Natural and Artificial Cracking of Oil Source Rocks and Unconventional Reservoirs*

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Abstract

Source rocks expel oil and gas when the internal pressure generated by volume-increase reactions due to the conversion of kerogen to solid bitumen and then to oil and gas exceeds the geostatic pressure. The rocks naturally rupture, oil and gas are expelled or pushed out, and the pressure drops below geostatic. This process is repeated many times as the source rock passes through the oil and gas maturity "windows." Primary oil and gas expulsion is very inefficient with less than twenty percent of the oil and gas generated ever leaving the source rock.

Unconventional reservoirs are most commonly suspended oil source rocks. They were once active but stopped generating prior to becoming spent due to cooling associated with overburden removal. Internal pressure is between hydrostatic and geostatic, depending on sealing capacity and other factors. Hydrocracking artificially ruptures the source rock and some additional oil and gas are pulled out by differential pressure between the source rock and the well bore. Like primary oil migration, the process is very inefficient and less than ten percent of the oil and gas remaining in the source rock is produced.

Many factors control the efficiency of both natural oil expulsion and artificial fracking oil and gas production. Some of these include the concentration and distribution of organic matter in the source rock, the anisotropy of both the organic matter and lithological units within the source rock, the brittleness variations of source-rock lithologies, natural and artificial frac barriers, oil and gas composition at various maturities, differential permeability of produced products, and a host of other factors which affect the efficiency of both source rocks and unconventional reservoirs.

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NATURAL AND ARTIFICIAL CRACKING OF OIL SOURCE ROCKS AND UNCONVENTIONAL RESERVOIRS

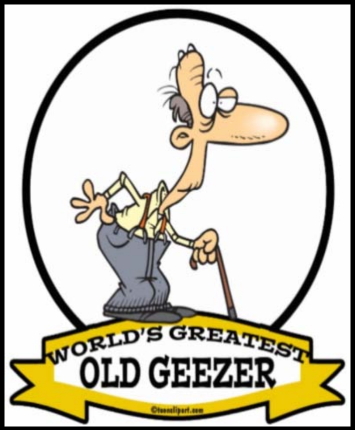
AAPG/SEPM Rocky Mt. Sectional Meeting, Denver, Colorado
July 21, 2014

Wallace G. Dow
Chief Geochemist

CIMAREX

IT'S ALL ABOUT CRACKS (IN ROCKS)

"How did I get roped into this talk anyway?"
They found an old geezer who can't run very fast!



A SHORT PRIMER ON ROCK CRACKS

1) All rocks crack.

2) Some rocks crack better than others.

3) Primary oil migration cracks rocks from within.

4) Tectonic forces crack rocks from without.

5) Most secondary oil/gas migration occurs in rock cracks.

6) It is easier to open old cracks than make new ones.

7) *Rock cracks are very important in oil/gas production.*

BUT FIRST WE NEED TO REVIEW A FEW *FRACTURE BASICS*

$$w = \frac{4(1-\nu)R}{\pi G}\Bigg[(p_w + \alpha) \int_{f_R}^{1} \sqrt{\frac{f_1^2 - f_{Rw}^2}{f_1^2 - f_R^2}}\, d f_1$$

$$- \left(p_w + \alpha \ln \frac{f_{Rw}}{f_R} \right) \int_{f_{Ro}}^{1} \sqrt{\frac{f_1^2 - f_{Ro}^2}{f_1^2 - f_R^2}}\, d f_1 +$$

$$+ \alpha \Bigg(\int_{f_R}^{1} \sqrt{\frac{f_1^2 - f_R^2}{f_1^2 - f_{Rw}^2}}\, d f_1 -$$

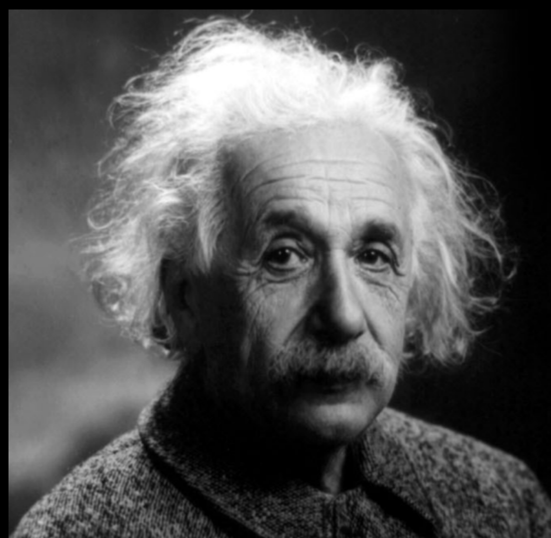
$$\int_{f_{Ro}}^{1} \sqrt{\frac{f_1^2 - f_R^2}{f_1^2 - f_{Ro}^2}}\, d f_1 \Bigg) +$$

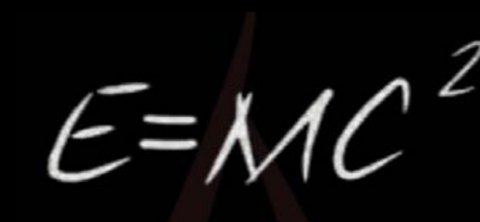
$$+ \alpha \sqrt{1 - f_R^2} \left\{ \ln \left[\frac{1 - \varepsilon}{1 - \sqrt{1 - f_{Rw}^2}} \left(\frac{f_{Rw}}{f_R} \right) \right] + \frac{S}{\alpha} \right\}$$

With apologies to Geertsma & Klerk, 1969

JUST KIDDING!

I never got past Einstein.





We should all be happy there are folks out there who *can* do the math.

ORIGINS OF ROCK CRACKS

AKA: FRACTURES, FISSURES, PARTINGS, & JOINTS

1) Oil generation & primary migration
2) Tectonic stresses
   a) Fault systems
   b) Flexures
   c) Impact craters
   d) Collapse features (salt, karst)
   e) Differential compaction
3) Pressure (stress) release due to overburden removal
4) Pressure (stress) release due to coring
5) Hydro-fracking

Natural
Artificial

WHY DO WE CARE ABOUT NATURAL CRACKS ANYWAY?

Hydro-fracking is what breaks up the rocks and lets the oil and gas flow out, and…………..

Because it takes half the pressure to re-open sealed natural cracks than to make new ones.

Because wells with many natural cracks produce better than those with few or none.

Tensile Testing
Results

- Failure along fracture, EVEN THOUGH THESE ARE SEALED
- Specimens with natural fractures are half as strong as those without

Post-test specimens

Specimen	Rupture (kpsi)
With natural fracture	
2T	2.45
5T	3.86
3B	3.29
No natural fracture	
9T	6.15
11T	6.41

From Gale and Holder (2008)

Gale et al., 2010

CONVENTIONAL SOURCE ROCKS = UNCONVENTIONAL RESERVOIRS

Calvin and Hobbs by Bill Watterson

……. my source rock is now my reservoir!

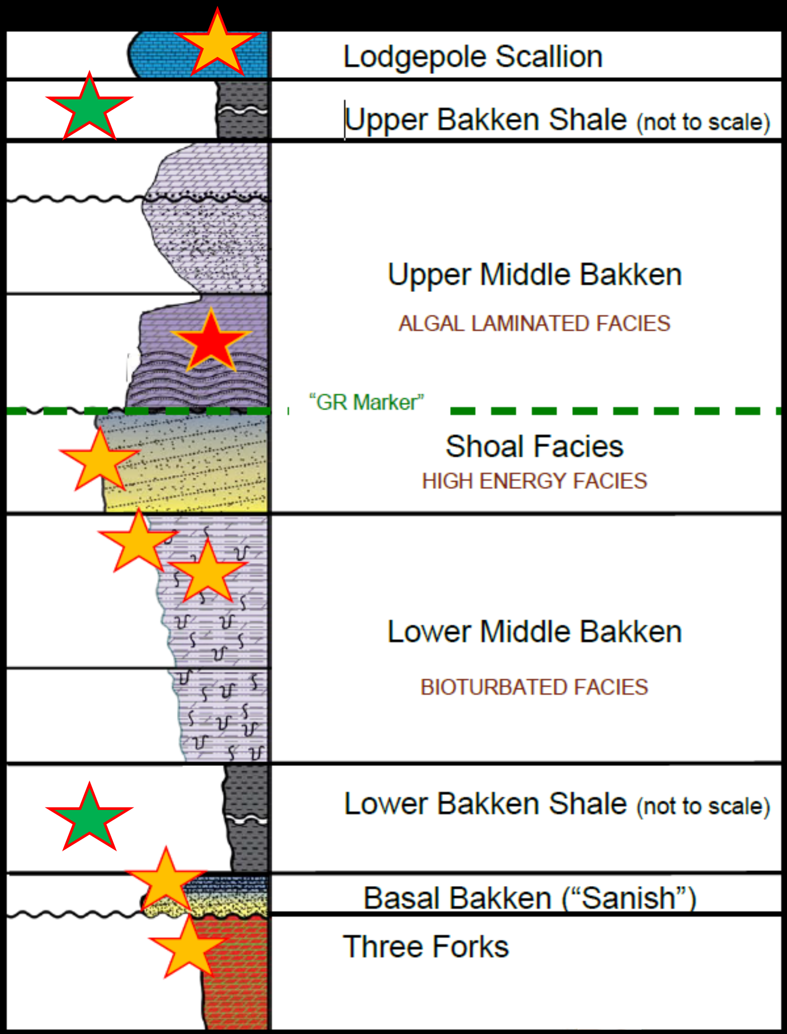
Quinn R. Passey et al, 2012

(Well…..sort of anyway)

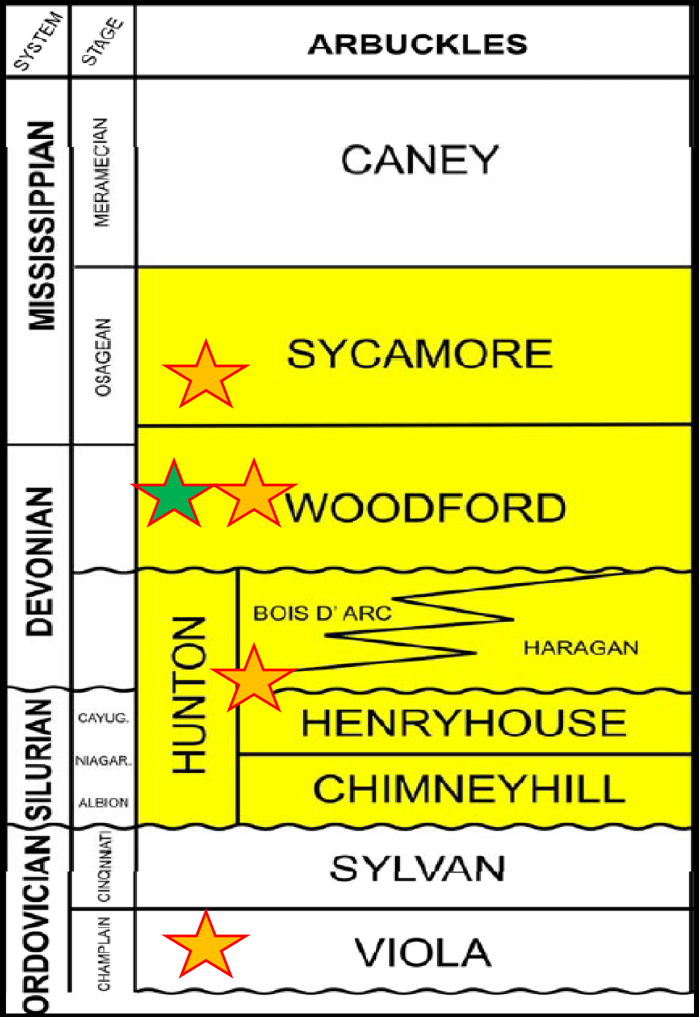
When conventional oil source rocks became unconventional reservoirs, geochemists learned more about them than ever before.

Anyone care to guess why?

Bakken and Woodford unconventional *petroleum systems* – not only source rocks



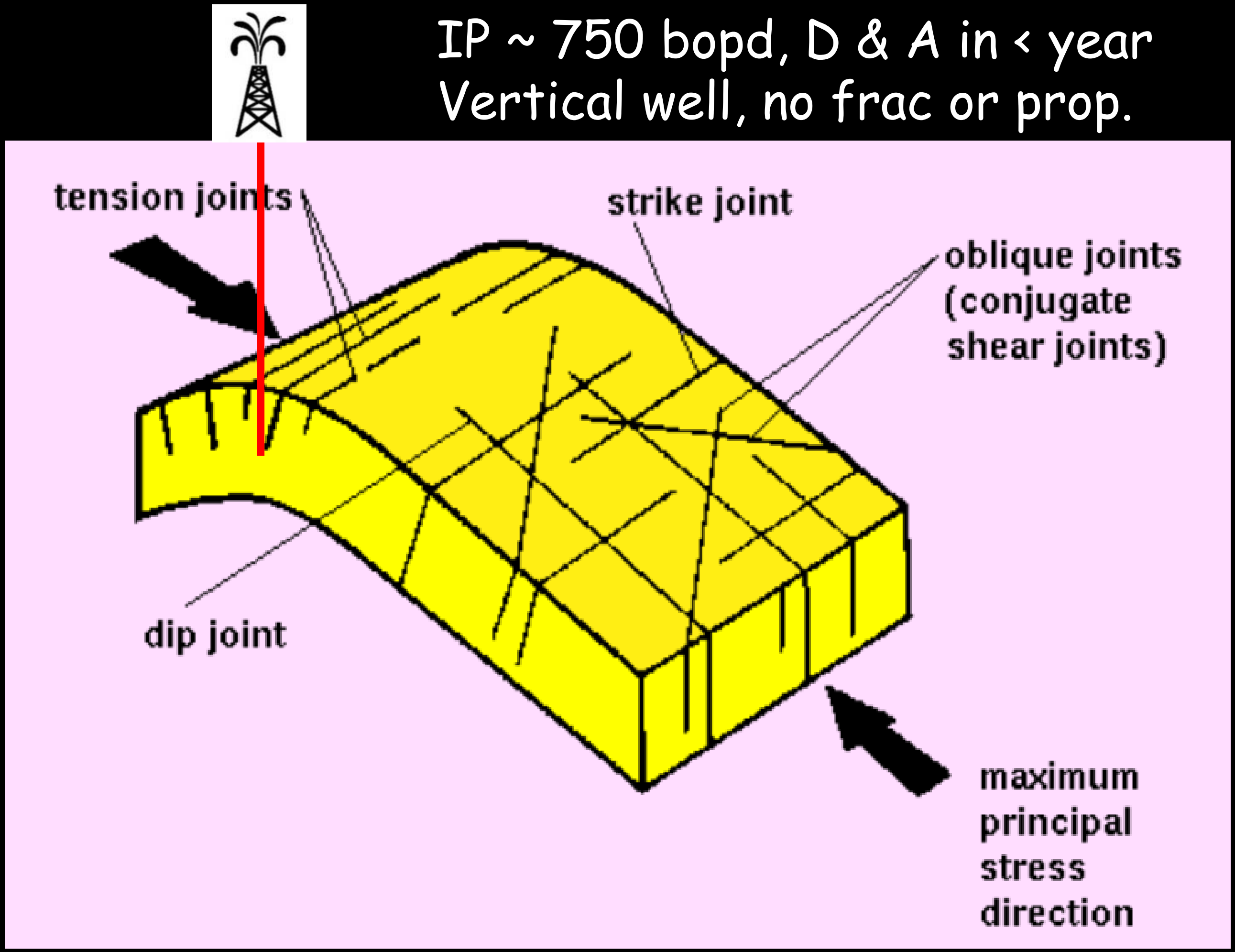
Grau and Sterling, 2011



Krystyniak, 2005

PAN AMERICAN HOVE # 1
UPPER BAKKEN *SHALE*, 1967

IP ~ 750 bopd, D & A in < year
Vertical well, no frac or prop.



http://homepage.usask.ca/

UNCONVENTIONAL RESERVOIRS DEFINITION AND CHALLENGE

THE DEFINITION:

Most *unconventional reservoirs* are *suspended* oil source rocks – once active but stopped generating prior to becoming spent.

THE QUESTION:

How did oil source rocks expel oil/gas and *how do we get them to give up some of the oil/gas which remains?*

SOURCE ROCK DEFINITIONS

- Source Rock – Generated and expelled enough oil or gas to form commercial accumulations.
- Active Source Rock – Actively generating oil or gas.
- *Suspended* Source Rock - Once active but has stopped generating prior to becoming spent. *
- Spent Source Rock – Completed the oil and or gas generation process.
- * *Usually due to cooling associated with overburden removal.*

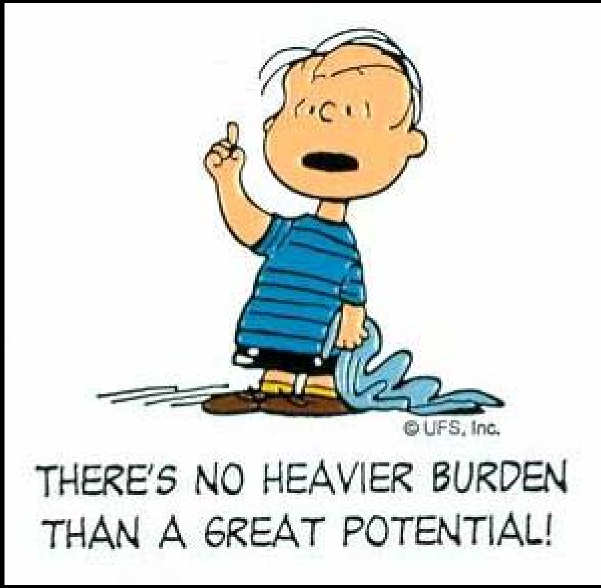
Dow, 1977

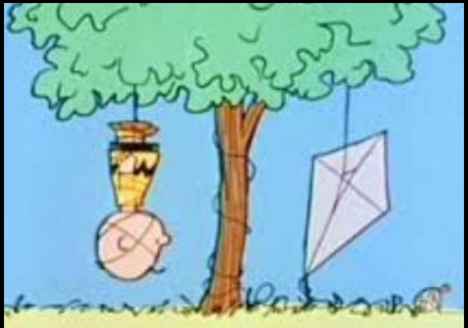
SOURCE ROCK DEFINITIONS

- Potential Source Rock – Capable of generating enough oil or gas to form commercial accumulations, but has *not yet done so due to thermal immaturity*.

