PS Our Current Working Model for Unconventional Tight Petroleum Systems: Oil and Gas*

Stephen A. Sonnenberg[1] and Lawrence Meckel[2]

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Abstract

The driving forces for conventional accumulations (structural or stratigraphic traps) are Forces of Buoyancy which are due to differences in densities of hydrocarbons and water. In contrast, the driving forces for unconventional tight accumulations are Forces of Expulsion which are produced by high pressures. That is an enormous difference and creates unconventional petroleum systems that are characterized by very different and distinctive characteristics. The Force of Expulsion pressures are created by the significant increase in volume when any of the three main kerogen types are converted to hydrocarbons. At those conversion times in the burial history, the rocks are already sufficiently tight so the large volumes of generated hydrocarbons cannot efficiently escape through the existing tight pore system thus creating a permeability bottleneck that produces an overpressured compartment over a large area corresponding to the proper thermal oil and gas maturities for that basin. The forces initially created in these source rocks can only go limited distances into adjacent tight reservoirs (clastics or carbonates) above or below the source. The exact distance will vary depending on the pressure increase, matrix permeability, and fractures of that specific tight reservoir system. In general, the distances are small, in the orders of 10s to 100s of feet for oil and larger for more mobile gas systems. Those exact distance numbers are subject to ongoing investigations. Because the system is a pore throat bottleneck with very little or minimum lateral migration, the type of hydrocarbons are closely tied to the thermal maturity required to generate those hydrocarbons. Thus the play concept begins with two important geochemical considerations: (1) where are the source rocks and what are the kerogen types and organic richness (TOC), and (2) where are they mature in the basin for oil, condensate, and gas in the basin. These parameters will very quickly define the fairway for the play. Then one has to add the critical information on the reservoirs themselves: composition (brittleness), thickness, and reservoir quality (matrix porosity and permeability). In summary, these tight unconventional petroleum systems (1) are dynamic and (2) create a regionally inverted petroleum system with water over oil over condensate over gas for source rocks with Type I or II kerogen types.

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Our Current Working Model For Unconventional Tight Petroleum Systems: Oil and Gas

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"OUR CURRENT WORKING MODEL FOR UNCONVENTIONAL TIGHT PETROLEUM SYSTEMS: OIL AND GAS"
STEVE SONNENBERG, CSM
LARRY MECKEL, CSM

The driving forces for conventional accumulations (structural or stratigraphic traps) are Forces of Buoyancy which are due to differences in densities of hydrocarbons and water. In contrast, the driving forces for unconventional tight accumulations are Forces of Expulsion which are produced by high pressures. That is an enormous difference and creates unconventional petroleum systems that are characterized by very different and distinctive characteristics.

The Force of Expulsion pressures are created by the significant increase in volume when any of the three main kerogen types are converted to hydrocarbons. At those conversion times in the burial history, the rocks are already sufficiently tight so the large volumes of generated hydrocarbons cannot efficiently escape through the existing tight pore system thus creating a permeability bottleneck that produces an overpressured compartment over a large area corresponding to the proper thermal oil and gas maturities for that basin.

The forces initially created in these source rocks can only go limited distances into adjacent tight reservoirs (clastics or carbonates) above or below the source. The exact distance will vary depending on the pressure increase, matrix permeability, and fractures of that specific tight reservoir system. In general, the distances are small, in the orders of 10s to 100s of feet for oil and larger for more mobile gas systems. Those exact distance numbers are subject to ongoing investigations.

A plot of the pressure data versus elevation for a given formation is critical in determining whether an accumulation is conventional or unconventional. Conventional accumulations will have hydrocarbon columns of 10s to 100s of feet with the pressure in the hydrocarbons and that in the water equal at the bottom of the accumulation (at the HC-water contact). In contrast, the unconventional accumulations will show HC column heights of 1000s of feet with the pressure in the hydrocarbon phase and the water phase being the same at the top of the accumulation (at the updip transition zone). Those significant differences are critical for understanding and differentiating these two play types.

Because the system is a pore throat bottleneck with very little or minimum lateral migration, the type of hydrocarbons are closely tied to the thermal maturity required to generate those hydrocarbons. Thus the play concept begins with two important geochemical considerations: (1) where are the source rocks and what are the kerogen types and organic richness (TOC), and (2) where are they mature in the basin for oil, condensate, and gas in the basin. These parameters will very quickly define the fairway for the play. Then one has to add the critical information on the reservoirs themselves: composition (brittleness), thickness, and reservoir quality (matrix porosity and permeability).

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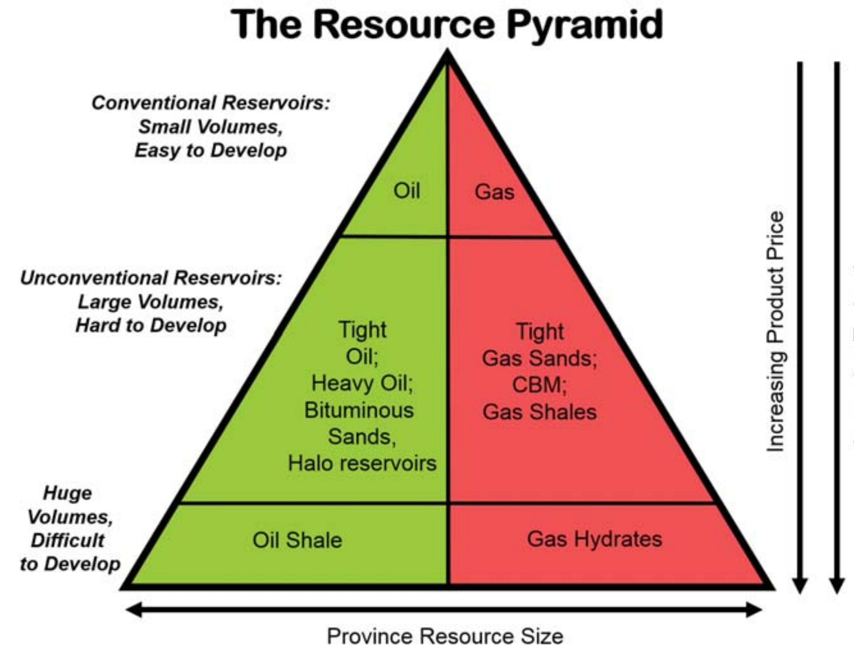
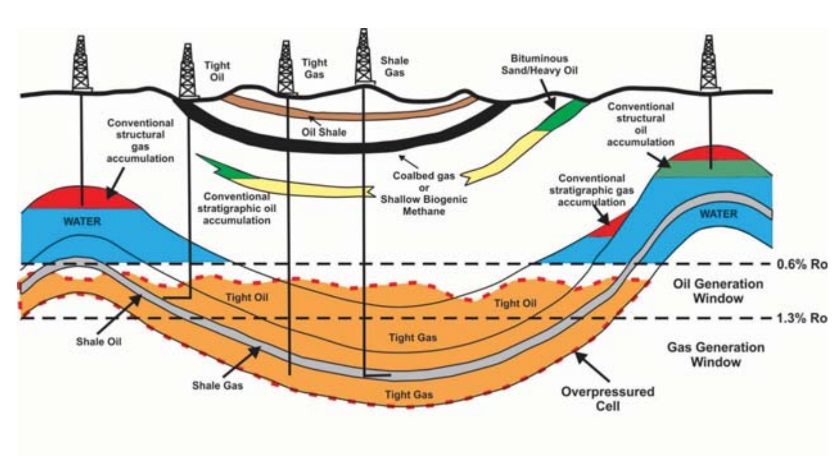
Outline

- Continuous (unconventional) versus discrete (conventional) traps
- Oil expulsion and accumulation
- Forces of expulsion versus buoyancy
- Abnormal pressure systems
- Microfractures
- Pressure compartments through time
- Residual oil and water saturations
- Inverted petroleum systems
- Check list for finding continuous accumulations
- Summary

