Mineralogy and Petrology Controls on Hydrocarbon Saturation in the Three Forks Reservoir, North Dakota*

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Abstract

The Three Forks reservoir forms the lower part of the "Bakken pool" in the North Dakota portion of the Williston basin. Oil production occurs from sandy to silty dolomitic lithologies in the upper portion of the Three Forks Formation. In most oil-productive areas of western North Dakota, three reservoir rock types can be defined in the upper Three Forks based on mineralogy, capillary pressure characteristics and water saturation distributions. The best Three Forks hydrocarbon saturations occur in brown to tan, sandy to silty dolostone. Within the productive oil column, this end-member lithology typically has 2-7% porosity (4.3% average) and 5-25% water saturation. The average mineral content is 63% dolomite, 31% quartz-feldspar and 3% illite (values less than 1% not listed). A second end-member rock type is green, silty, dolomitic mudstone that typically has 5-11% porosity (8.9% average) and 40-90% water saturation. The average mineral content is 35% dolomite, 31% quartz-feldspar, 30% clay minerals (23% illite, 4% chlorite, 3% illite-smectite), and 2% pyrite-marcasite. The third rock type consists of mixed brown and green, sandy to silty dolostone, with intermediate reservoir rock properties. It includes laminated and brecciated lithologies.

Due to small pore-throat sizes, oil column heights greater than 3,000 feet would have been needed to achieve observed hydrocarbon saturations in a water-wet system. Under these conditions, the oil column is too thin to be explained by simple buoyancy-driven oil emplacement. Based on an analogy with very low permeability, continuous gas reservoirs, it is inferred that either: 1) hydrocarbon emplacement occurred at a shallower depth where permeability was higher, or 2) overpressure

(current or ancient) that developed during maturation of overlying Bakken shales was required to emplace oil in rocks with existing very low permeability.

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Anderson, W.G., 1986, Wettability literature survey — Part 1: rock/oil/brine interactions and the effects of core handling on wettability: Journal of Petroleum Technology, (Oct. 1986), p. 1125-1144.

Fall, A., P. Eichhubl, S.P. Cumella, R.J. Bodnar, S.E. Laubach, and S.P. Becker, 2012, Testing the basin-centered gas accumulation model using fluid inclusion observations: southern Piceance basin, Colorado: AAPG Bulletin, v. 96, p. 2297-2318.

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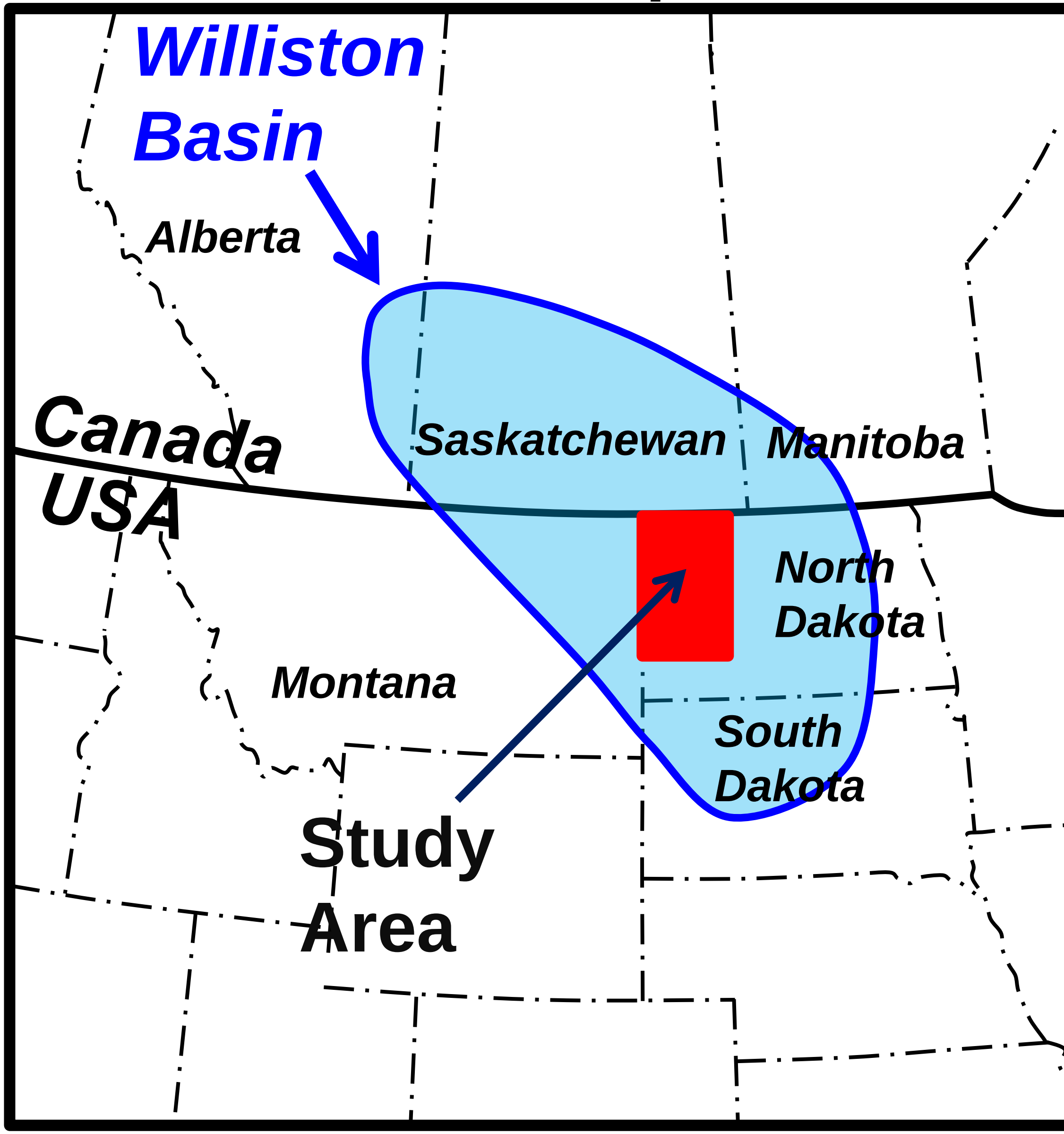
David M. Petty

