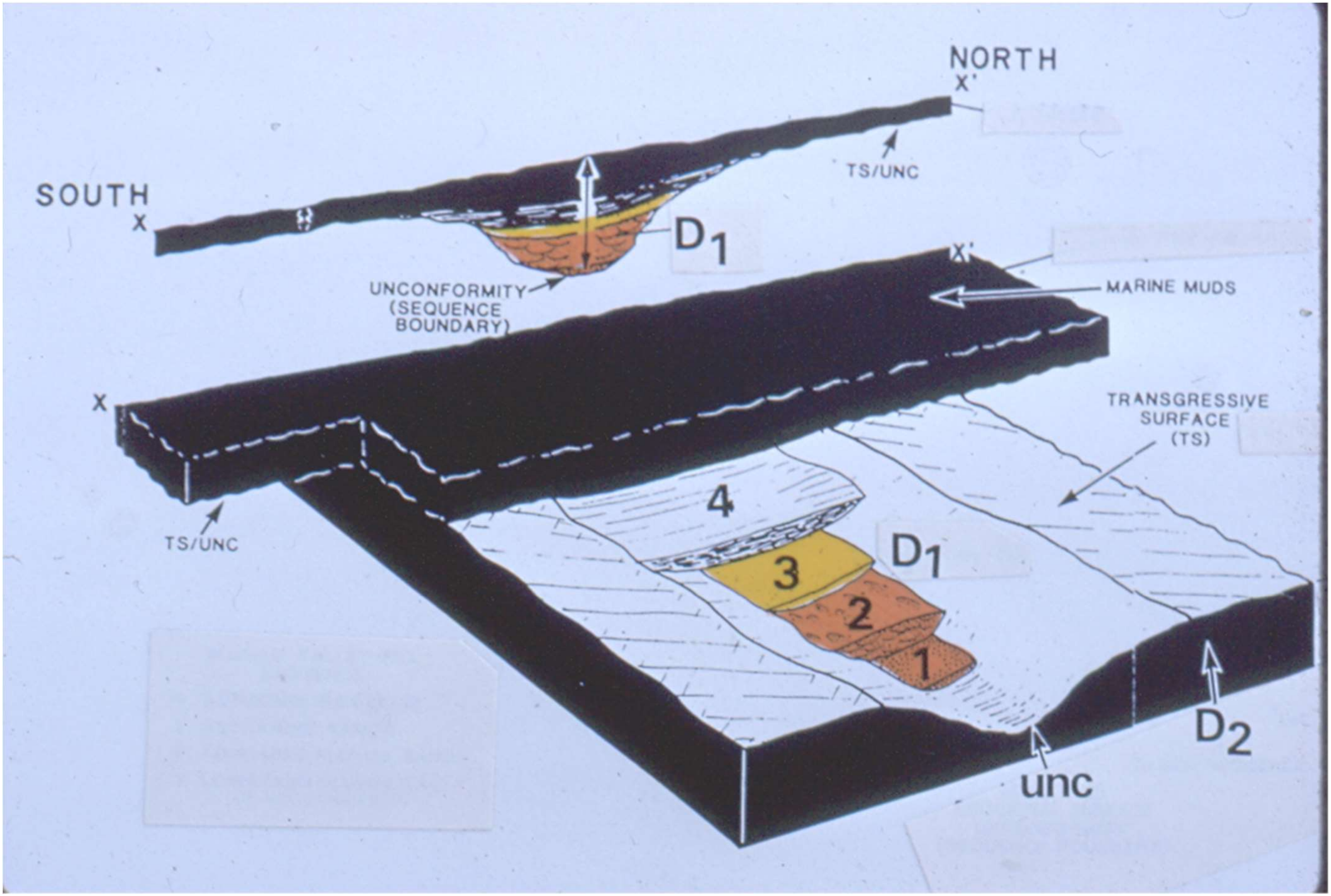


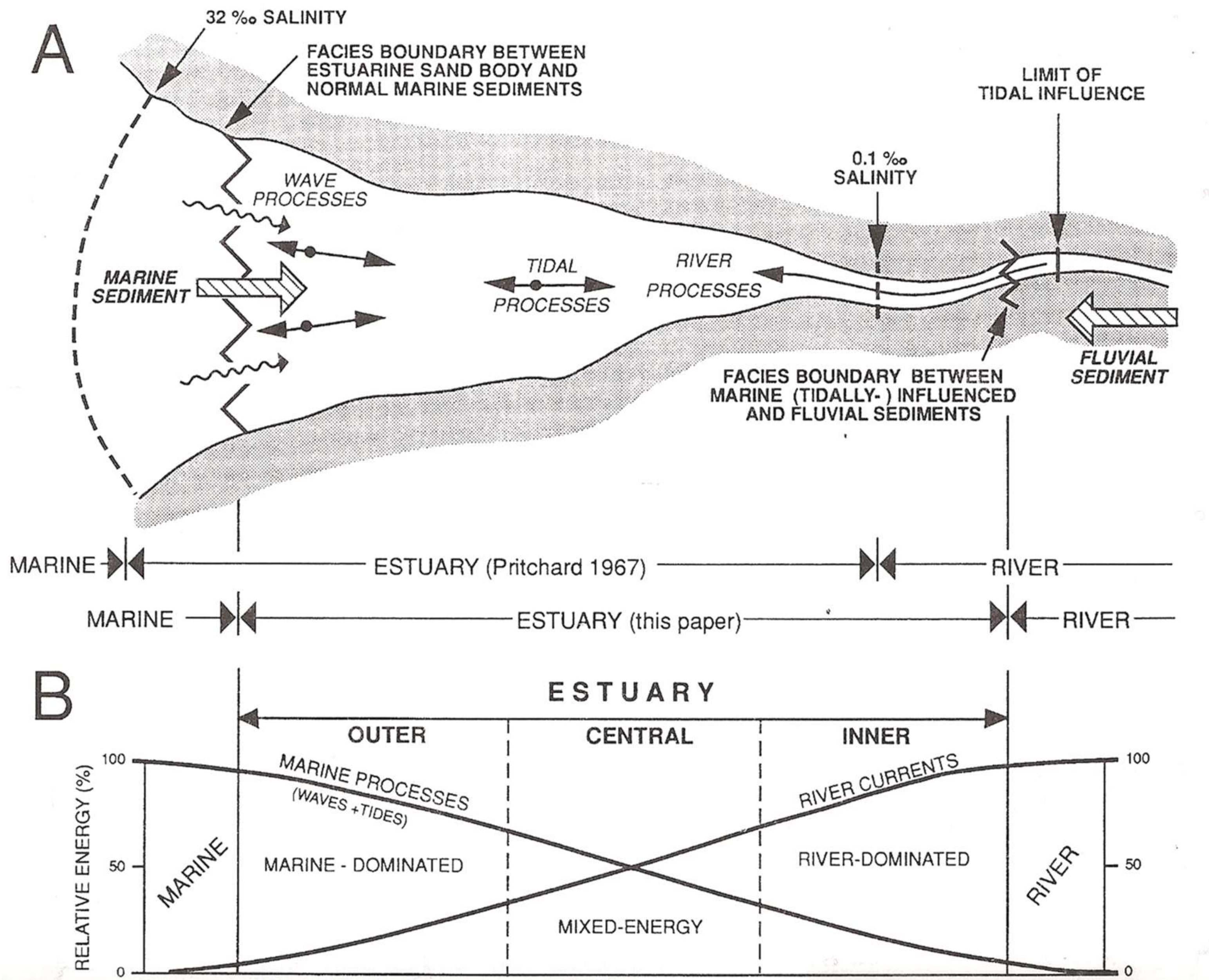
D Valley Fills

- Regional incisement into Huntsman
- 1/4 to 1/2 mi wide
- 30 to 50 ft thick
- Fluvial to estuarine
- Examples: Zenith, Sooner, Lanyard fields