The Resource Pyramid





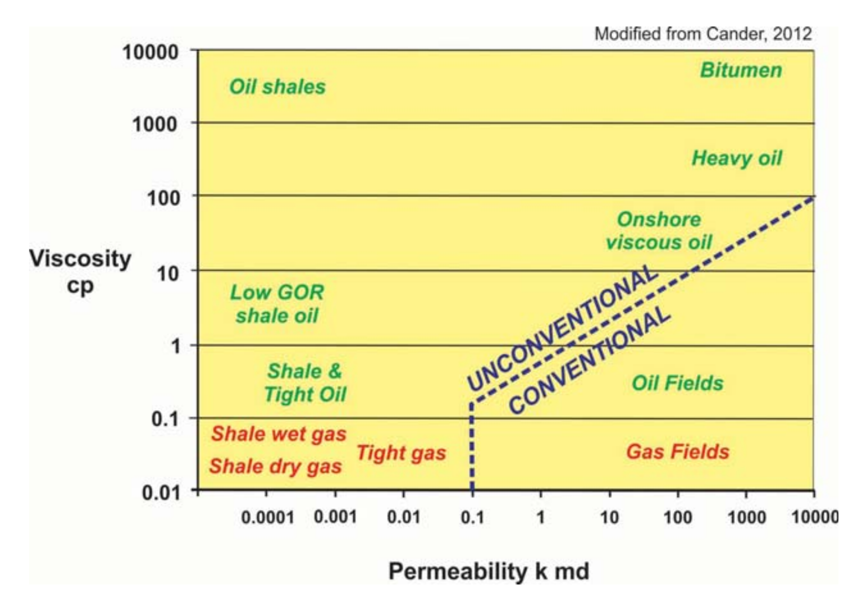
- **Conventional (Buoyancy driven)**
  - Structural
  - Stratigraphic
  - Combination
- **Unconventional**
  - Coalbed Methane
  - Shallow Basin Methane (biogenic)
  - Shale Gas
  - Shale Oil
  - Tight Oil
  - Oil Shale
  - Tar Sands

What Makes it Unconventional?

1. Quality of the reservoir (tight to very tight)
2. Type of trap (continuous)
3. State the gas or oil is in (sorbed, tar, solid, kerogen)
4. Physical laws that control occurrence (generally not buoyancy driven)
5. Viscosity and permeability
6. Technology required to produce/extract

In general, the gas or oil is difficult to produce for some reason.

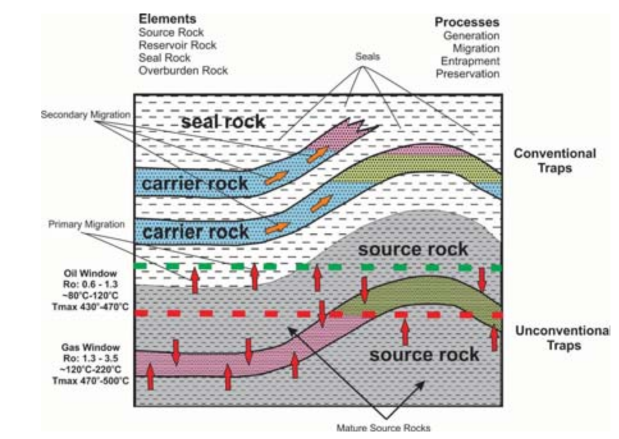
Viscosity & Permeability



Deep Basin Continuous Accumulations

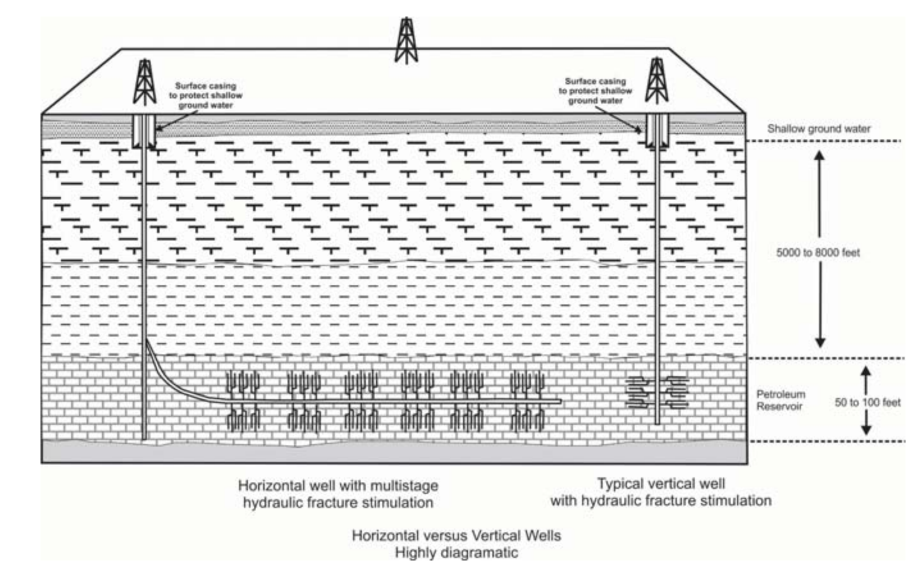
- Pervasive accumulations that are hydrocarbon saturated
- Not localized by buoyancy
- Abnormally pressured (high or low)
- Commonly lack downdip water
- Updip contact with regional water saturation
- Low-permeability and low matrix porosity reservoirs
- Reservoirs may be single or vertically stacked
- Commonly enhanced by fracturing
- Associated with mature source rocks that are either actively generating or have recently ceased generation
- Hydrocarbons of thermal origin
- Fields have diffuse boundaries
- Inverted Petroleum Systems

The Petroleum System

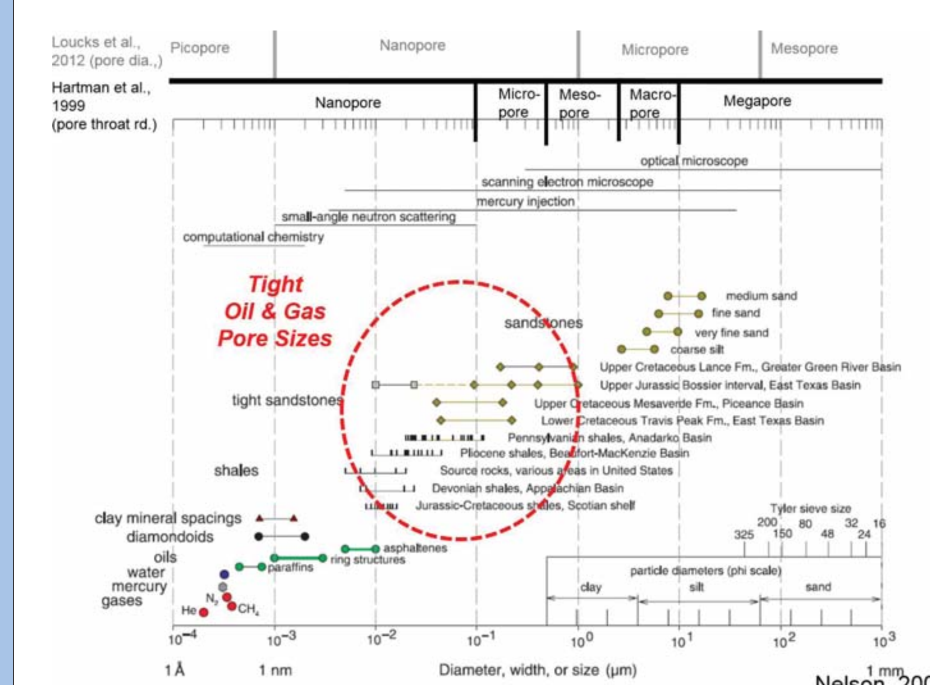


Keys:
- Source
- Seal
- Maturity
- Expulsion
- Migration
- Reservoir
- Trap
- Preservation