Dow, 1977

Potential:
Possible, not active,
capable of becoming.





Don't let a little hang-up get you down.

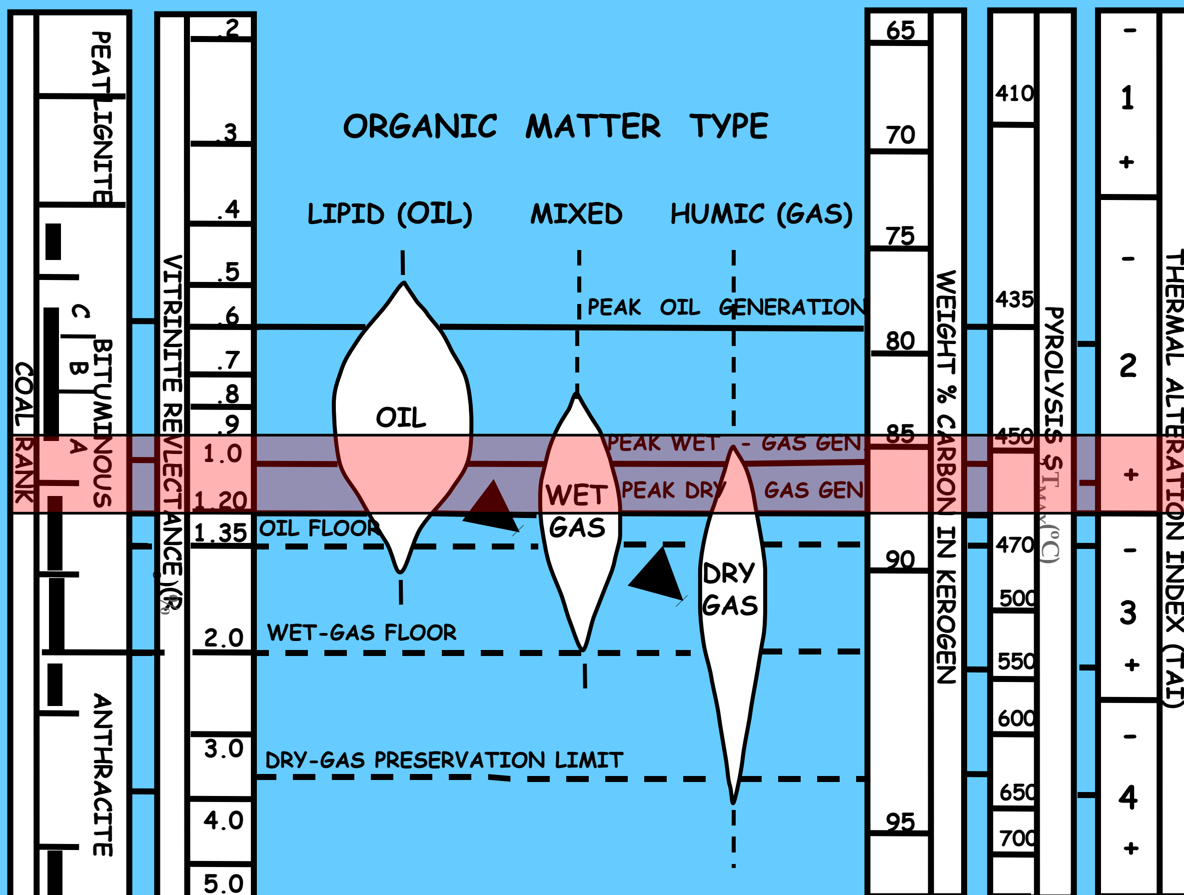
OIL
S. R.

Potential

Active/
Suspended

Spent

ZONES OF PETROLEUM GENERATION AND DESTRUCTION



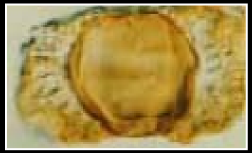
Unconventional liquids maturity "sweet spot"

CORRELATION OF VARIOUS MATURATION INDICES AND ZONES OF PETROLEUM GENERATION AND DESTRUCTION

Dow, 1977

HOW OIL SOURCE ROCKS FORM AND FUNCTION

Living Organic Material – Unstable after death



Diagenesis

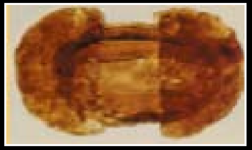
Little or no Heat

Kerogen - Chemically Stable

Catagenesis

Low to High Heat

Oil & Gas - Thermally Stable



Dow, 2011

Organic Matter Types that have *High Hydrogen Contents* make Crude Oil - *and Most Natural Gas!*

"Oil-prone source rocks comprise sediments that are high in organic carbon and contain organic material sufficiently hydrogen rich to convert mainly to oil during catagenesis. Such organic materials include plankton, algae, spores, pollen, leaf cuticle, tree resin, and anaerobic bacteria."

Passey et al., 2010

HOW ARE OIL & GAS MADE FROM PLANT/ANIMAL REMAINS?

Living Organic Material – Unstable after death

Diagenesis

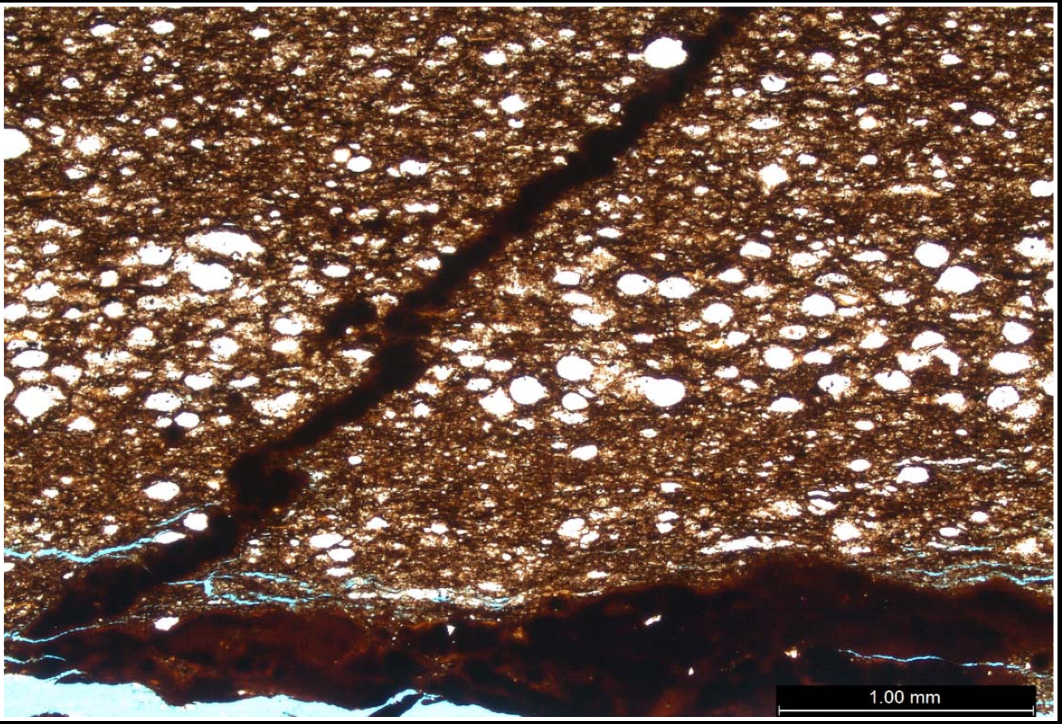
Kerogen - Chemically Stable

Solid Bitumen →

Catagenesis

Oil & Gas – Thermally Stable

SOLID BITUMEN IS SQUEEZED INTO PORES & FRACTURES DURING EARLY OIL GENERAION (0.5 - 0.6% Ro)

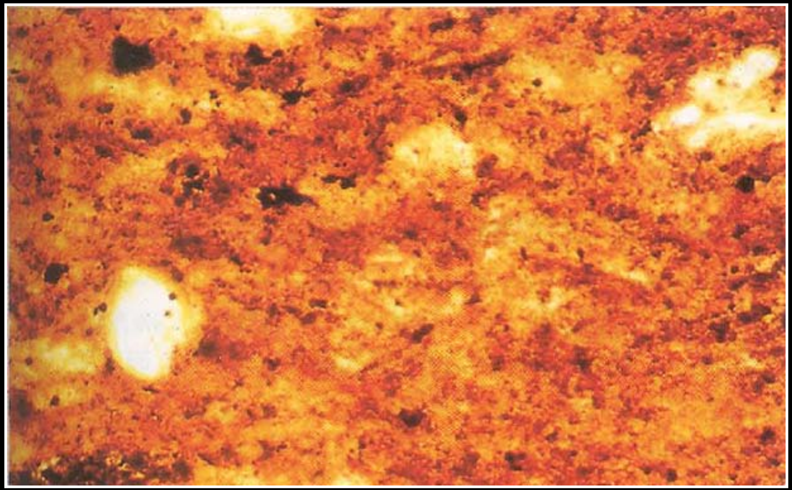


Dow, 2012

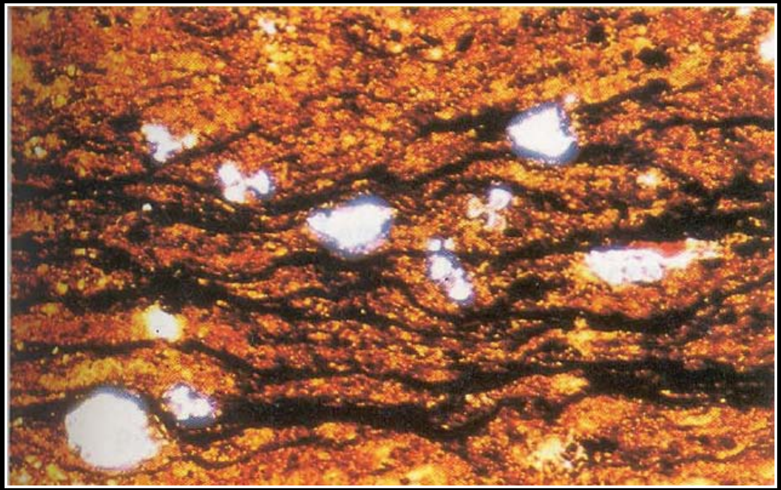
Hand from Perez & Marfurt, 2013

THIN SECTIONS COMPARING IMMATURE AND EARLY MATURE WOODFORD SHALE SOURCE ROCK

Pre-oil generation Woodford Shale

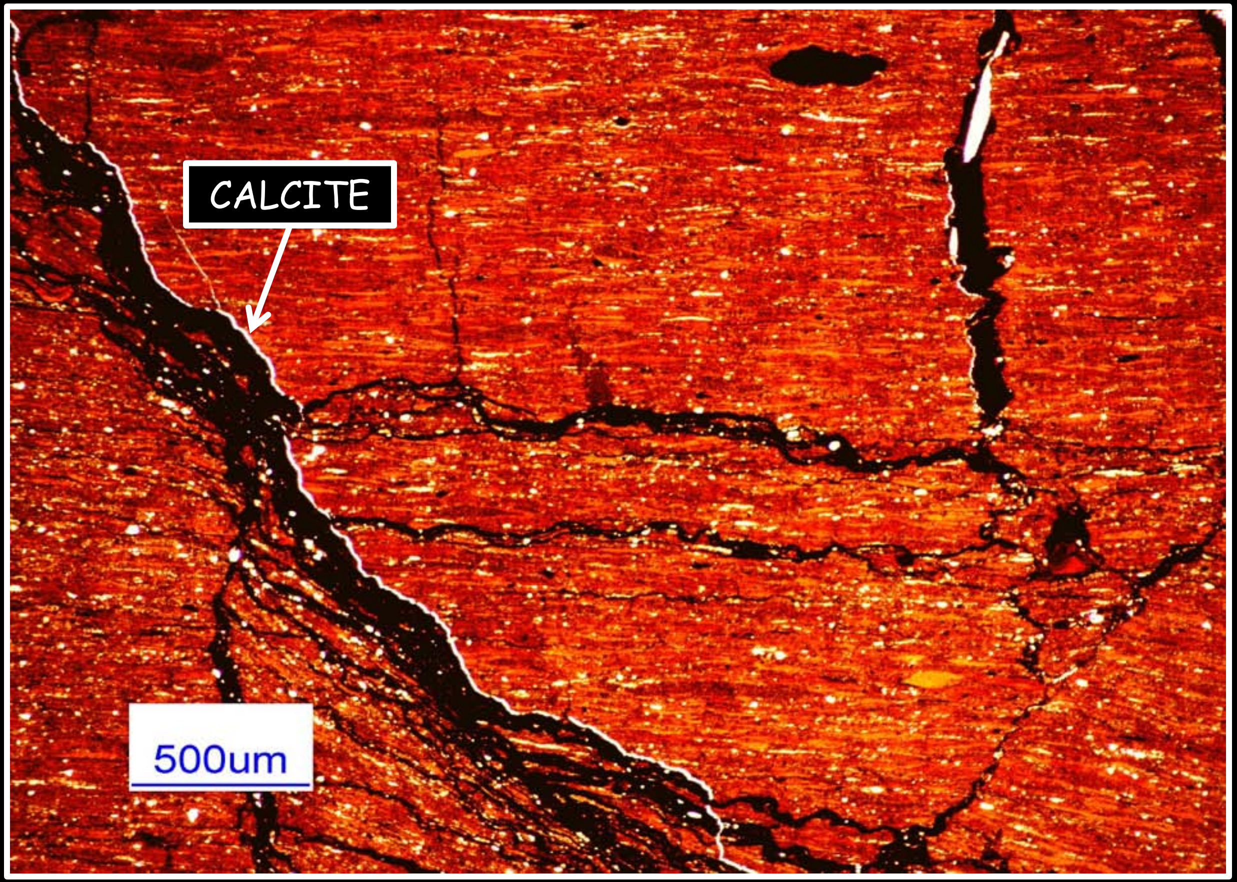


Early oil generation Woodford Shale with solid bitumen in fractures



M. D. Lewan

SOLID BITUMEN IN THIN SECTION WITH EARLY DIAGENETIC CALCITE



SOLID BITUMEN IN REFLECTED LIGHT MICROSCOPY *(WHOLE ROCK MOUNTS)*

Not Migrated

Migrated

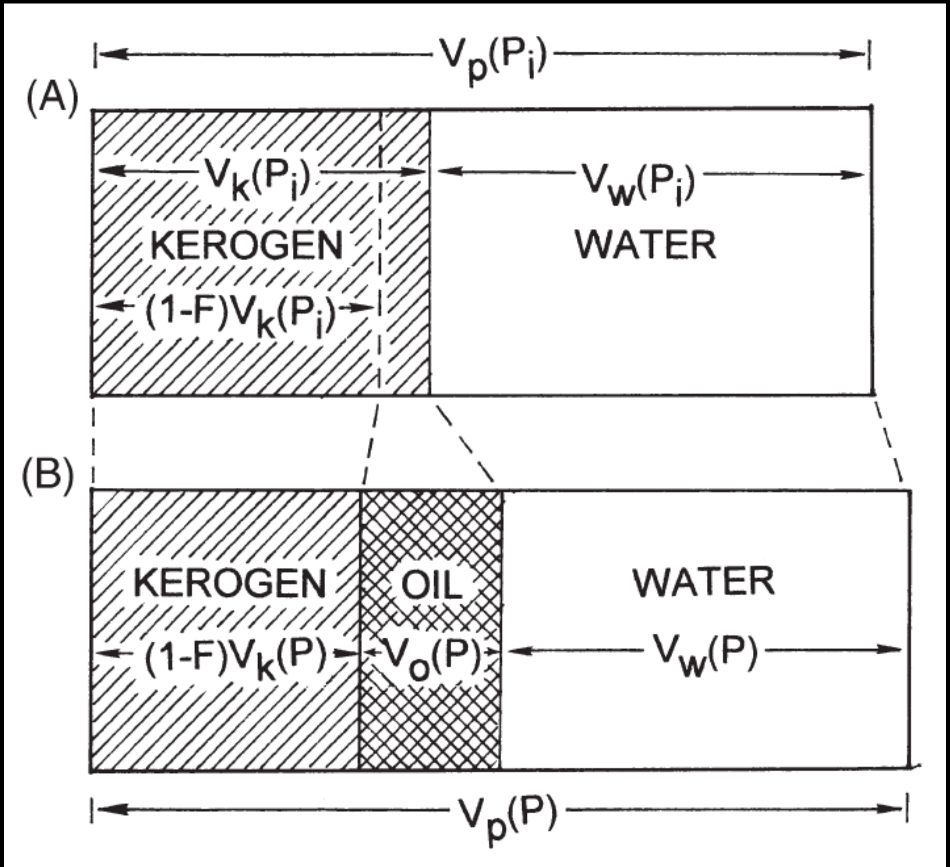
W. Dow

CONCEPTUAL MODEL OF OIL AND GAS GENERATION - 1

- Organic-rich source rocks are exposed to heat during burial.
- A portion of the kerogen is converted *solid bitumen* and then to oil and gas.
- This results in a *volume increase [and gas generation]* which increases the porosity and internal pressure of the source rock.