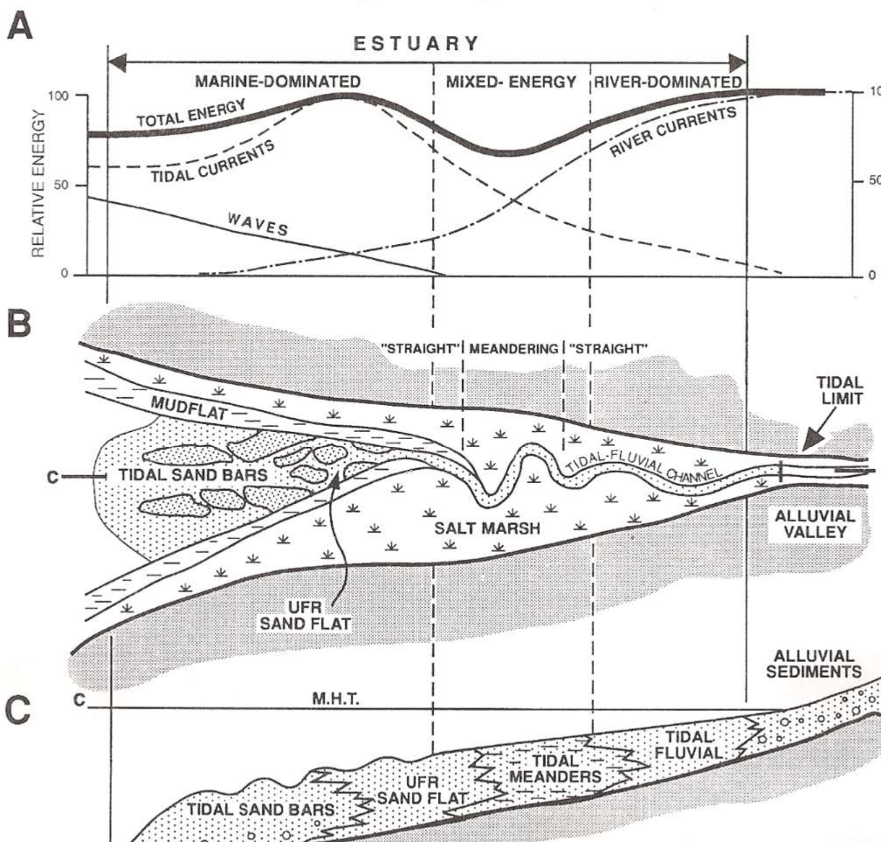


Montgomery, 1997

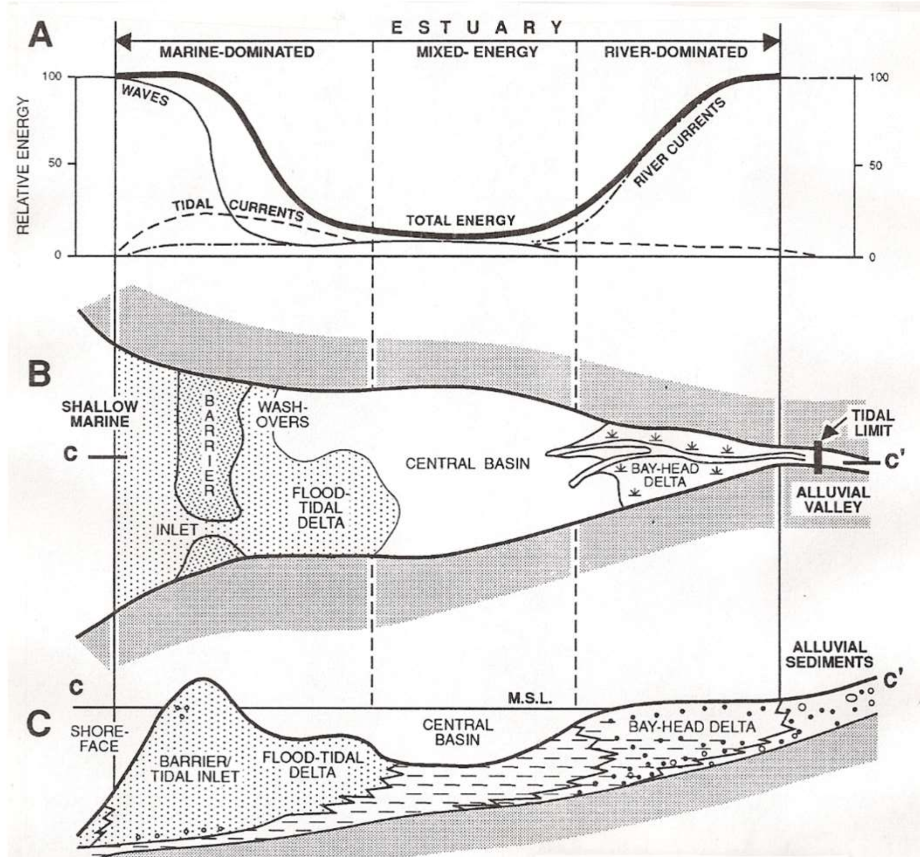

NORTH
X'
TS/UNC
SOUTH
X
D1
UNCONFORMITY (SEQUENCE BOUNDARY)
X'
MARINE MUDS
X
TRANSGRESSIVE SURFACE (TS)
4
TS/UNC
D1
3
2
1
D2
unc



Dalrymple et al., 1992



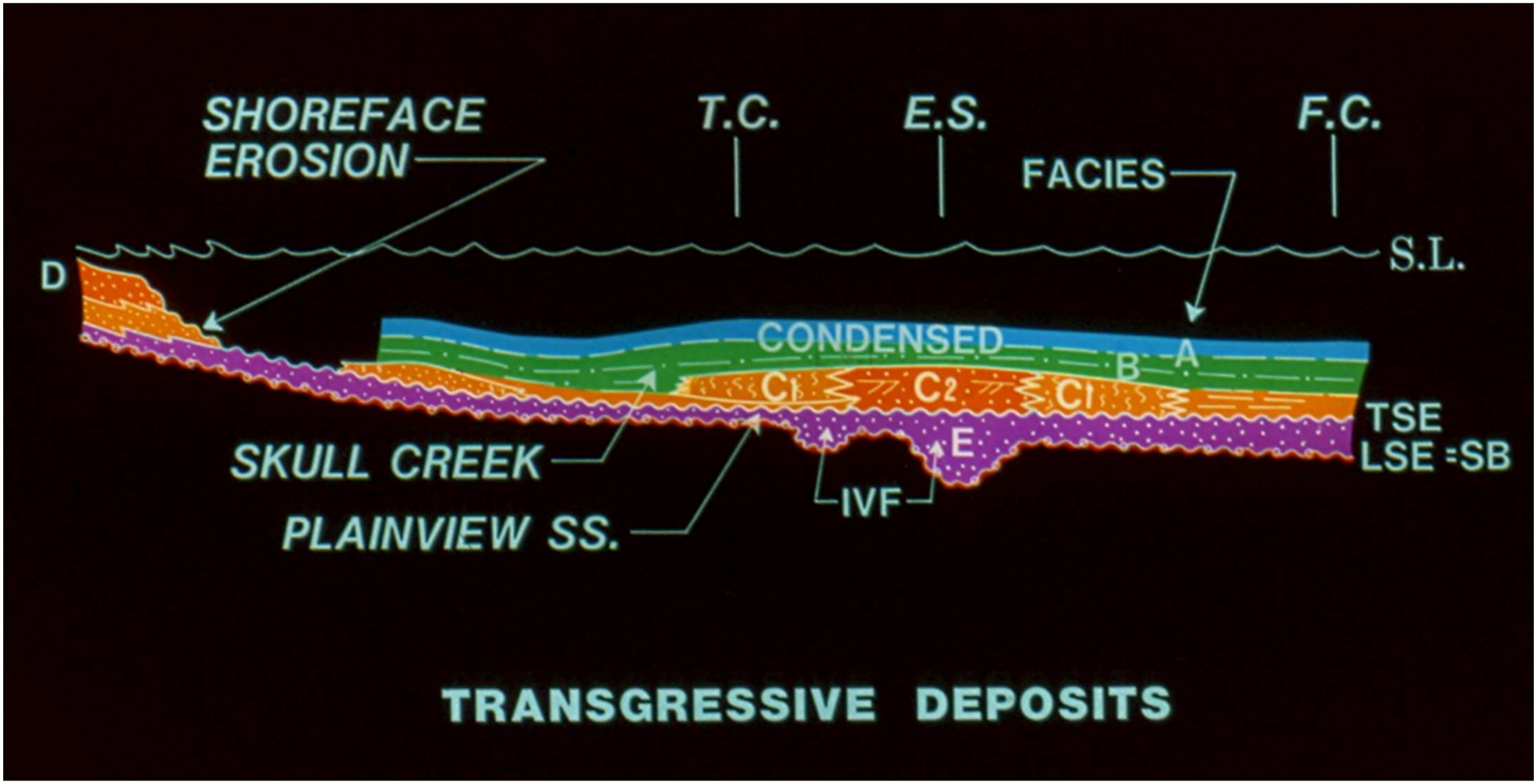
Dalrymple et al., 1992



Dalrymple et al., 1992

D Transgressive

- Above TSE
- < 20 ft thick
- Up to 6 miles long 2 miles wide
- Located near terminus of VFs
- Examples: Dragoon, Comanche Crk., Irondale fields