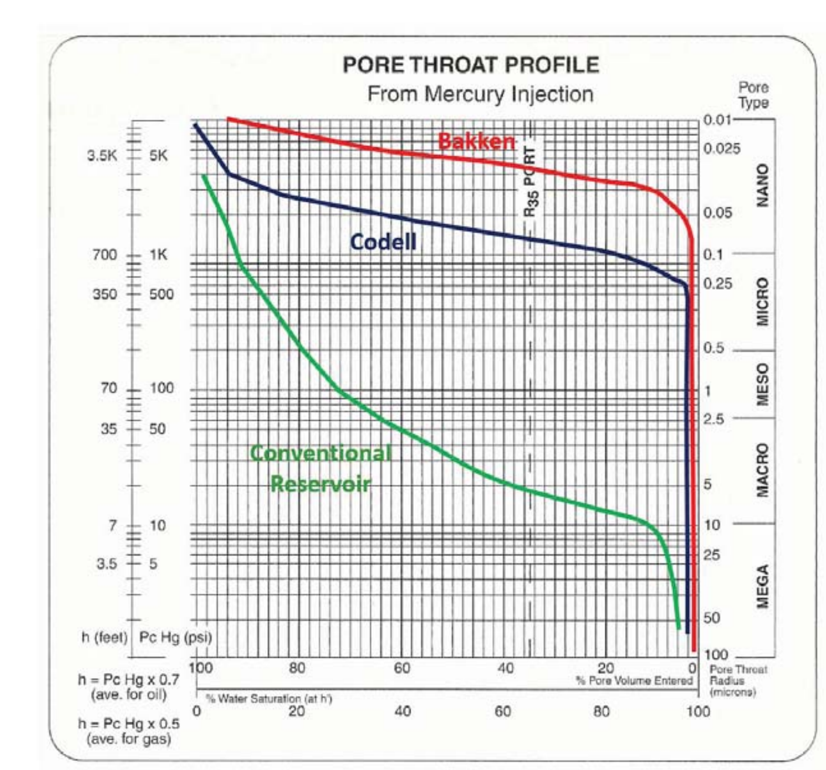
Technology Needed



Small Pore Sizes



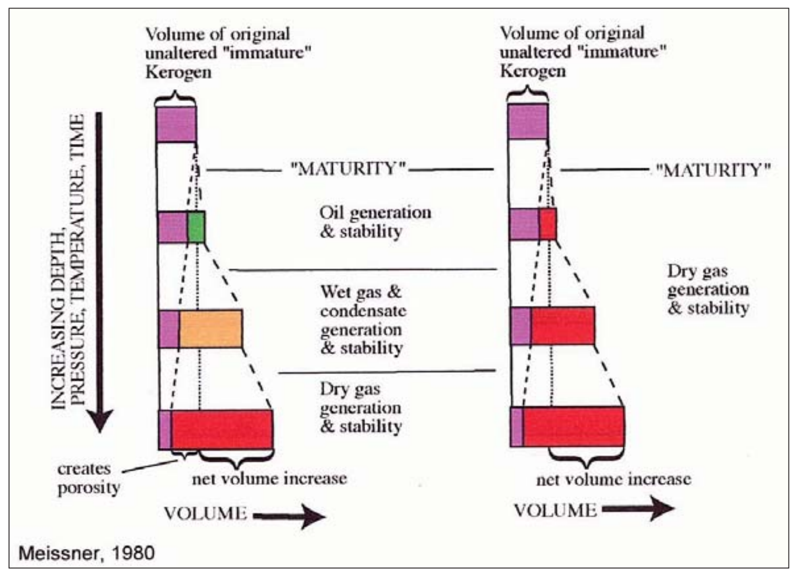
MICP and Unconventionals



Unconventional Petroleum Systems
2

Forces of Expulsion

The driving forces result from changes in volume as kerogen matures



Net Volume increases in sapropelic and humic kerogens with increasing thermal maturity (Meissner, 1980)

This large volume change in tight rock creates FORCES OF EXPULSION (Pressure Driven)

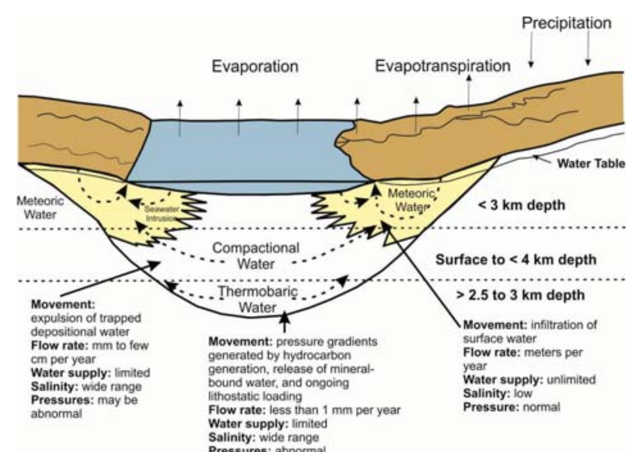
Very different from the FORCES OF BOUYANCY (Density Driven) we are used to for Conventional Systems

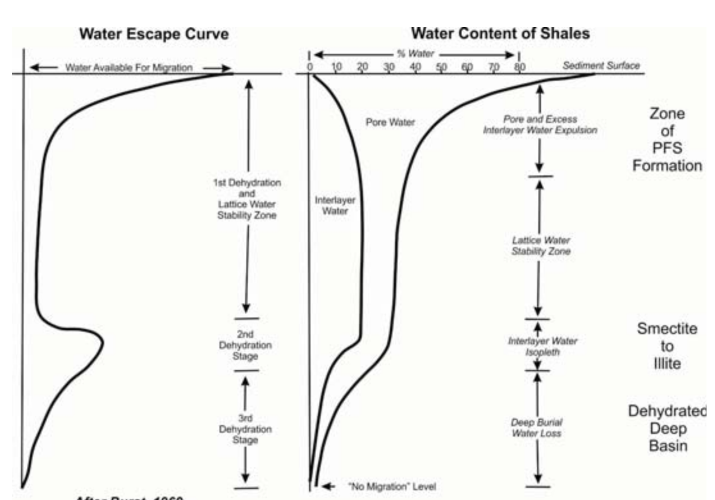
Forces of Expulsion

- Initially creates an over-pressured compartment
- Drives remaining water out of system (helps dehydrate the system)
- Forces oil and condensate into very tight pore space resulting in low water saturations
- Creates vertical extensional fractures & horizontal bedding parallel fractures

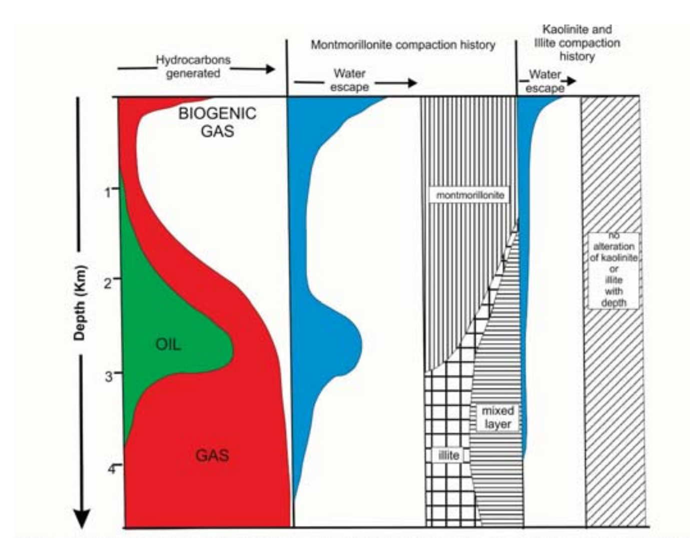
Where Did All the Water Go?