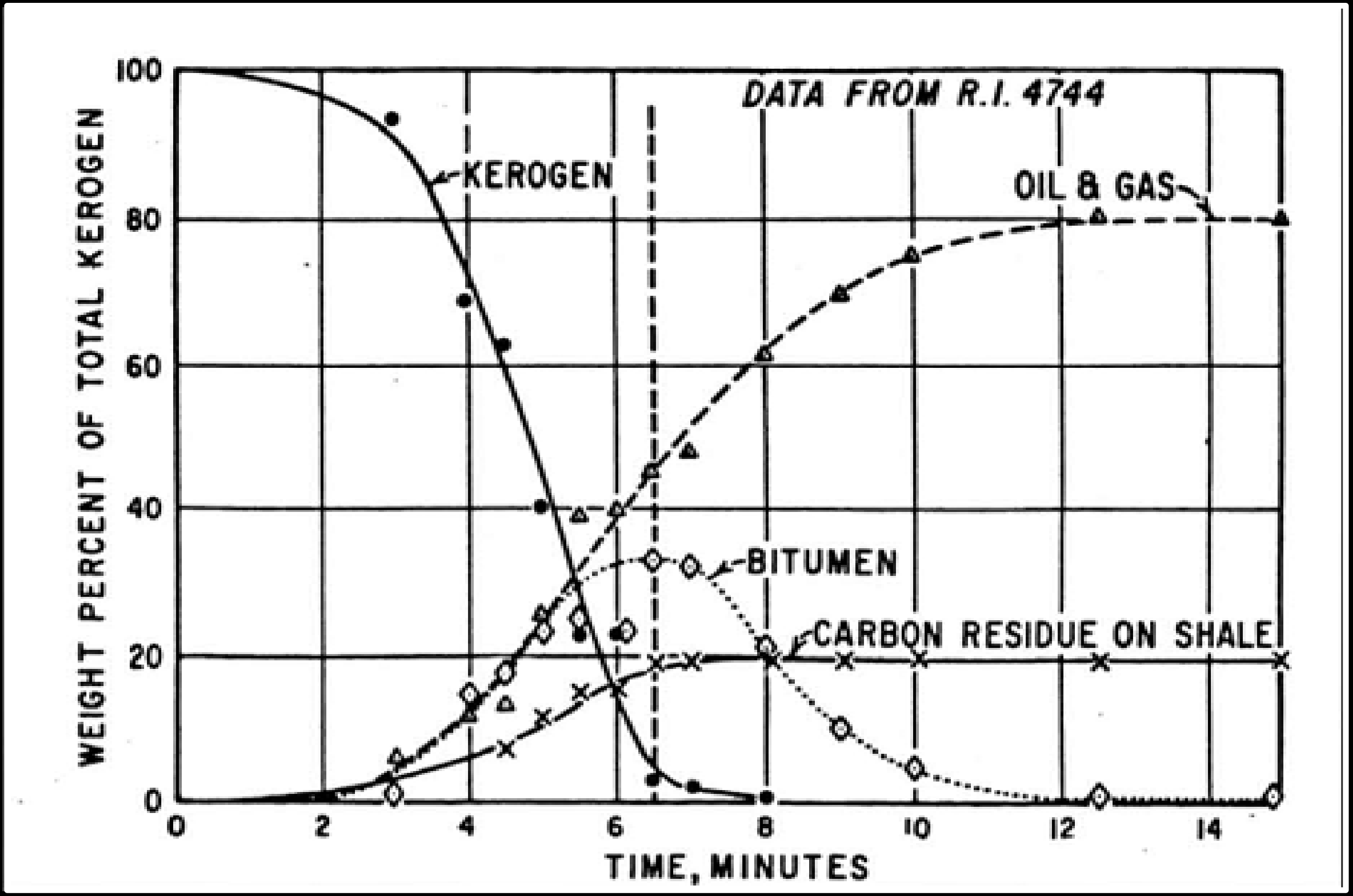
Momper, 1979

CONVERSION OF KEROGEN TO OIL IS A VOLUME AND PRESSURE INCREASE REACTION



Berg & Gangi, 1999

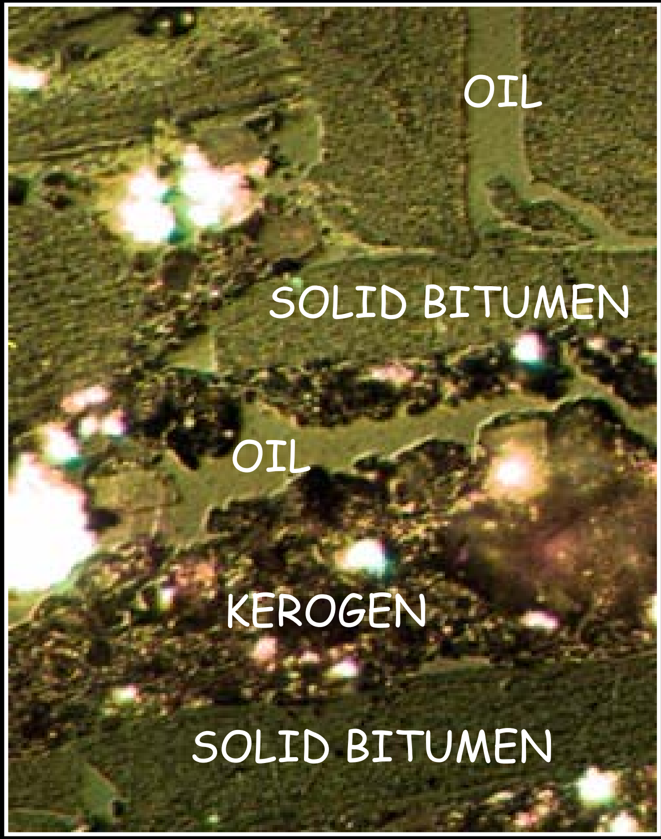
OIL SHALE RETORT PRODUCTS IN THE LABORATORY

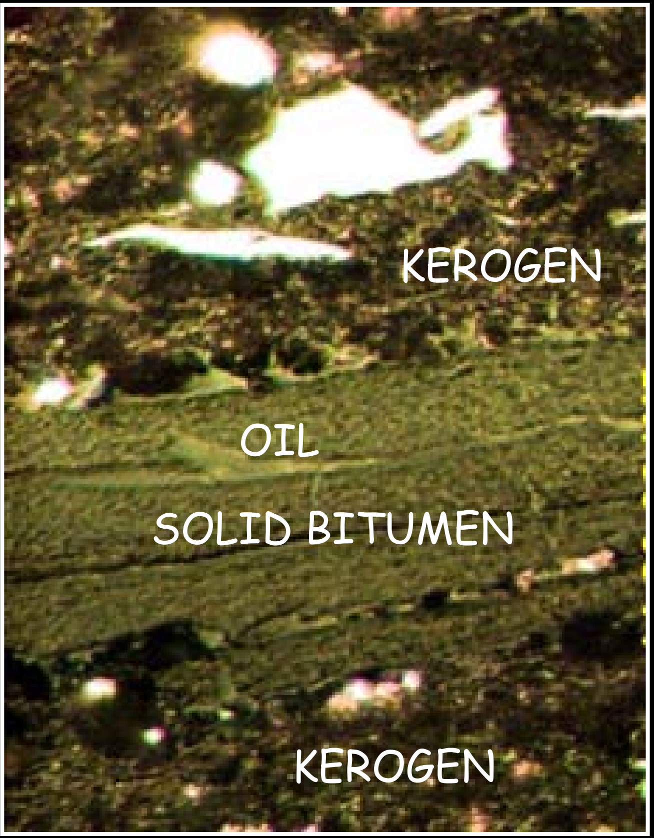


Allred, 1967

KEROGEN, SOLID BITUMEN, AND OIL IN REFLECTED LIGHT

High TOC oil source rock, 0.75% Ro, dried out core, asphaltic oil residue preserved.



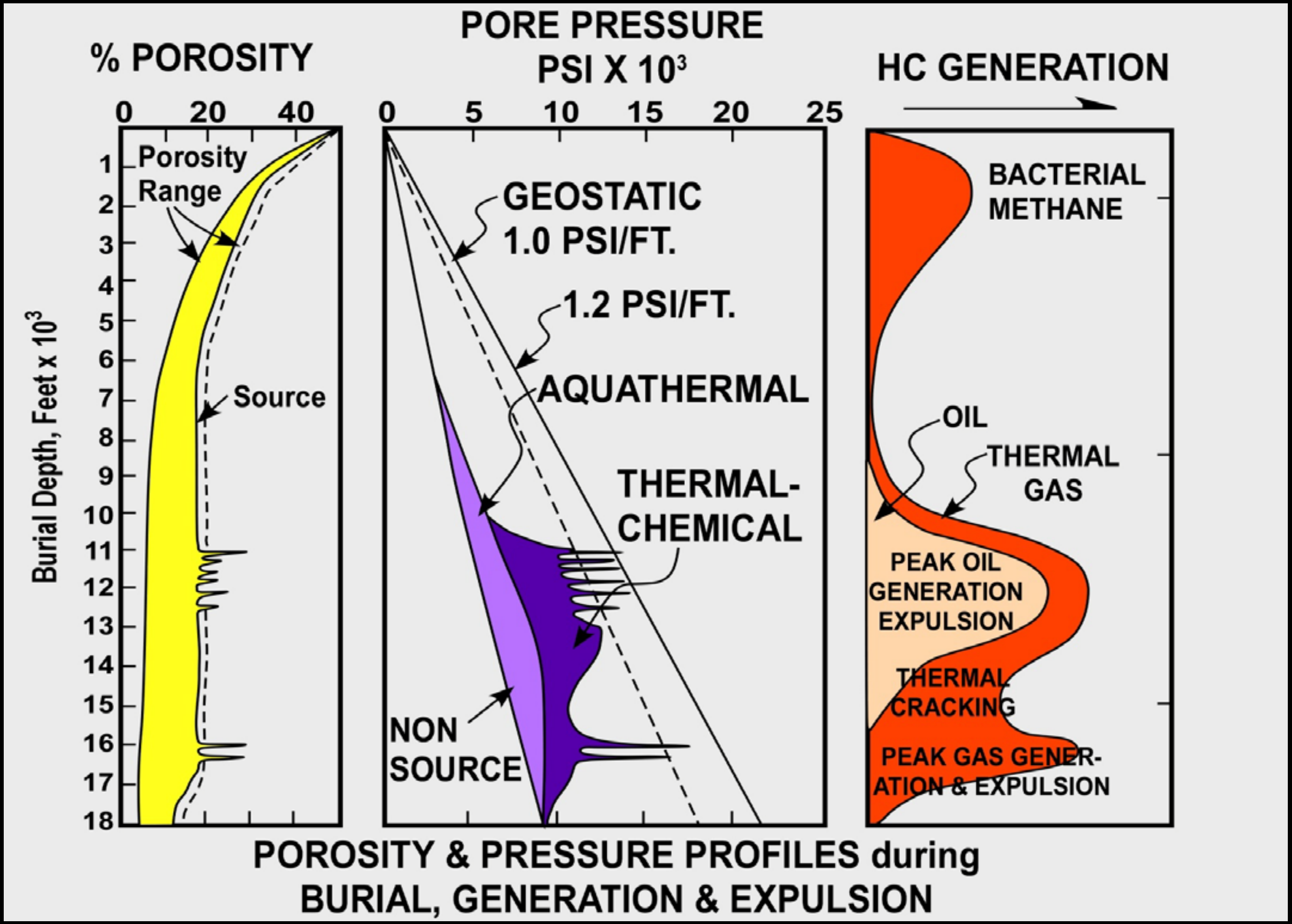


CONCEPTUAL MODEL OF OIL AND GAS GENERATION - 2

- When the pressure exceeds geostatic, *the rock ruptures,* oil and gas are expelled, the *fractures close*, and the source rock returns to near pre-generation porosity and pressure.
- This process is repeated many times as the source rock passes through the oil and gas generation maturity “windows”.
- Oil expulsion is *very inefficient* and ~80% of the oil generated never leaves the source rock (unconventional reservoirs) and ultimately is converted to condensate and then to wet gas, dry gas, and finally graphite.

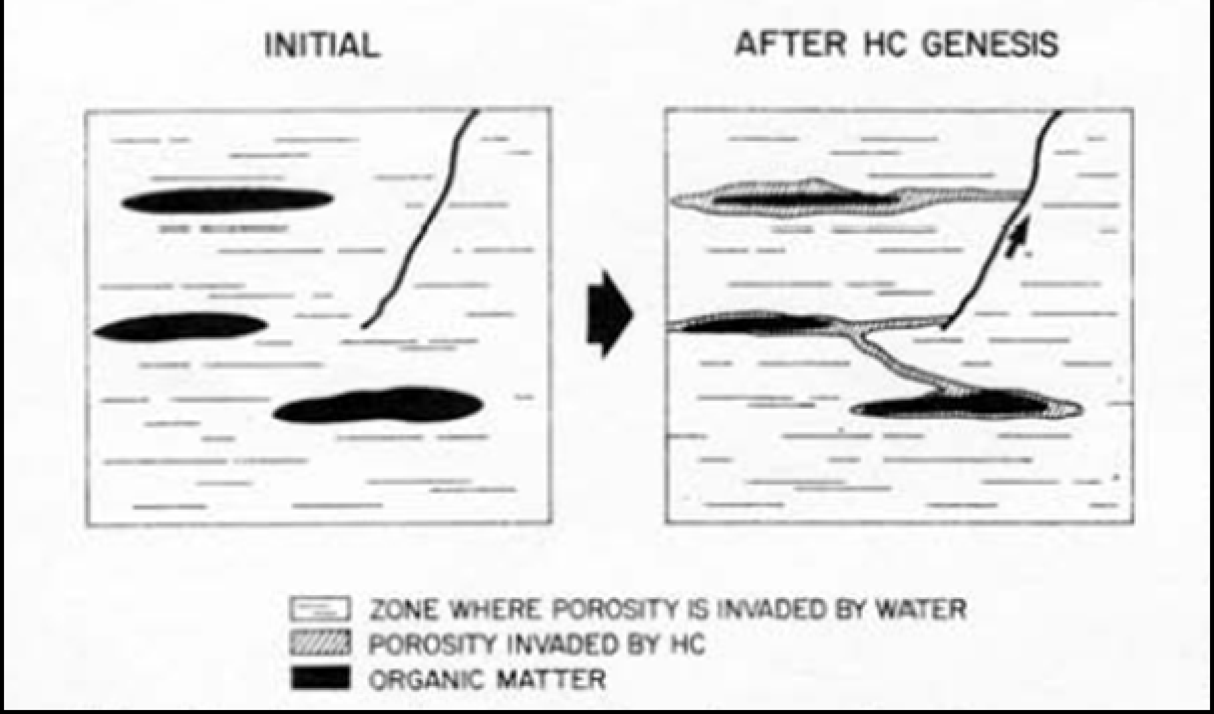
Momper, 1979

NOTIONS OF SOURCE ROCK PRESSURE COOKERS



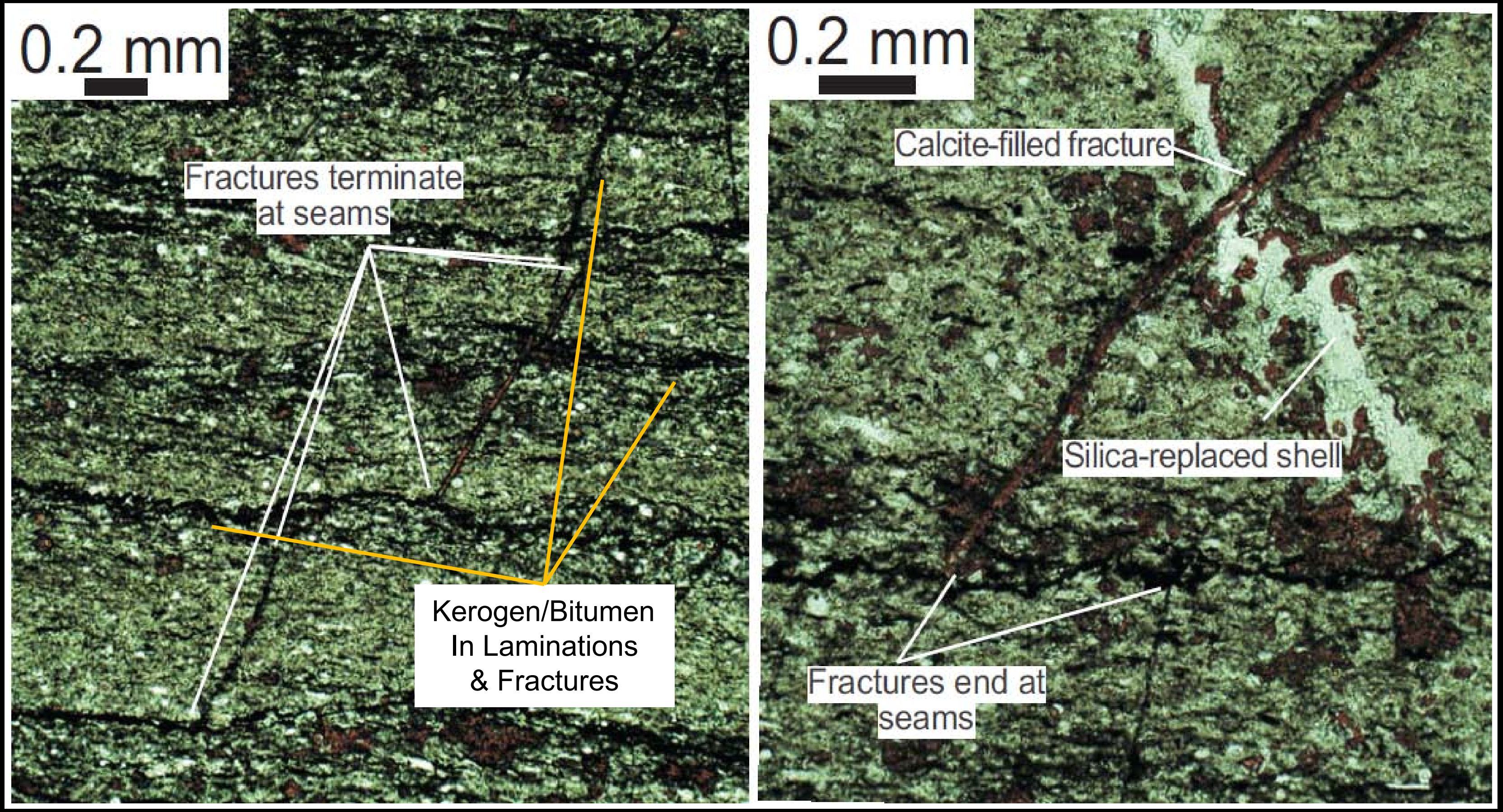
AAPG Distinguished Lecturer, Jim Momper, 1979