SHOREFACE
EROSION
T.C.
E.S.
F.C.
FACIES
S.L.
D
CONDENSED
B
A
C1
C2
C1
TSE
LSE =SB
SKULL CREEK
E
PLAINVIEW SS.
IVF
TRANSGRESSIVE DEPOSITS

Low Stand Delta

- Prod. from distributary channel >> delta front
- Occur at distal end of VFs
- Little or no incisement into Huntsman
- Narrow and thin
- Fracturing is important
- Examples: Krauthead Field area

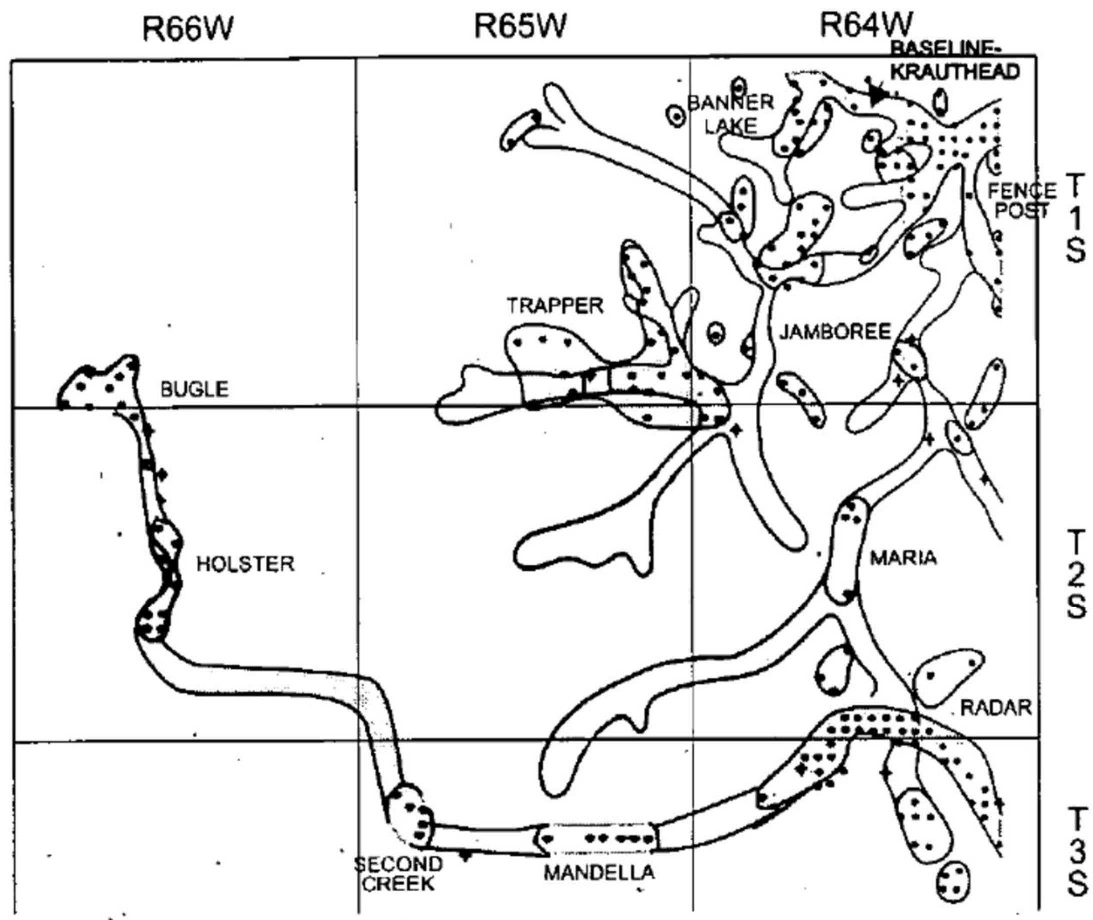


Figure 18. Oil wells producing from D-1 and D-2 sandstones. Syndepositional faults control thicknesses of valley fill in D-1 Sandstone and abrupt changes in trends (refer to Figure 16).

Waterfloods

D Waterfloods

- Historically poor recovery & high gas saturation at depletion
- Reservoir heterogeneity & management
- Successful floods
  - Injection by reservoir compartment
  - Unconventional pattern

Poor Waterflood Performance

- Complex reservoir compartmentalization
- Preferential directions of fluid flow, related to original depositional heterogeneity
- Rapid lateral facies changes
- Completion practices

D Waterfloods

- Notorious for poor response during waterflooding
- Primary recovery factors average 15.9%
- Average incremental 1.8% under waterflood

Table 2. Recovery Data for Fields in Vicinity of Sooner Unit*

Field Name	Township, Range	Area (acres)	OOIP (Mbbl)	Primary EUR Mbbl/ % OOIP	Waterflood Incremental/% OOIP	Recovery Factor Total (%)
Bijou	T4-5N, R59-60W	1180	7410	1400/18.9	170/2.2	21.1
Bijou, West	T4N, R60W	1320	7540	1198/15.9	13/0.2	16.1
Buckingham	T8N, R58W	480	2740	389/14.2	0	14.2
Greasewood	T6N, R61W	240	1235	248/20.0	19/1.5	21.5
Jackpot	T6-7N, R59W	1440	5515	1381/25.0	381/6.9	31.9
Masters	T5N, R60W	360	4070	335/08.2	19/0.5	8.7
Orchard, East	T4N, R60W	360	1237	301/24.3	7/0.6	24.9
Orchard, West	T4N, R60W	200	766	132/17.2	0	17.2
Roggen, NW	T2N, R63W	200	1462	204/14.0	37/2.5	16.5
Roggen, SE	T2N, R63W	1050	6267	496/07.9	56/0.9	8.8
Total		6830	38,242	6084/15.9	702/1.8	17.5

*Data from Sippel, 1996.

Montgomery, 1997

Table 1. Reservoir Rock and Fluid Data, Sooner Unit*

Average Depth	6300 ft
Maximum Gross	55 ft
Average Net	17 ft
Permeability to Air	21 md
Dykstra-Parsons Coefficient	0.74
Oil Gravity	41° API
Oil Viscosity	0.36 cp
Mobility Ratio	0.30

*Data courtesy Mark Sippel Engineering, Inc.

Montgomery, 1997

Dykstra-Parsons Coefficient: common descriptor of reservoir heterogeneity values 0 to 1. It measures reservoir uniformity by the dispersion or scatter of permeability values. A homogeneous reservoir has a permeability variation that approaches zero, while an extremely heterogeneous reservoir would have a permeability variation approaching one. The coefficient is expressed as follow: **V=(k50-k84.1)/k50** V: coefficient of Permeability Variation k50: Permeability mean k84.1: Permeability mean plus a standard deviation

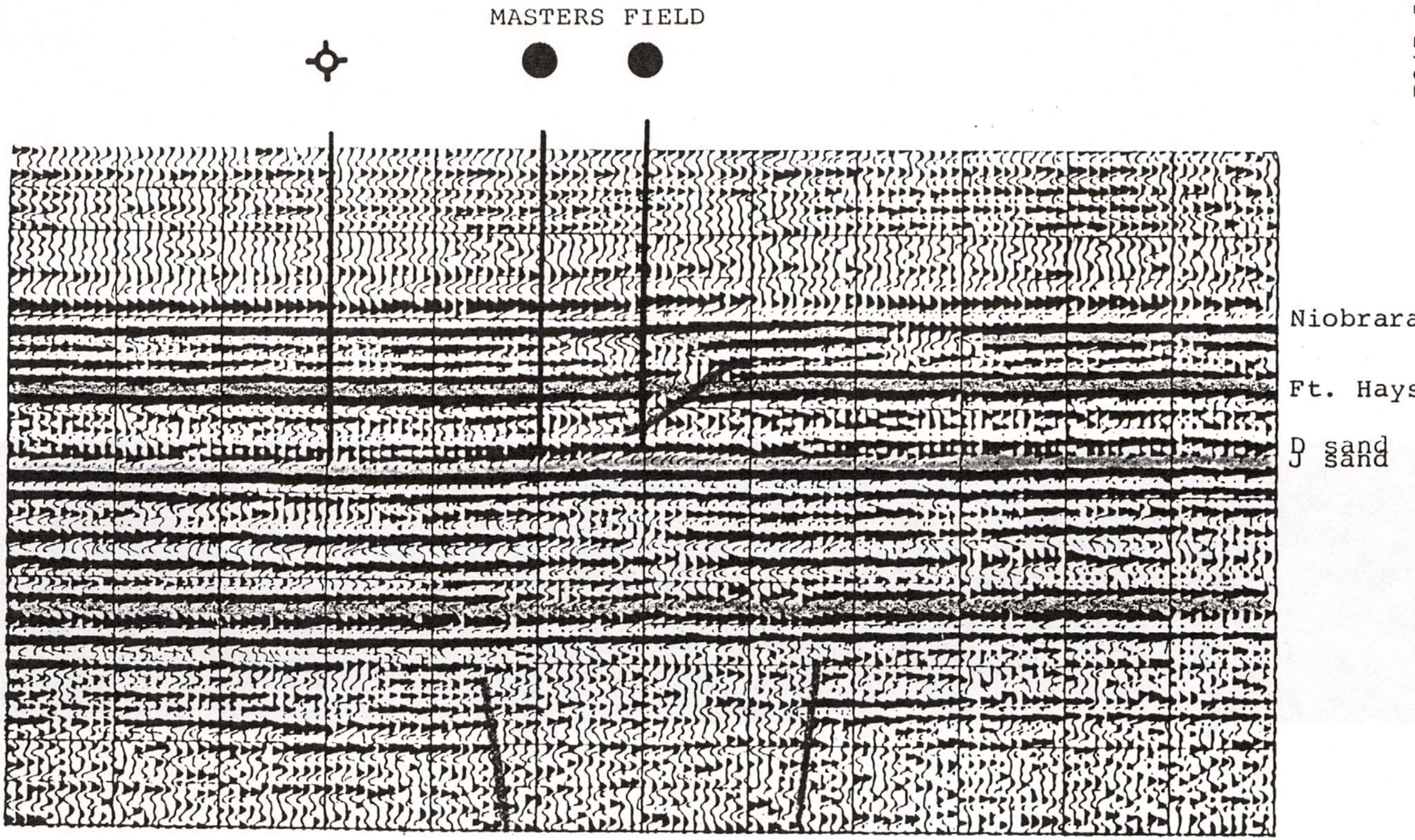
Mobility ratio: ratio of the permeability of the formation to a fluid, divided by the fluid viscosity
$\lambda = k/\mu$ where = mobility, md/cp; k = effective permeability, md; μ = fluid viscosity, cp