- Compaction dewatering
- Hydrogenation of kerogen
- Conversion to CO2
- Other reactions
- Displaced from reservoir
- System dehydrated
- Pervasive hydrocarbon saturation



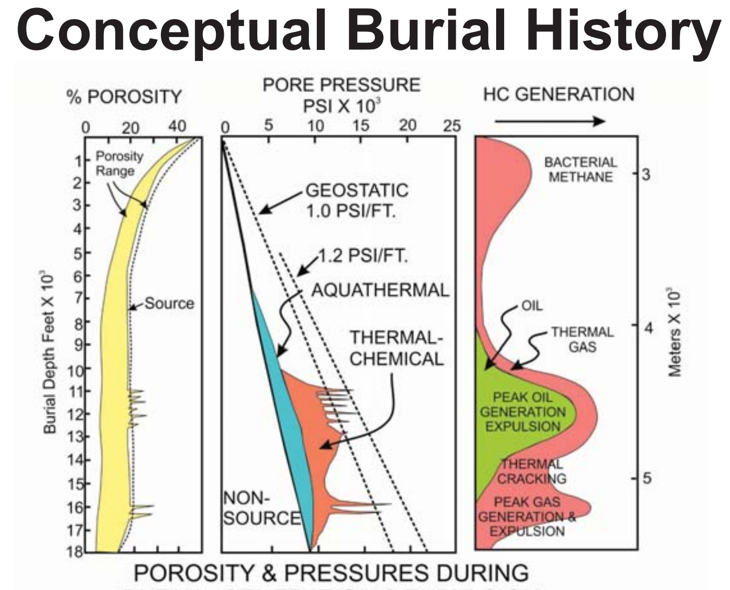


Water Loss Curves (Burst, 1969)



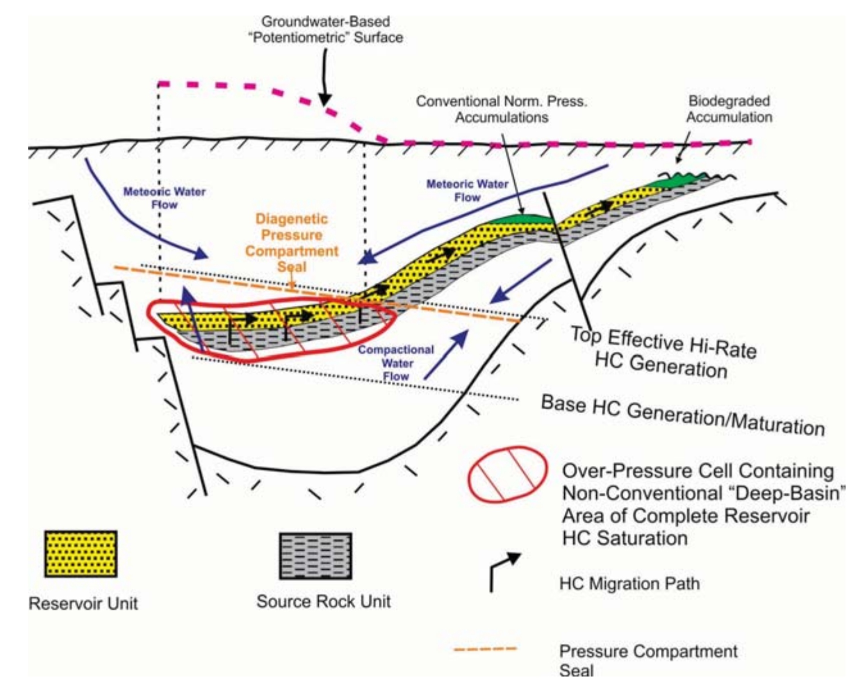
Oil and gas generation and clay mineralogy as a function of depth

Conceptual Burial History

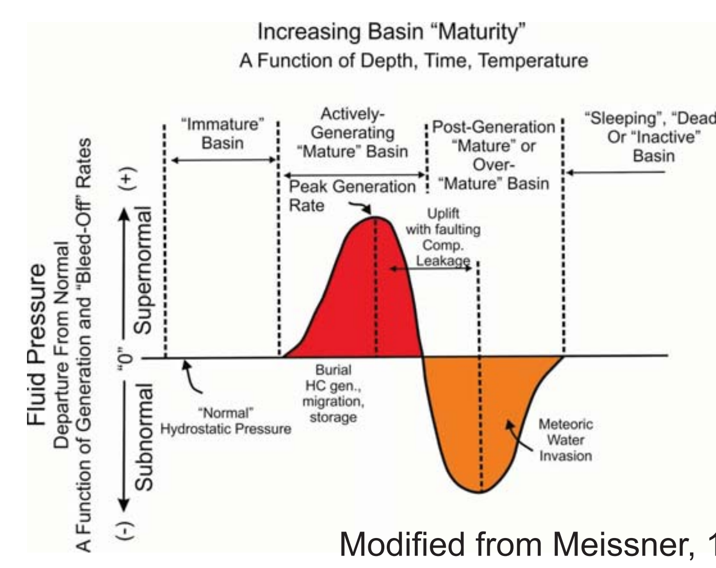


Modified from Momper, 1981

Pressure Compartments & Seals



Modified from Meissner, 1997



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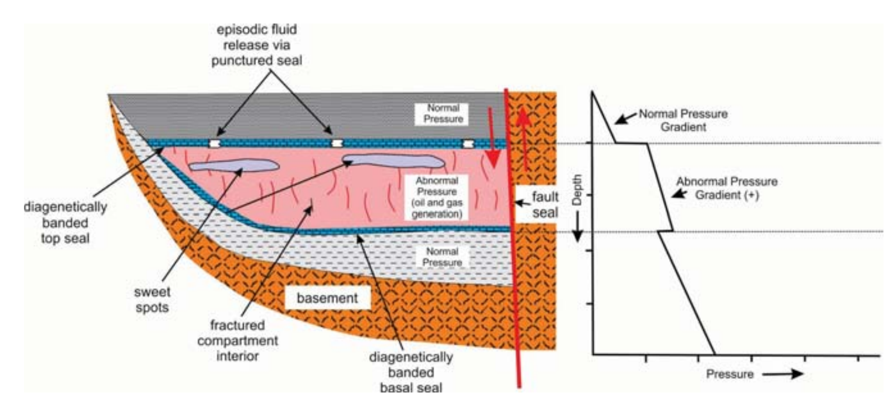
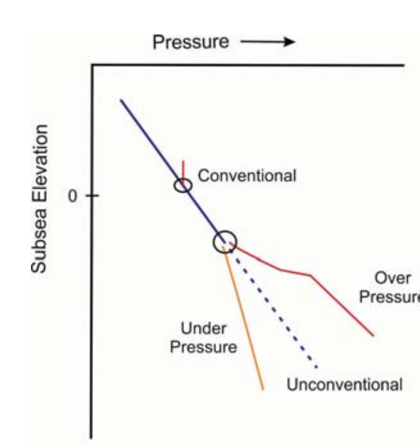


