PS Geologic Factors Controlling Production in the Codell Sandstone, Wattenberg Field, Colorado*

Stephen A. Sonnenberg[1]

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Abstract

The Upper Cretaceous Codell Sandstone is a major pay in the giant Wattenberg Field of the Denver Basin. Vertical well completions in the Codell date back to 1981. The vertical wells have a history of successful hydraulic refracturing. New horizontal wells (2011 to P) with initial production of 100 to 700 BOPD (GOR ~10,000 cf/bbl) indicate substantial remaining reserves in the formation. Geologic factors important for production include: proximity to thermally mature source beds; thickness; geothermal gradients; pressure gradients; fault bounded reservoir compartments; gas-oil ratios; sufficient reservoir quality (phi-h). The Codell in Wattenberg is characterized by low porosity (<10%) and permeability (< 0.1 md). The Codell is 5 to 20 ft thick across the Wattenberg Field and has formation pressure gradients that range from 0.45 to 0.66 psi/ft. Geothermal gradients range from 1.8 to 2.5^{o}F/100 ft. The highest GORs in the field correspond to the highest geothermal gradients. The sandstone is very fine to fine grained and bioturbated. Thin (< one ft thick) hummocky cross stratified beds are present in the Codell. Depositional environment is interpreted to be a shallow marine shelf setting. Clay content within the pay interval is approximately 20% and consists of 40–45% mixed layer illite-smectite, 30–40% illite, 10–30% chlorite, and up to 7% glauconite. The Codell is a low-resistivity, low-contrast pay. The fault-bounded reservoir compartments form mainly from a well-developed polygonal fault system. Polygons are generally about 1.5 square miles in size. The orientation of the polygons is influenced by pre-existing basement fault systems. The Codell unconformably overlies the Fairport chalk member of the Carlile Formation and is unconformably overlain by either the Juana Lopez or the Fort Hays Limestone Member of the Niobrara Formation.

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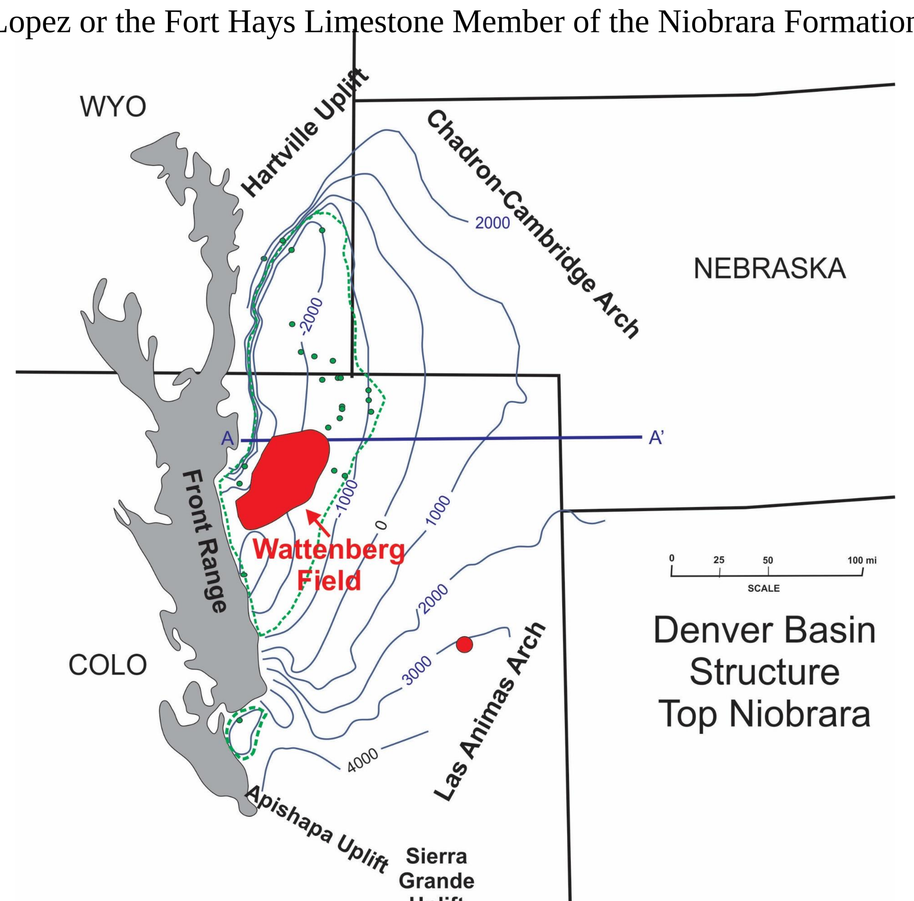
ABSTRACT

The Upper Cretaceous Codell Sandstone is a major pay in the giant Wattenberg Field of the Denver Basin. Vertical well completions in the Codell date back to 1981 and were hydraulic fracture stimulated. The vertical wells have a history of successful hydraulic refracturing. New horizontal wells (2011 to P) with initial production of 100 to 700 BOPD (GOR ~10,000 cf/bbl) indicate substantial remaining reserves in the formation.

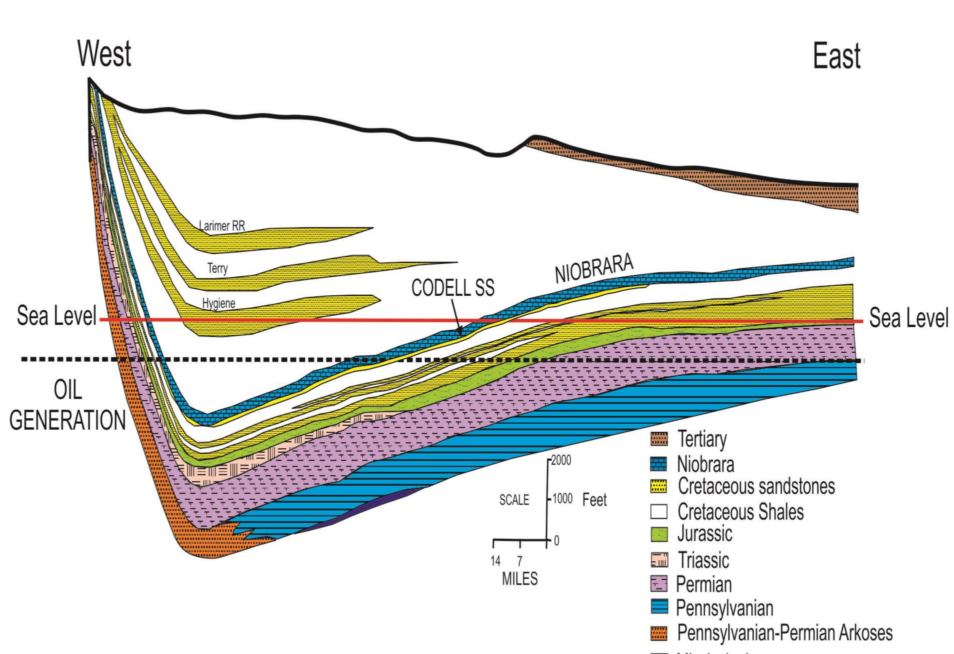
Geologic factors important for production include: proximity to thermally mature source beds; thickness; geothermal gradients; pressure gradients; fault bounded reservoir compartments; gas-oil ratios; sufficient reservoir quality (phi-h). The Codell in Wattenberg is characterized by low porosity (<12%) and permeability (< 0.1 mD). The Codell is 5 to 20 ft thick across the Wattenberg Field and has formation pressure gradients that range from 0.45 to 0.66 psi/ft. Geothermal gradients range from 1.8 to 3°F/100 ft. The highest GORs in the field correspond to the highest geothermal gradients. The sandstone is very fine to fine grained and bioturbated. Thin (< one ft thick) hummocky cross stratified beds are present in the Codell. Depositional environment is interpreted to be a shallow marine shelf setting. Clay content within the pay interval is approximately 20% and consists of 40-45% mixed layer illite-smectite, 30-40% illite, 10-30% chlorite, and up to 7% glauconite. The Codell is a low-resistivity, low-contrast pay.

The fault-bounded reservoir compartments form mainly from a well-developed polygonal fault system. Polygons are generally about 1.5 square miles in size. The orientation of the polygons is influenced by pre-existing basement fault systems.

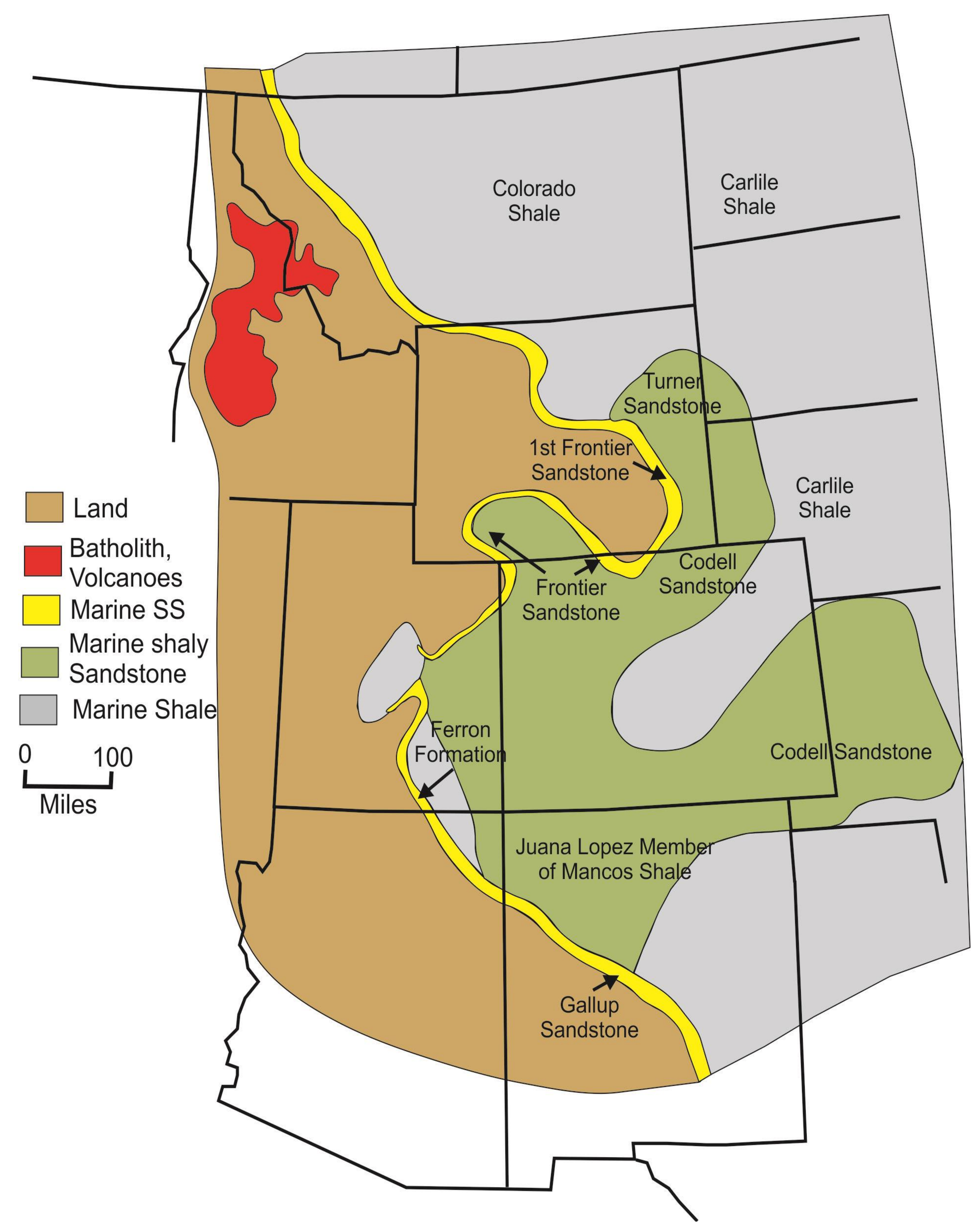
The Codell unconformably overlies the Fairport chalk member of the Carlile Formation and is unconformably overlain by either the Juana Lopez or the Fort Hays Limestone Member of the Niobrara Formation.



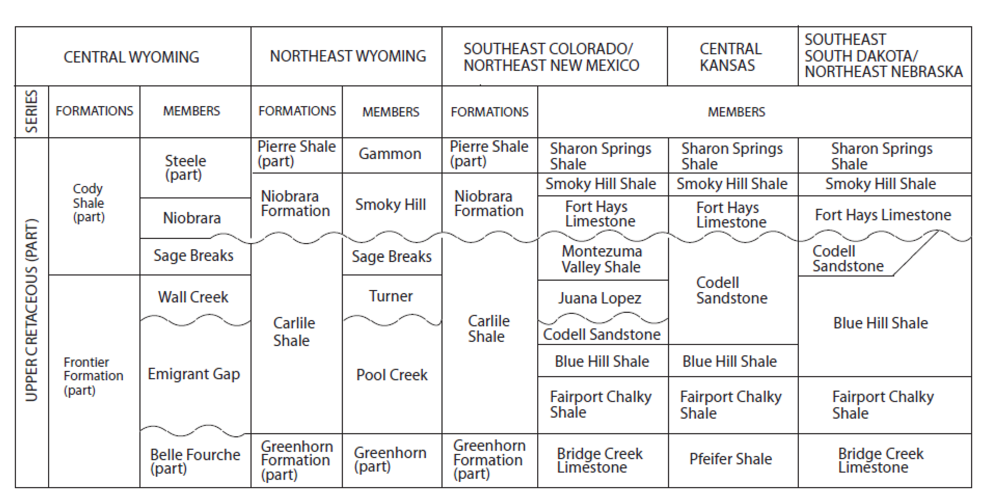
Structure map top Niobrara and current areas of Codell production (red – gas, green – oil). The dashed green line indicates areas where source rocks are thought to be thermally mature.



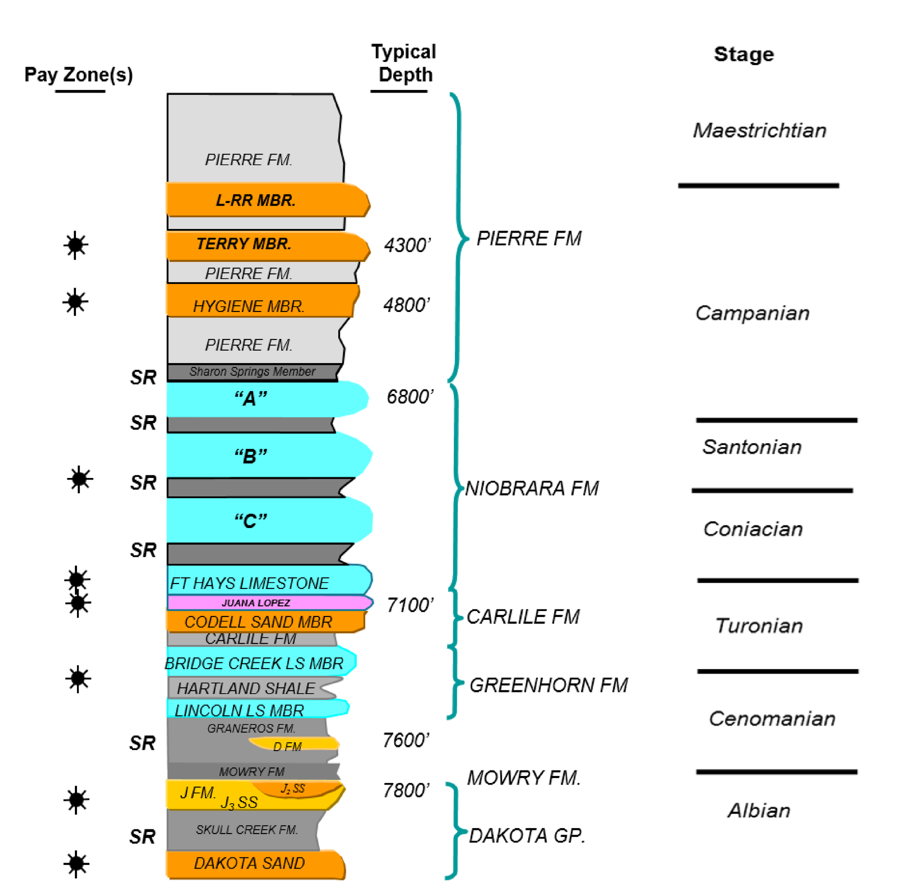
Diagrammatic cross section A-A' (west to east) illustrating the asymmetric nature of the Denver Basin and the occurrence of the Codell Sandstone beneath the Niobrara Formation.



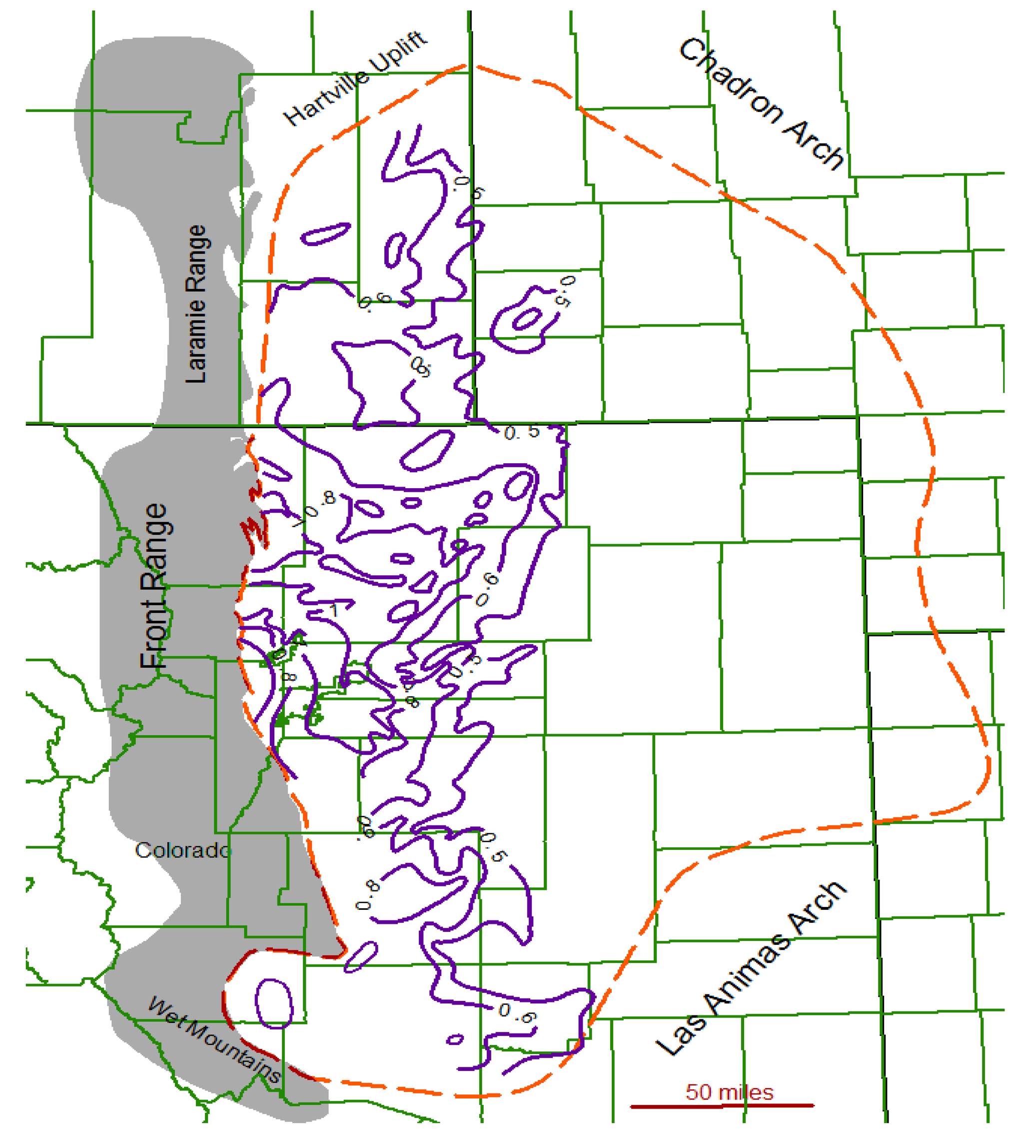
Paleoenviornment map for Middle Carlile time (modified Mallory, 1972).