Mobility ratio in a waterflood is defined as the mobility of the displacing fluid divided by the mobility of the displaced fluid: $M = (k_{rw}/\mu_w) / (k_{ro}/\mu_o)$

Reservoir Management

- Reservoir compartments
  - Pressure surveys, production history, etc.
- Infill drilling locations (prod + inj)
- Realignment of injection wells
- Controlling injection by operational compartments (pressure data & water-cut information)

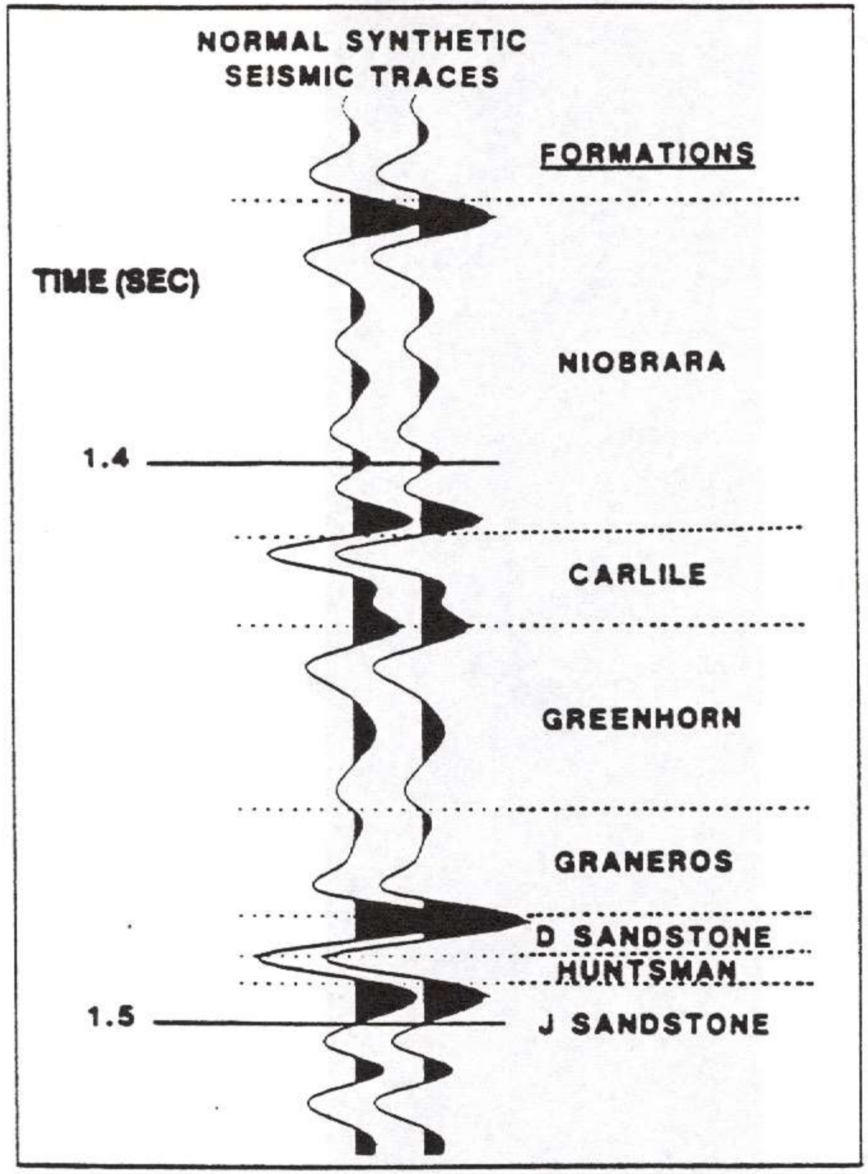
Seismic



Line B - Final Stack

Figure 37.

Plybon, 1983



Normal synthetic seismic traces made from sonic log from Amoco 2 Champlin 287 (NW1/4 SW1/4 Sec. 17, T. 3 S., R. 62 W.). Dashed lines denote formation boundaries. The synthetic illustrates the response expected on seismic from a 52-ft thick D Sandstone (from Sonnenberg, 1987).