PRIMARY MIGRATION OCCURS ALONG BEDDING AND CRACKS



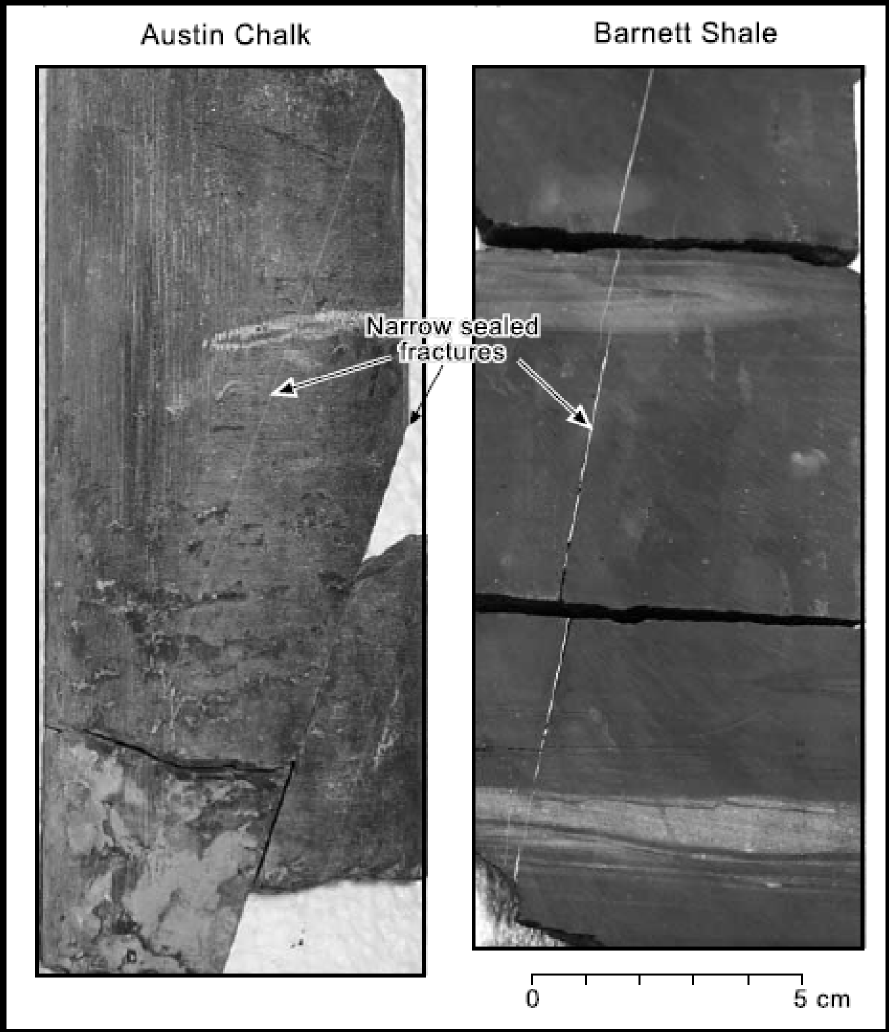
Ungerer et al., 1983

PRIMARY MIGRATION OCCURS ALONG BEDDING AND CRACKS



Loucks, 2009

NATURAL CRACKS IN SHALE



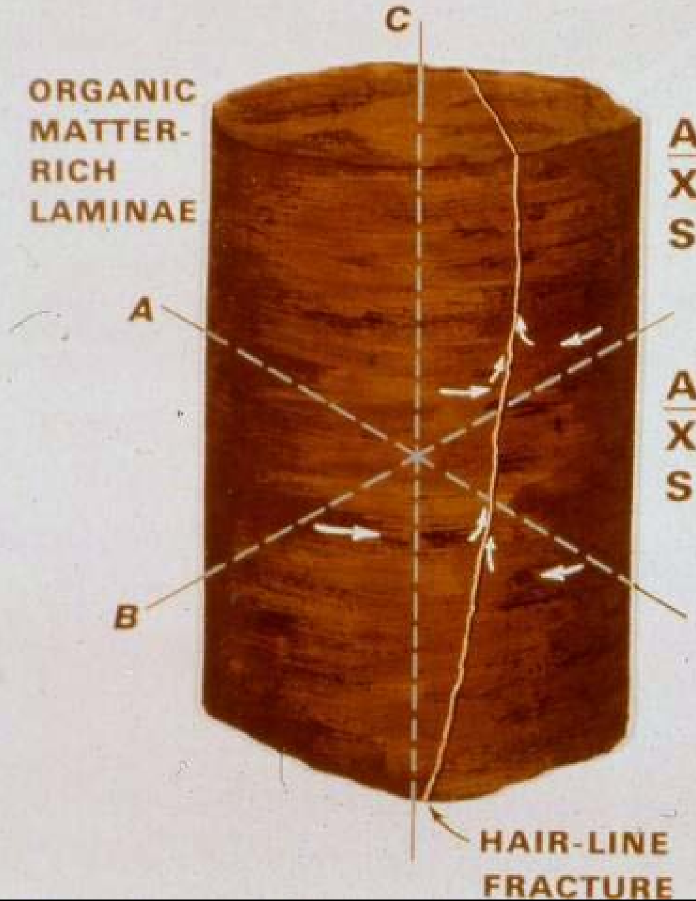
Gale, et at, 2007

New Albany Shale

Gale, 2013

SHALE HETEROGENEITY AND ANISOTROPY

OIL-SOURCE; PEAK GENERATION



CONVENTIONAL CORE

ALONG C-AXIS ⊥ to bedding
X-RAY: Preferred Orientation of Clays
SEM: Well-packed Arrangement of Overlapping, Stacked 'Leaves'

ALONG A-& B-AXES II to bedding
X-RAY: Random Clay Orientation
SEM: Open Flaky Texture; Fissility Evident

↖ Preferential Fluid-Migration Directions

Momper, 1979

HOW SHEAR AND TENSILE CRACKS FORM

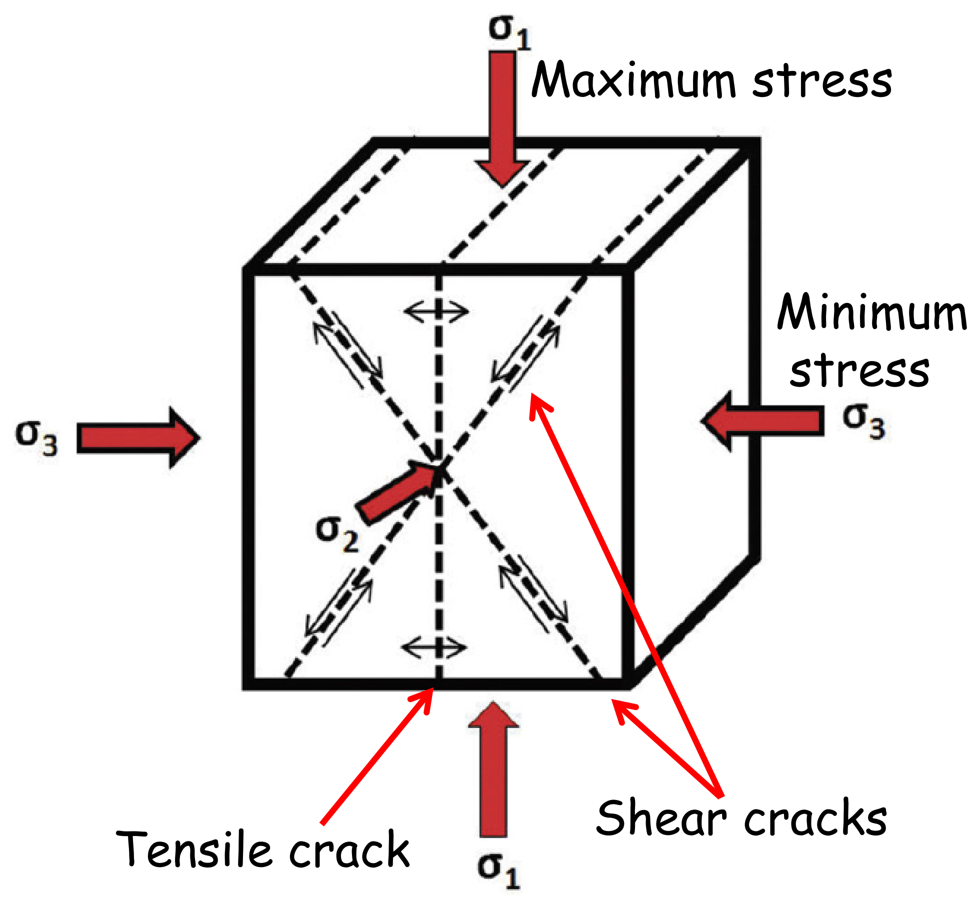
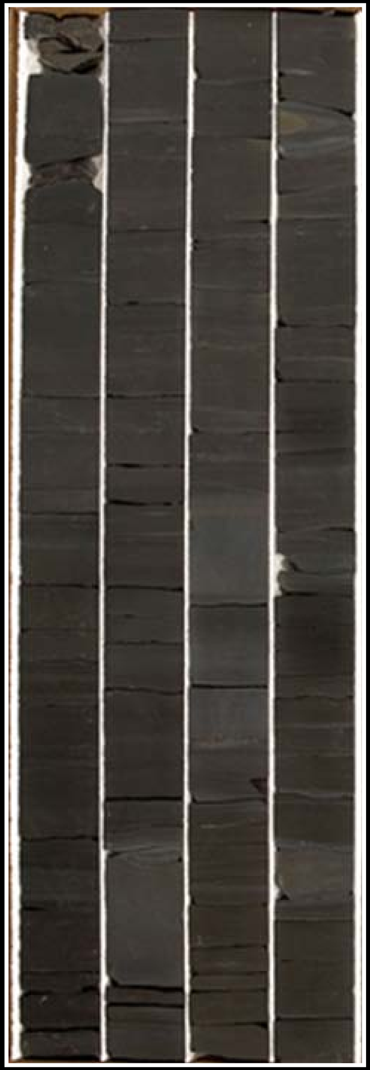


Figure 2. Sketch of the three compressive fracture planes with possible orientation of tensile and shear fractures. Note that $\sigma_1 > \sigma_2 > \sigma_3$.

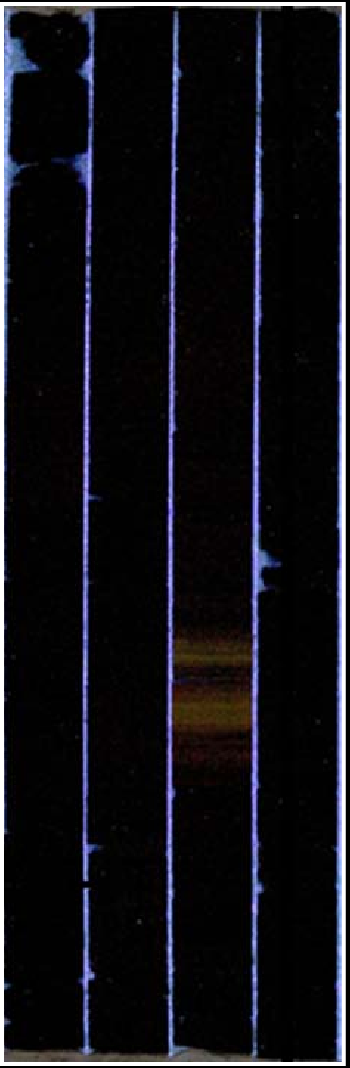
http://csegrecorder.com/

SLABBED CORE PHOTOS

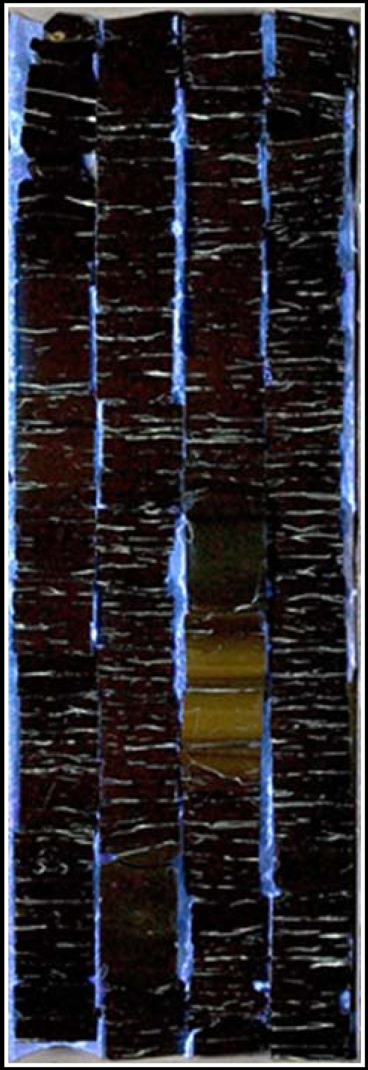
White light



Fluorescent light.



Fluorescent light with solvent.

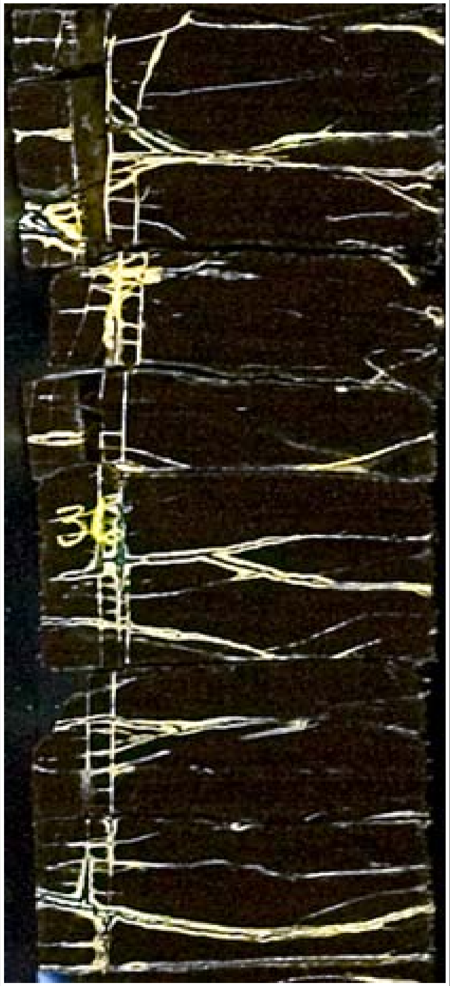


W. Dow

CRACK ENHANCEMENT WITH SOLVENT

5 Seconds.

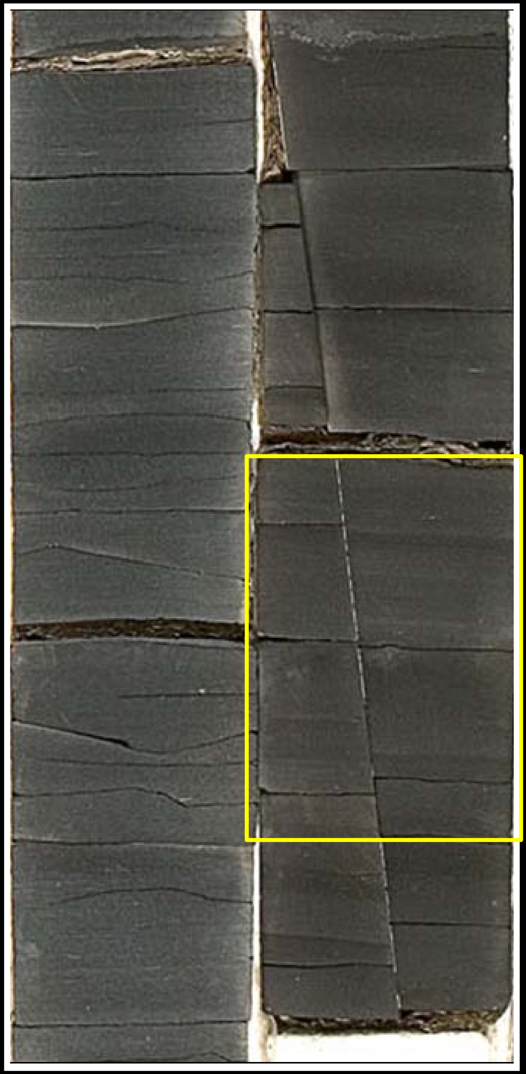
60 Seconds.