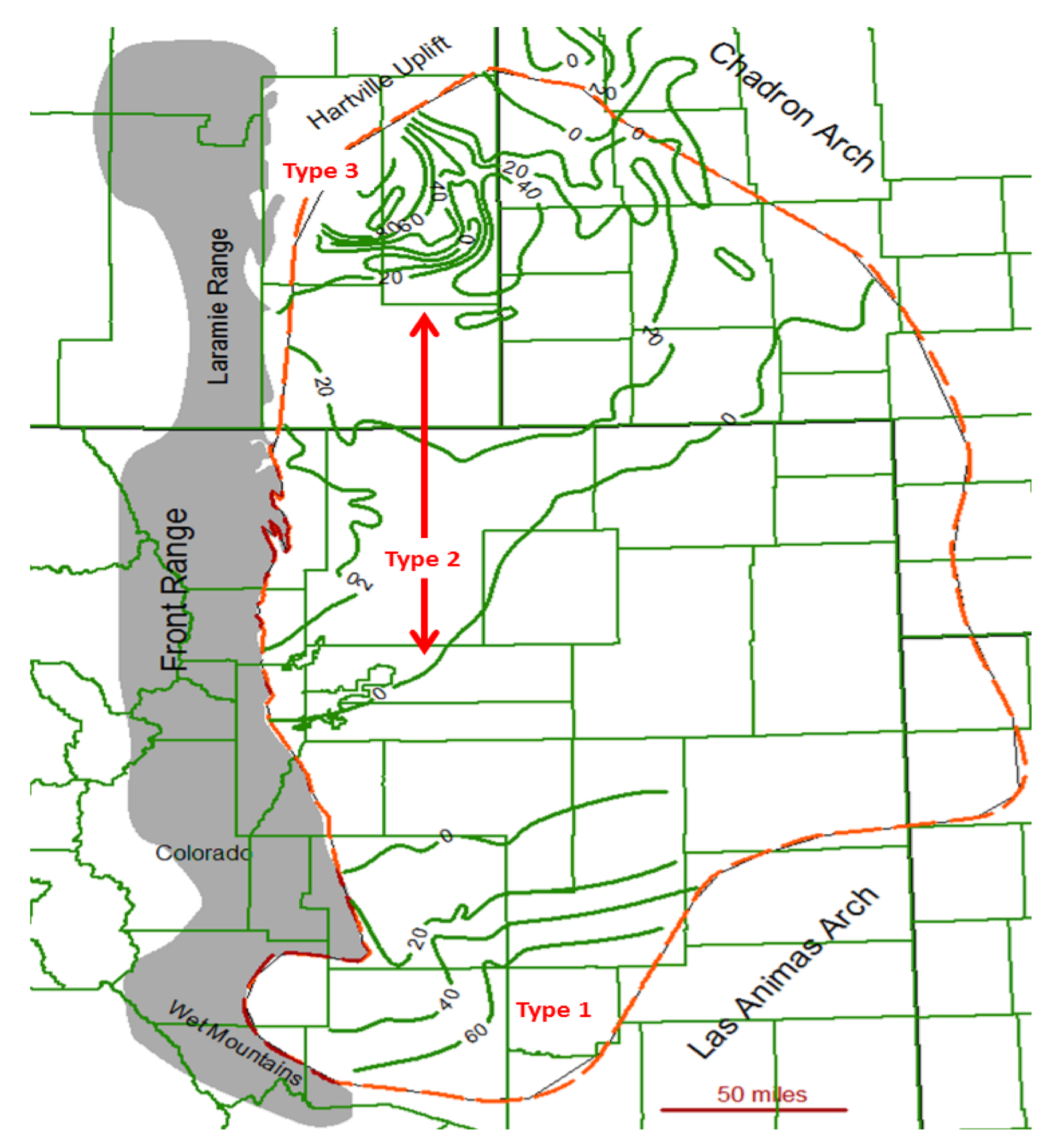
Correlation chart for Codell Sandstone, from Merewether 2007



Stratigraphic column for producing Cretaceous reservoir rocks in the greater Wattenberg area. Source beds for reservoir rocks are indicated by the SR symbol. The oil and gas symbols indicate producing horizons.



Source rock maturity map for the Niobrara Formation from Smagala et al., 1984. Ro values greater than 0.6 indicate probable areas of mature source rocks.

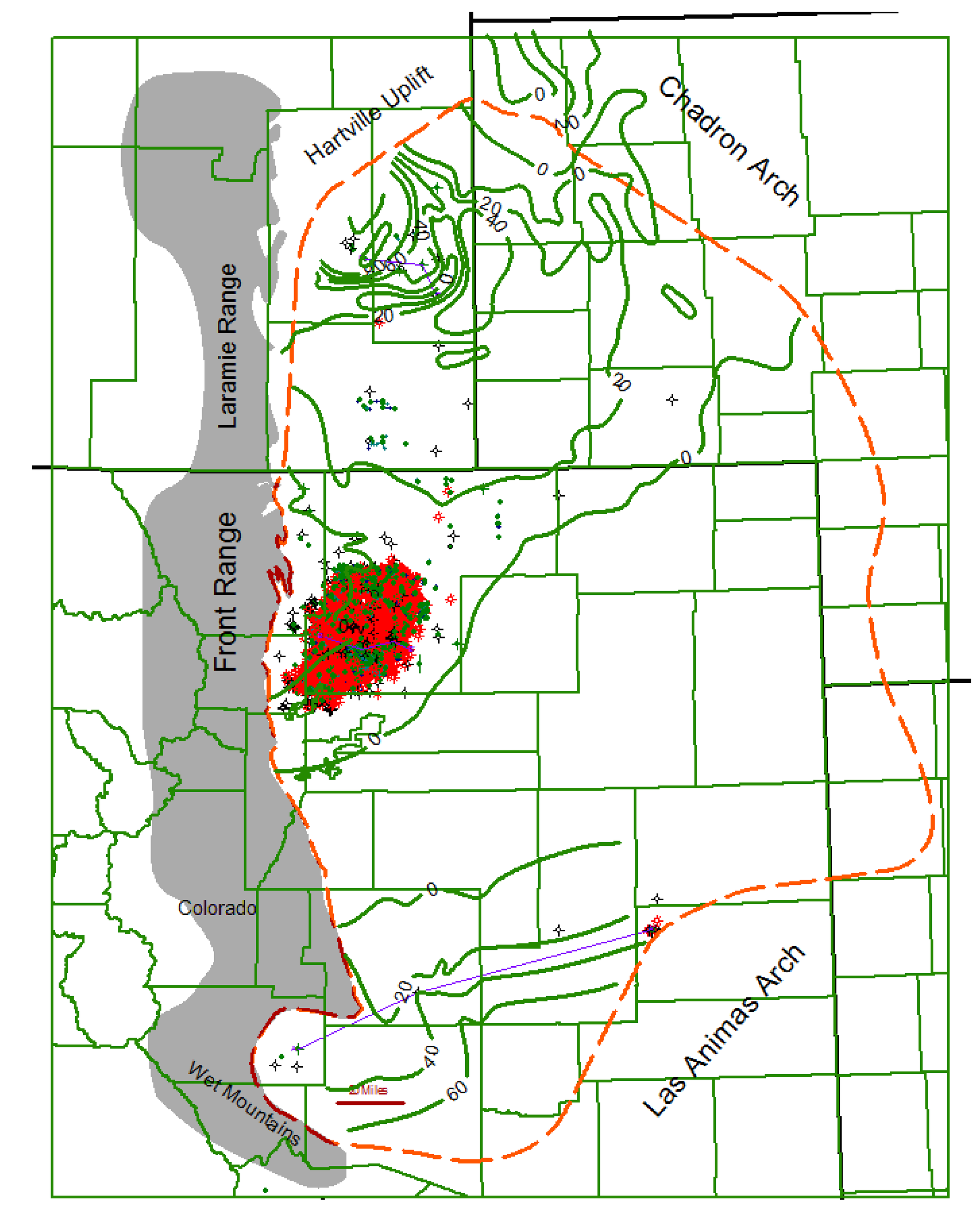


Isopach of the Codell Sandstone, Denver Basin (modified from Weimer and Sonnenberg, 1983).

Type 1 Sandstone: Marine shelf or shoreline bars; good porosity and permeability; sheet-like distribution

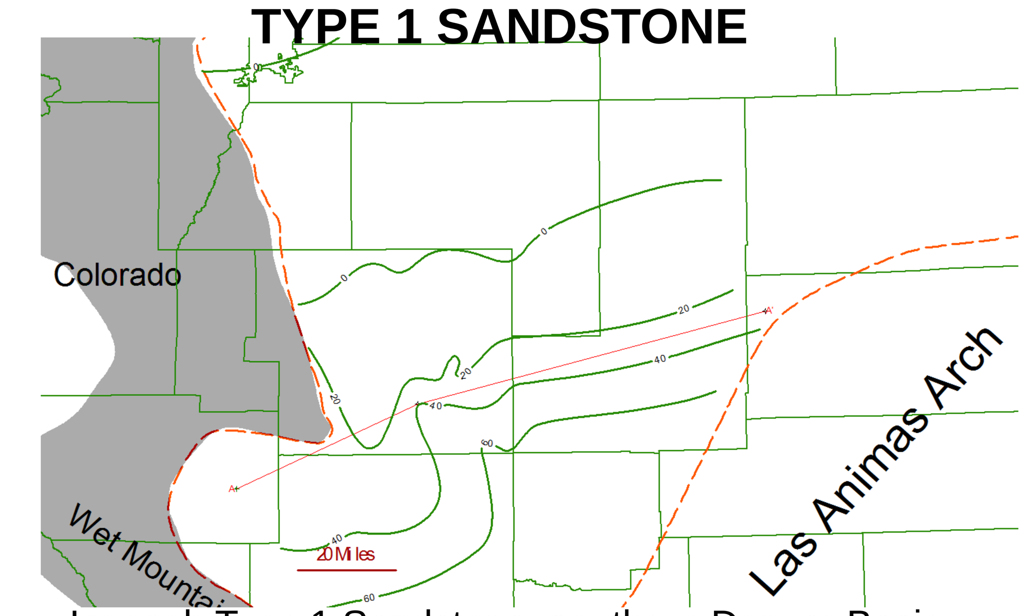
Type 2 Sandstone: impermeable, bioturbated, fine-grained marine shelf sandstone; contains thin hummocky cross stratified beds; no central bar facies present (eroded?); most of the existing production comes from this sandstone type

Type 3 Sandstone: fine-grained, parallel to cross stratified to ripple cross stratified; contains sparse burrows; deposited in intertidal to marine environments, contains abundant authigenic clays that reduce porosity and permeability

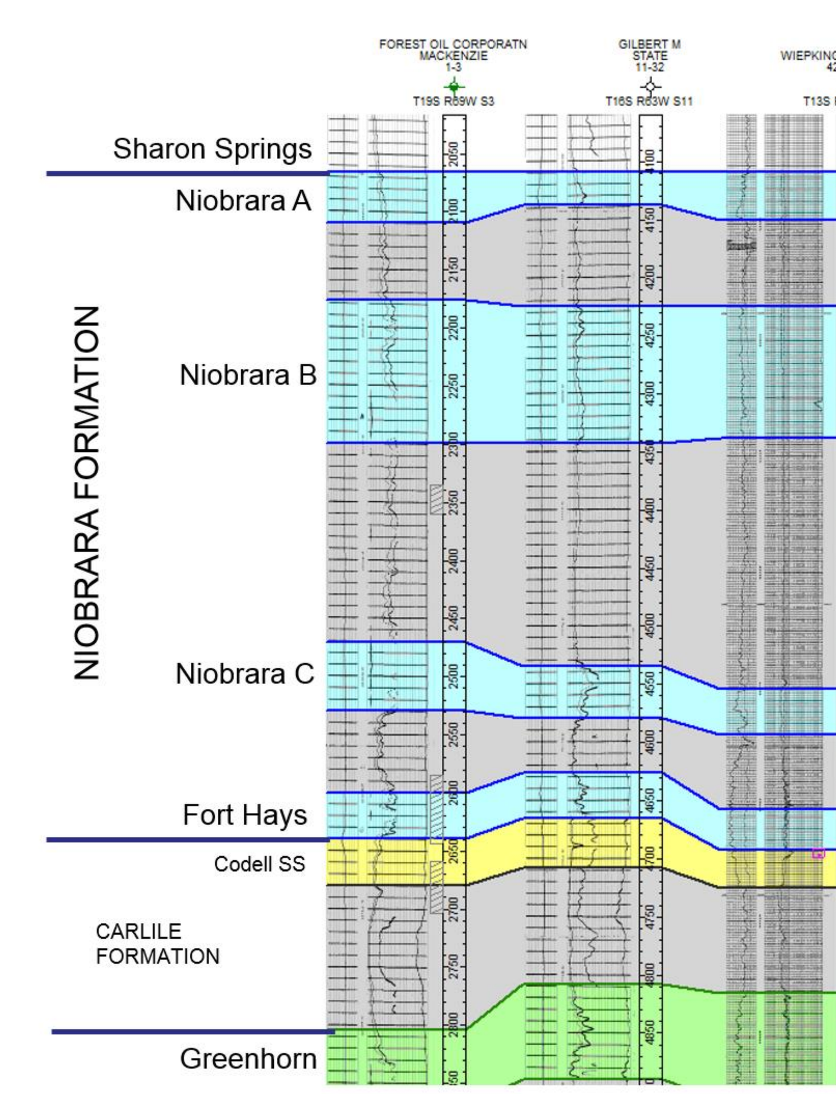


Isopach of the Codell Sandstone, Denver Basin (modified from Weimer and Sonnenberg, 1983). Map shows current Codell producers.

TYPE 1 SANDSTONE



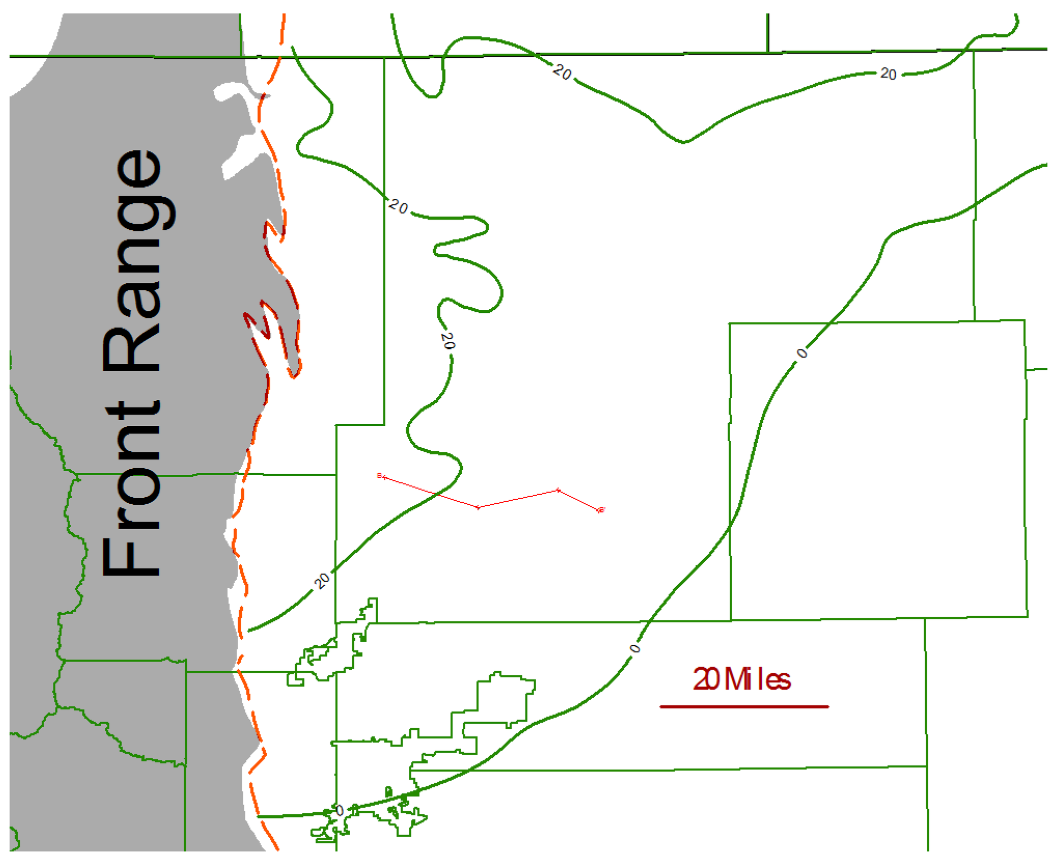
Isopach Type 1 Sandstone, southern Denver Basin



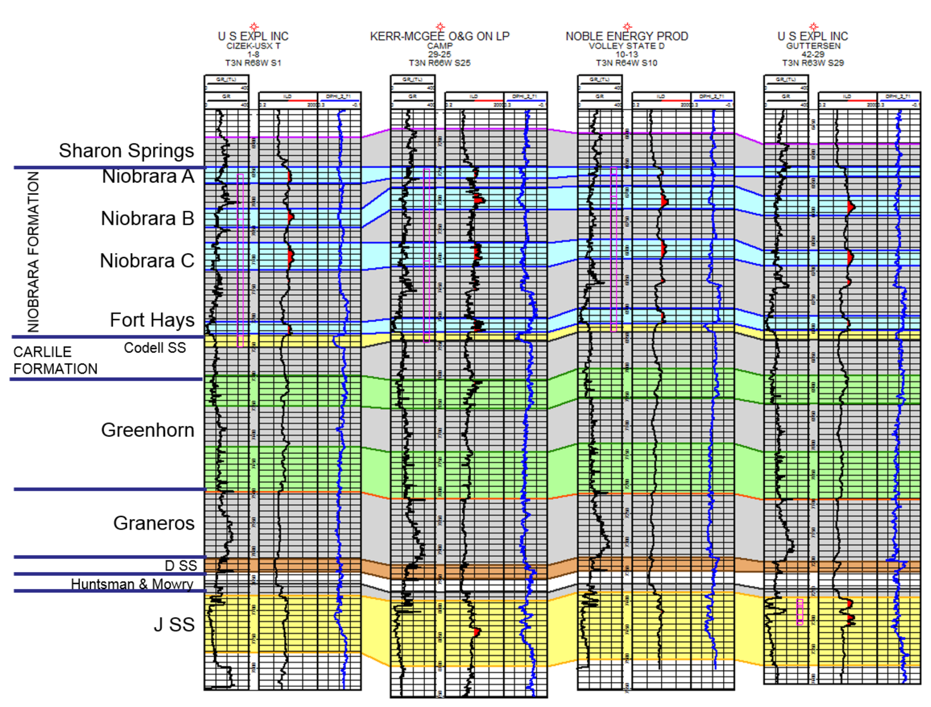
Cross-section Type 1 Sandstone, southern Denver Basin