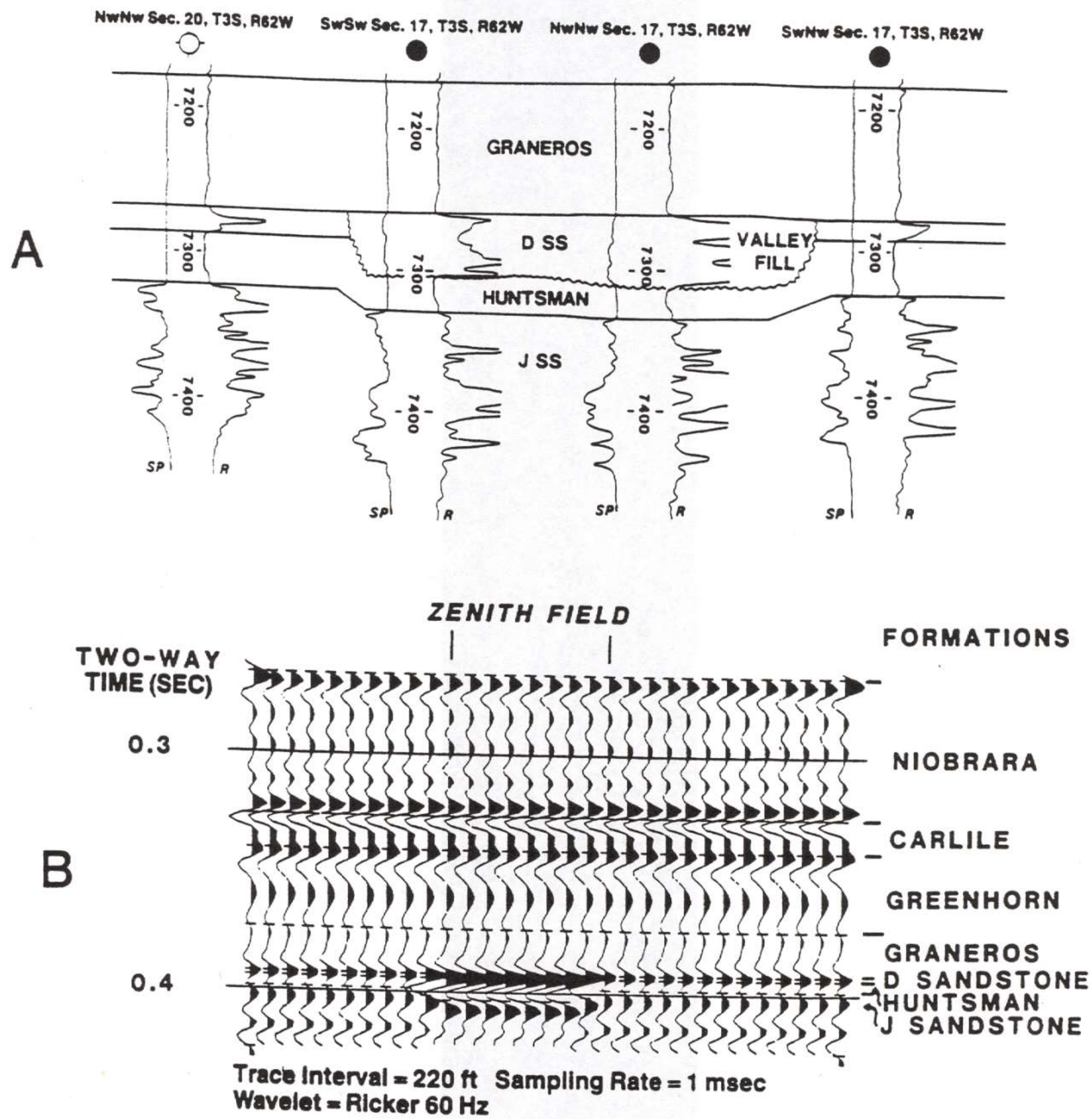
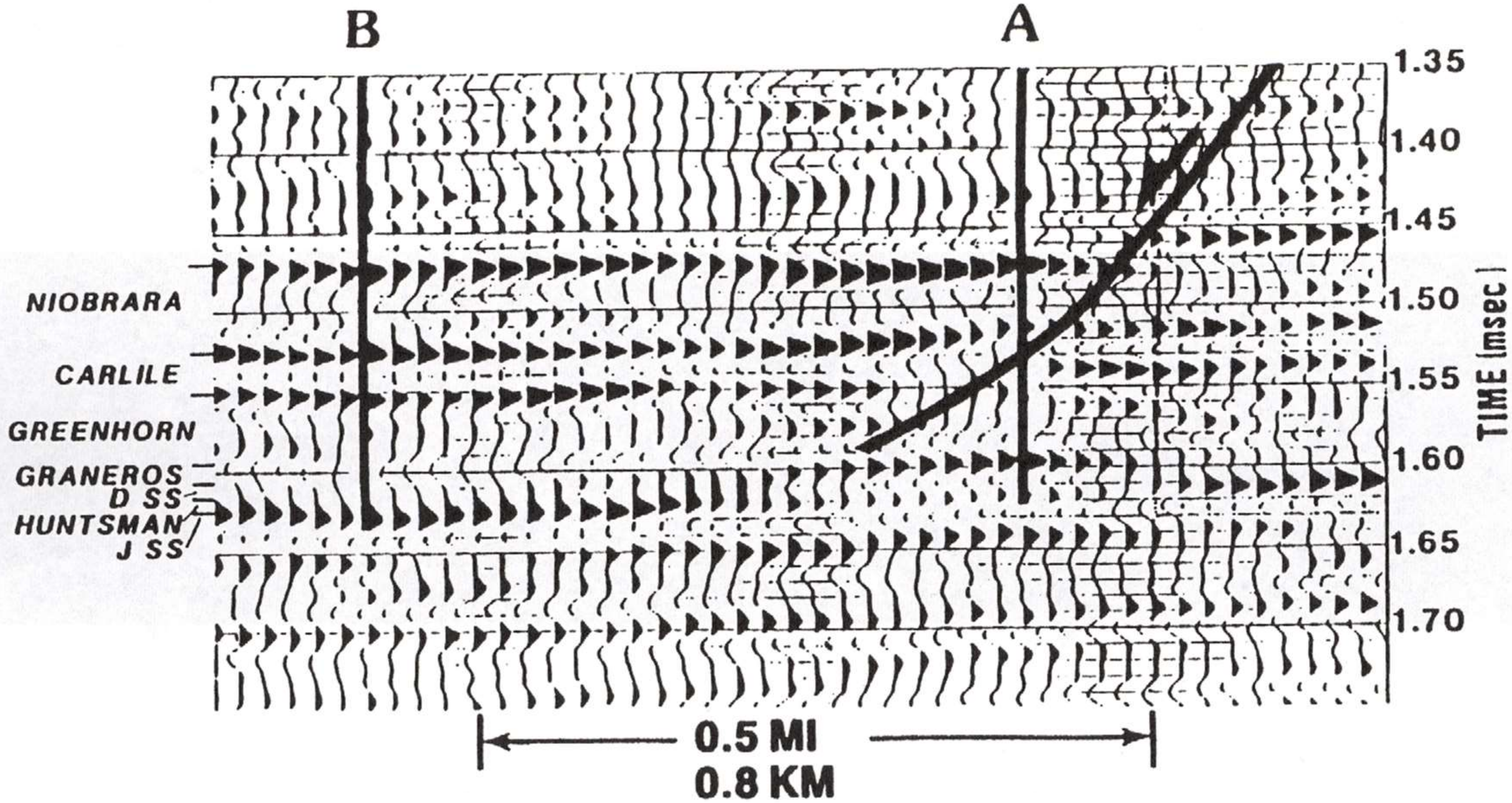
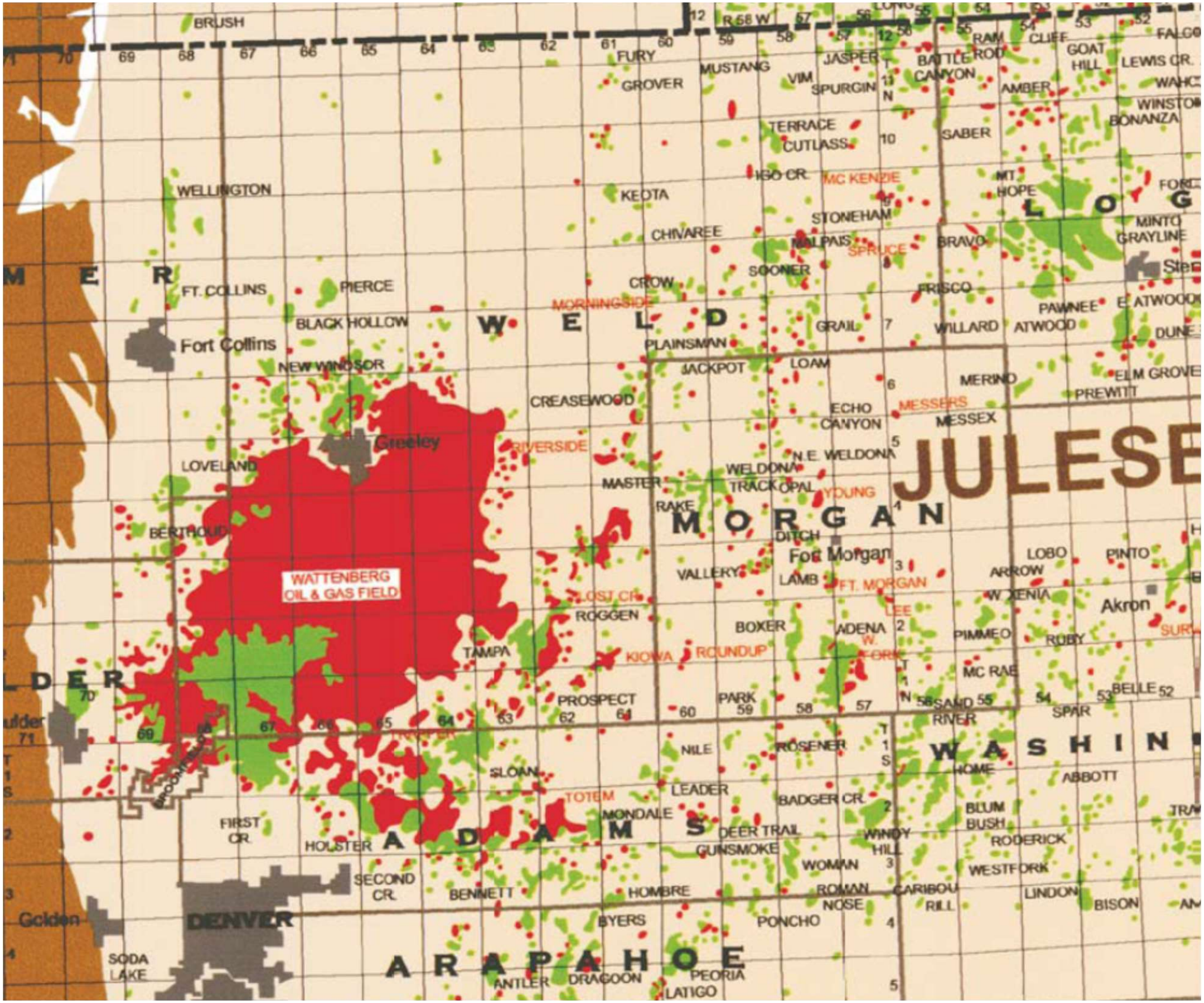


Figure 9. Two-dimensional geologic (a) and normal polarity seismic model (b) across Zenith field. Dashed lines denote formation boundaries. The thickness of the D Sandstone was varied from 10 to 52 ft back to 10 ft across the model to reflect the presence of the valley-fill deposits (from Sonnenberg, 1987).