Modified from Ortoleva, 1994

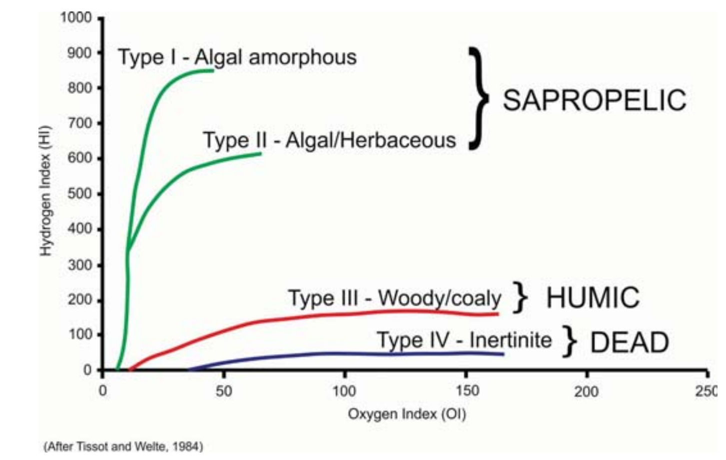
Typical Pressure Plots

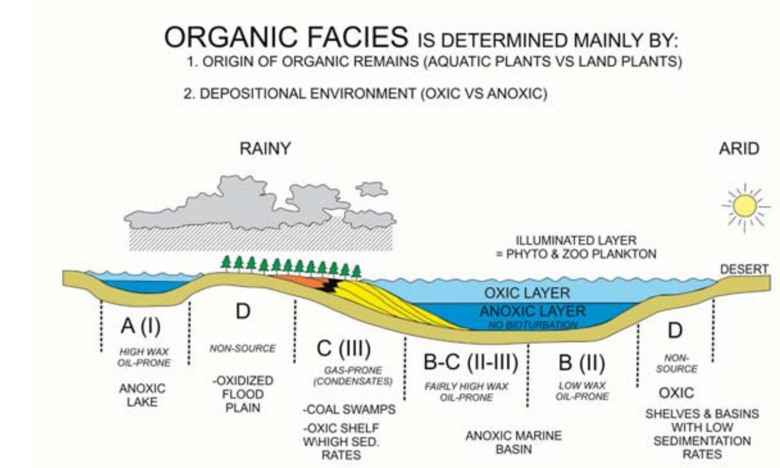
- UNCONVENTIONAL ACCUMUL 100s to 1000s of feet Pw = Phc at TOP accumulation (see lower circle)
- CONVENTIONAL ACCUMUL Typically 10s of feet Pw = Phc at BOTTOM accumul (see upper circle)

Going upward: slanted into water line or slanted away.



Source Beds And Unconventionals





Jones and Demaison, 1980

Kerogen Types For Unconventionals

Shale Gas
Type I, II
Largely sorbed gas; very low matrix k, fractures (?); Source = reservoir
Ex: Barnett, Marcellus

Shale Oil
Type I, II
Very low matrix k, source = reservoir
Ex: Eagle Ford, Niobrara, Green River

Shallow Biogenic Gas (e.g., Niobrara)
Type I, II
High ϕ, low k, partly sorbed
Ex: Niobrara eastern CO

Tight Gas
Type I, II, III
Partly sorbed; low matrix k; fractures, Source ≠ reservoir
Ex: Williams Fork, J SS, Codell, Frontier, Turner

Tight Oil
Type I, II
Low matrix k, analogous to tight gas, clastics or carbonates, Source ≠ reservoir
Ex: Bakken, Niobrara, Barnett

CBM
Type III (Coal)
Sorbed gas; thermogenic or biogenic; source = reservoir
Ex: Fruitland Coals, Cameo, Ferron, Ft. Union

Tar Sands
Type I, II
Biodegraded oil, long range migration,
Ex: Canadian Tar Sands

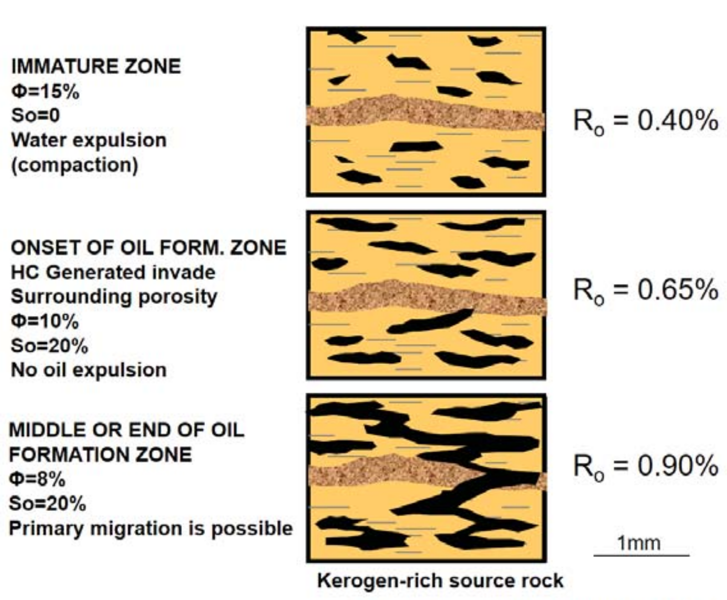
Oil Shale
Type I, II
Immature kerogen, requires artificial heating
Example: Green River

Unconventional Petroleum Systems 3

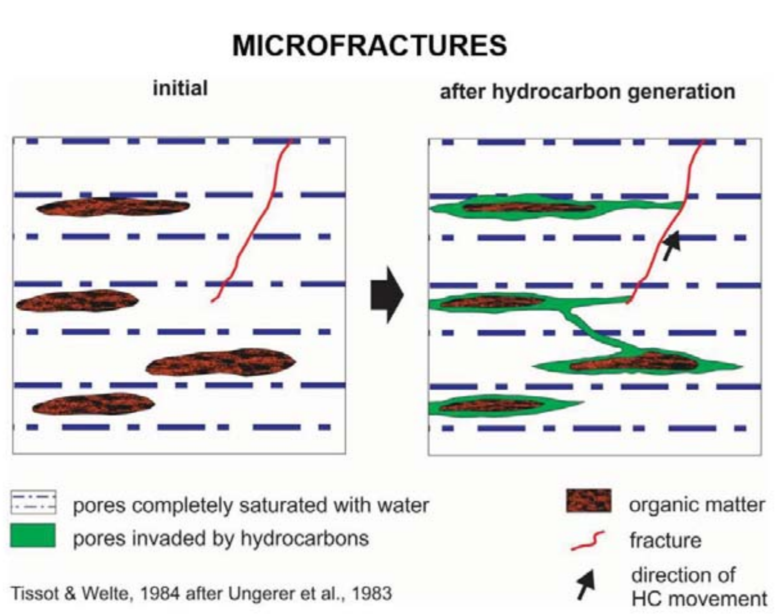
Microfractures

- Very common in organic-rich source rocks
- Dilate when we frack the well with high pressures
- Resulting in really good IPs
- But collapse (?) when pressure is drawn down
- Resulting in 50-80% first year declines
- Challenge: how to keep them open for years not months

Organic Richness and Continuous Oil-Saturated Network



after Katz, 2012 after Durand, 1988

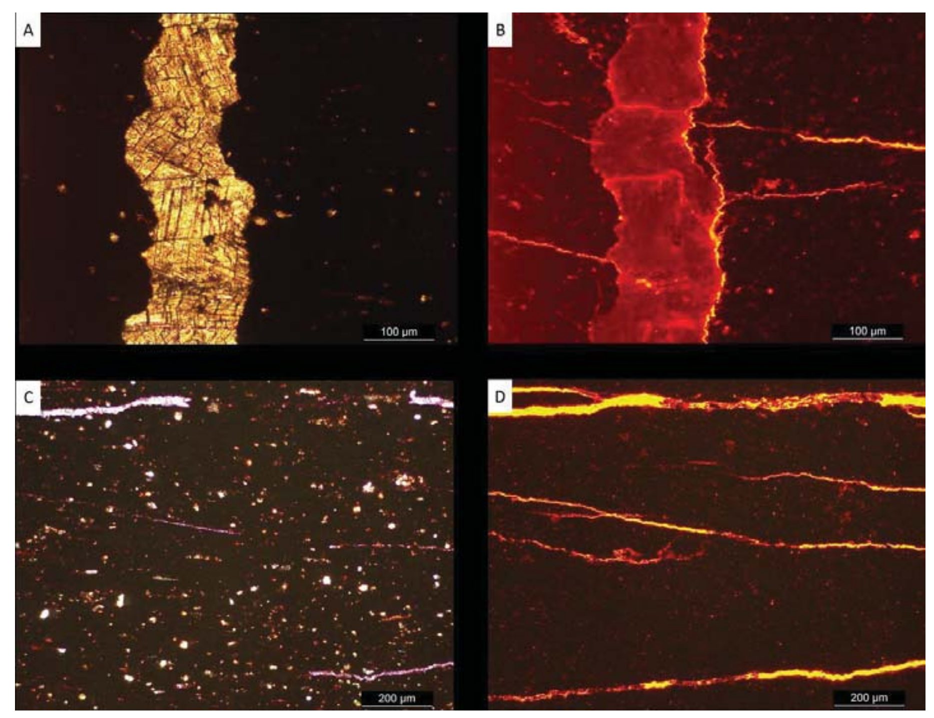


"The pressure within the fluids formed in the pores of the source rock increases constantly in proportion to the formation of products of Kerogen evolution. If this pressure rises above the mechanical resistance of the rock, microcracks will be formed that will be several orders of magnitude larger than the natural channels of the rock and will make the outflow of an oil or gas phase possible until this pressure falls again below the threshold, so that the cracks are closed and a new cycle is started"