Codell Sandstone, Denver Basin
2

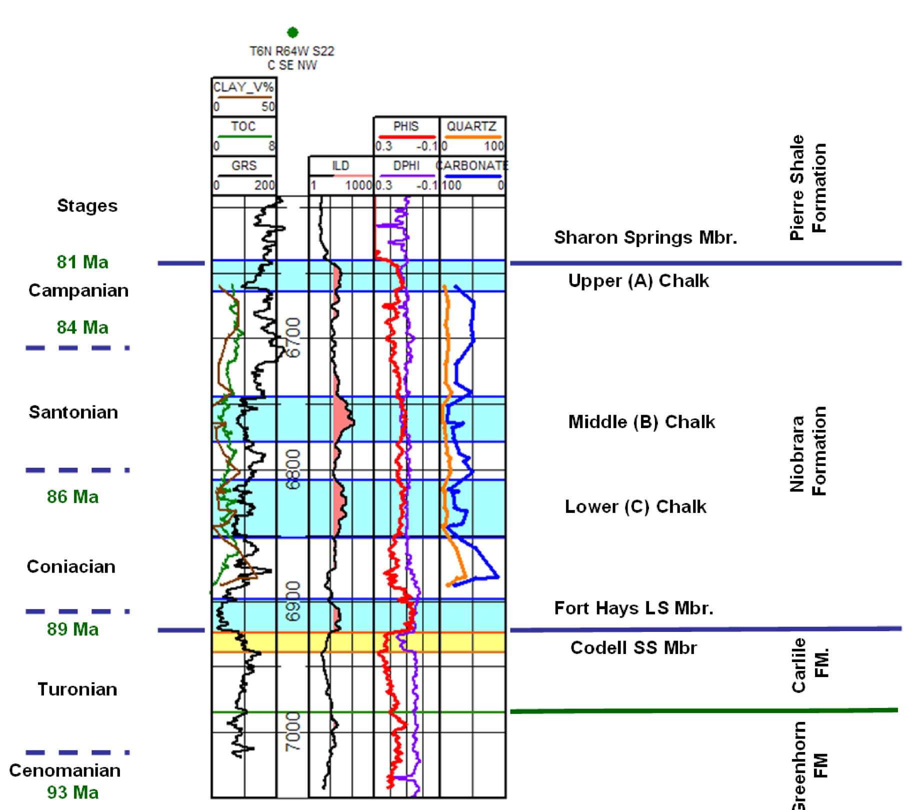
TYPE 2 SANDSTONE



Isopach Type 2 Sandstone, central Denver Basin

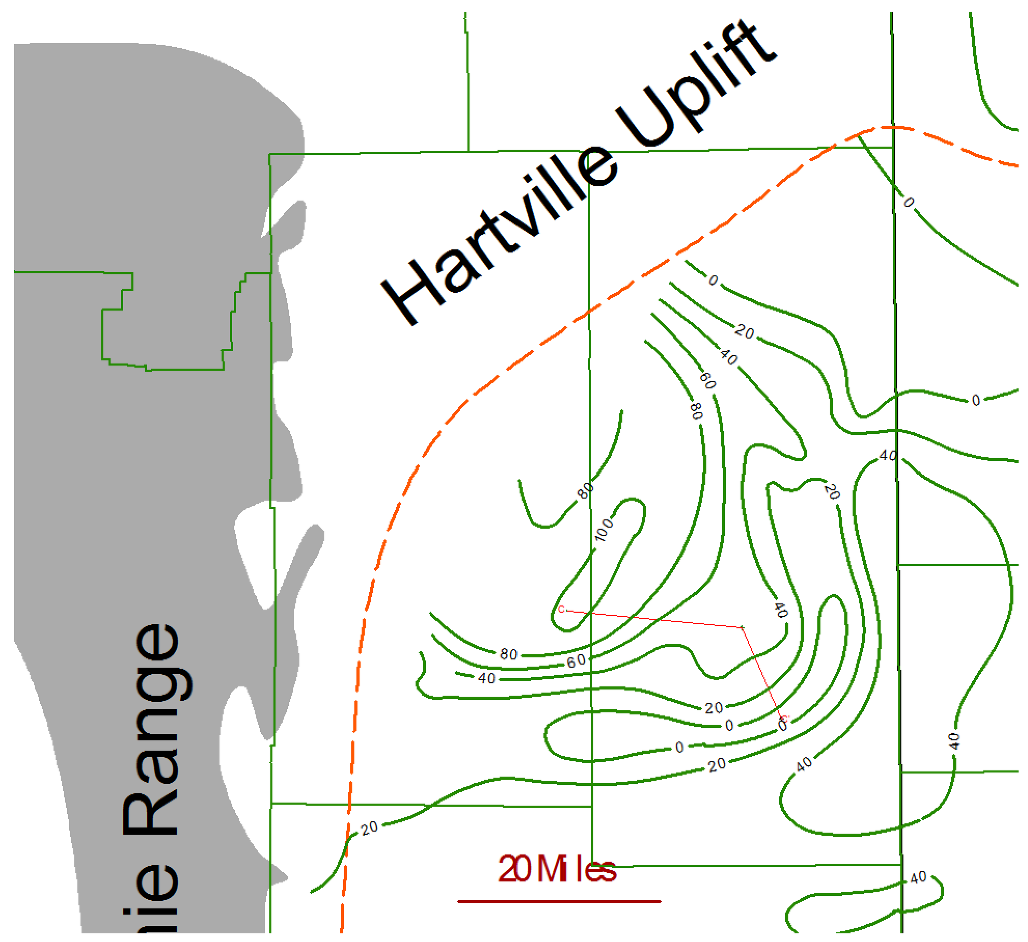


Cross-section Type 2 Sandstone, central Denver Basin

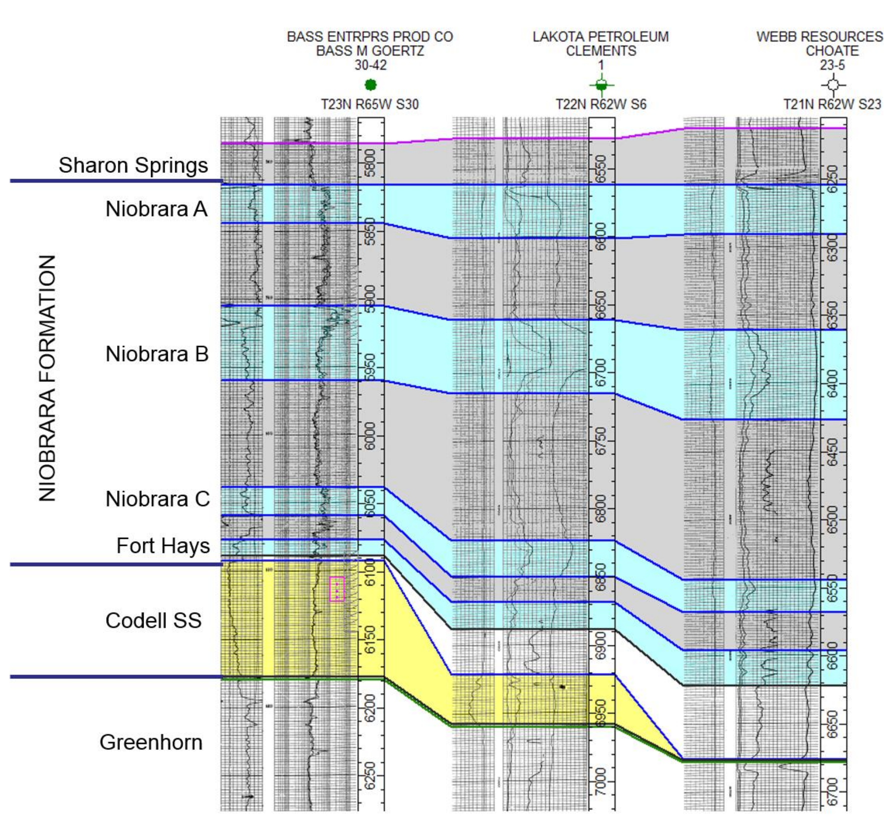


Type log, Niobrara and Codell, Wattenberg Field

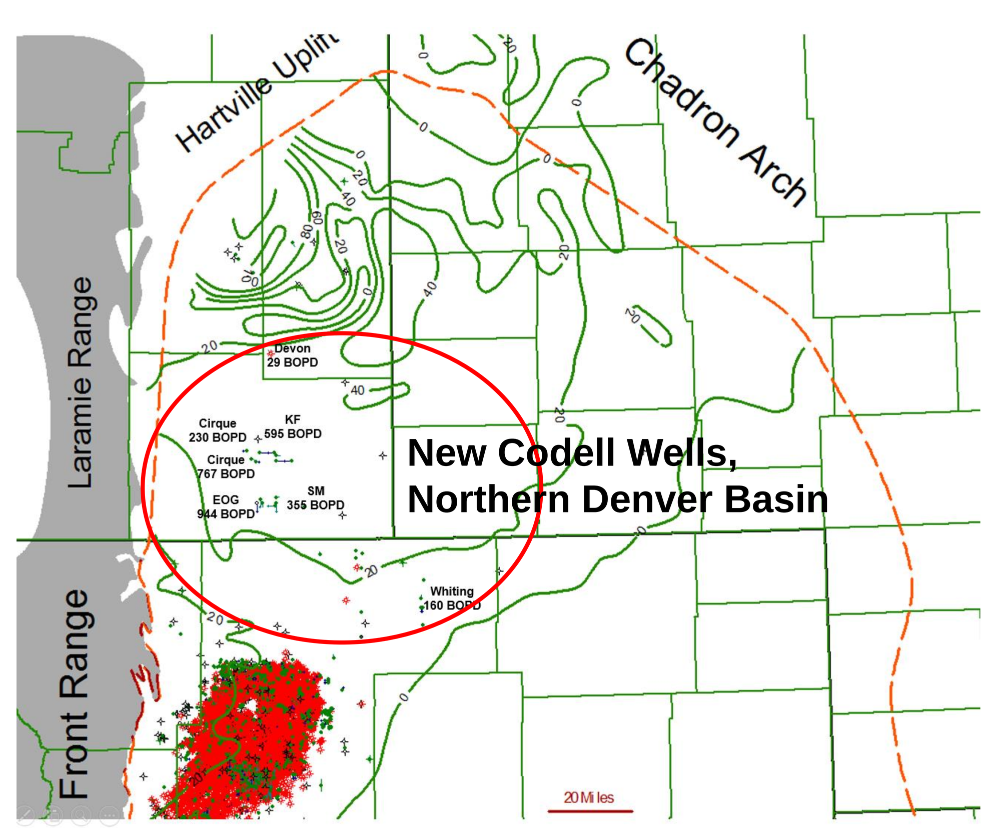
TYPE 3 SANDSTONE



Isopach Type 3 Sandstone, northern Denver Basin

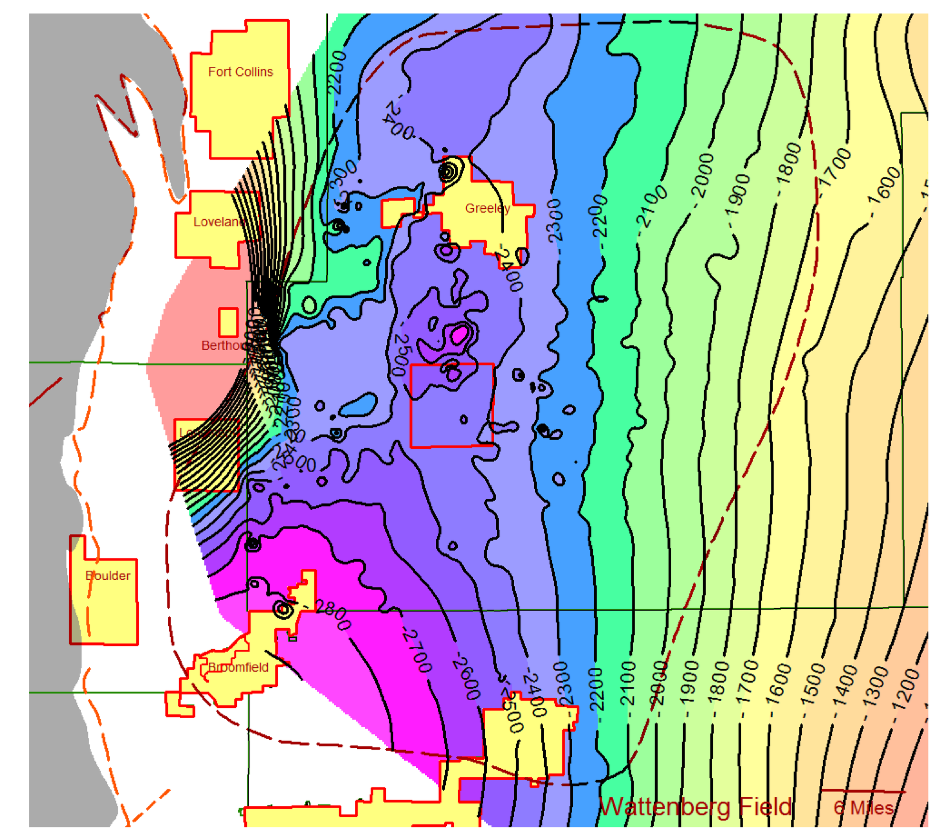


Cross-section Type 3 Sandstone, northern Denver Basin

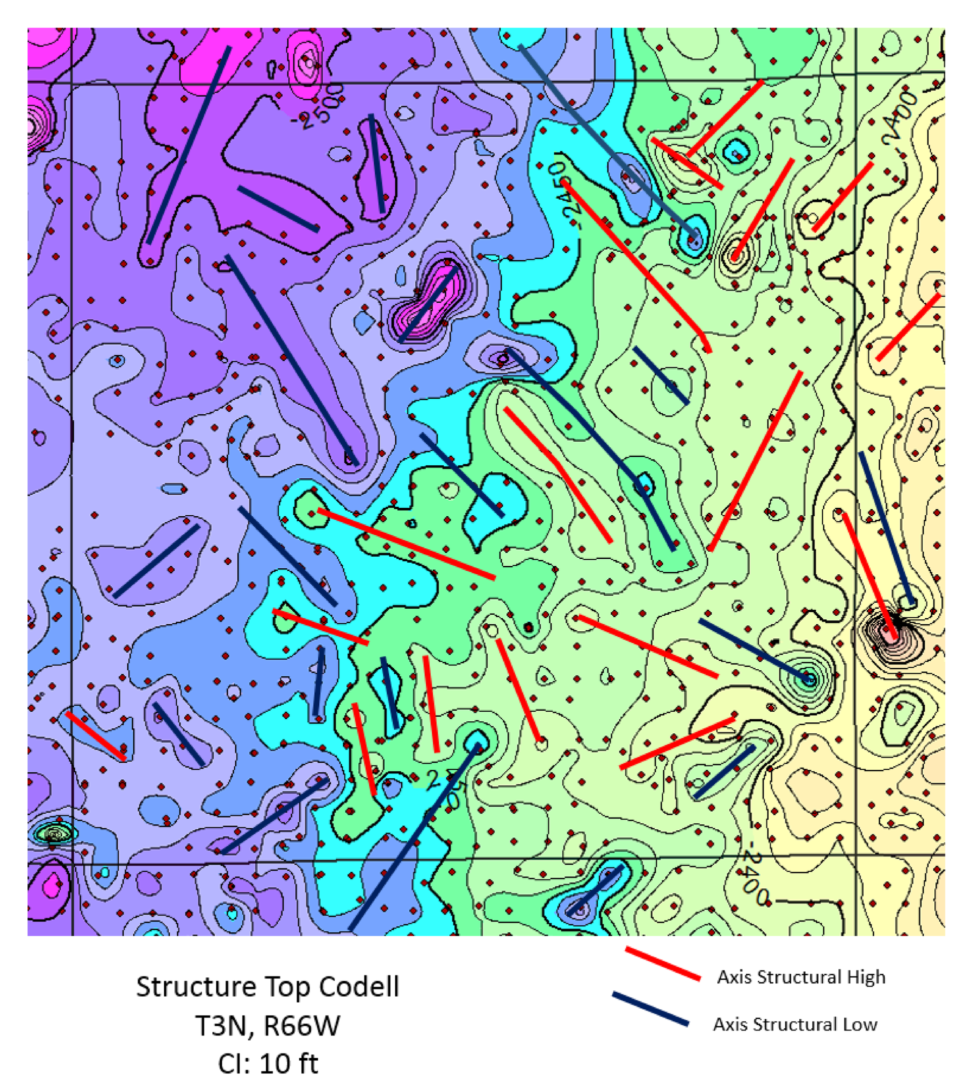


Drilling activity map northern Denver Basin. New drilling activity is occurring in SE Wyoming part of Denver Basin. Wells are being drilled horizontally and fracture stimulated.

Wattenberg Field Structure

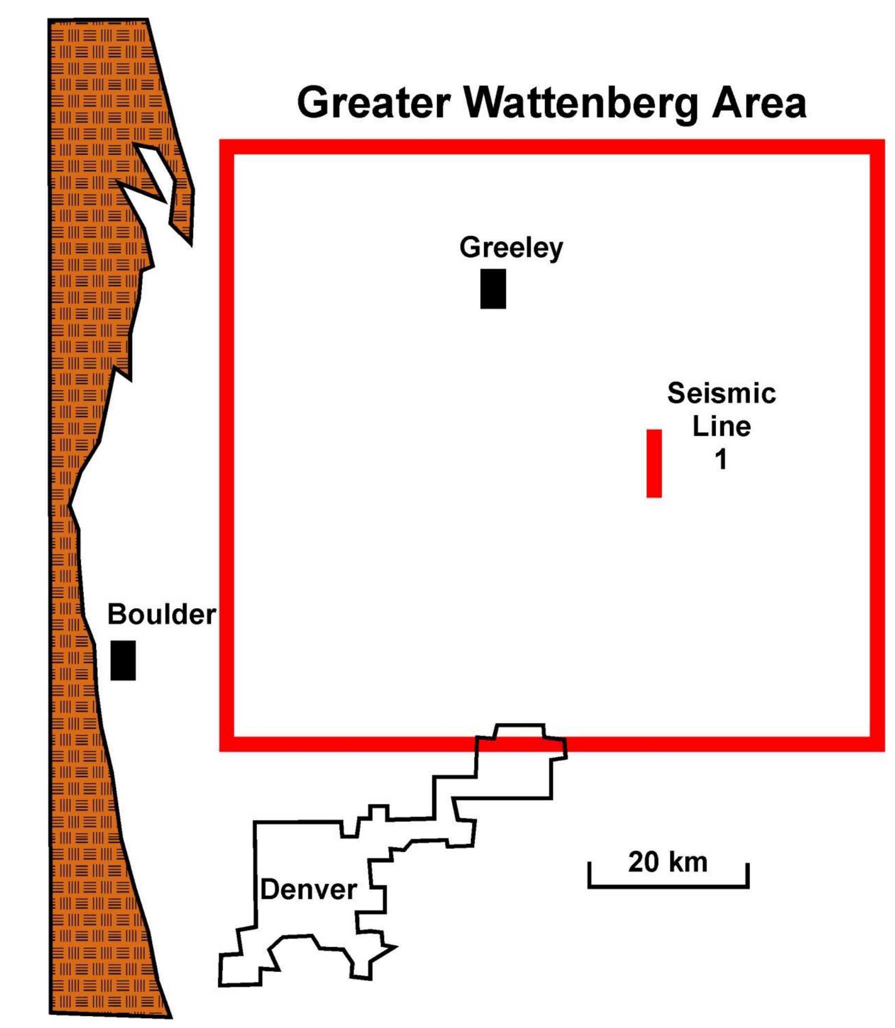


Structure map top Codell Sandstone, Wattenberg Field area (well control not shown). Contour interval is 100 ft. Outline of wells assigned to Wattenberg shown by dashed outline. Wattenberg is regarded as a basin-center accumulation which straddles the synclinal axis of the Denver Basin.