Seismic line over a portion of Zenith field. Line is perpendicular to D valley fill deposits. Thicknesses of the D Sandstone in wells A and B are 58 ft and 16 ft, respectively. Note listric fault does not penetrate D Sandstone level (from Sonnenberg, 1987).

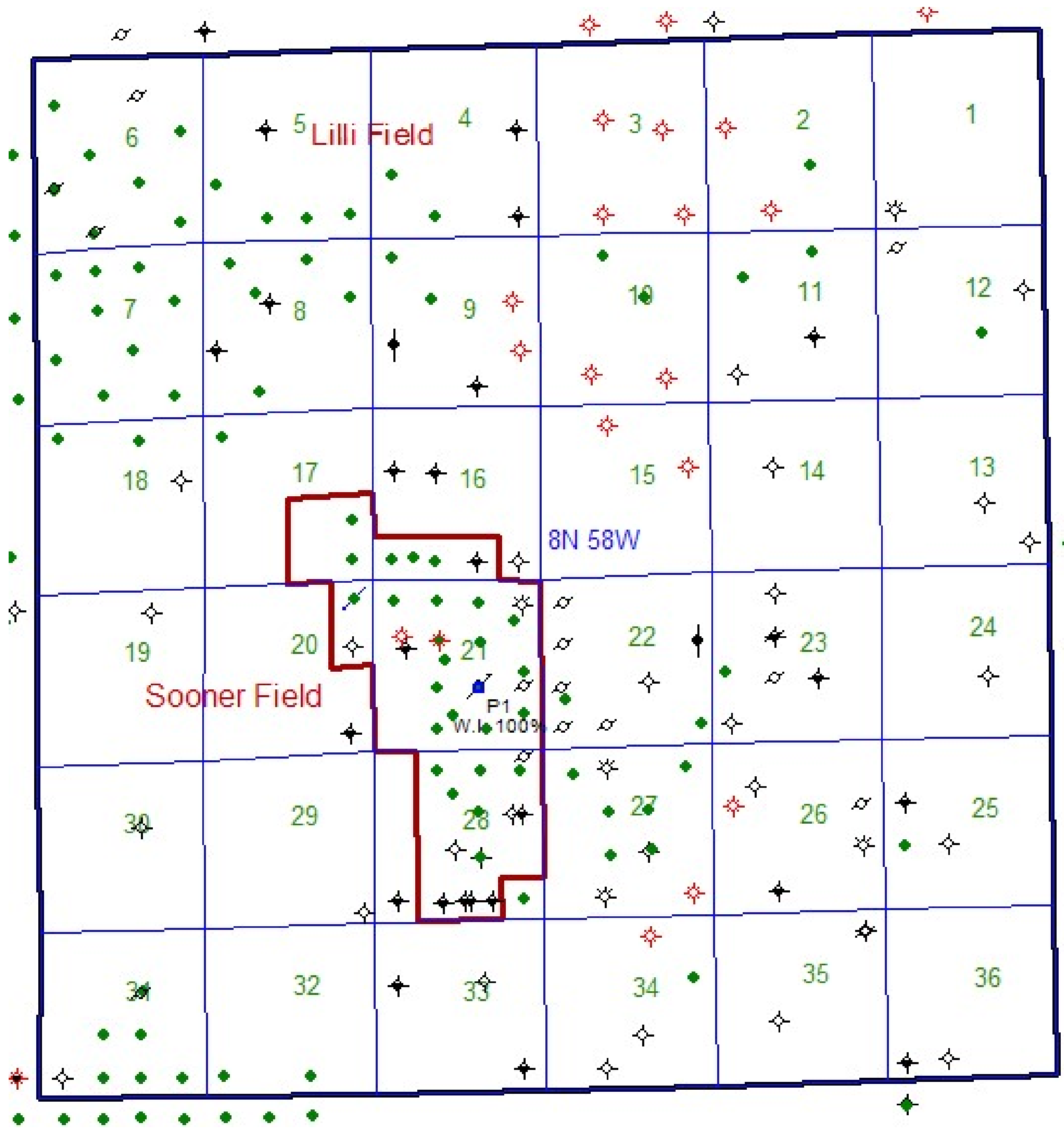

WATTENBERG OIL & GAS FIELD
W E L D
M O R G A N
A D A M S
A R A P A H O E
W A S H I N
JULESB
Fort Collins
Greeley
Fort Morgan
Akron
DENVER
WELLINGTON
FT. COLLINS
PIERCE
BLACK HOLLOW
NEW WINDSOR
LOVELAND
BERTHOUD
KEOTA
CHIVAREE
CROW
MORNINGSIDE
PLAINSMAN
CREASEWOOD
RIVERSIDE
MASTER
JACKPOT
LOAM
ECHO CANYON
MESSERS
MESSEX
MERINO
N.E. WELDONA
WELDONA
TRACK
OPAL
YOUNG
RAKE
DITCH
VALLERY
LAMB
FT. MORGAN
LOST CR.
ROGGEN
BOXER
ADENA
W. FORK
KIOWA
ROUNDUP
TAMPA
PROSPECT
PARK
SLOAN
TOTEM
MONDALE
LEADER
NILE
ROSENER
BADGER CR.
DEER TRAIL
GUNSMOKE
WINDY HILL
WOMAN
ROMAN NOSE
HOMBRE
BENNETT
SECOND CR.
FIRST CR.
HOLSTER
BYERS
PONCHO
ANTLER
DRAGOON
PEORIA
LATIGO
SODA LAKE
Golden
FURY
GROVER
MUSTANG
VIM
JASPER
SPURGIN
TERRACE
CUTLASS
IGO CR.
MC KENZIE
STONEHAM
MALPAIS
SPRUCE
SOONER
GRAIL
BATTLE CANYON
RAM ROD
CLIFF
GOAT HILL
LEWIS CR.
AMBER
SABER
BONANZA
MT. HOPE
BRAVO
FRISCO
WILLARD
ATWOOD
PAWNEE
E. ATWOOD
MINTO
GRAYLINE
ELM GROVE
PREWITT
LOBO
PINTO
ARROW
W. XENIA
PIMMEO
RUBY
MC RAE
SAND RIVER
SPAR
BELLE
HOME
ABBOTT
BLUM BUSH
RODERICK
WESTFORK
CARIBOU RILL
LINDON
BISON
BRUSH

Sooner Field

- Disc. 1985, W.F. 1992
- Depth - 6300 ft
- 40 - ac pattern
- Gross thickness 55 ft; net pay 17 ft
- Fluvial to estuarine V-F ss
- Cum Prod: 1.8 MMBO, 7.1 BCF

Sooner Field

• Original oil-in-place:	6,900,000 STB
• Original Solution Gas:	3,500,000 MCFG
• Cum. To Unitization 10/1/88:	772,000 STB
• Cum to 2/1/93:	1,102,000 STB
• Predicted Primary Recovery:	980,000 STB
• Primary Recovery Factor:	14.2%


Lilli Field
Sooner Field
8N 58W
P1
W.I. 100%
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
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21
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32
33
34
35
36