B.Tissot & R. Pelet, 1971

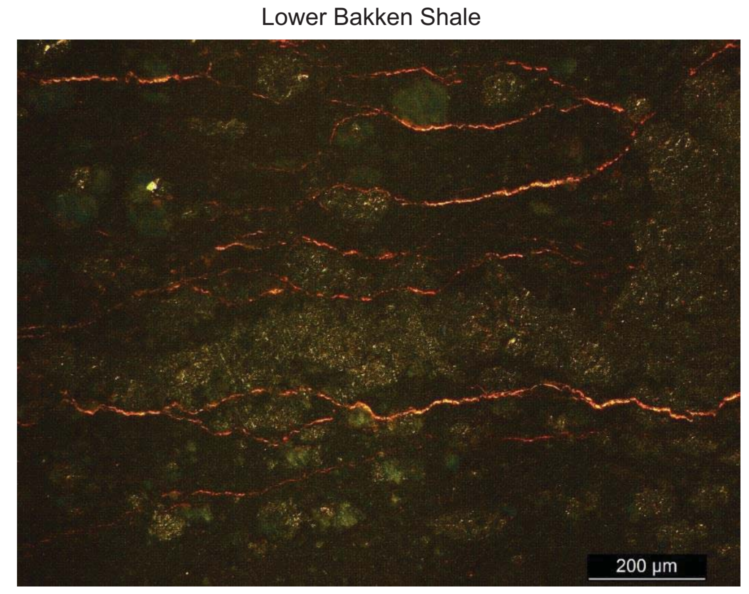
Microfractures

Lower Bakken Shale



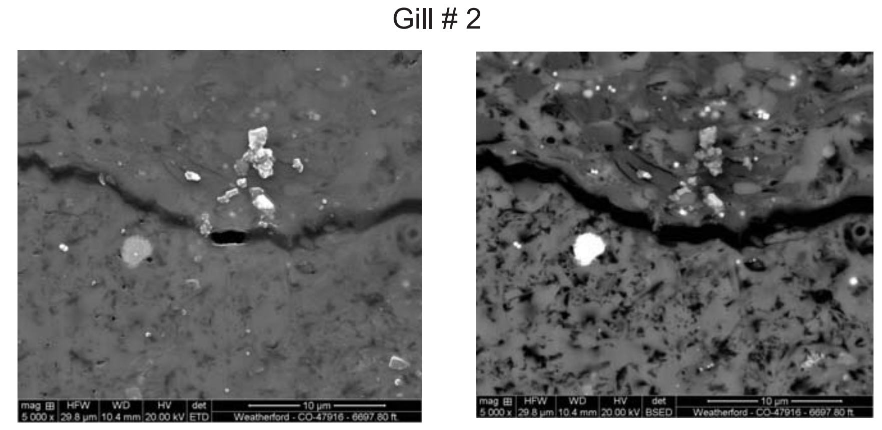
Photomicrograph of the lower Bakken shale showing a mineralized vertical fracture within extremely tight matrix as seen in the normal light (A). When viewed under UV light (B), bedding-parallel fractures appear to extend across the matrix and intersect the vertical fracture providing the high permeability pathways and increase the interporosity flow between the matrix and the fracture system. In C and D, bedding-parallel fractures appear to be filled with bitumen as they can strikingly be seen under the UV light (D). (Al Duhailan, 2015)

Lower Bakken Shale



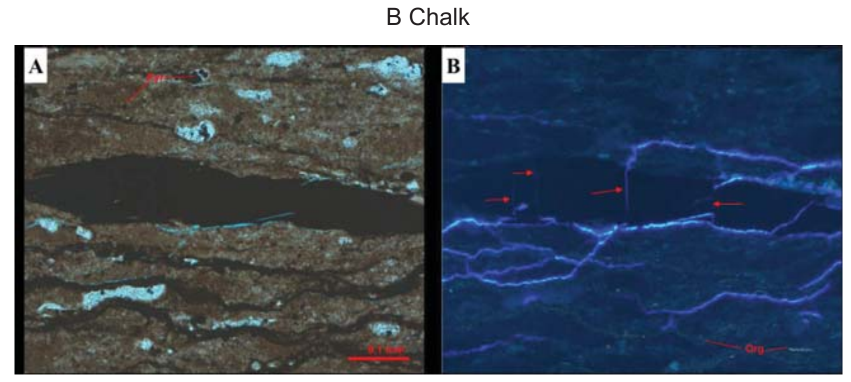
Photomicrograph from the lower Bakken Shale containing abundant radiolaria and bedding-parallel fractures. (Al Duhailan, 2015)

Niobrara Formation
Gill # 2



A marl: 6697 ft

Niobrara Formation
Lee 41-5
B Chalk

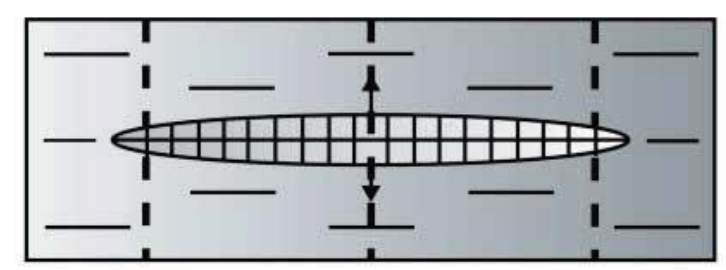


Photomicrographs showing an example of petroleum-expulsion fractures within the B chalk bench in the Denver Basin. The fractures appear as bedding-parallel fractures mimicking the wispy stylolitic laminations (Well name: Champlin Lee 41-5). Al Duhailan, 2015

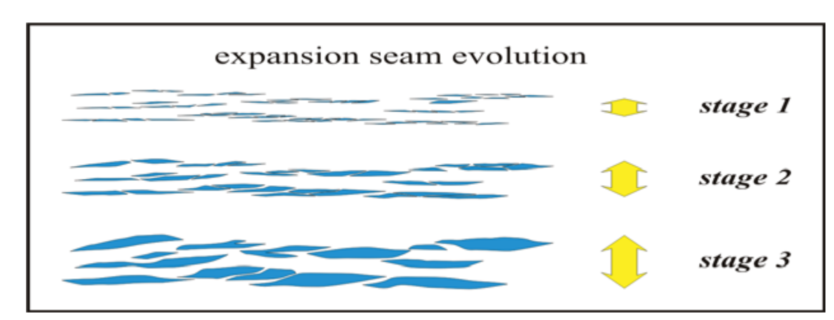
Beef Fractures

- Bedding-parallel, calcite-filled fractures named by quarrymen "beef" fractures based on their resemblance to the fibrous fascia seen in beef (Cobbold and Rodrigues, 2007)
- Organic-rich, calcareous shales commonly host these features.