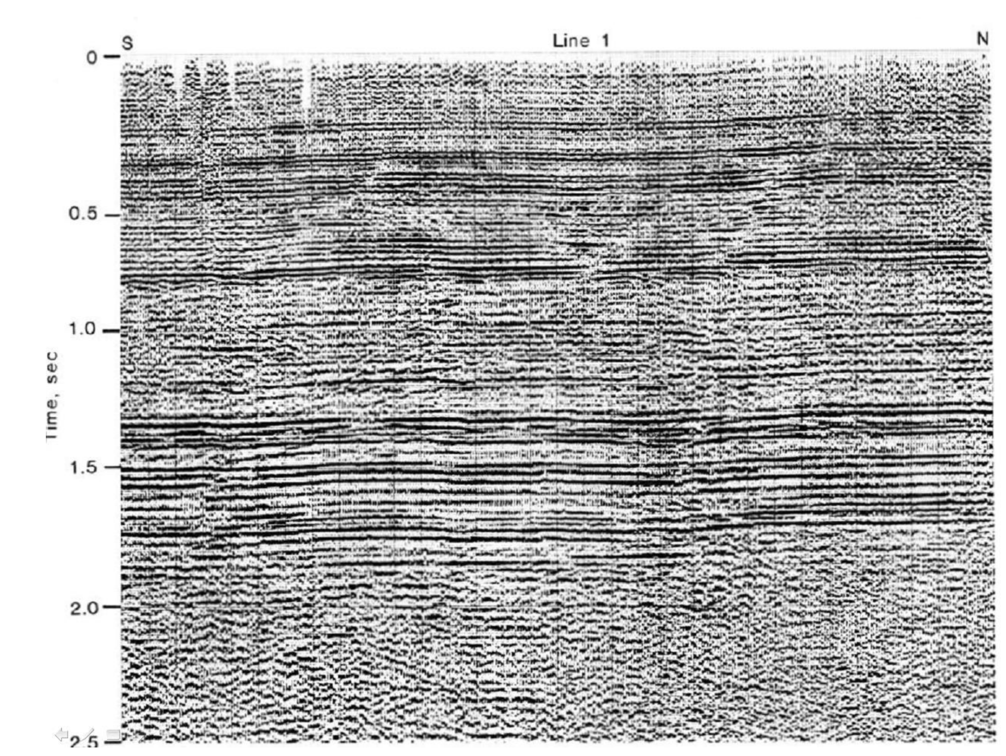


Structure map top of Codell Sandstone for T3N, R66W. Contour interval is 10 ft. Axes of structural highs and lows shown by red and blue lines. Note somewhat random orientation of axes.

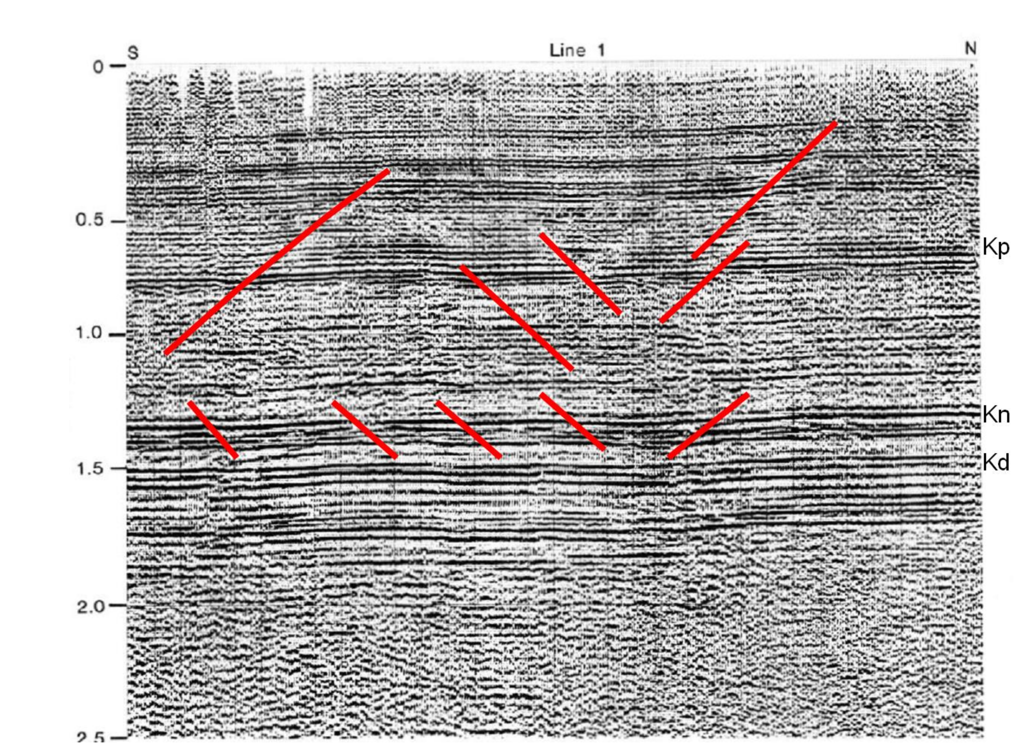
Wattenberg Faulting



Location map of seismic line shown below. Red outline is Greater Wattenberg area.



2-D seismic line from Wattenberg Field, from Davis 1985.



2-D seismic line with interpreted faults. Kn = Niobrara; Kd = Dakota Sandstone; Kp = Pierre marker.

Codell Sandstone, Denver Basin
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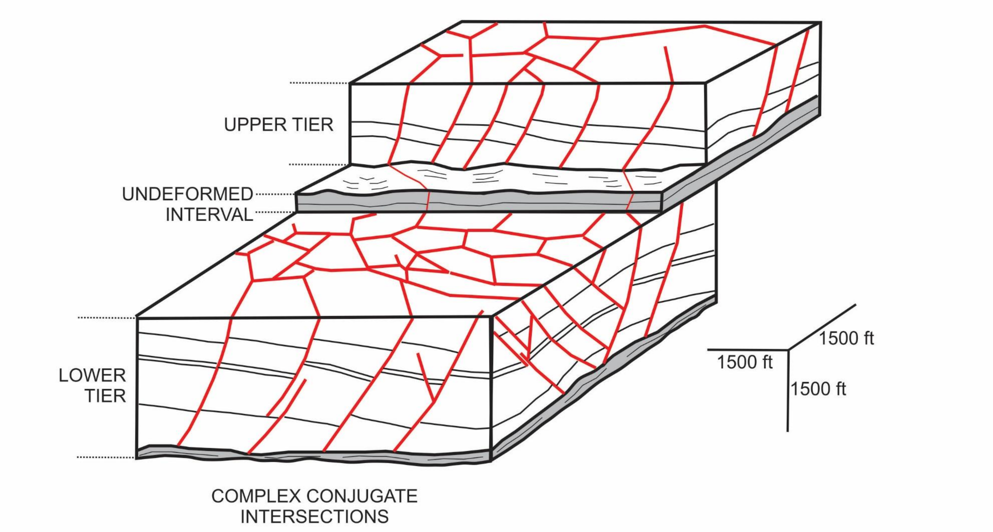
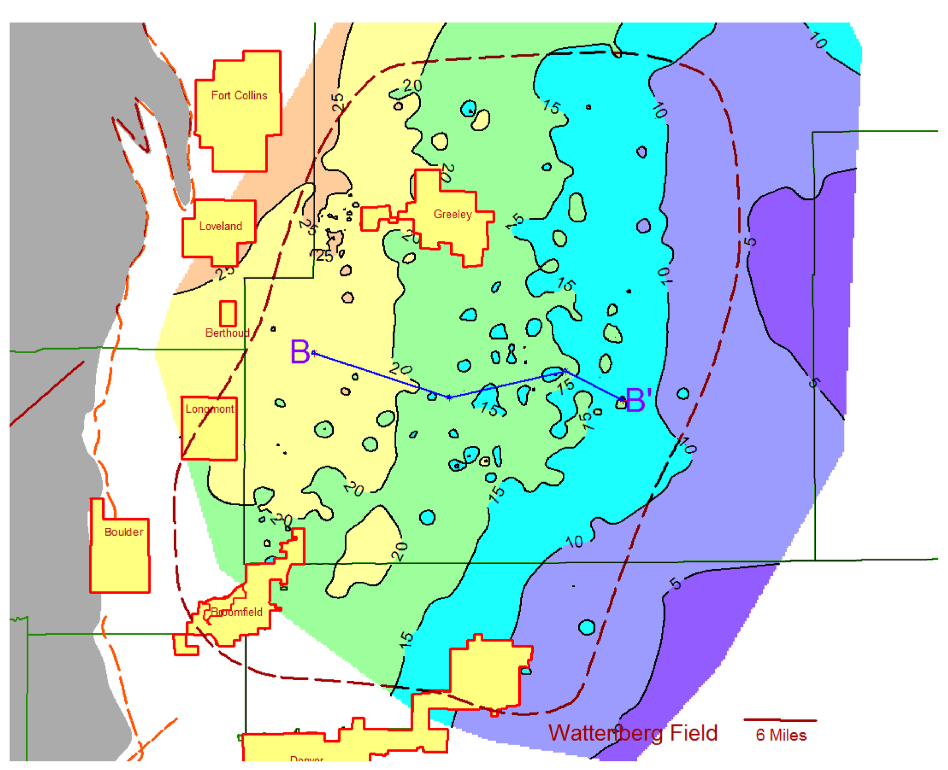
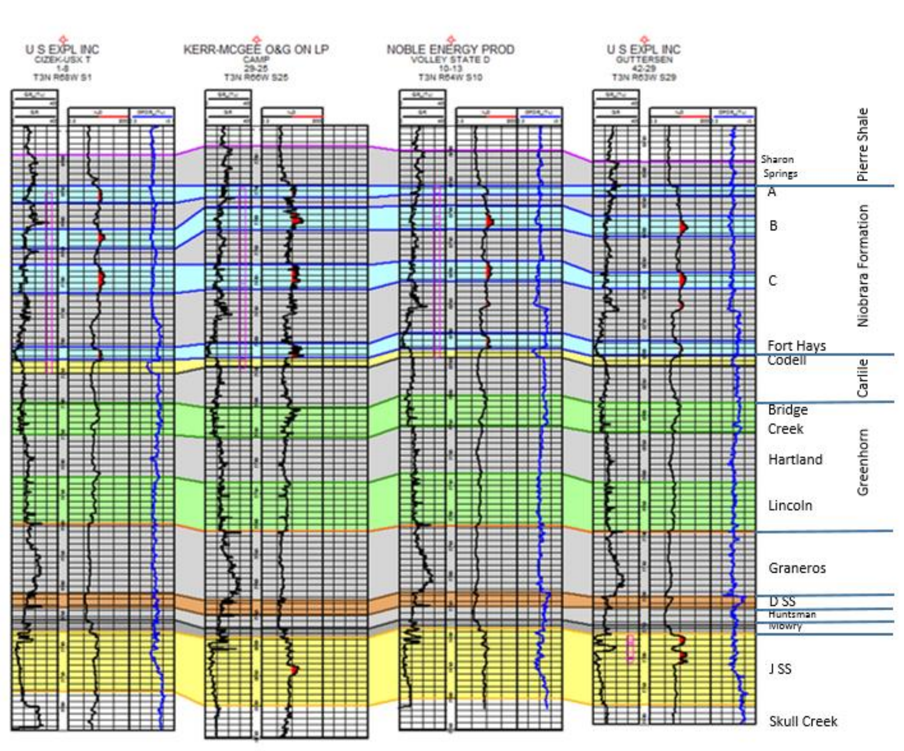


Model illustrating polygonal fault model, from Cartwright, 2013.

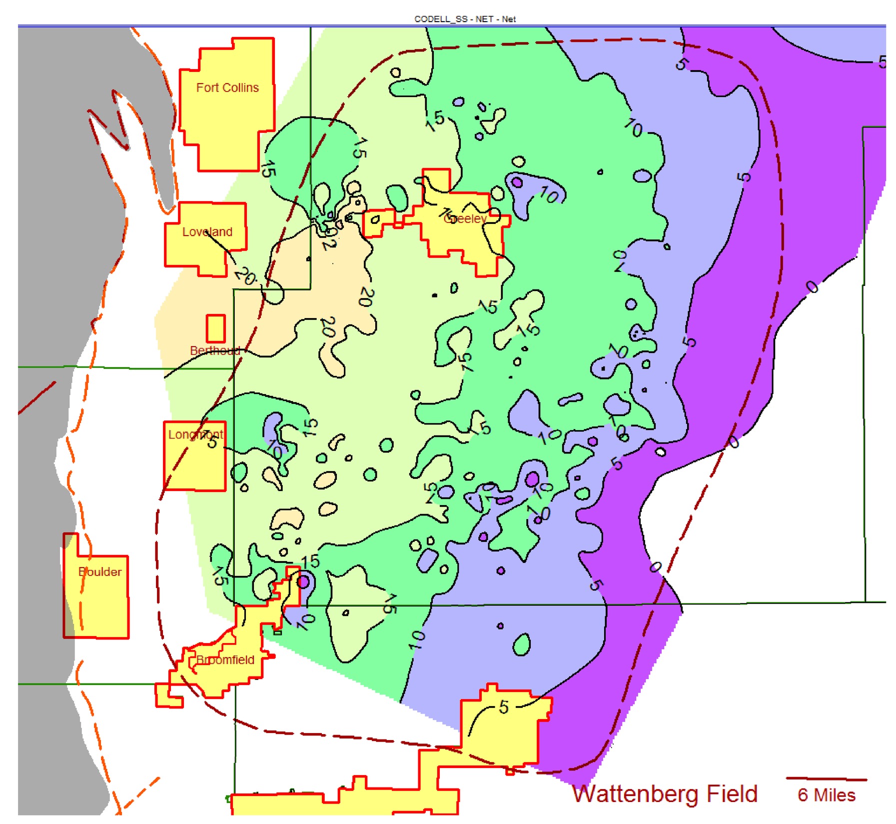
Wattenberg Field Stratigraphy



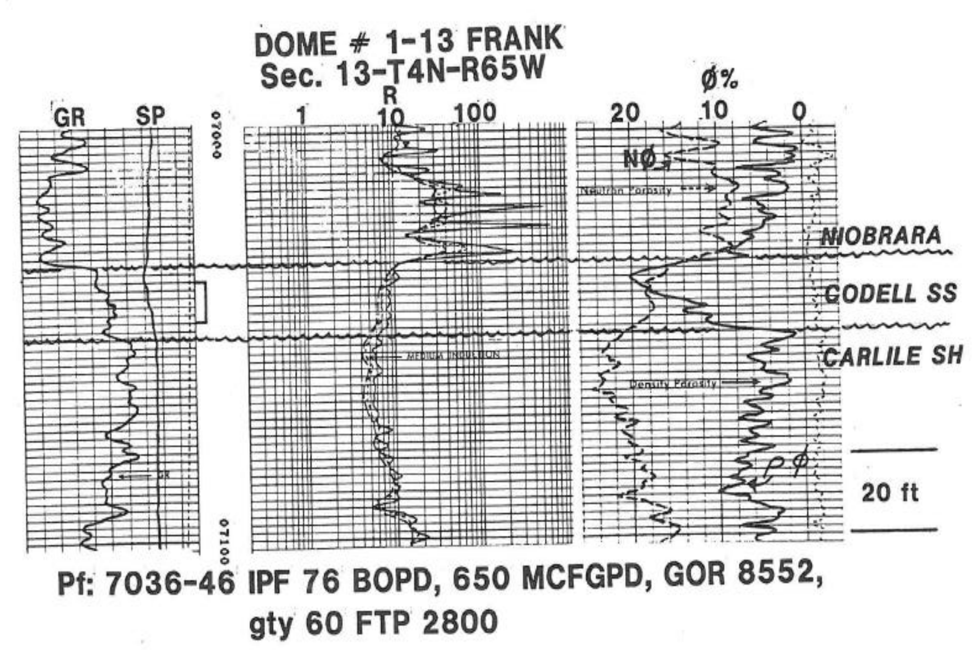
Isopach map of Codell Sandstone, Wattenberg Field. Contour interval is 5 feet.



West to east cross section across Wattenberg Field showing the Codell Sandstone and adjacent units.



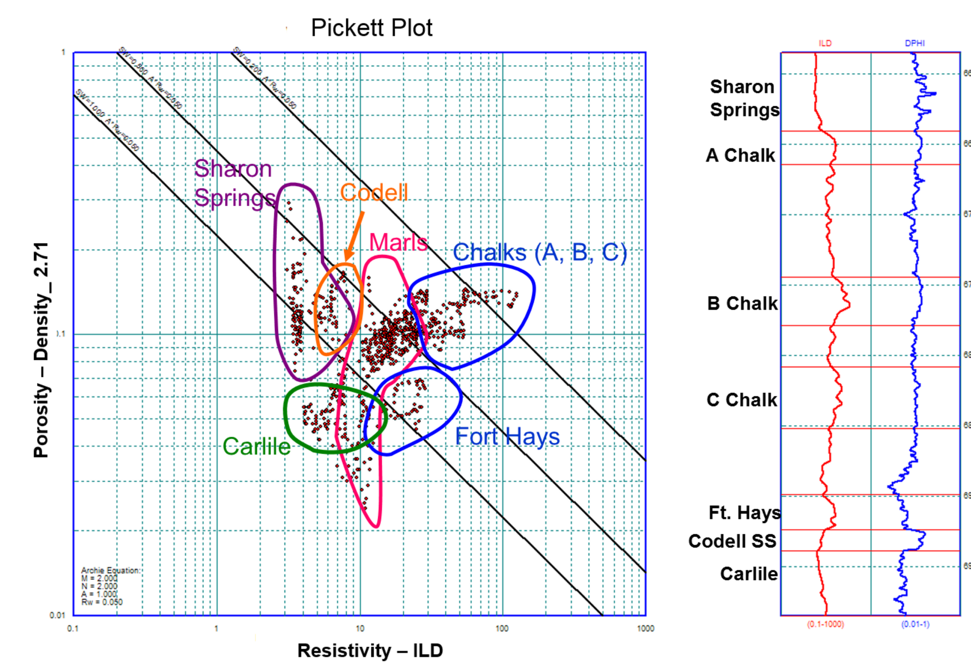
Isopach map of net sandstone in Codell interval defined by porosity great than 10 percent. The highest net values occur on west side of map area.



Well log for the Codell Sandstone interval from a typical well in Wattenberg Field. The Codell Sandstone is a low resistivity, low contrast pay because of the clay and pyrite content of the sandstone.

Well Number:	Dome Franks #1-13		
Sample Depth:	7030'	7031.5'	7037'
Whole Rock Mineralogy			
Quartz	77	69	75
Potassium Feldspar	-	-	-
Plagioclase	6	7	7
Calcite	4	9	5
Siderite	-	-	tr
Pyrite	tr	tr	-
Illite-Smectite	11	12	9
Illite+Mica	2	2	2
Kaolin	tr	tr	tr
Chlorite	1	2	2
Relative Clay Abundance			
Illite-Smectite	77	75	70
Illite	11	14	15
Kaolin	2	1	-
Chlorite	9	11	14
% Smectite in Illite-Smectite	25-30	25-30	20-25

XRD analysis of the Codell Sandstone from the Dome # 1-13 Frank well (see figure 7). The Codell is a clay-rich, highly quartzose, bioturbated sandstone in the Wattenberg area. From USGS CRC.



Pickett plot of Niobrara and Codell illustrating petrophysical analysis suggesting that Codell is wet.

Dome Frank
13-T4N-R65W
Permeability Data
2700 psi
Net Effective Stress

Depth:	Perm (md)
7030	0.000661
7031.5	0.000299
7037	0.000779

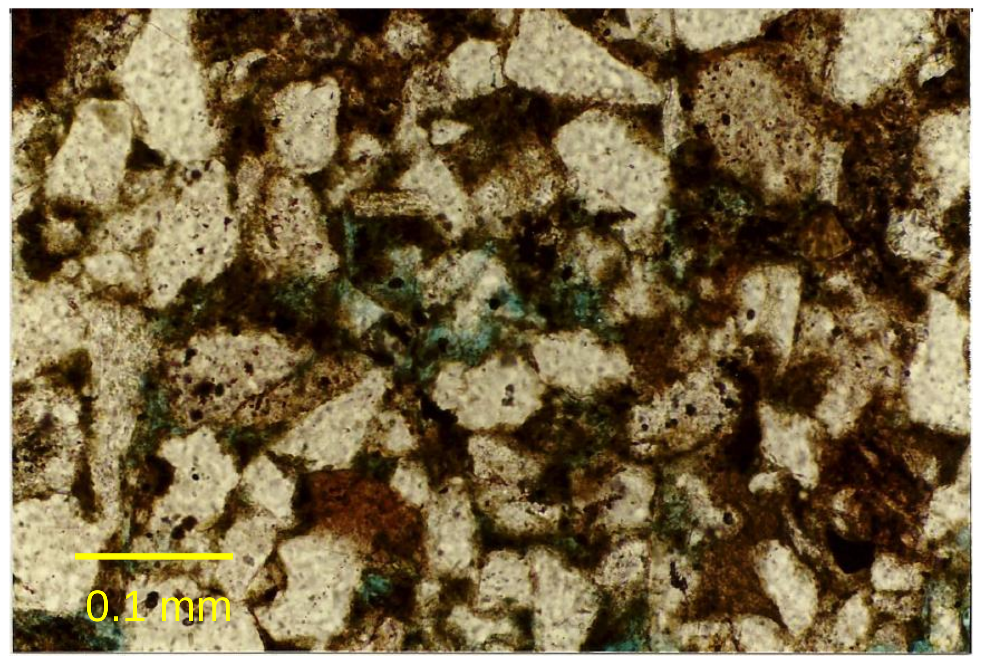
USGS CRC DATA

Permeability data from Codell Sandstone, Dome Frank well.