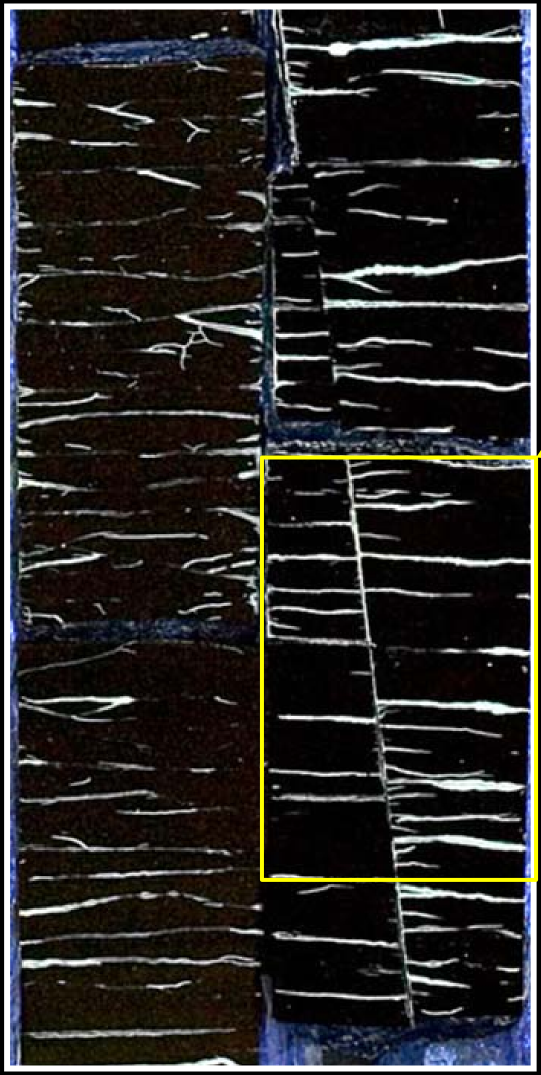


W. Dow

SOLVENT ENHANCED CRACKS

Bedding plane partings and high angle shear fractures.



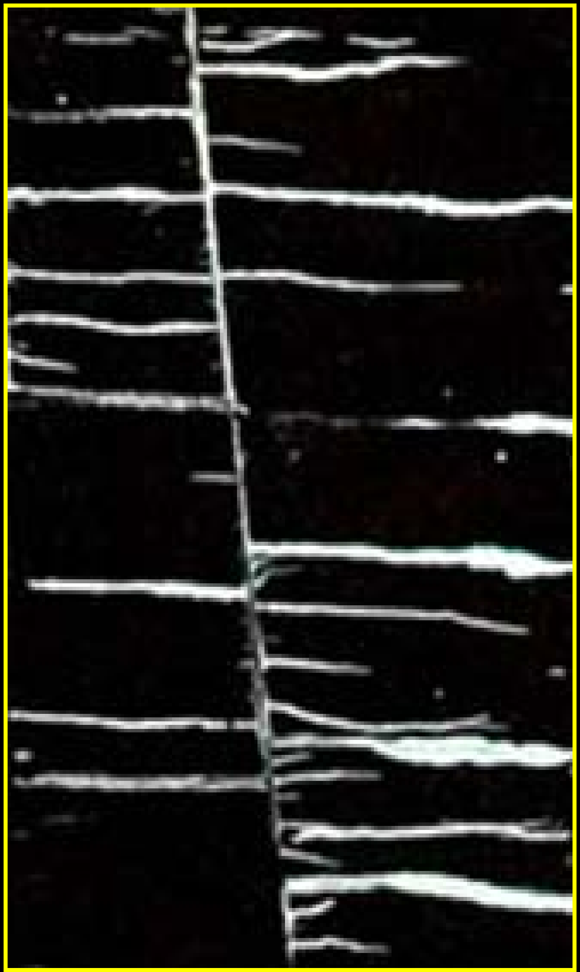


Next slide

W. Dow

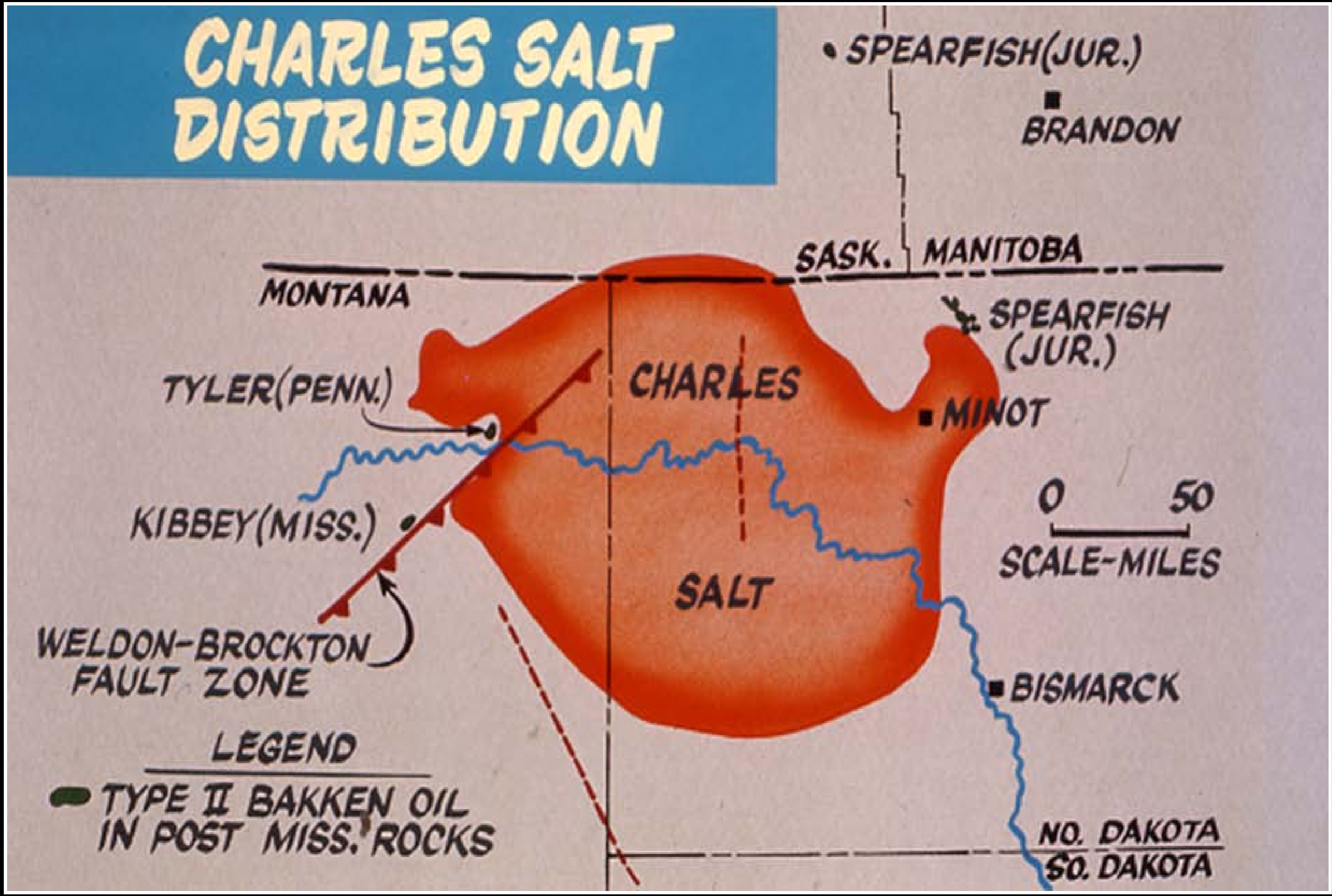
SOLVENT ENHANCED CRACKS

Fluorescent in bedding plane partings and high angle stress cracks.



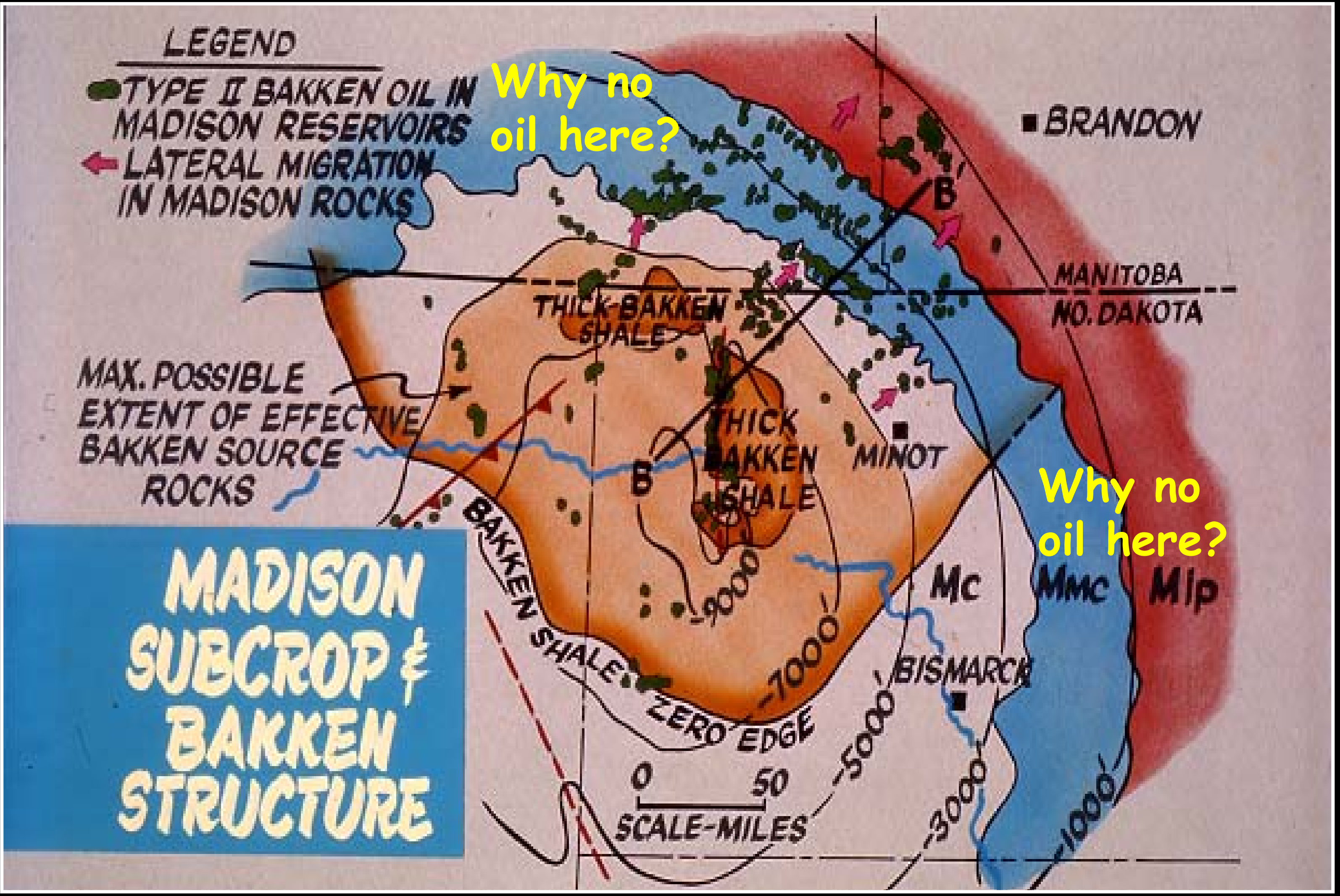
W. Dow

WILLISTON BASIN BAKKEN OILS



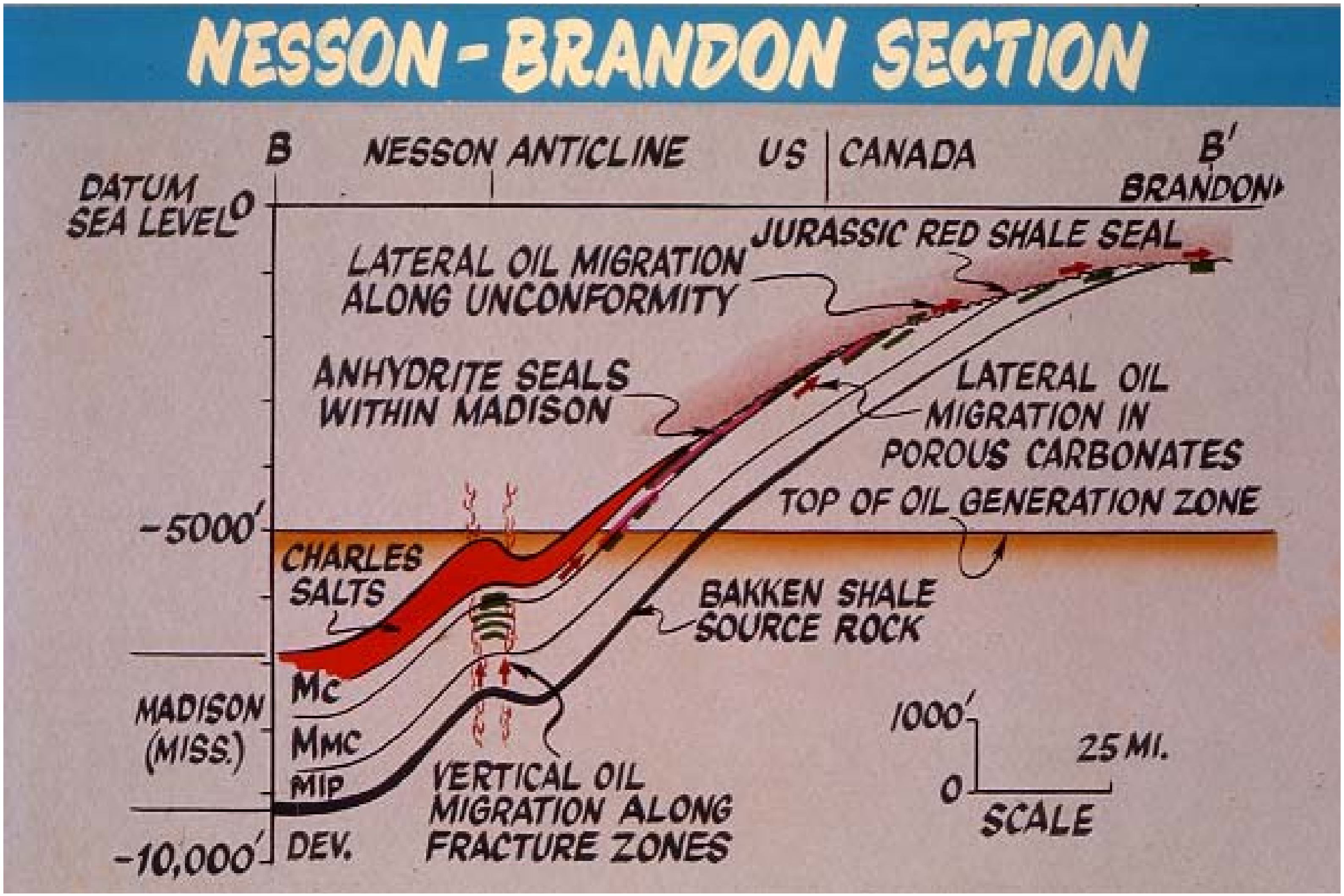
Dow, 1972

WILLISTON BASIN BAKKEN OILS



Dow, 1972

WILLISTON BASIN BAKKEN OILS



Dow, 1972

PERMEABILITY OF FAULT ZONES

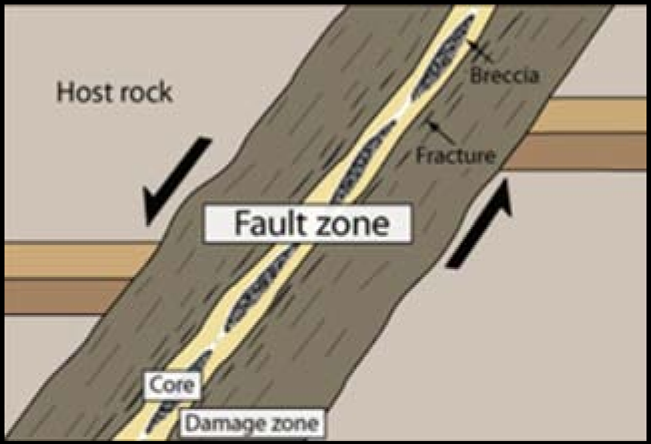
1) Faults form when shear cracks link up.

2) Damage zone forms and pores and cracks get interconnected.

3) Damage zone becomes very permeable.

4) Permeability is controlled by the local stress field.