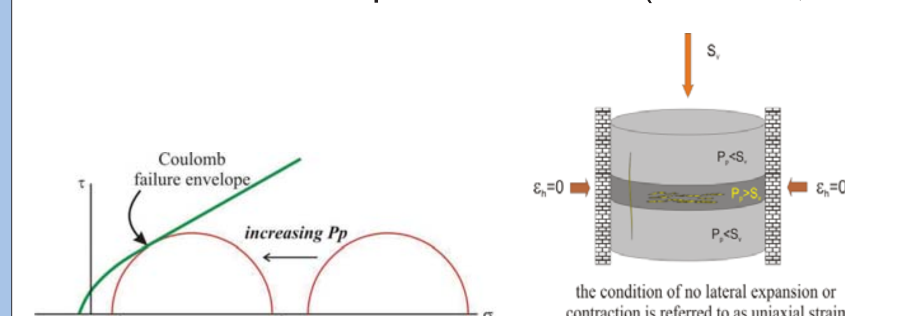
Formation of Beef Fractures



Horizontal vein opens vertically, so fibers are straight and form quasi-vertically
Often complexed with solid or liquid hydrocarbons



Evolution of beef expansion seams (Jamison, 2013)



Mohr stress diagram illustrating the change in stress with increasing pore pressure (Jamison, 2013). Uniaxial strain diagram **on right (bounding rocks restrict lateral expansion.**

"Beef Fractures" in Shales correlate with:

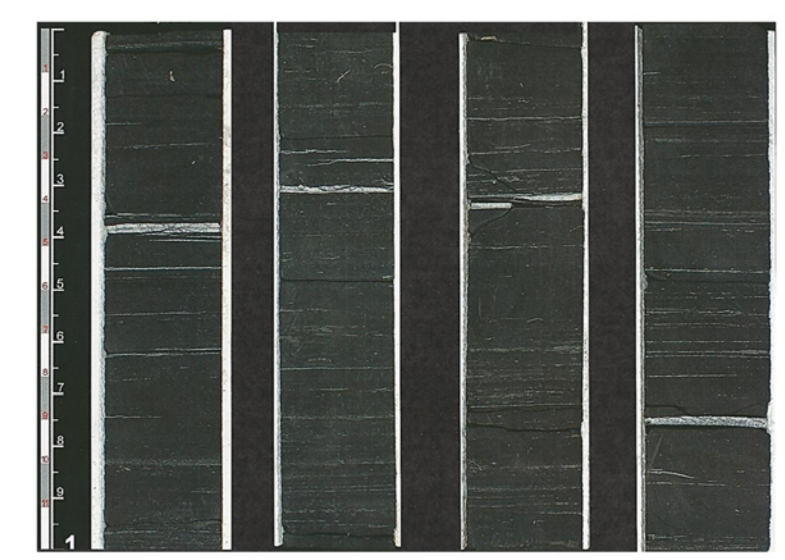
1) Organic-richness
2) Thermal maturity
3) Overpressuring
4) Mechanical anisotropy
5) Calcareous material in the shales (e.g., coccoliths in the Mesozoic examples)

Mechanisms for forming Beef

1. Crack-seal: Vein calcite crystals infill pre-existing fractures
2. Force of crystallization: Crystal growth exerts stress
3. Hydrocarbon expulsion creating fractures due to volume expansion and increase in pressure by petroleum expulsion from kerogen (e.g., Momper, 1978; Meissner, 1978; Lewan, 1987)

Haynesville

- Gas production & pressure gradient 0.9 psi/ft
- Depths between 10,000 and 13,500 ft and ranges in thickness from 200 to 350 ft
- Natural fractures in the Haynesville exist as bedding-parallel veins of fibrous calcite (beef fractures), which are pervasive within the highly overpressured and anisotropic intervals
- Commonly misinterpreted as ***Inoceramus*** shell fragments



Bedding-parallel veins of fibrous calcite (Beef's) in the Haynesville.
(Core sample Sample 10H #1, Red River Ph., LA)

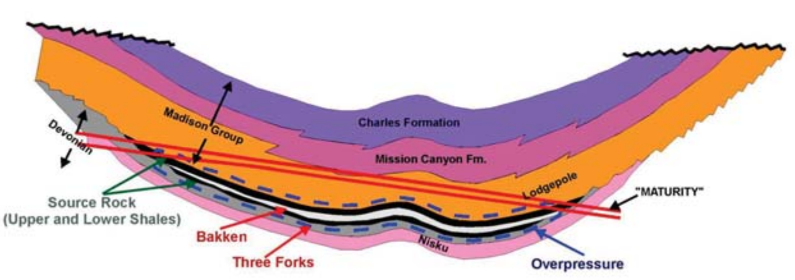
Vaca Muerta, Neuquén Basin

Core slab piece, Vaca Muerta Formation, showing three fracture types: 1) non-mineralized, closed bedding-parallel fractures, 2) bitumen-filled, bedding-parallel fractures, 3) bedding-parallel, calcite-filled fractures (Duhailan, 2014)

Unconventional Petroleum Systems
4

Forces of Expulsion And Residual Hydrocarbon Saturation

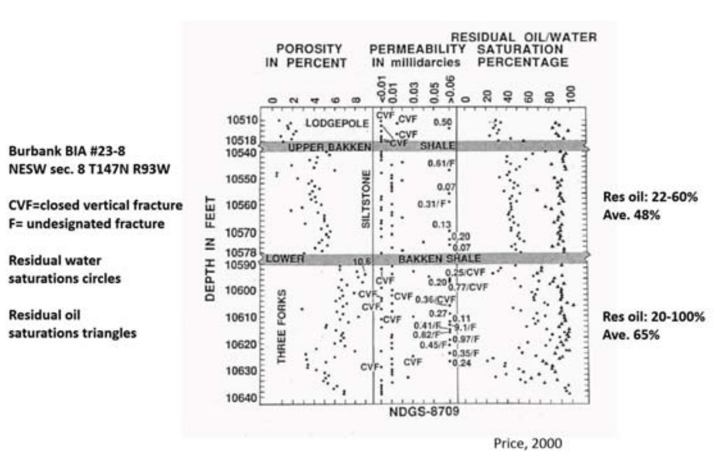
Bakken Petroleum System



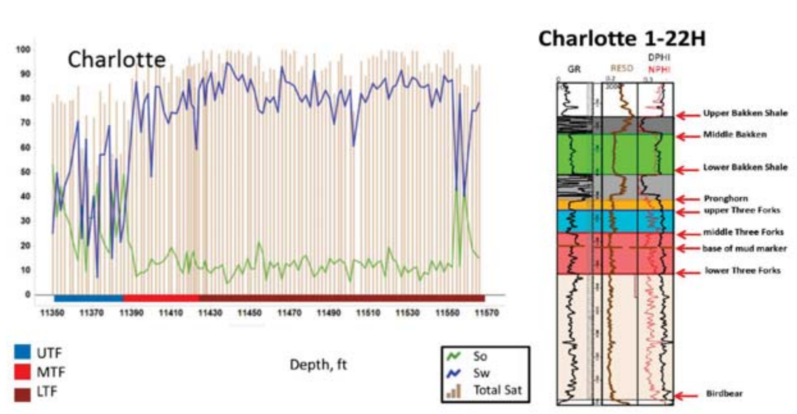
Reservoirs:
Middle Bakken, Pronghorn & Three Forks

Source Beds:
Upper & Lower Bakken Shales

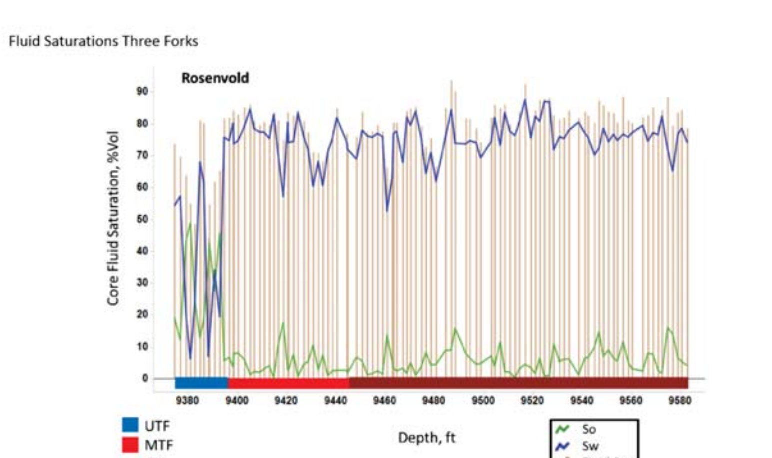
"what was made in the Bakken, stayed in the Bakken PS"