Core photos of from the Dome #1-13 Frank core. The Codell Sandstone is a bioturbated, silty, clay-rich sandstone. From USGS CRC, 2013.

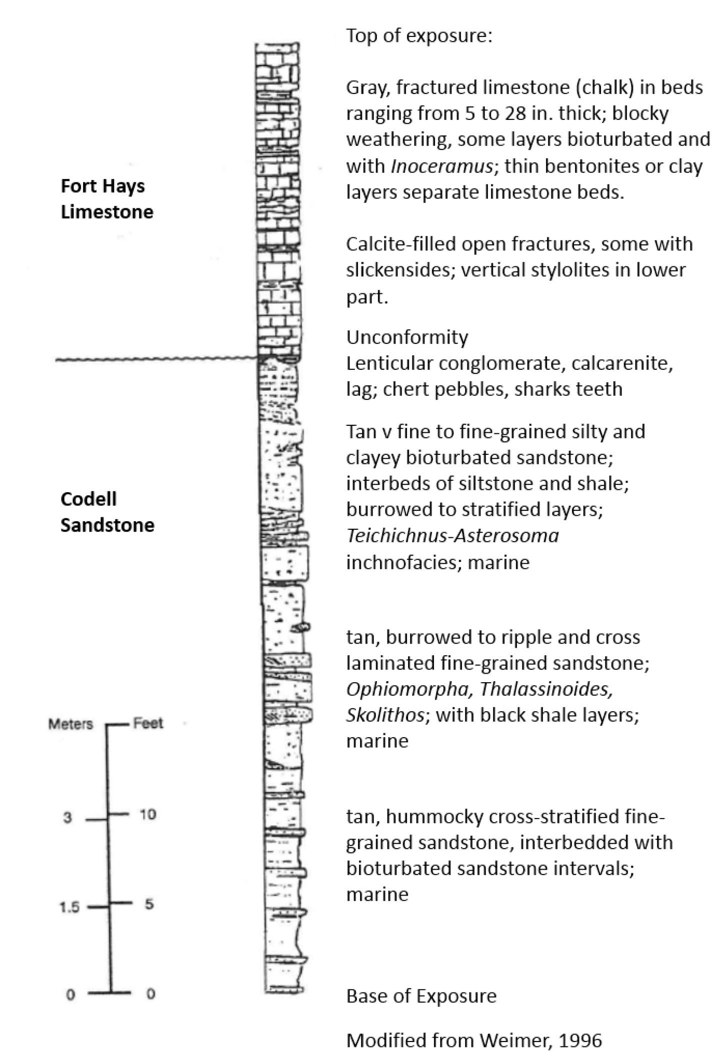
Petrographic Analysis

- Moderately well sorted, very fine- to fine-grained sublitharenites and subarkose
- Slight to moderate compaction
- Ductile deformation of incompetent grains
- Partial dissolution of chert, and mica
- Porosity and permeability inhibiting cements include: Mixed layer illite/smectite, illite, chlorite, quartz overgrowths, and calcite



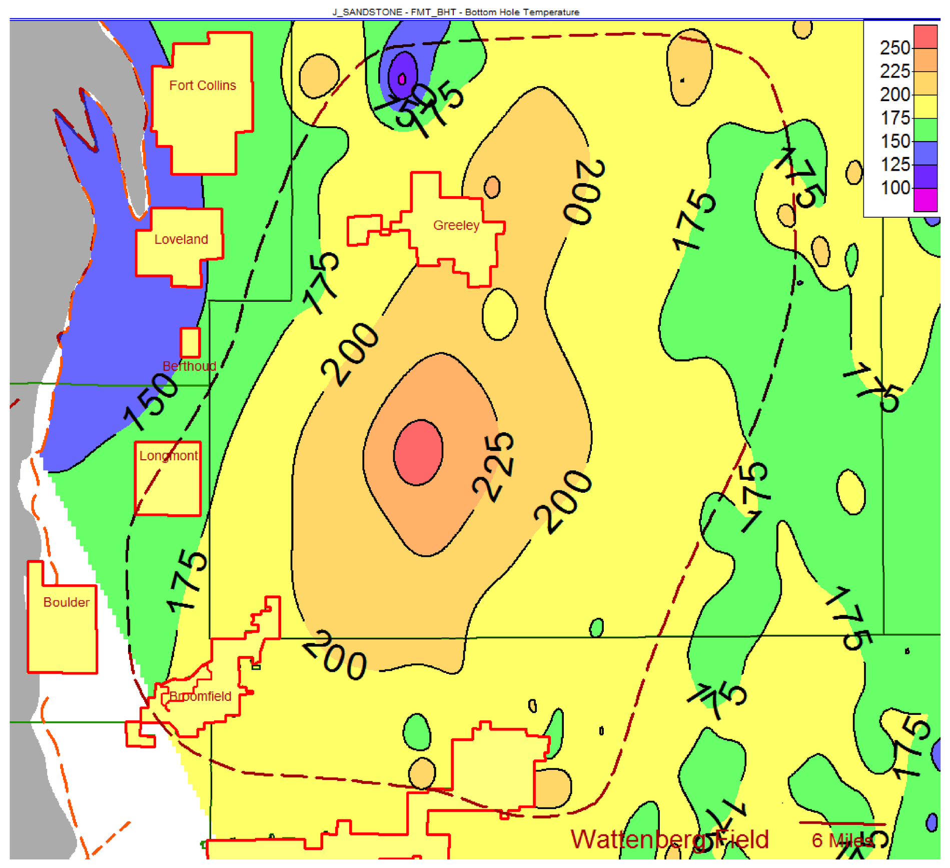
Plain polarized light photomicrograph, Codell Sandstone. Note fine-grained nature of sandstone, and porosity development in blue.

"More than 80% of the porosity has pore throats smaller than 0.25 μm in diameter, which by all standards, is a microsized pore throat. Traditional sandstone pore throats are larger than 5 μm, while siltstone pore throats are larger than 2 μm" Pagano, 2006

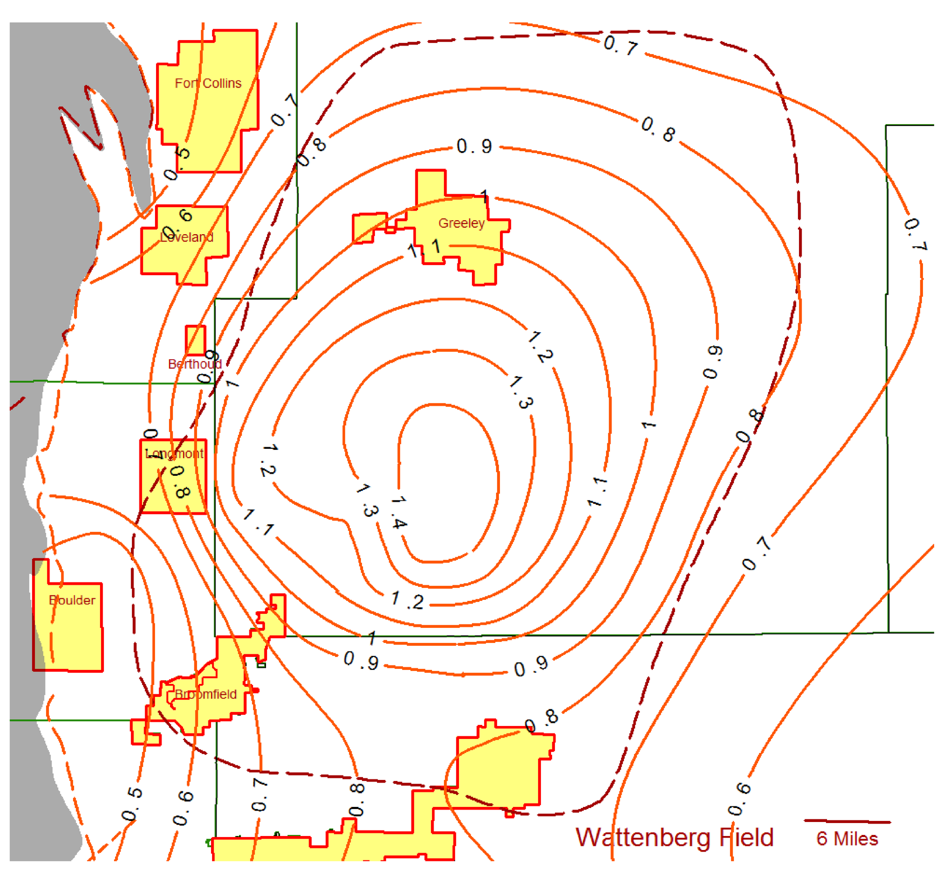


Outcrop description of Codell Sandstone, HW 36, north of Boulder, CO.

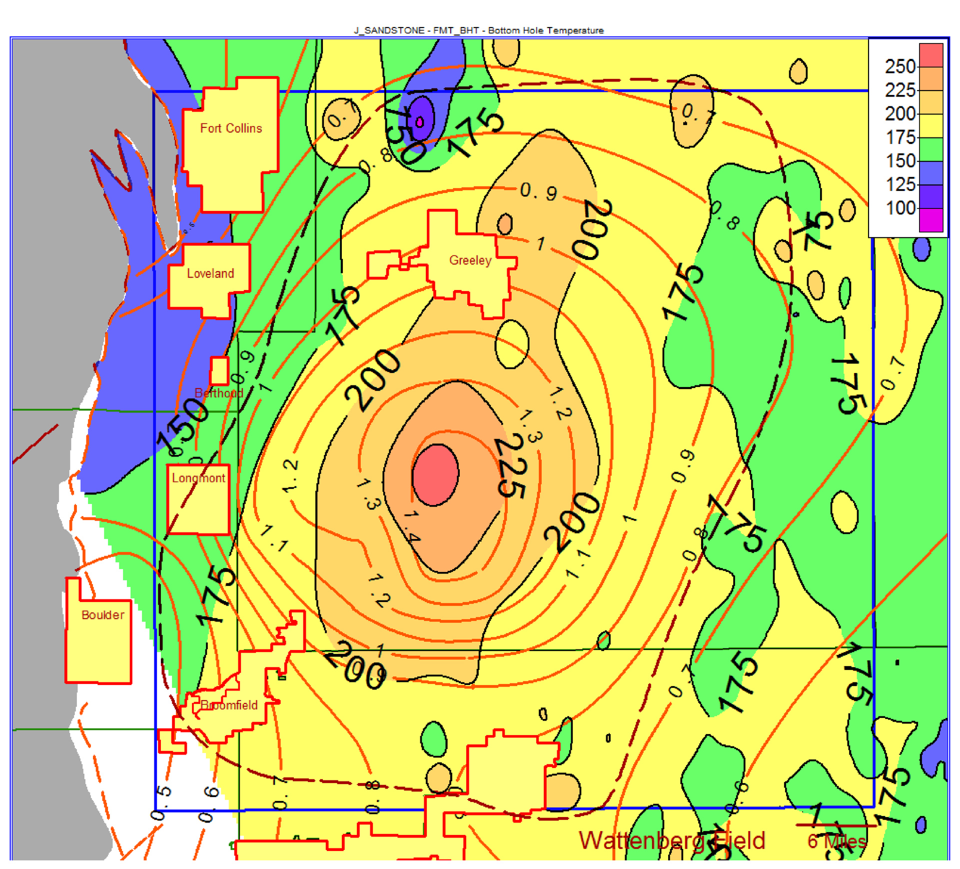
Codell Sandstone, Denver Basin
4



Bottom hole temperature map, J Sandstone, Wattenberg Field.



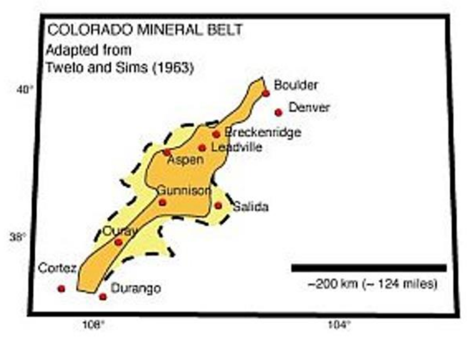
Vitrinite reflectance map, J Sandstone, from Higley and Cox, 2007

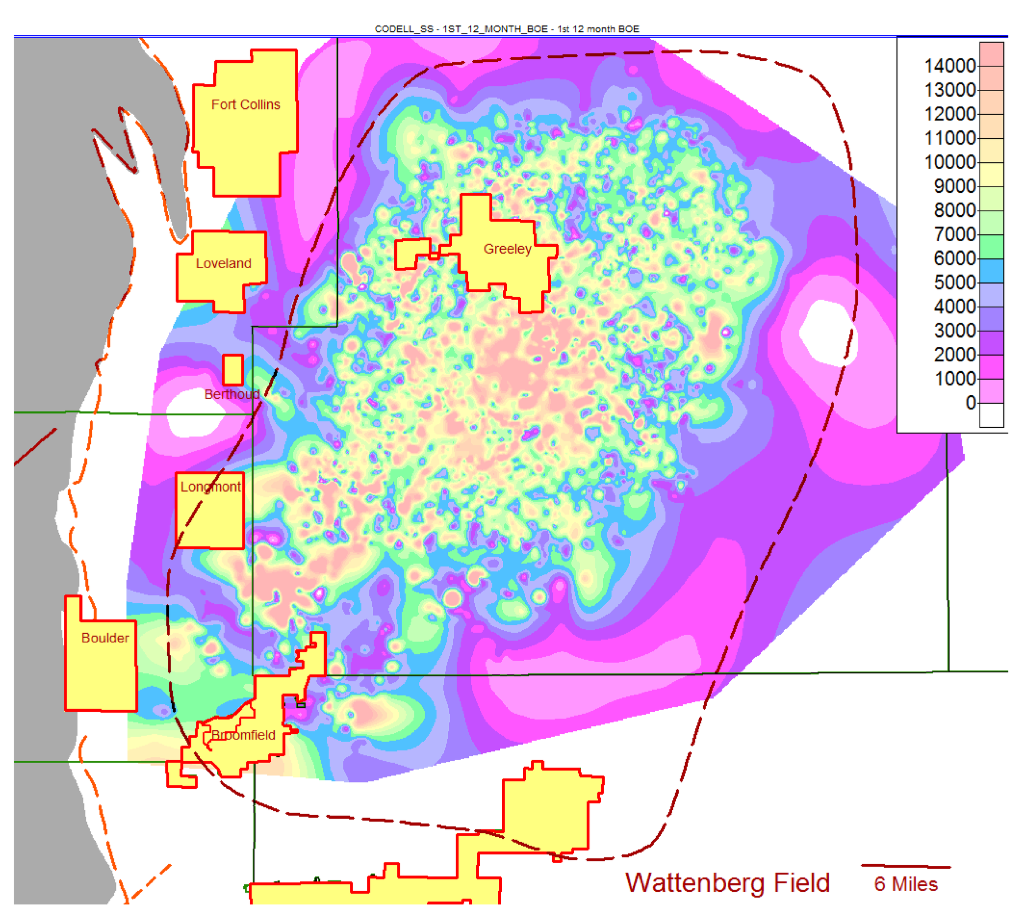


Iso-temperature from J Sandstone DST's and vitrinite reflectance contours for J Sandstone. Temperatures range from less than 175 ºF to over 250 ºF. Contour interval for bottom hole temperatures is 25 degrees. Vitrinite reflectance contours range from 0.5 to 1.4 percent. Contour interval for vitrinite reflectance 0.1.