Gudmundsson, 2000

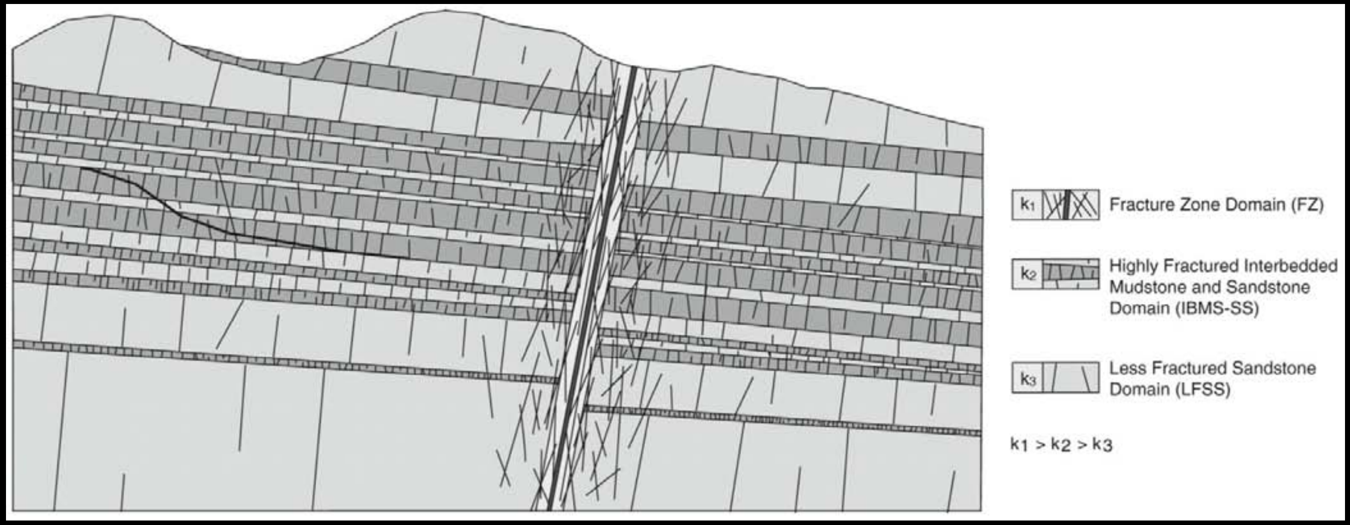


Tectonor

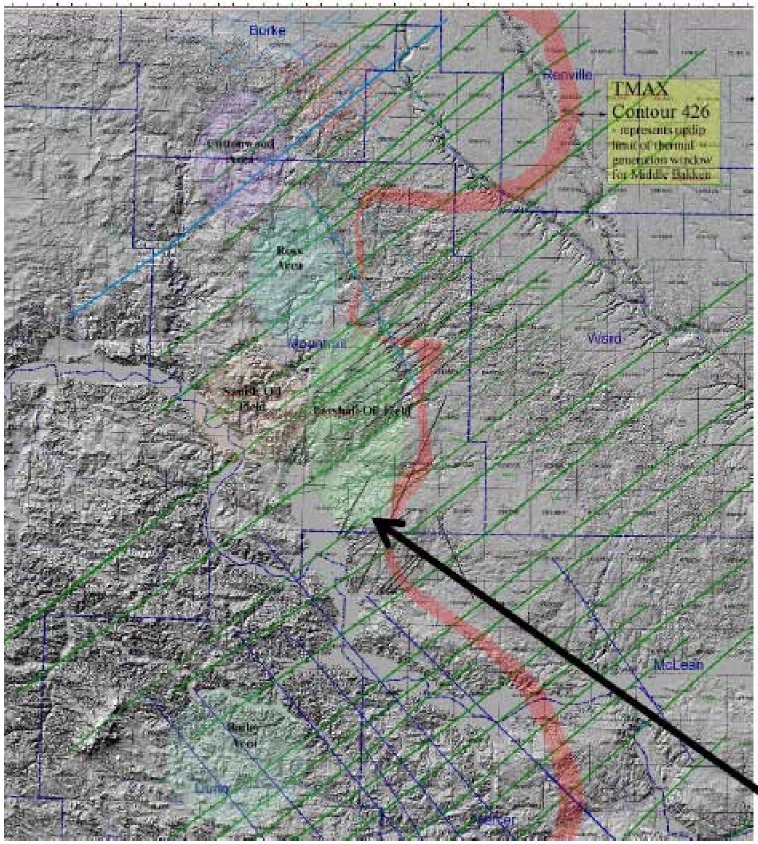
WILLISTON BASIN SHEAR FAULTS

The Williston Basin contains many:

1) Basement controlled faults
2) Periodically active entire stratigraphic column.
3) Affects deposition, salt solution, etc.
4) Expressed as surface lineaments.



Role of Fractures in the Bakken Play



Digital Elevation Map

Scales of Fracturing

- Regional
- Macro/Reservoir Scale
- Microfractures (Rock Fabric Scale)

Fracture content in Bakken important in reservoir development

★ More Fractures = More Production

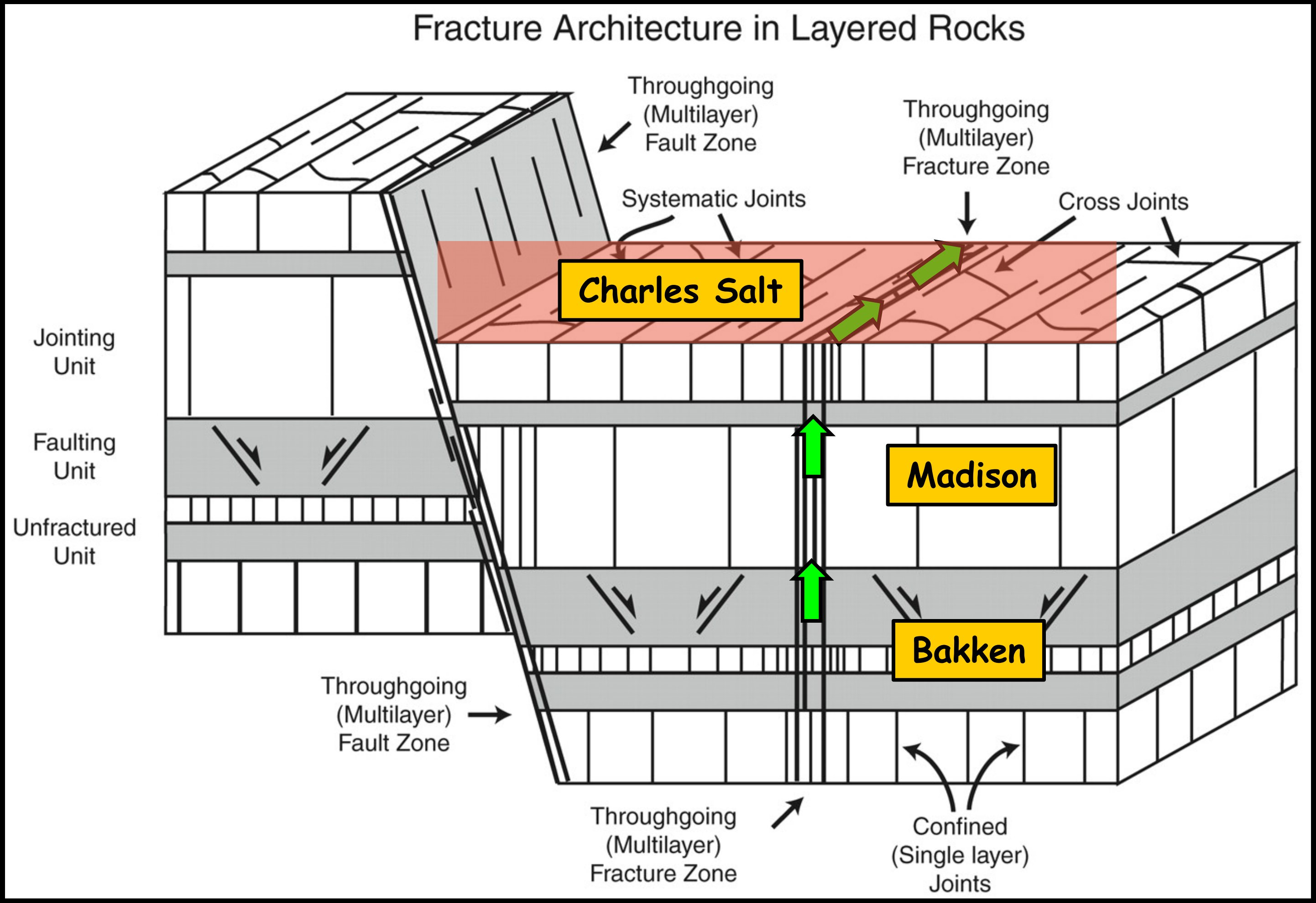
Fractures affect basement heat flow

★ Variations in Thermal Maturity controlled by Fractures

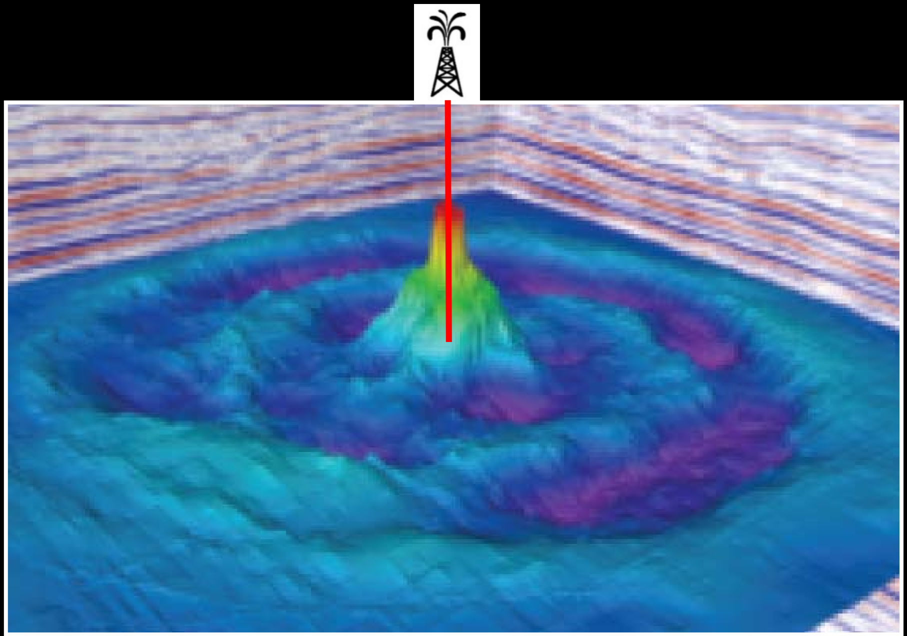
Pressure cells are occasionally bound by sealing fractures.

Grau & Sterling, 2011

BAKKEN OIL LATERAL MIGRATION OCCURS IN FAULT - FRACTURE ZONES



TRUE OIL, RED WING CREEK IMPACT CRATER, WILLISTON BASIN, N.D.



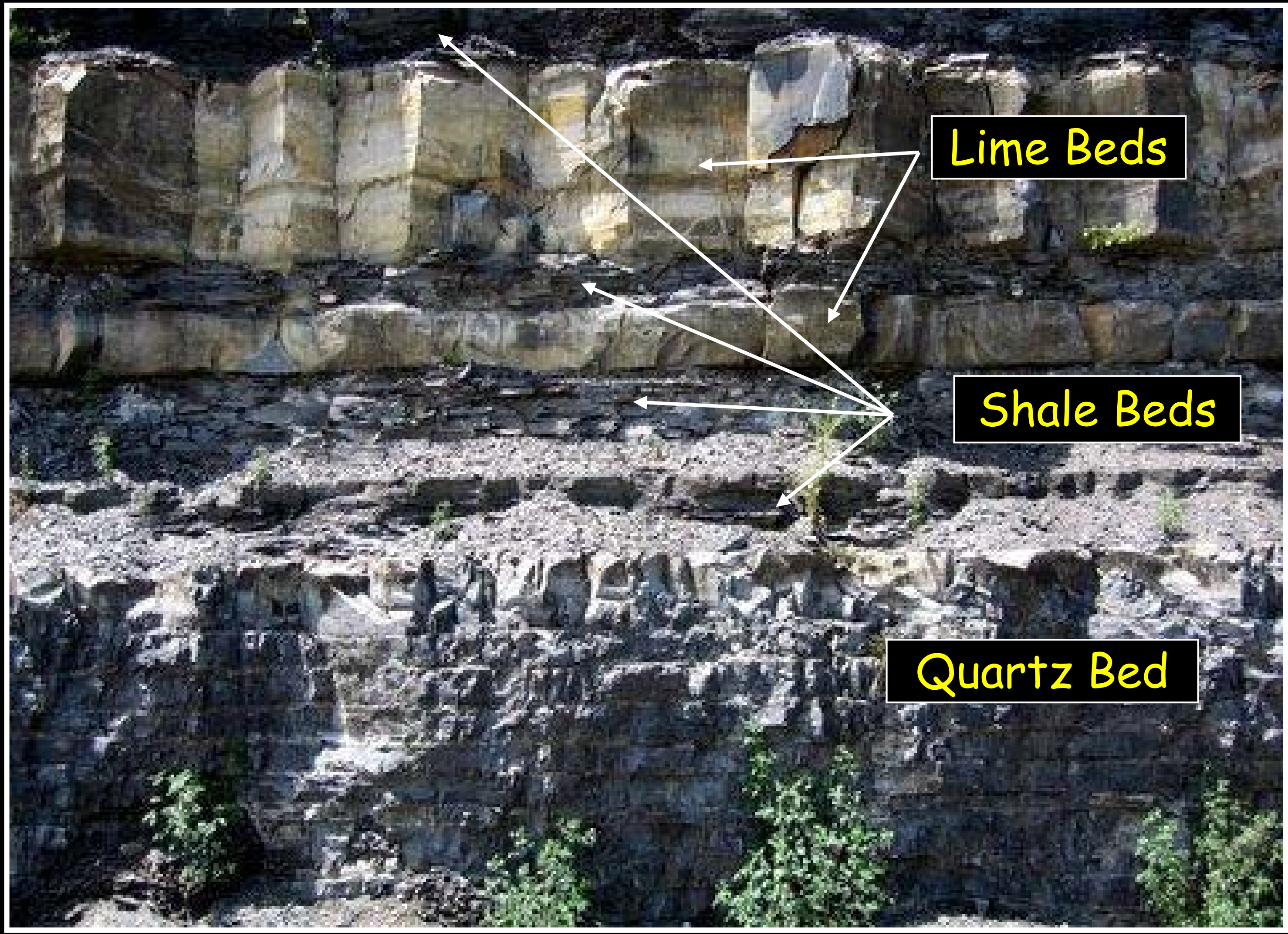
Barton et al., 2010

1600' oil column in *highly fractured* & brecciated tight Mission Canyon carbonate in the central uplift area. Bakken source rocks. Produced 17 million bbl oil and 700 mmcf gas from 26 wells since 1972.

HOW DO OUTCROP CRACKS RELATE TO SUBSURFACE CRACKS.

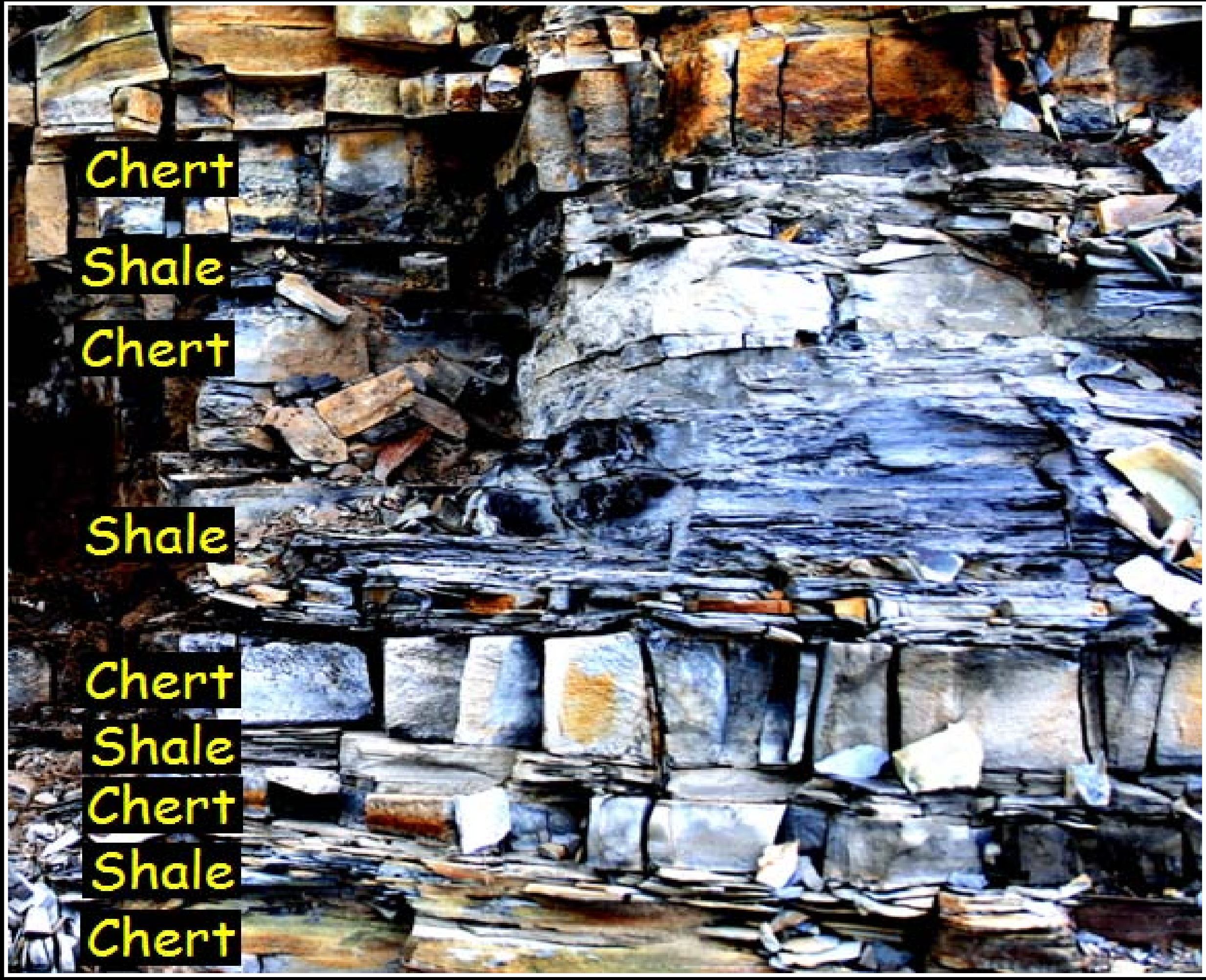
They can provide some idea how different lithologies will crack, but overburden (stress) removal and weathering can result in many more types of cracks than are present in the subsurface.