Price, 2000



Bazzell, 2014

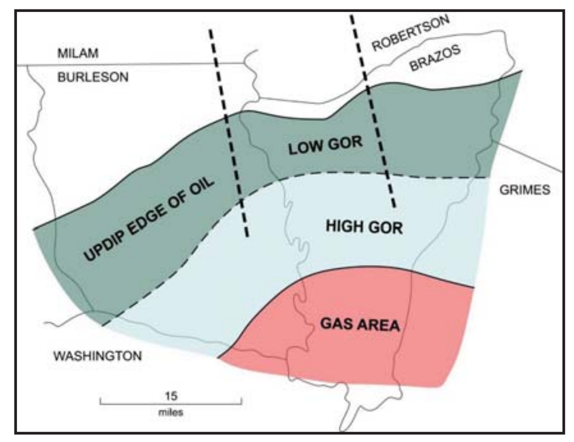


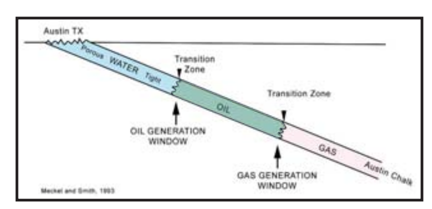
Bazzell, 2014

Look At Some Typical Sws

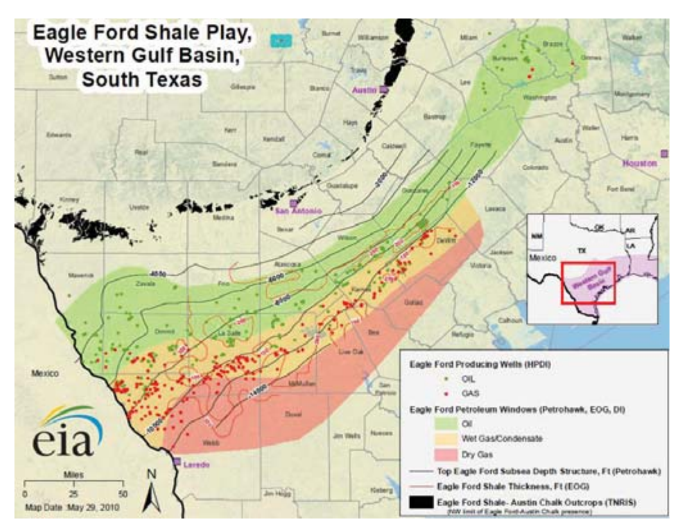
- Most of the units are at irreducible water saturation which for these tight rocks requires those enormous forces of explusion pressures.
- Some typical Sw values:
  - Wasatch at Altamont: < 10%
  - Cardium at Pembina: < 20%
  - Austin Chalk in Texas: < 20%
  - Spraberry in W. Texas: 20 – 30 %

Examples of Inverted Systems

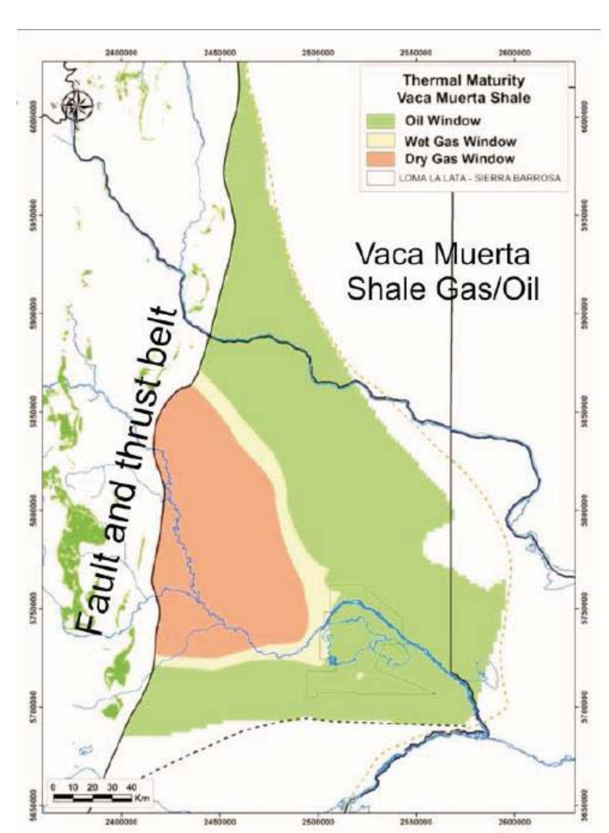




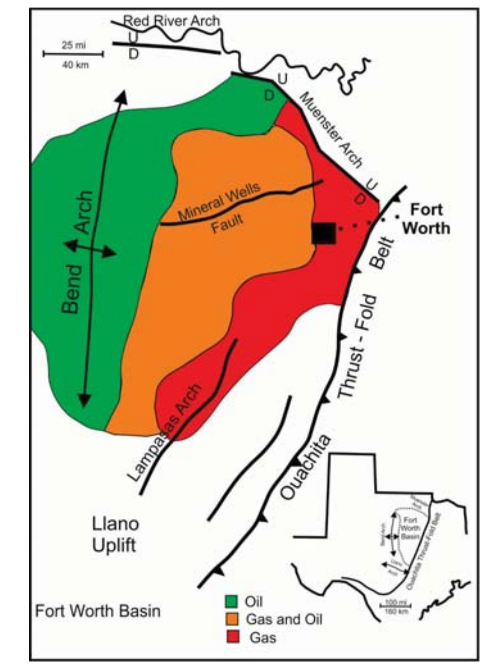
Austin Chalk, East Giddings Field (Meckel and Smith, 1993)



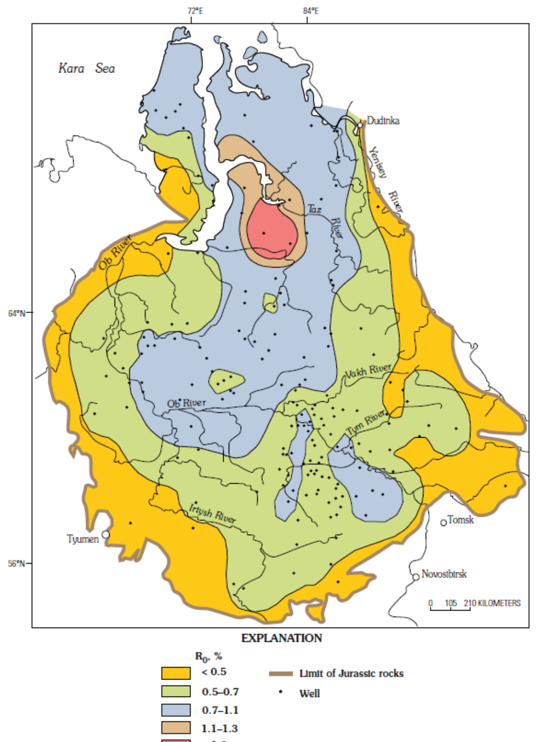
Eagle Ford, Gulf Coast



Vaca Muerta, Neuquén Basin, Argentina
Soldo, 2015



Barnett Shale, Fort Worth Basin



Vitrinite reflectance Bazhenov Shale, West Siberian Basin, Ulmishek, 2003

The Unconventional Check List

- Continuous type of Accumulation
- Areally or vertically pervasive
- Hydrocarbon saturation (O or G)
- Abnormally pressured
- Lack of down-dip water
- Low ϕ & k
- Lack of obvious seal or trap
- Oil or gas generation window
- Updip transition to wet
- Enhanced sweet spots
- Large calculated OOIP or OGIP
- Tectonically "quiet"

Summary

- Unconventional resource plays are 'changing the game'
- It all starts with good to excellent source beds
- Type I & II Source Beds
- Type III OM too disseminated
- Source beds mature over large areal extent
- Natural fracturing enhances tight reservoirs
- Inverted systems common
- Horizontal drilling and fracture stimulation technology important in tight oil & gas plays

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