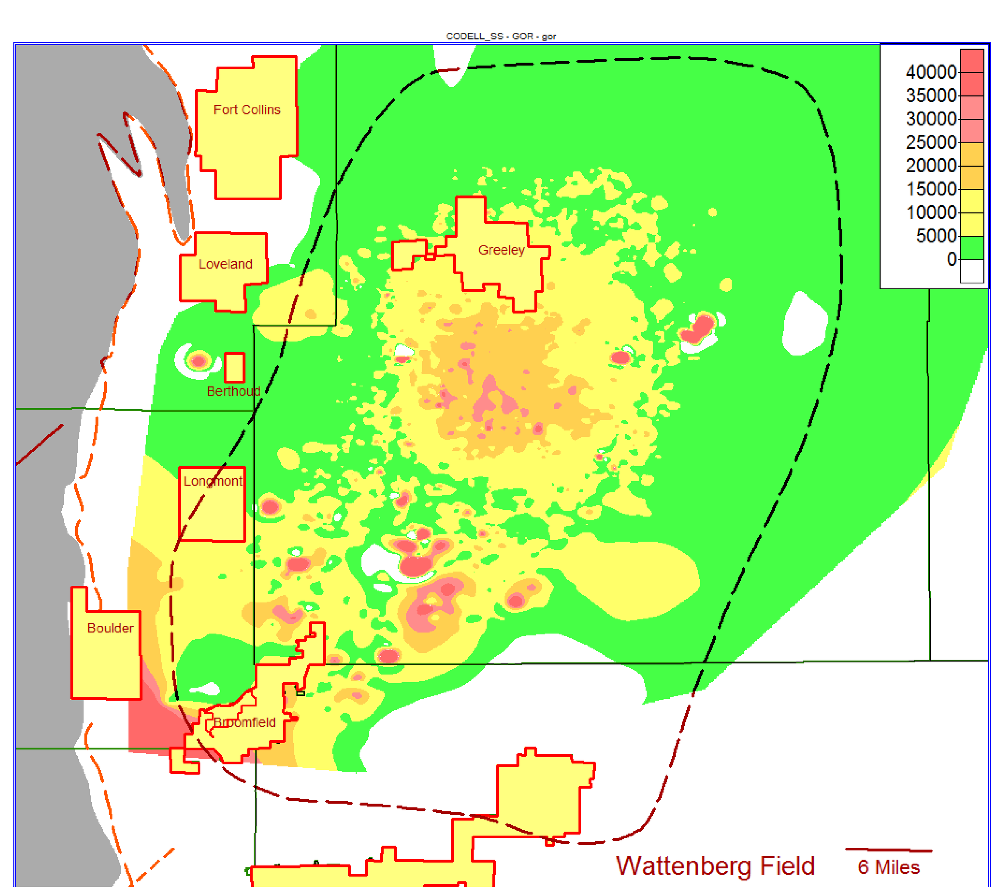
Wattenberg Thermal Anomaly

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

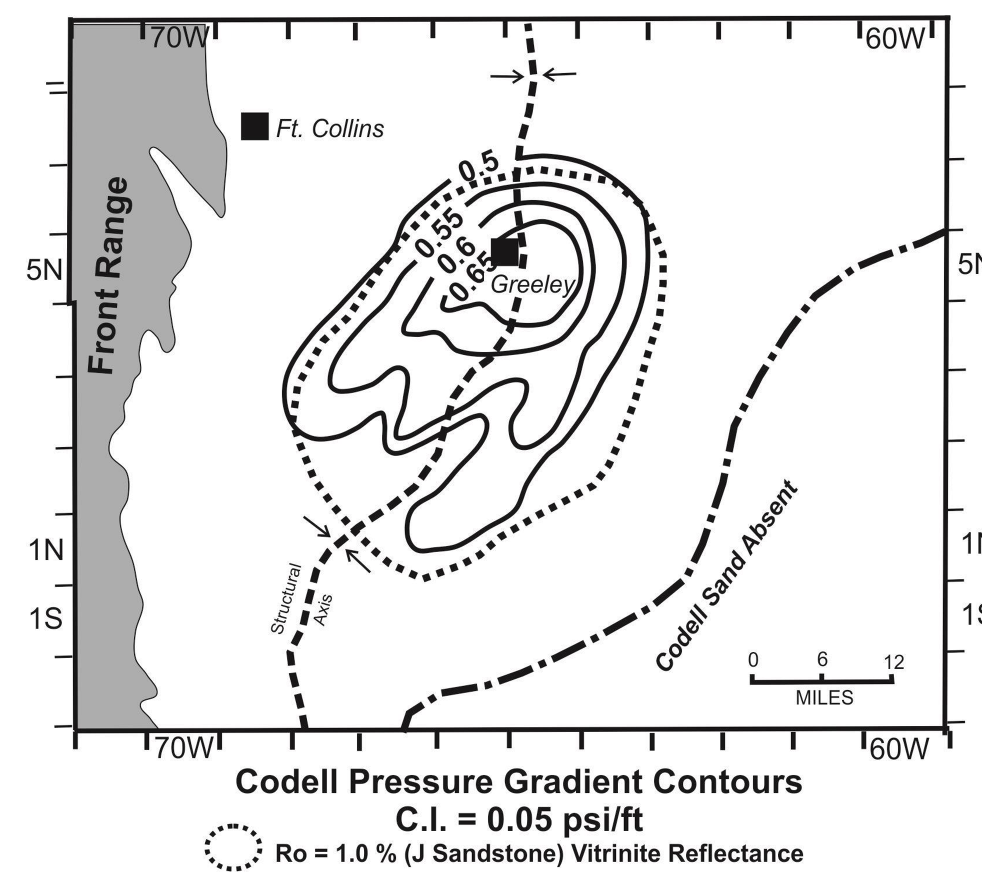




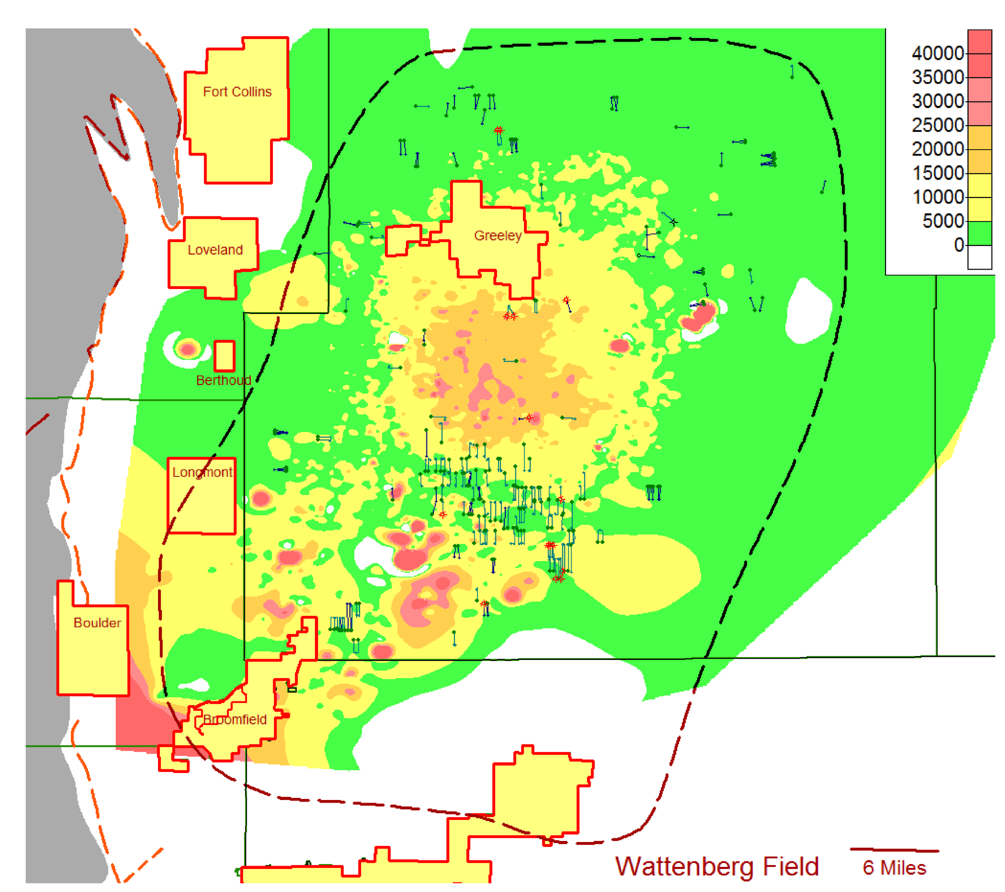
Barrels of oil equivalent production map for Codell Sandstone for first 12 months production. The production sweet spot areas are shown by yellow and red colors.



Gas oil ratio map for Codell producers. Note the high GOR area south of Greeley.



Codell pressure gradient contour map for Wattenberg Field (from Birminham, 2001). Highest pressures coincide with highest temperatures and highest GOR areas.



Location of some of the new horizontal Codell wells drilled from 2011 to P. Most wells are located in liquid-rich areas or areas flanking the high GOR area.

SUMMARY

The Codell Sandstone in the Wattenberg Field is a tight unconventional reservoir.

Geologic factors important for production include: proximity to thermally mature source beds; geothermal gradients; pressure gradients; fault bounded reservoir compartments; gas-oil ratios; sufficient reservoir quality (phi-h).

Drainage areas for Codell wells is quite small. Refracs of the Codell have proven to be highly successful in many areas of Wattenberg Field. Horizontal drilling and multistage fracture stimulation is now being utilized in Wattenberg development.

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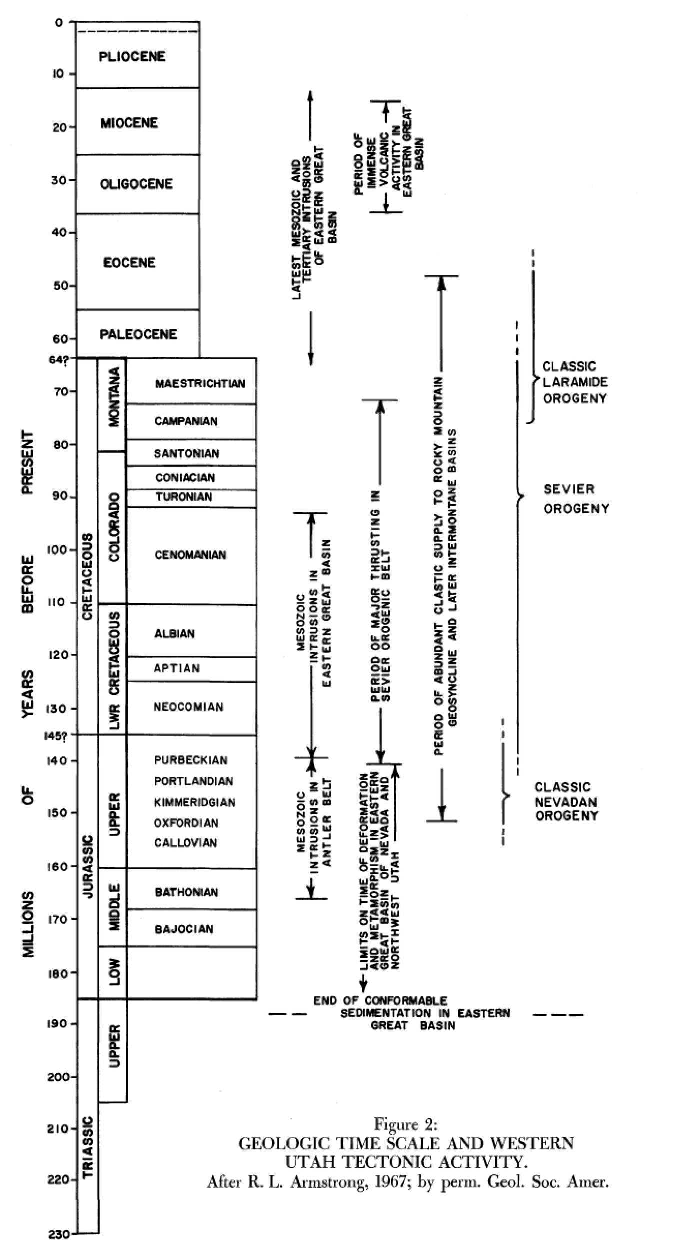
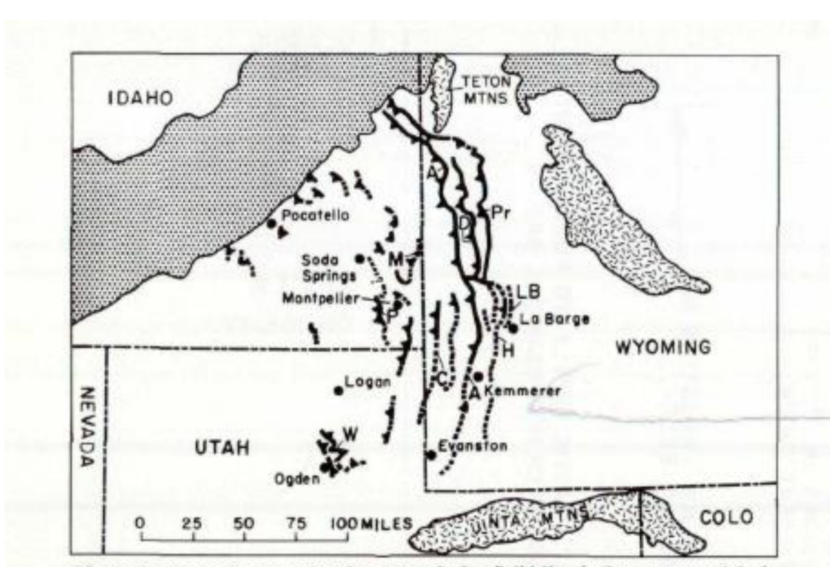
The Codell Regressive Sandstone Event
Thrust belt movement, sea level changes, paleogeography diagrams

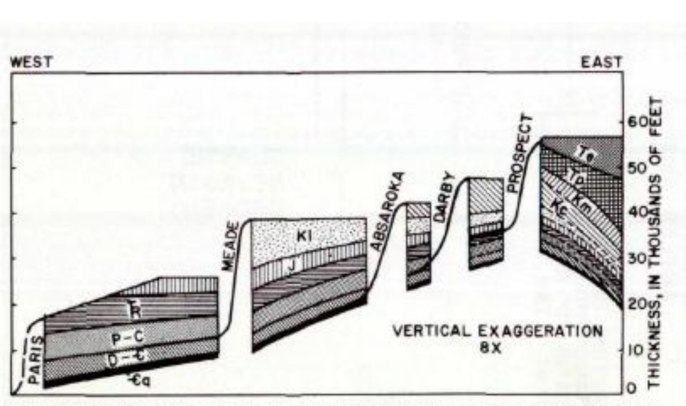
Thrust Belt Tectonics



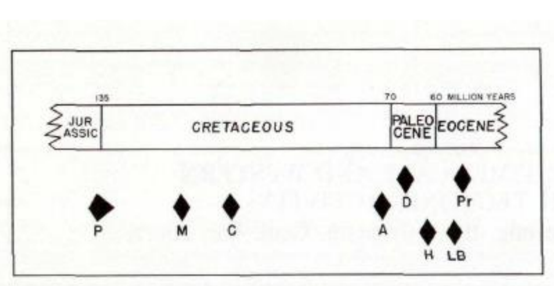
RMAG, 1972



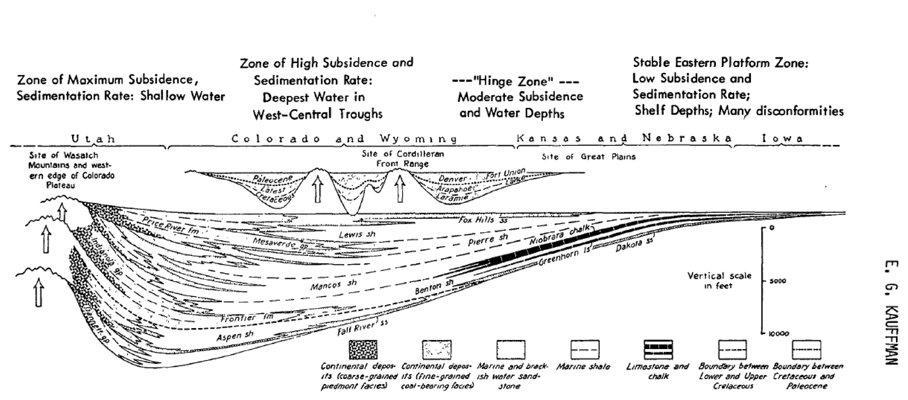
Major Thrust sheets, RMAG, 1972



Stratigraphic sections in thrust sheets, RMAG, 1972

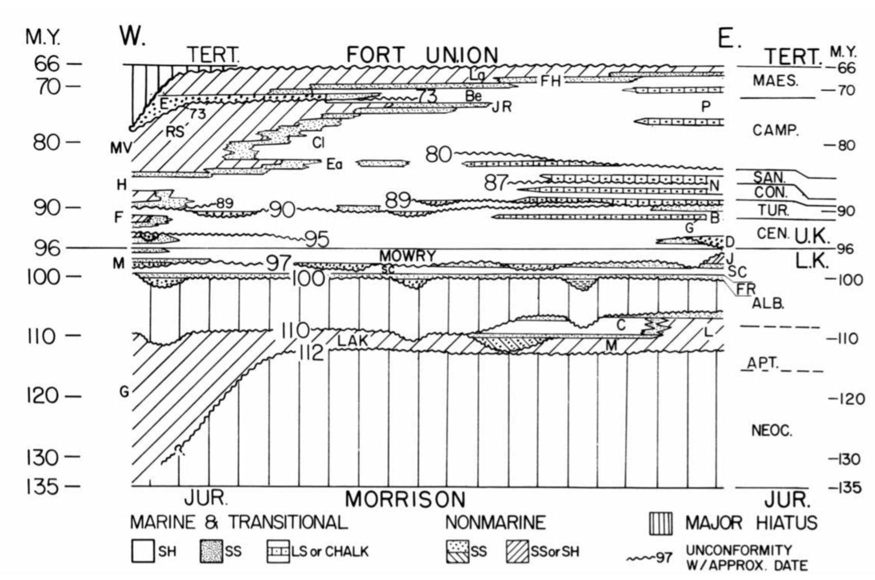


Estimated principal movement of thrust sheets, RMAG, 1972

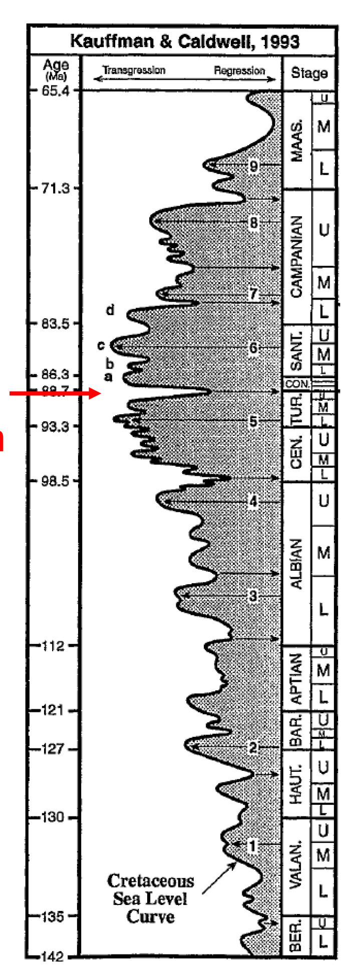


Kauffman, 1977

Unconformities and Sea Level Changes



Unconformities, Weimer, 1983



Niobrara
Codell
Greenhorn

Transgressions and regressions, from Longman et al., 1998 after Kauffman & Caldwell, 1993

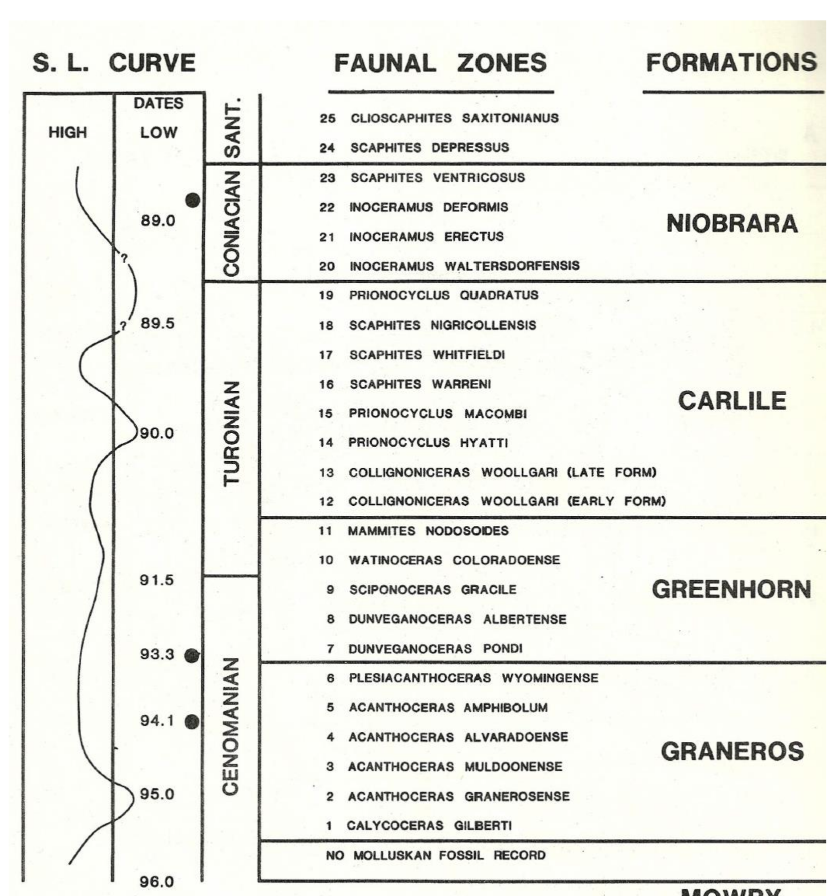
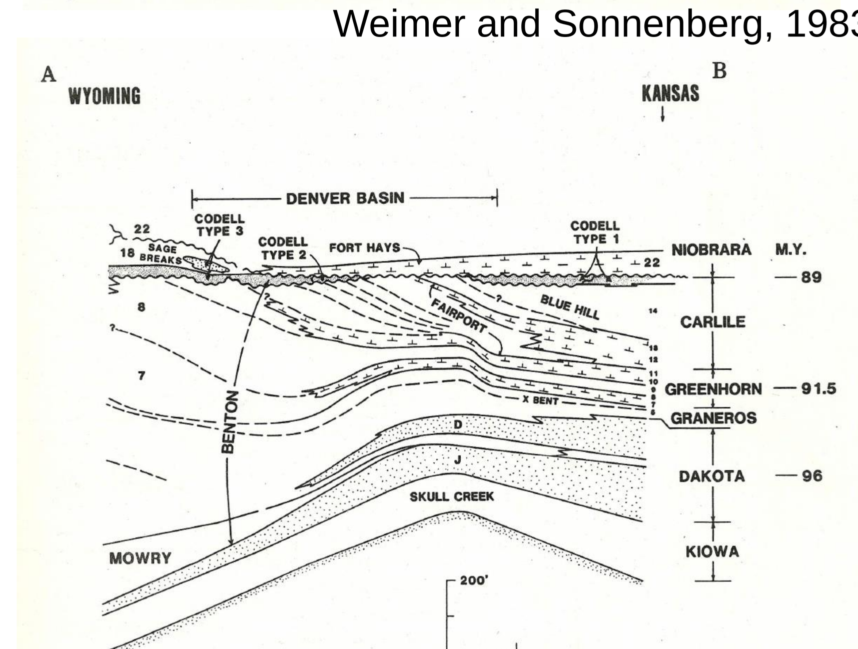