UPPER FAYETTEVILLE, ARKANSAS



Dow, 2005

WOODFORD OUTCROP, I 35 ROAD CUT, ARDMORE BASIN, OK

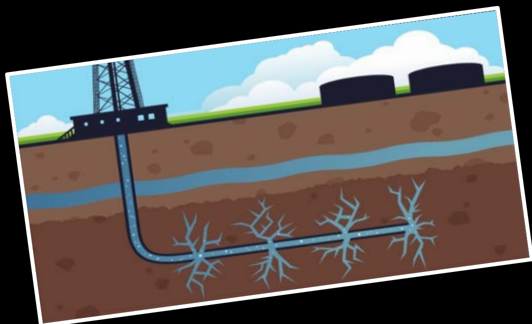


Dow, Miller, Lewan, 2011

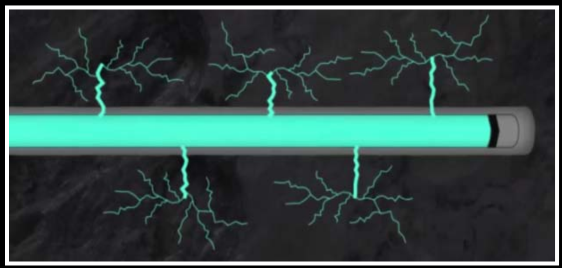
WHAT DO ARTIFICAL HYDRAULIC CRACKS *REALLY* LOOK LIKE?

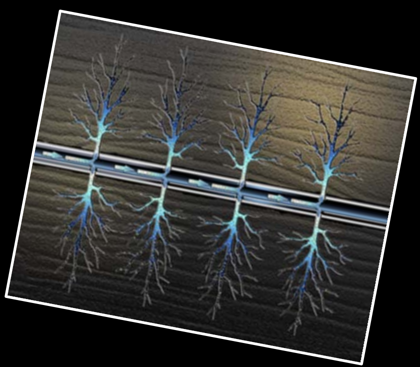
Nobody really knows but there are many ideas. Most of the illustrations were made by artists, not scientists.

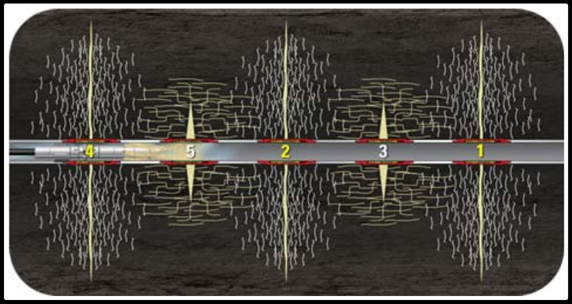
NOT LIKELY ANY OF THESE!

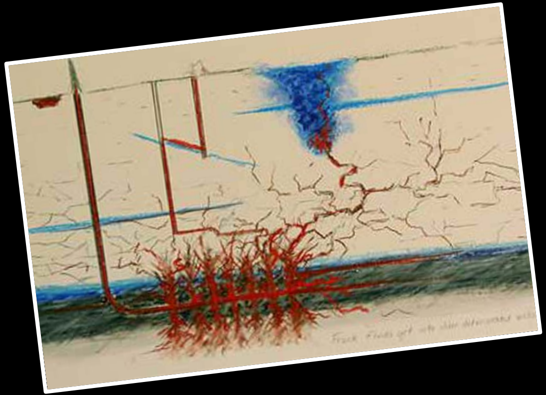


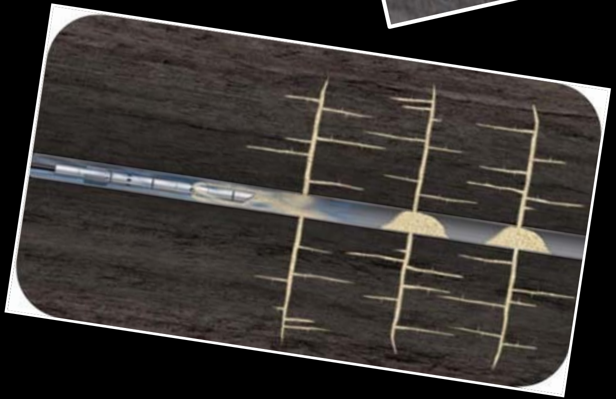
?









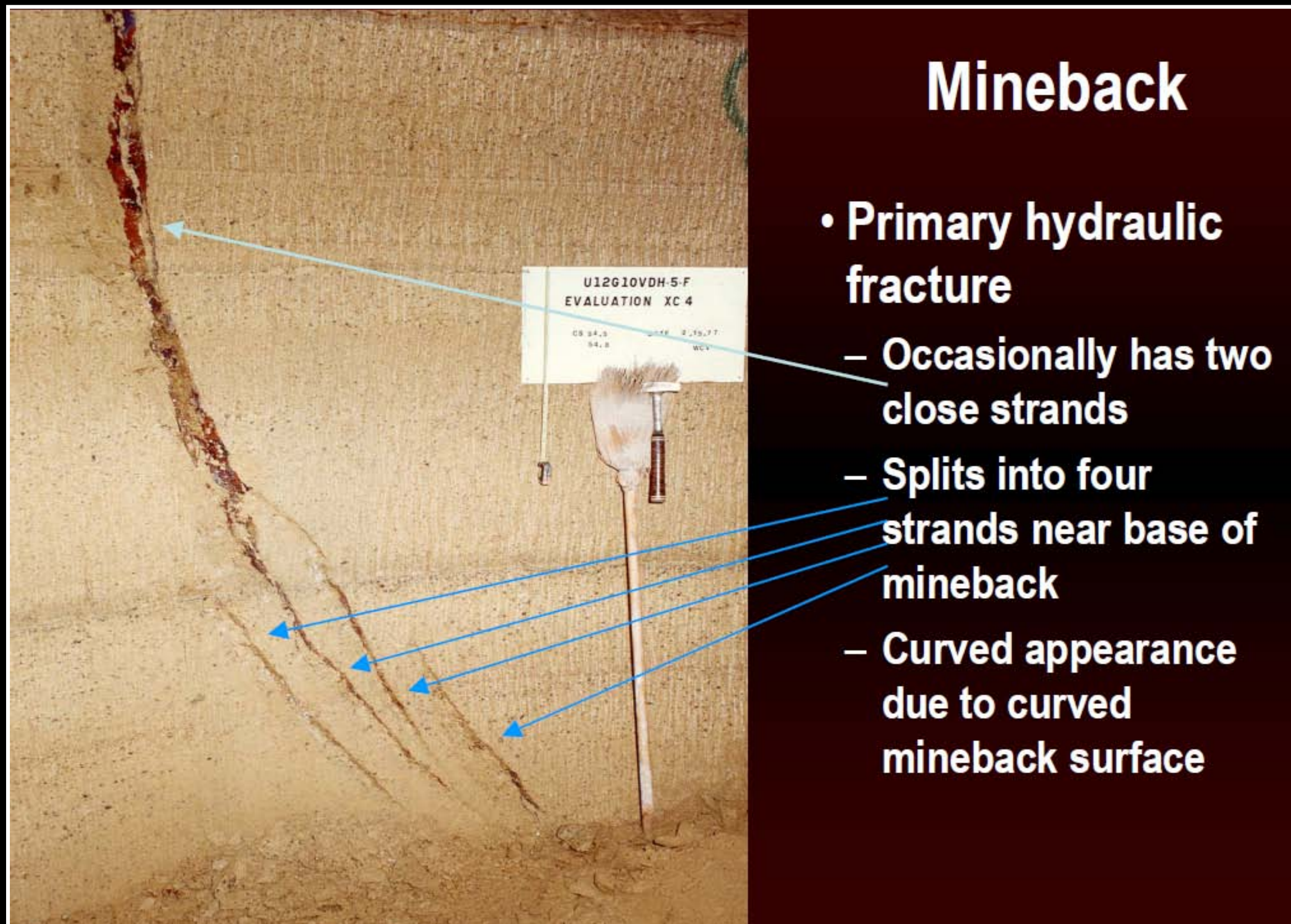


MINEBACKS ARE *NOT* A GOOD ANALOG FOR UNCONVENTIONAL RESERVOIR CRACKS BECAUSE:

Temperature is too low.
Pressure is too low.
Stress field is wrong.
Lithology is different.

- But you can see cool sand-filled cracks

PROPPED HYDRAULIC CRACKS IN SANDSTONE, NEVADA TEST SITE



Kevin Fisher, Halliburton

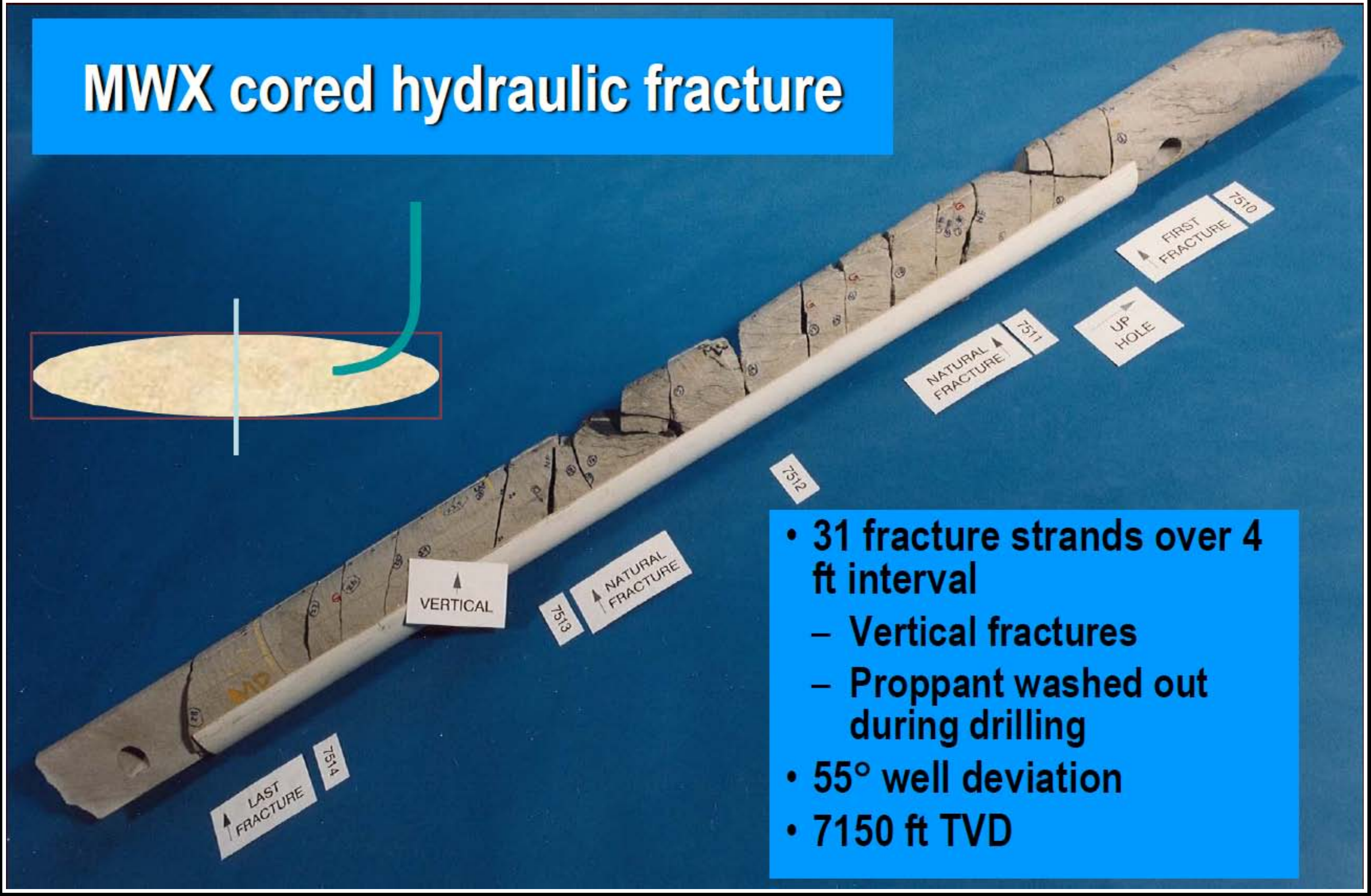
CORED HYDROFRACS ARE *NOT* ALWAYS USEFUL BECAUSE THE SAND PACK TENDS TO FALL OUT.

But you can identify artificial cracks because they can contain hydrofrac chemicals.

Here's an idea!

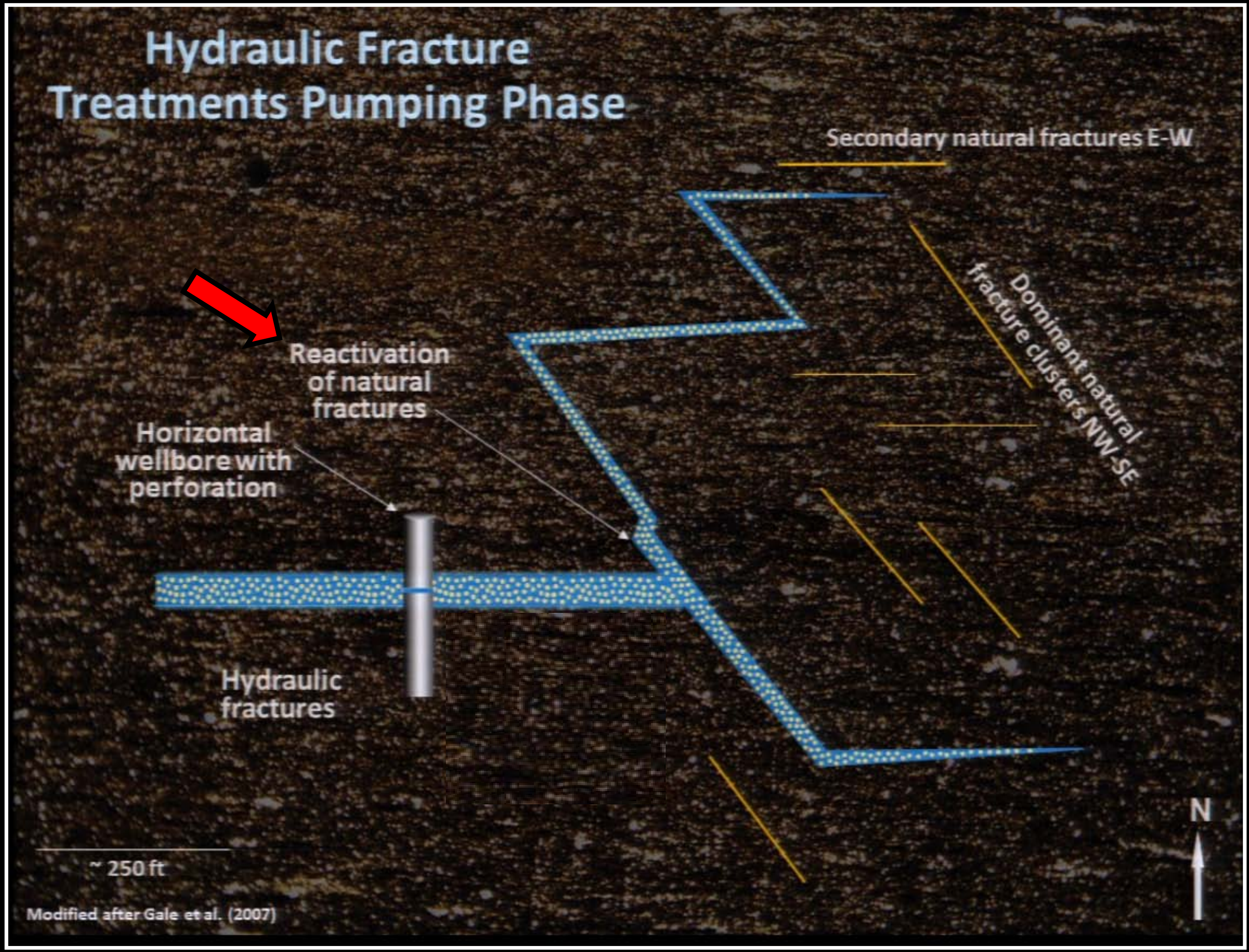
May be a large service company should put together a multi-client project to core and study a hydrofrac'ed zone in a played-out unconventional reservoir!