Sooner Field 3-D Survey

- October 1992
- 7.7 mi^2

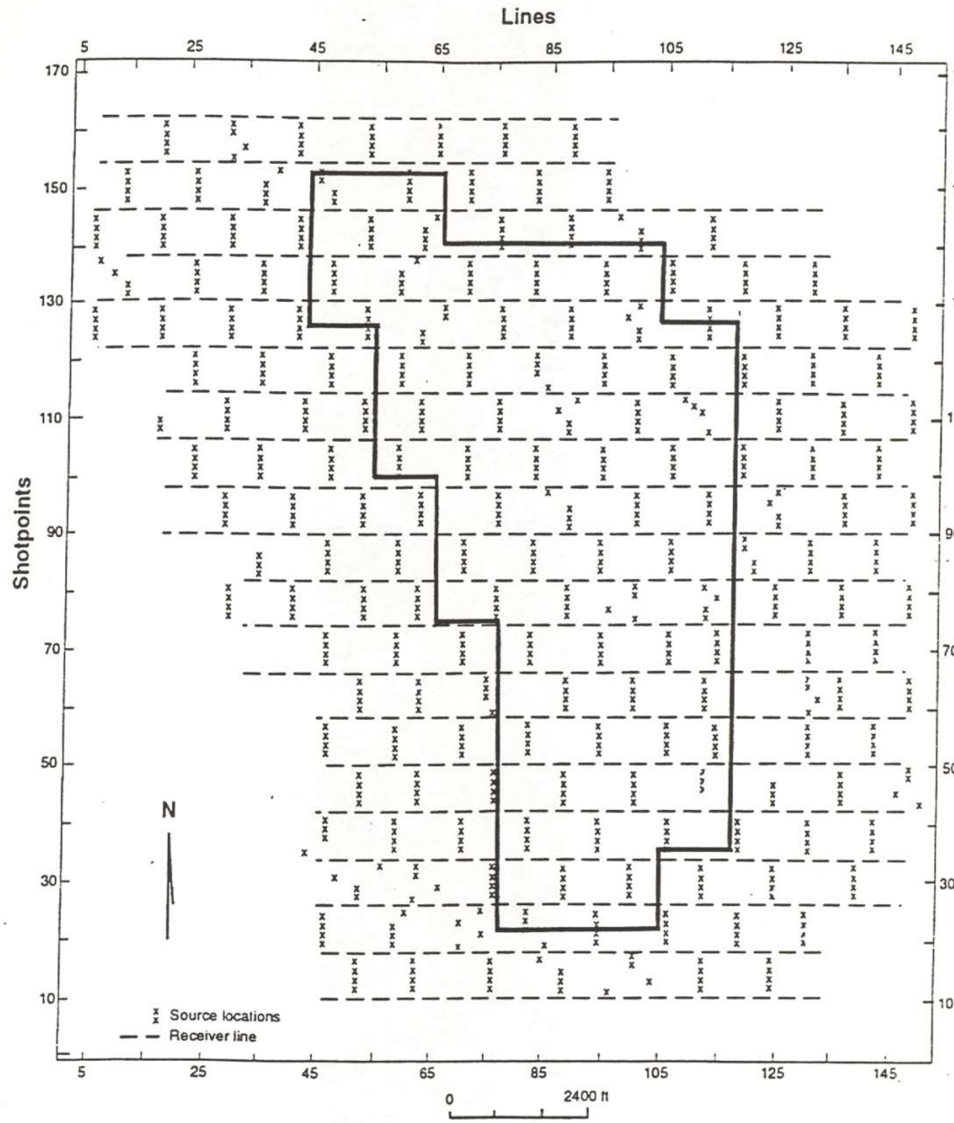
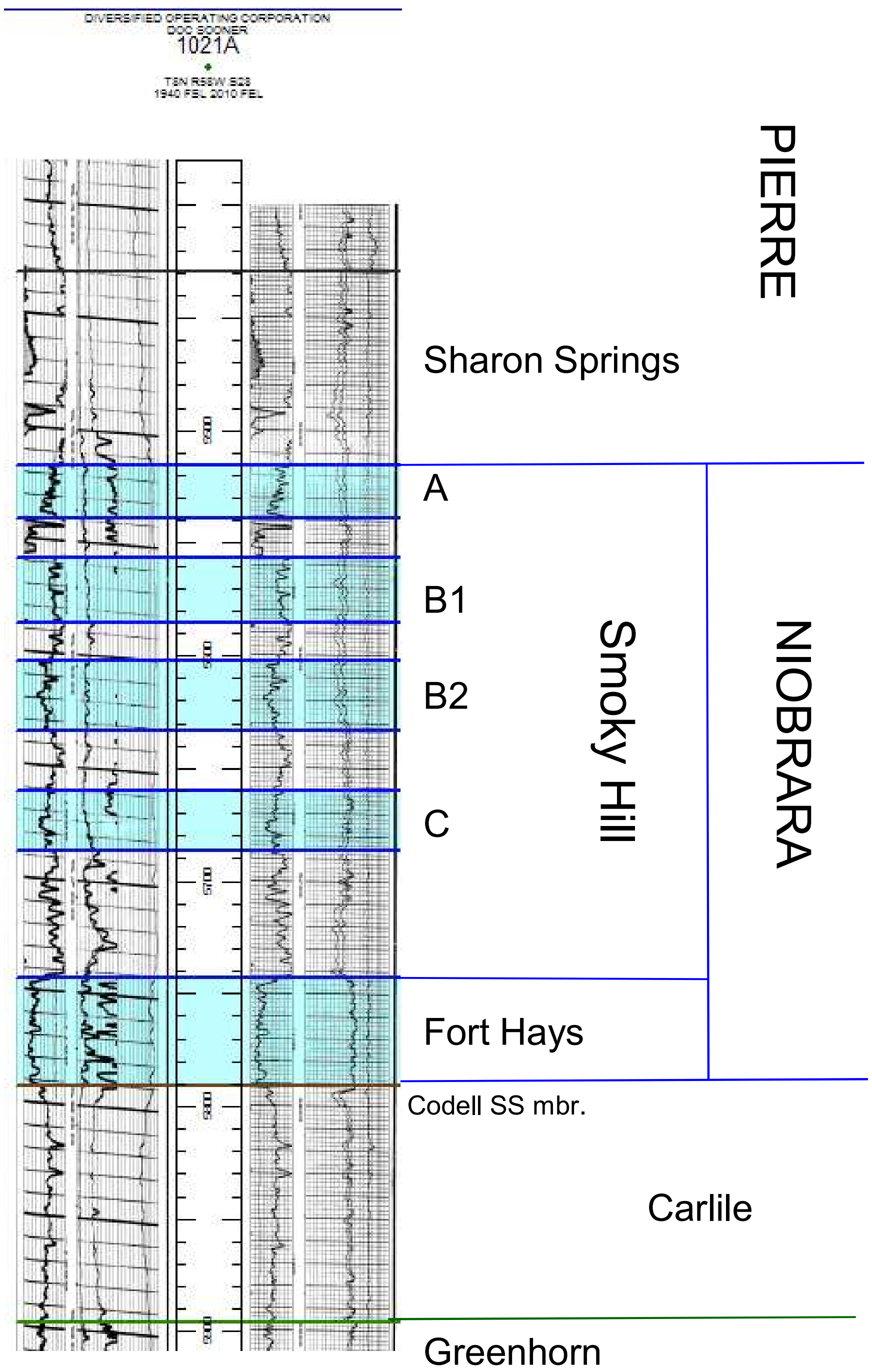


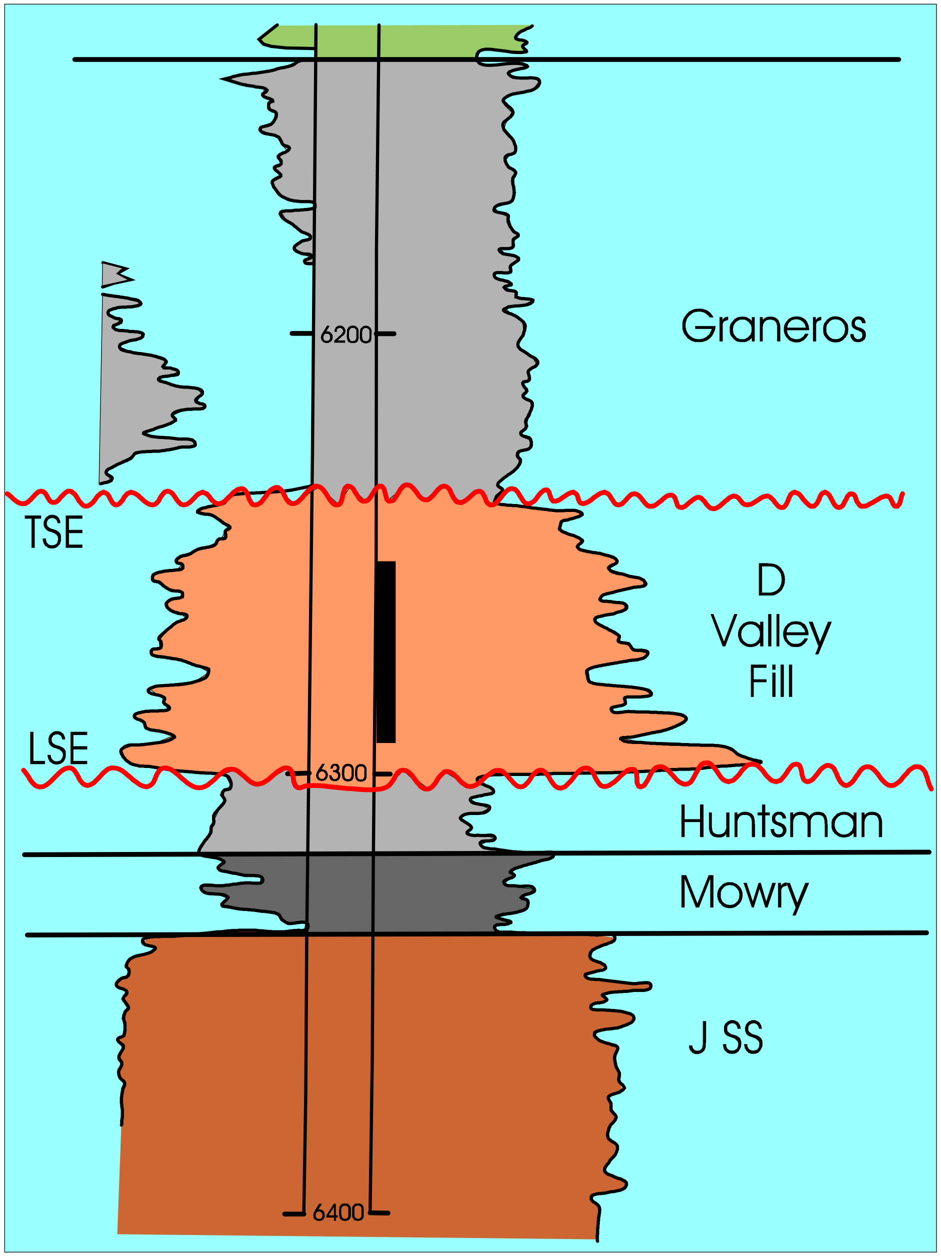
Figure 9 - The source-receiver geometry used to produce a 3-D image of the D reservoirs within the Sooner Unit. The heavy line defines the boundary of the Sooner Unit property.