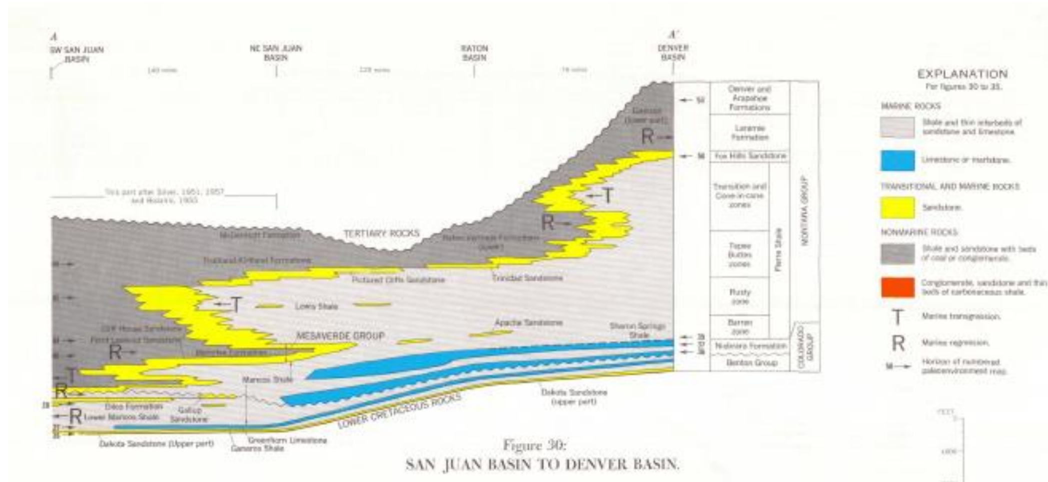
Figure 3 Faunal Zones and Formations with Sea Level Curve

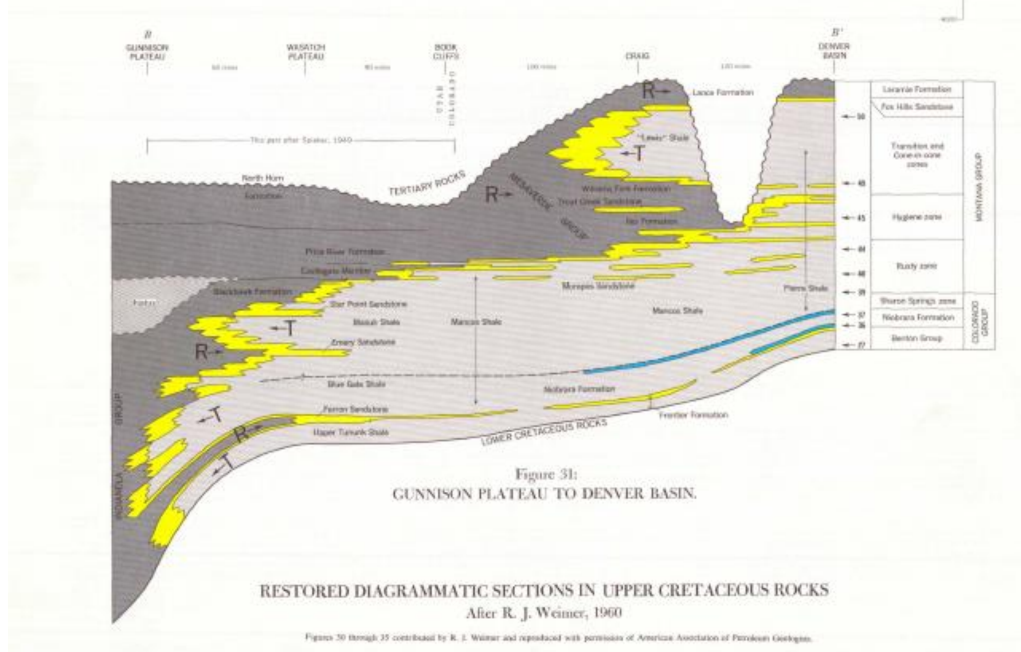
Weimer and Sonnenberg, 1983

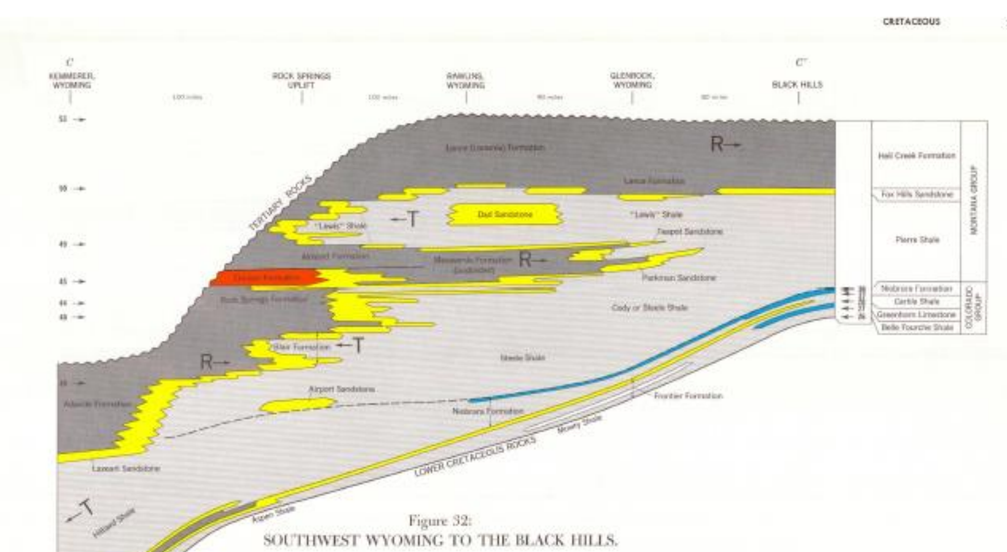


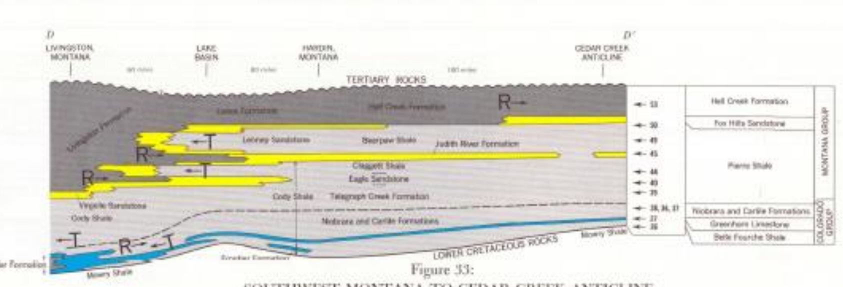
Weimer and Sonnenberg, 1983

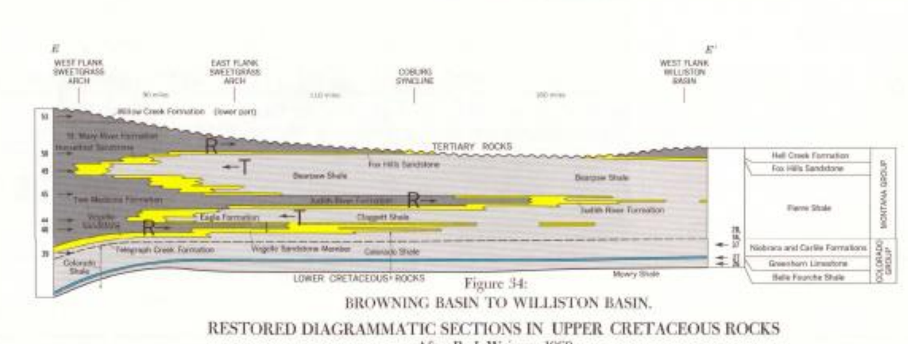
Weimer Cross Sections, from RMAG Atlas, 1972

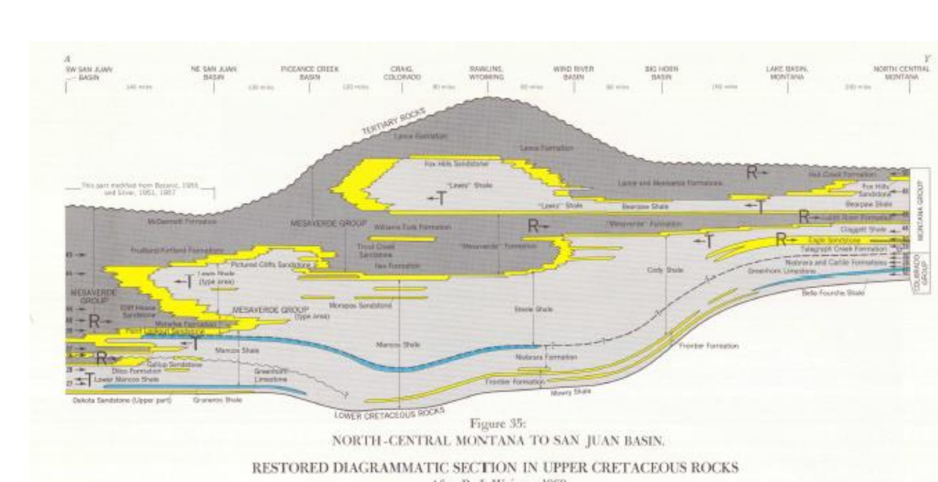






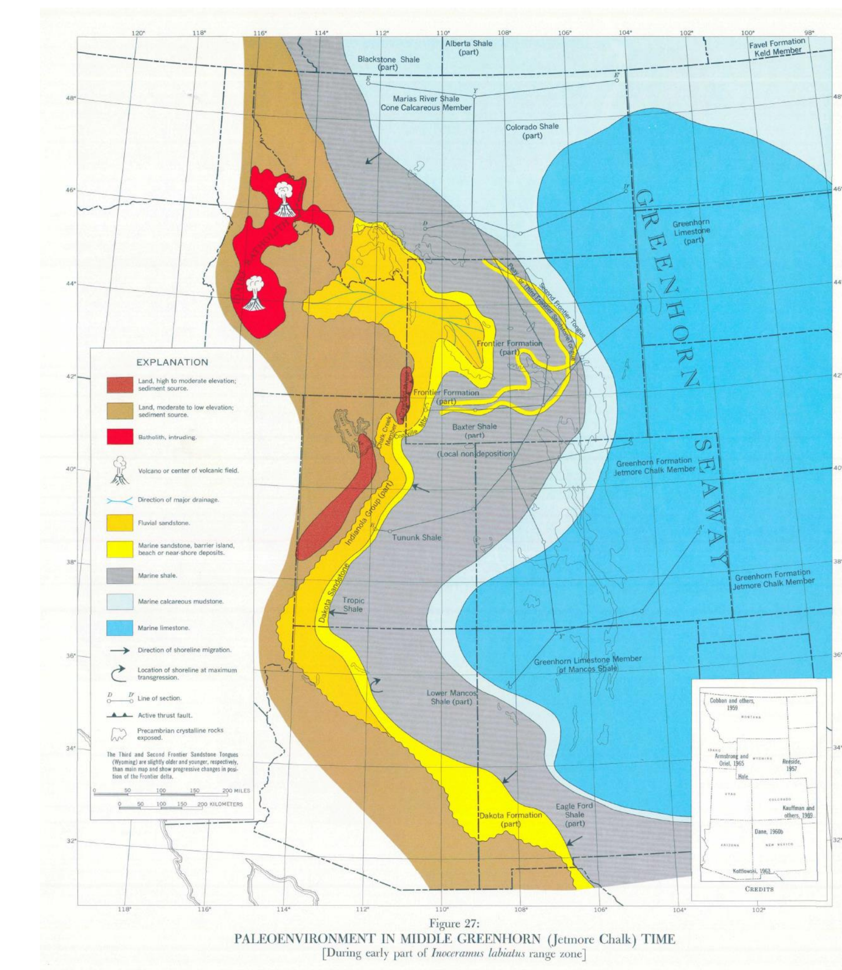




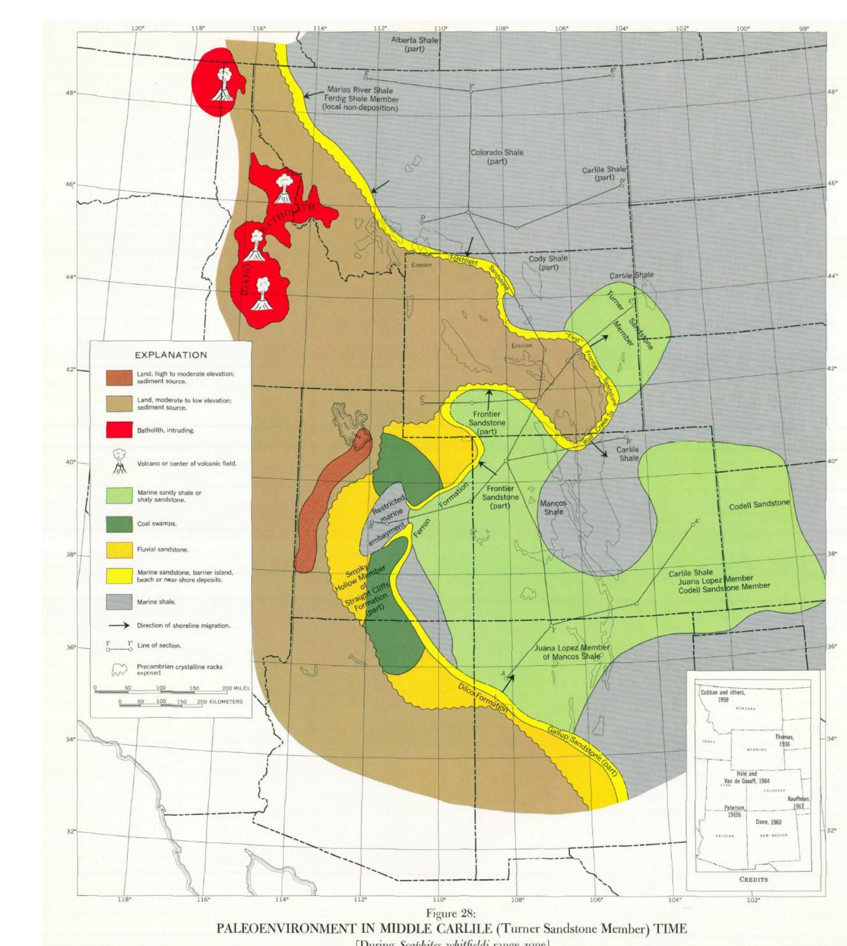


RMAG, 1972

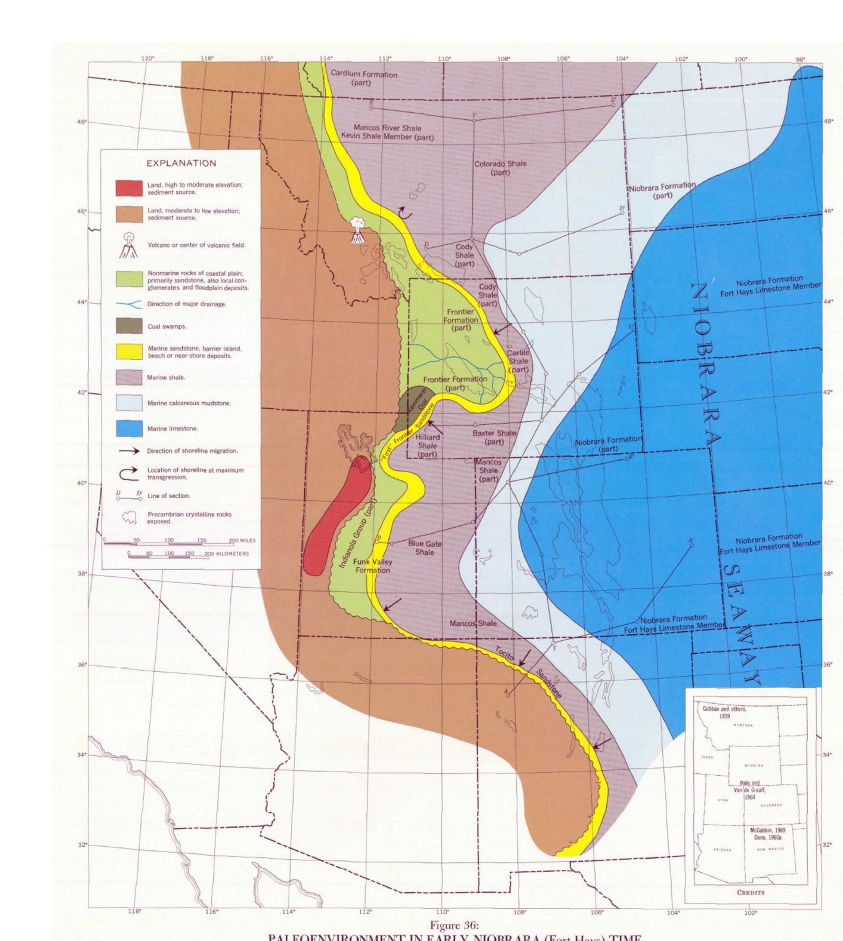
Paleogeography diagrams, from RMAG Atlas, 1972



RMAG, 1972



RMAG, 1972



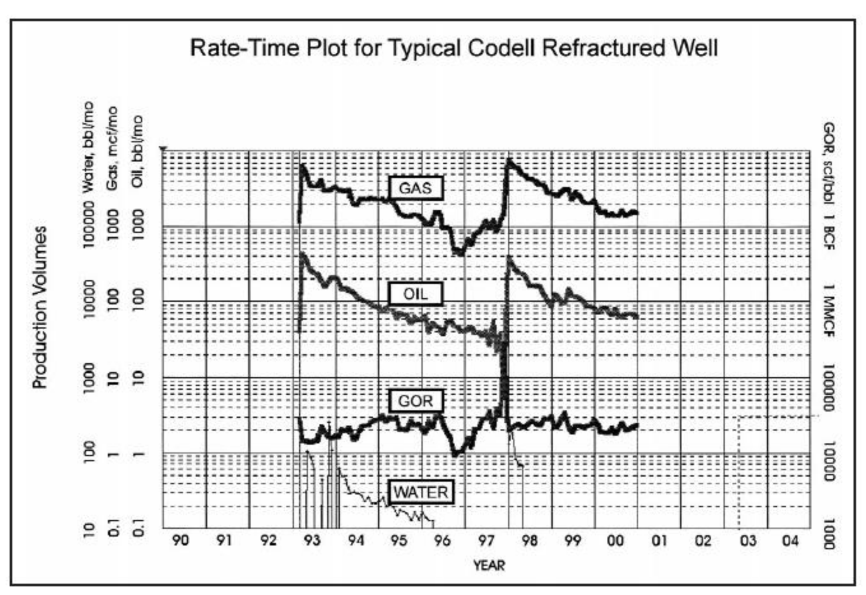
RMAG, 1972

Codell Refracs
Over 4,000 in Wattenberg Field

REFRACS

Concepts advanced to why refracs work in the Codell

1. Improved completion and stimulation practices
2. Extension of existing fracture half-lengths leading to increased reservoir drainage
3. Reorientation of hydraulic fractures leading to increased reservoir drainage
4. Combination of 2 and 3 above