CORED HYDRAULIC CRACKS IN PALUDAL MESAVERDE SAND



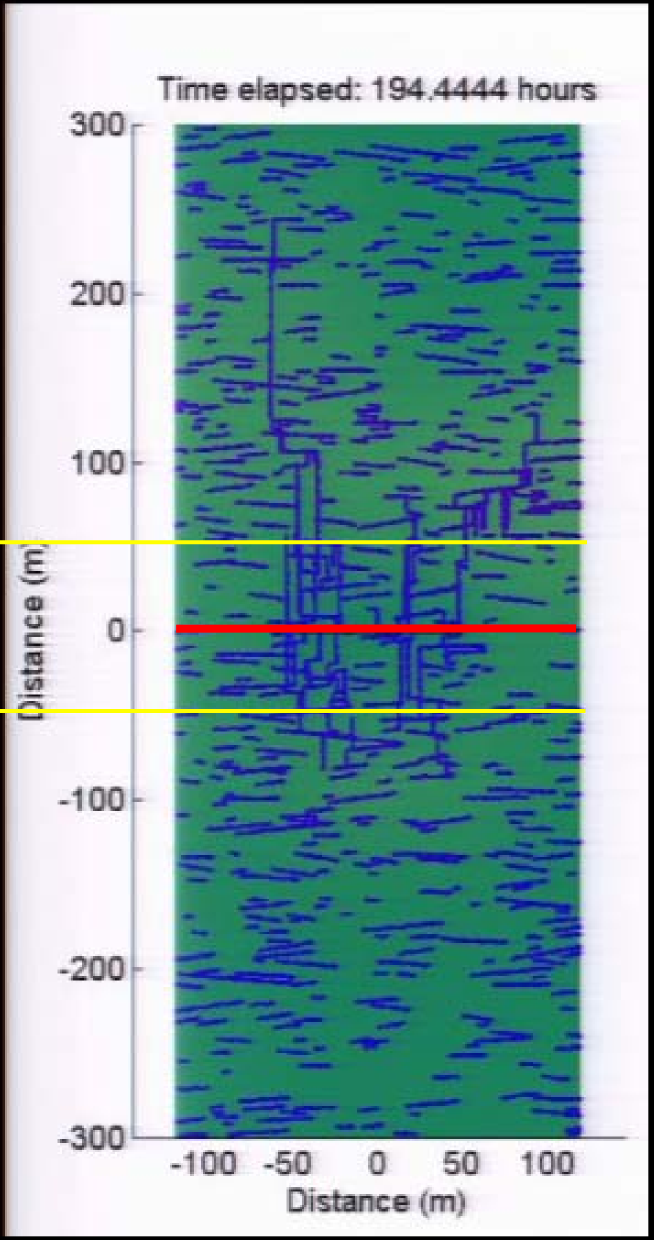
K. Fisher *after* Warpinski et al., 1993

HYDRAULIC FRACTURING MODEL



F. Javadpour, 2014

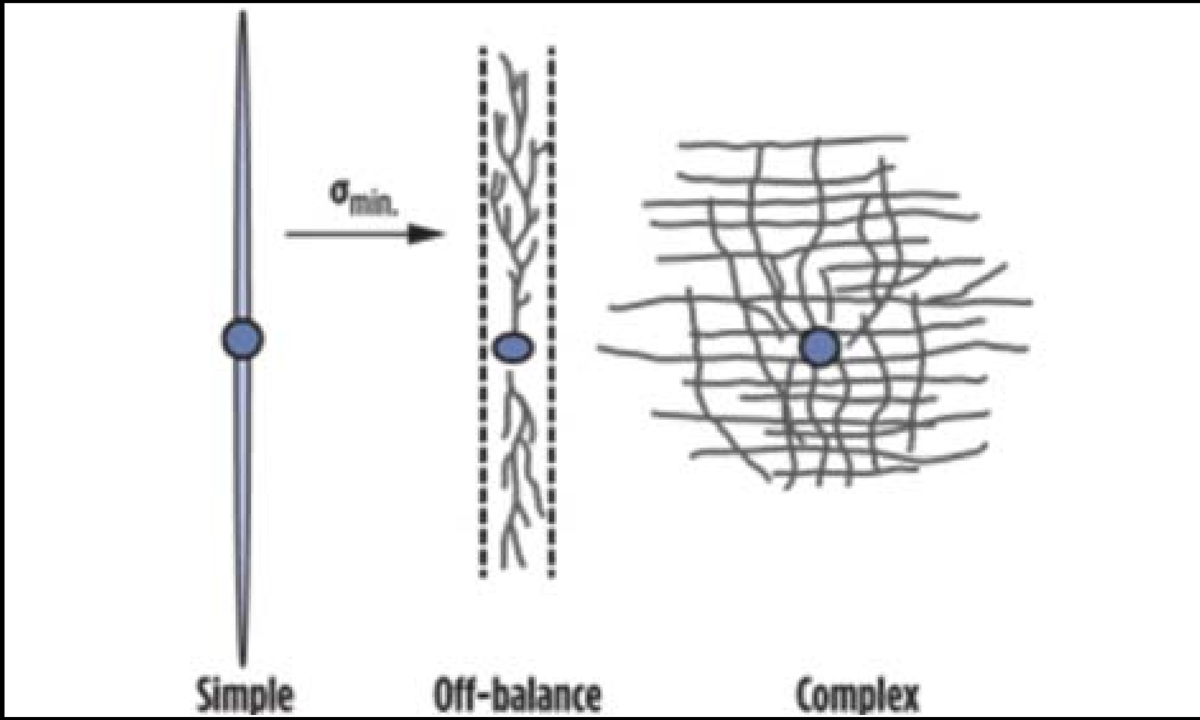
Greatest crack density is within 50 m of lateral.



F. Javadpour, 2014

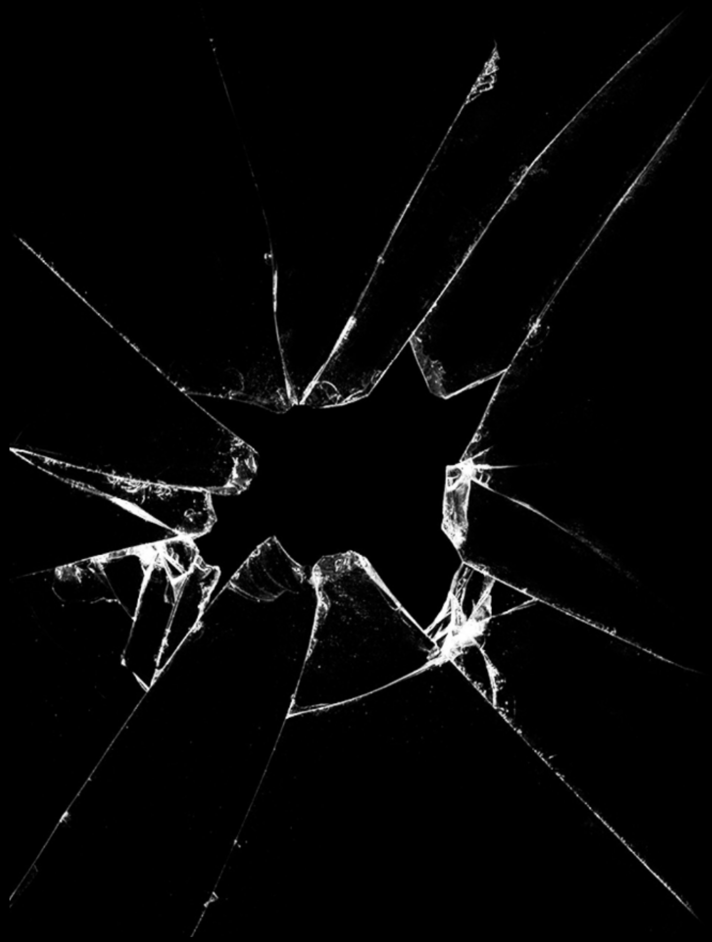
CRACK INTENSITY DECREACES AWAY FROM POINT OF ORIGIN IN ROCKS AND GLASS ALIKE

CRACK GROWTH PATTERN TYPES



Daneshy, 2013

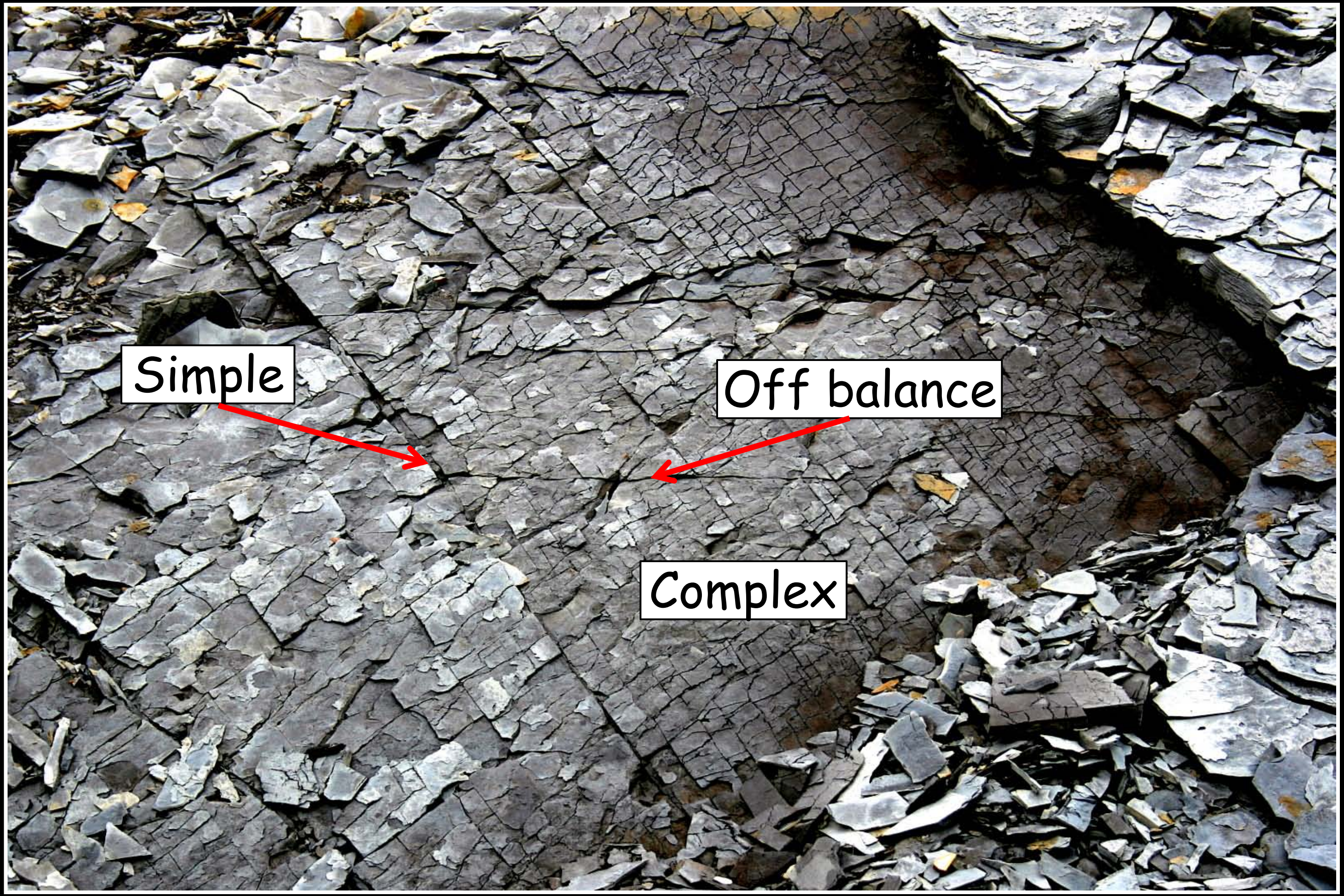
BASIC CRACK TYPES



Simple – longest, most conductive, *least surface area.*

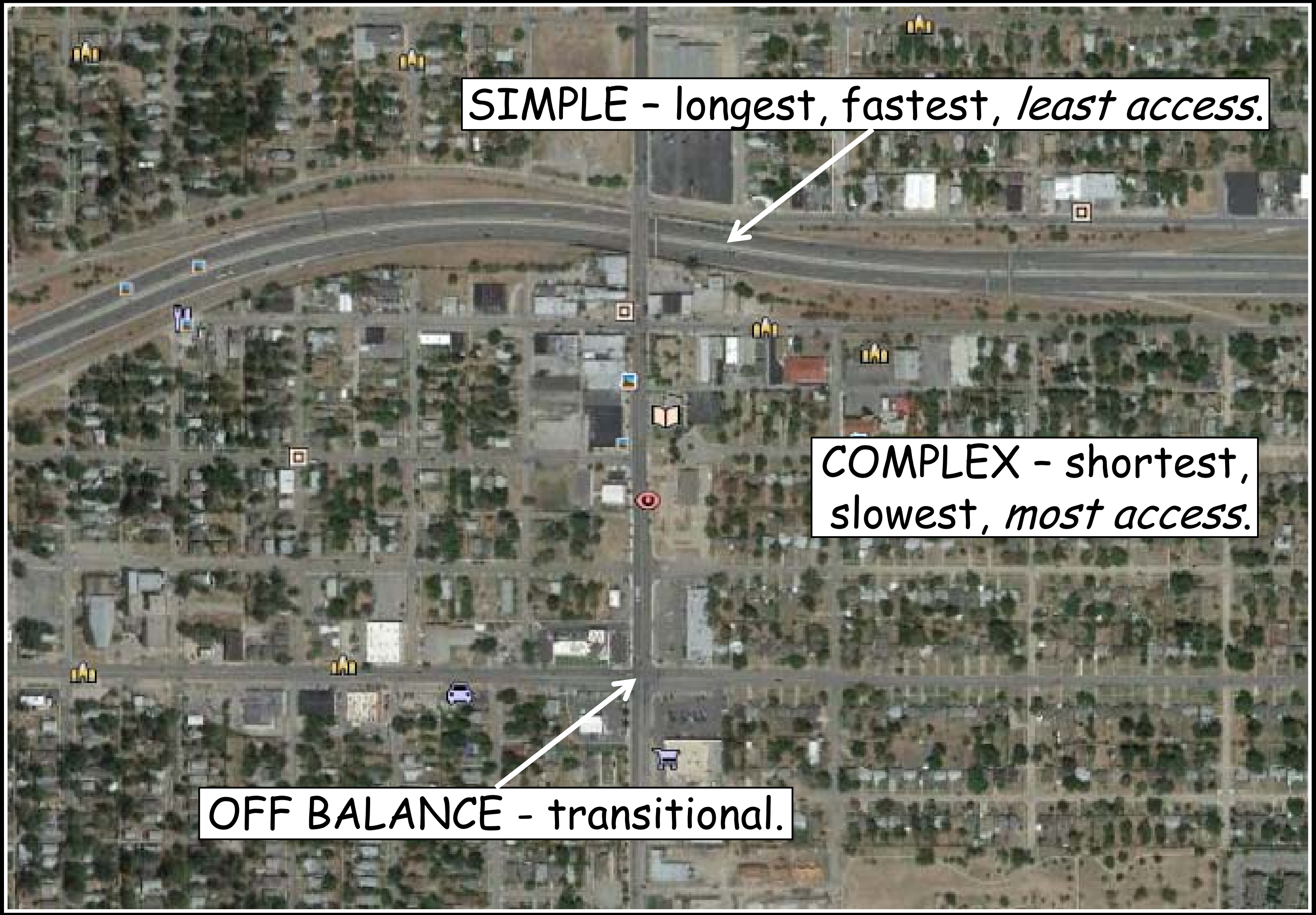
Complex – shortest, least conductive, *most surface area.*

WOODFORD OUTCROP SILICEOUS SHALE FRACTURE TYPE ANOLOGY



Dow, Miller, Lewan, 2011

ROAD FRACTURE TYPE ANOLOGY.

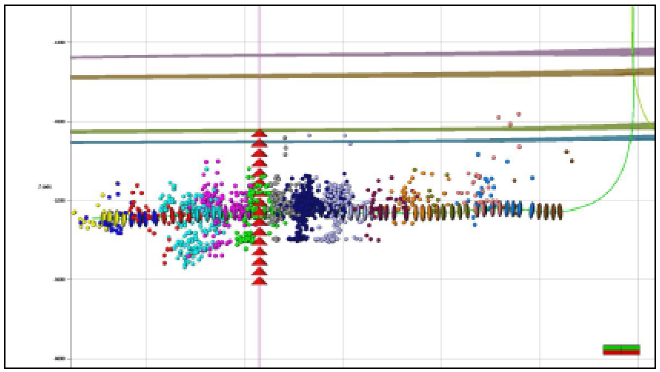


Google Earth, 2012

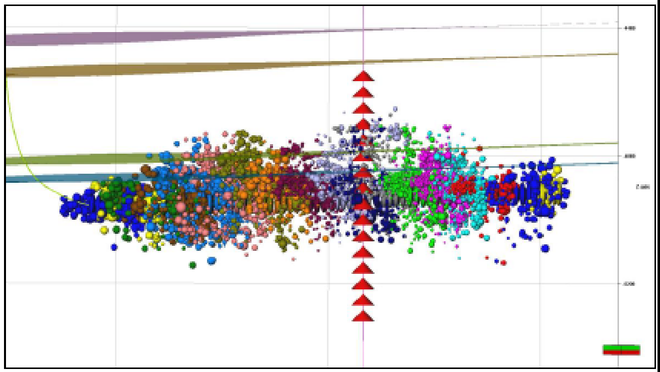
TREND IS TOWARD FOCUSED, HIGH DENSITY COMPLEX FRACS

Engineering: Stimulated Rock Volumes (SRVs)

Side Views



Well #1: Smaller SRVs
Better IP, IP 30, (EUR? maybe)



Well #2: Larger SRVs
Lesser IP, IP 30, (EUR? maybe)

Potential Re-Think on SRVs:

SRV ↓ (Scale Down)
Frac Height & Length ↓(Scale Down)
Near Well Bore Frac Complexity ↑ (Scale Up)
Recovery Factor Must ↑ (Scale Up)

LONE STAR

Dally, 2014

UNCONVENTIONAL *OIL* RESERVOIRS NEED:

1) Maturity between ~ 0.9 and 1.2% Ro for gas drive.
2) High TOC and hydrogen-rich kerogen.
3) Rock matrix porosity for oil storage.
4) Frac-able silica or carbonate rock for permeability.
5) Overpressure is a good thing.
6) *Natural fracturing helps*.

EMBRACE ROCK CRACKS!

THEY ARE YOUR FRIENDS.