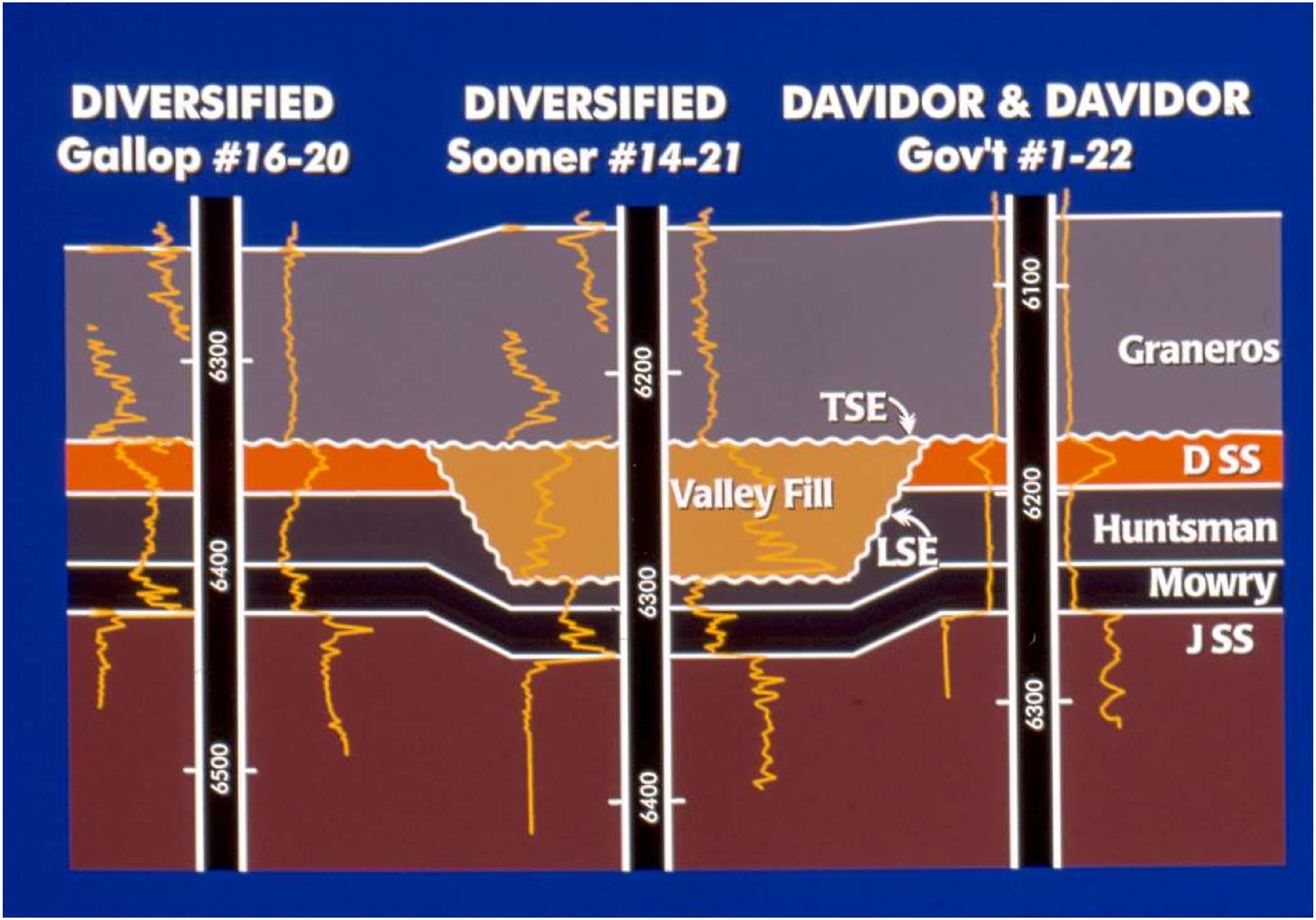


Type Log
Sooner Field Area
Denver Basin

Type Log Sooner Field

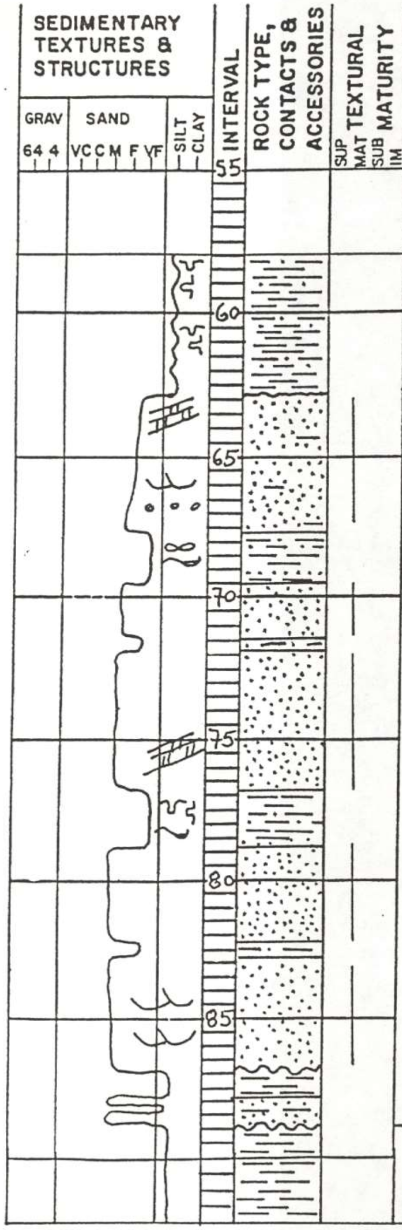
- Diversified Sooner 14-21
- Pfs: 6253-6290
- IPF: 511 BOPD, 400 MCFD




DIVERSIFIED
Gallop #16-20
DIVERSIFIED
Sooner #14-21
DAVIDOR & DAVIDOR
Gov't #1-22
6300
6400
6500
6200
6300
6400
6100
6200
6300
Graneros
TSE
D SS
Valley Fill
Huntsman
LSE
Mowry
J SS

Well No. Fed. Sooner #7-21
Location Sec 21, T8N, R58W
Weld County, CO

Date Dec. 31, 1992
Strat. Unit "D" Sandstone
Measured by F. G. Ethridge



DESCRIPTIONS

6287 ft (core depth)=
6287 ft (log depth)

Alternating shale and siltstone; alternating laminate of high bioturbation and low to no bioturbation; horizontal and vertical burrows; some escape burrows; some laminae of shale are coaly or highly organic w/pyrite concretions.

TSE (?)

Very fine-grained sandstone; quartz to subarkosic arenite; styolites in thin clay laminae; ripple-drift cross-strata; trough x-beds; clay clasts; lenticular and flaser bedding;

Alternating very fine-grained sandstone and shale or siltstone.

Abundant muscovite flakes at contact

LSE

Uniform, dark grey shale; no obvious bioturbation