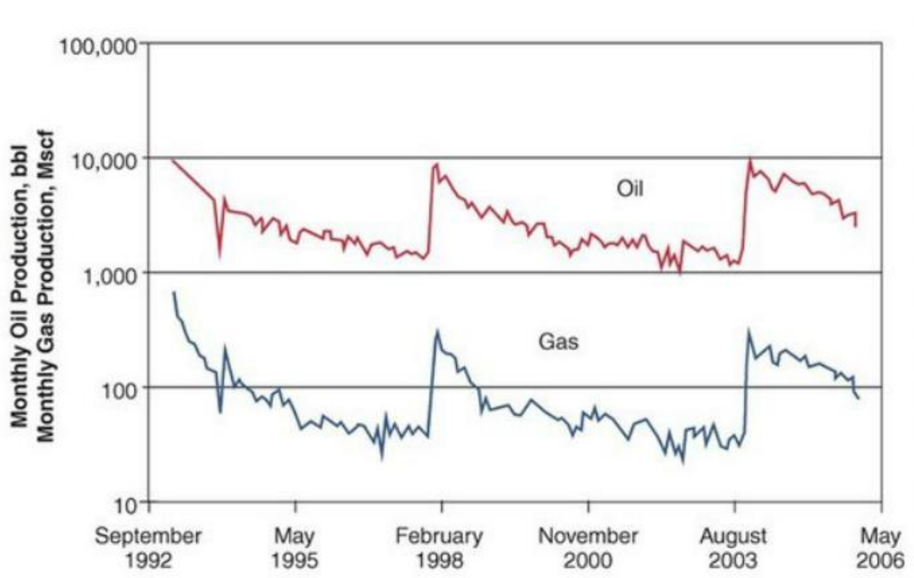


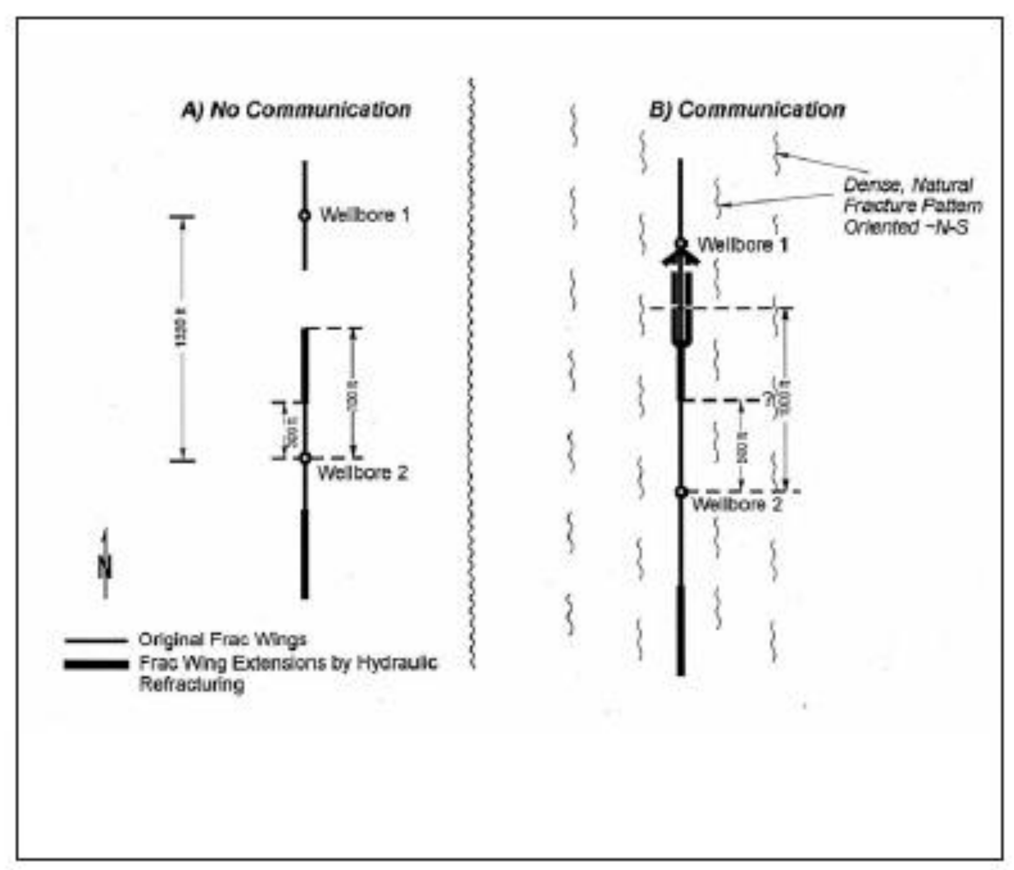
Fig. 4—Production after initial treatment, refracture, and trifracture of Codell interval (Pagano 2006).

Why do refracs work? (mechanisms)
From Vincent, 2014

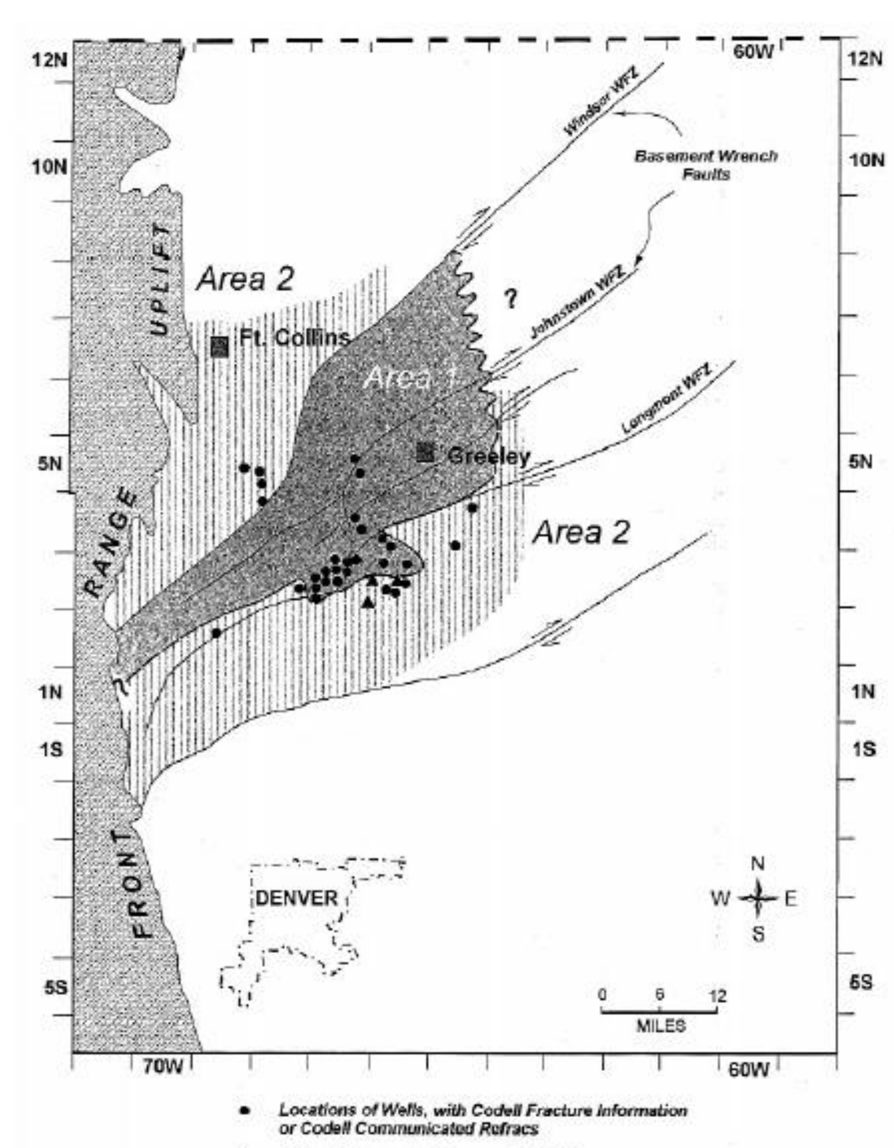
- Enlarged frac (more reservoir contact)
- Improved pay coverage in vertical wells
- Better lateral coverage in horizontal wells
- Increased frac conductivity
- Restore conductivity lost – frac degradation
- Address unpropped poorly propped portions
- Improved wellbore-to-frac connection/conductivity
- Reorientation
- Use of more suitable frac fluids
- Re-energizing natural fissures
- Other mechanisms

Extension of existing fracture half-lengths

Typical refrac design: 260,000 lbs proppant and 135,000 gals cross-linked gel performed to reduce screen-out risk and maximize fracture half-length; From Birmingham et al., 2001



Hydraulic fracture and refracture wing diagram for Codell reservoir (Birmingham et al., 2001)



Hydraulic fracturing and refracturing communication directions between wells parallel natural fracture orientations. Data for Codell (based on FMS information and communicated wells) and J Sandstone (communicated wells only). Area 1 N-S orientation; Area 2 E-W orientation From Birmingham et al., 2001

Reorientation of hydraulic fractures

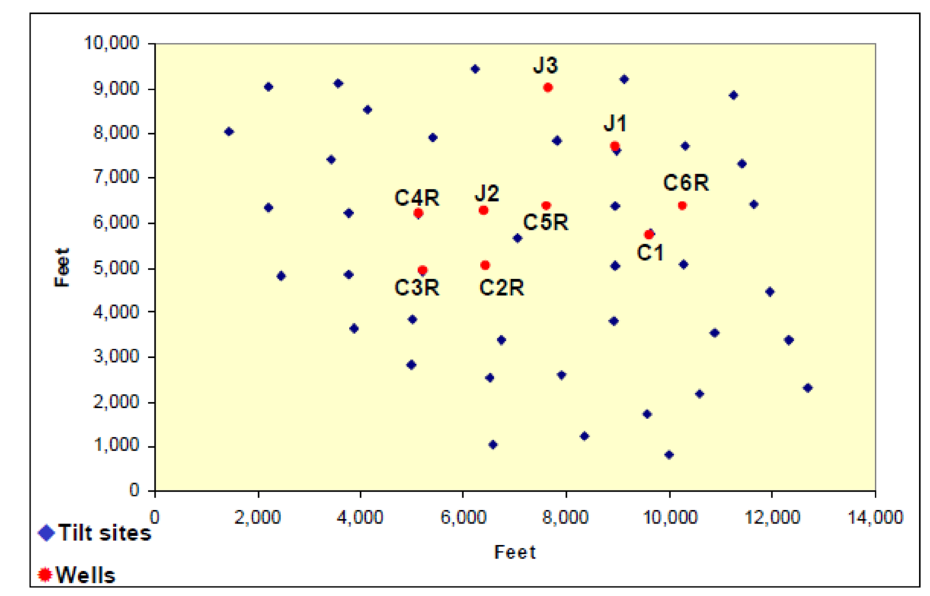


Figure 3. Surface tiltmeter array and treatment wells.

Wolhart et al., 2007

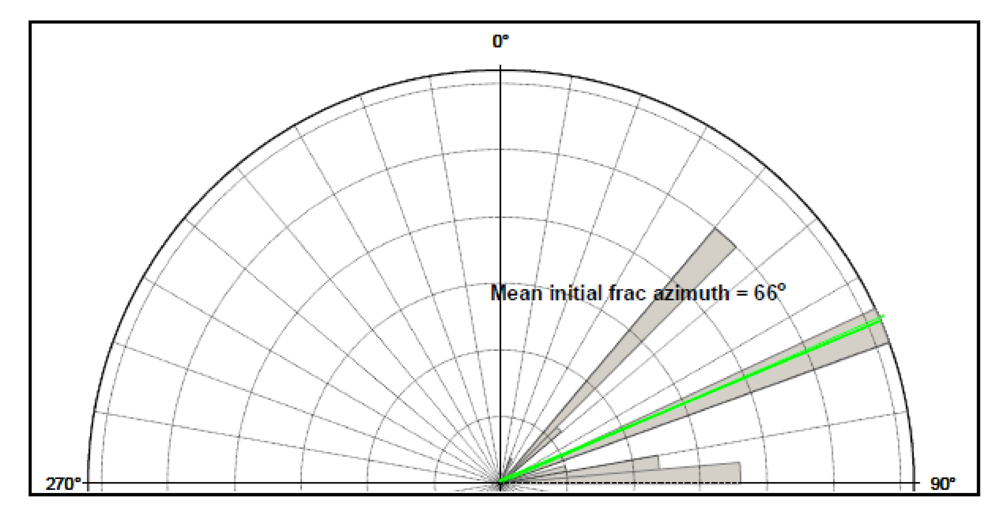


Figure 4. Rose diagram showing fracture azimuth from initial fracture treatments in the J-Sand and Codell.

Wolhart et al., 2007

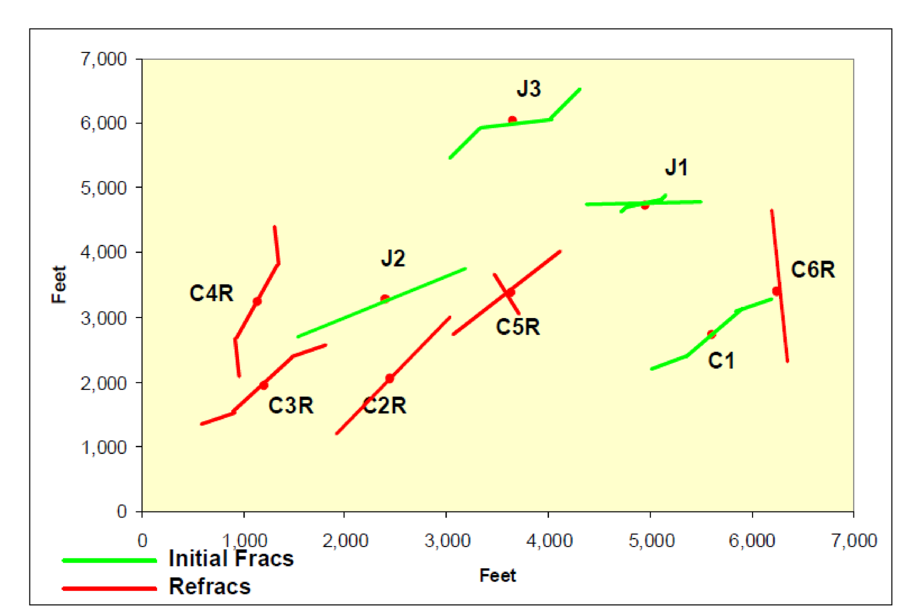


Figure 6. Plan view showing fracture azimuth results from surface tiltmeter mapping.

Wolhart et al., 2007

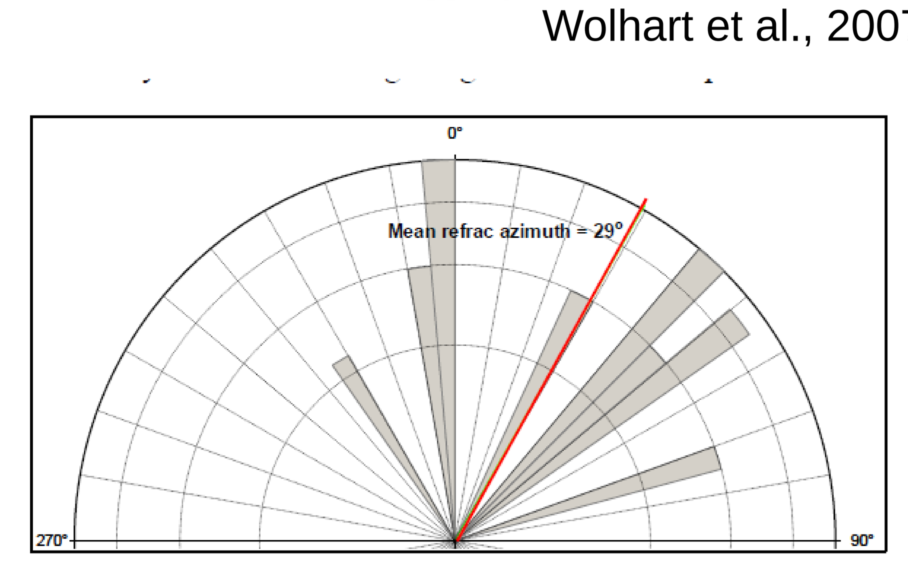


Figure 5. Rose diagram showing fracture azimuth from refracture treatments in the Codell.

Wolhart et al., 2007

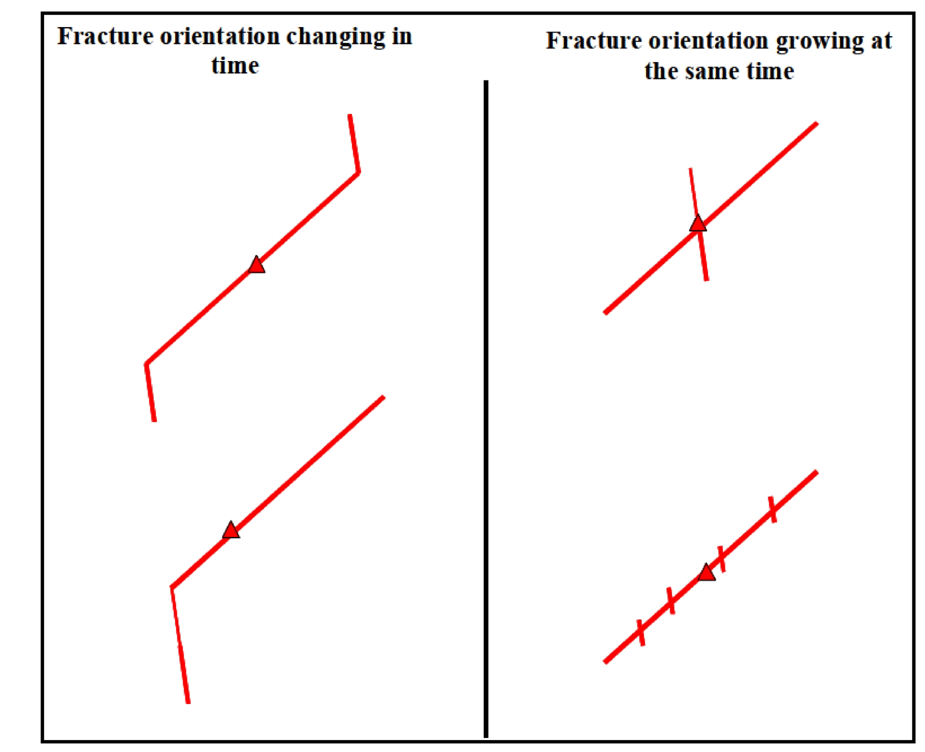


Figure 7. Possible orientation for multiple fracture azimuths for a well.

Wolhart et al., 2007

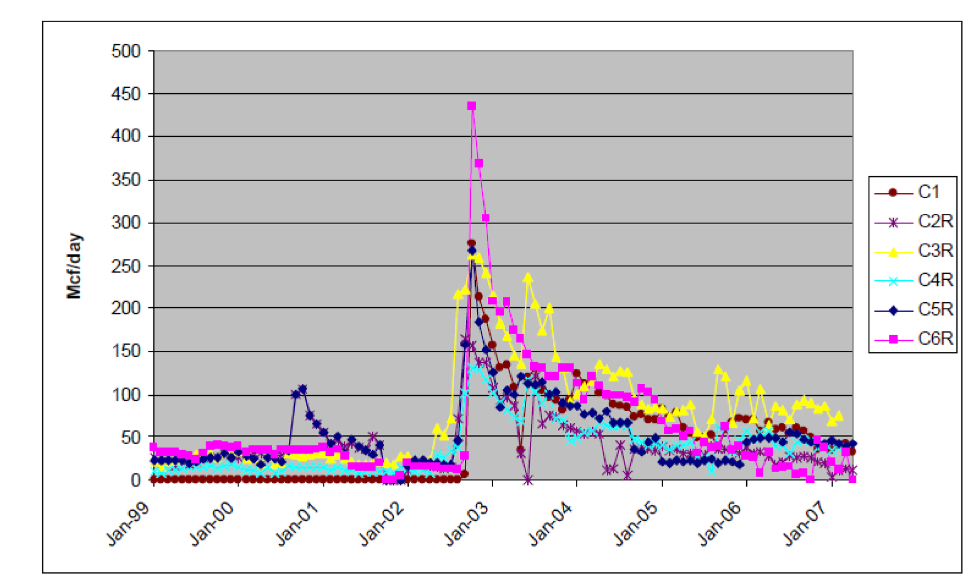


Figure 8. Production results for Codell wells.

Wolhart et al., 2007

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