April 9, 2014

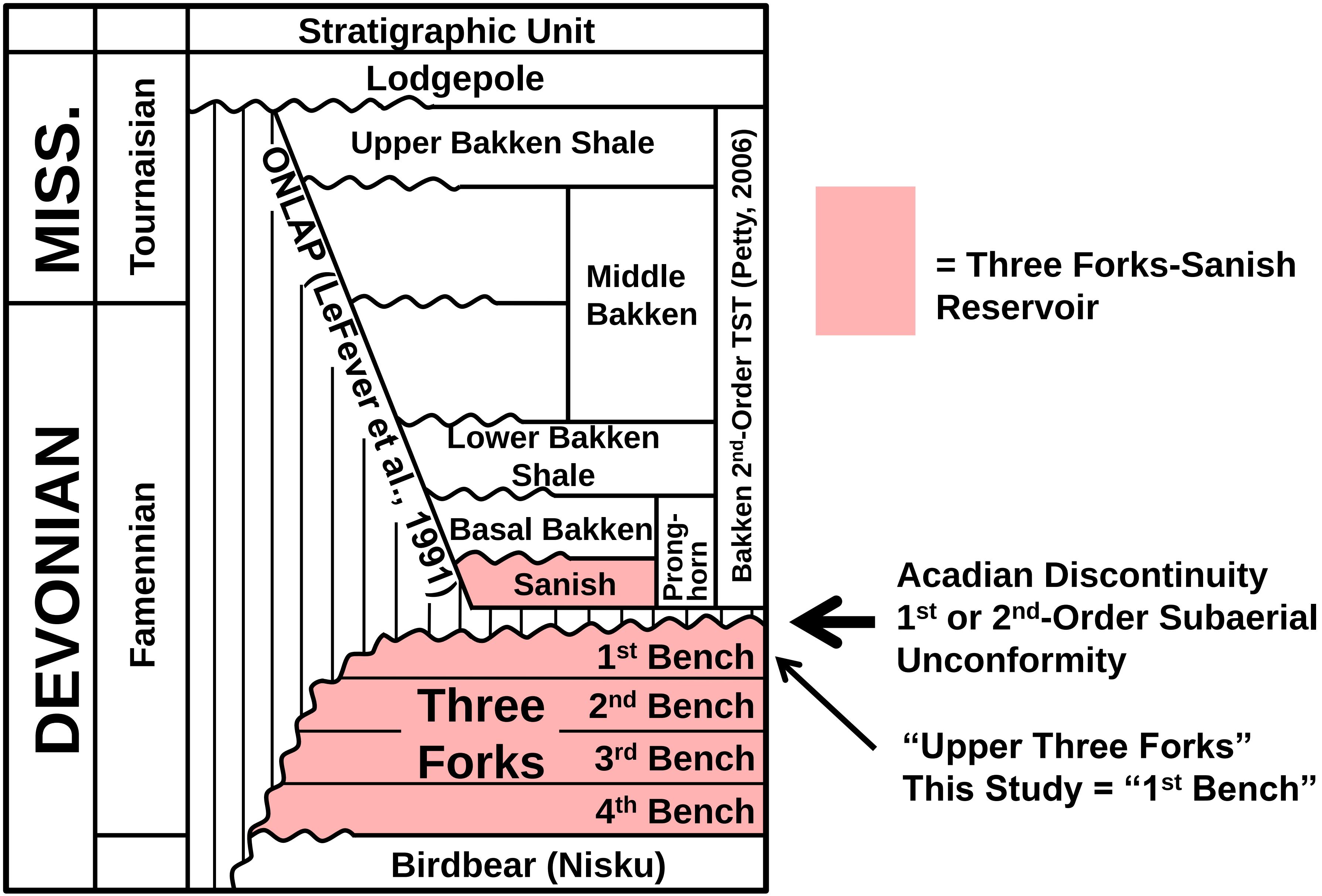
Location Map



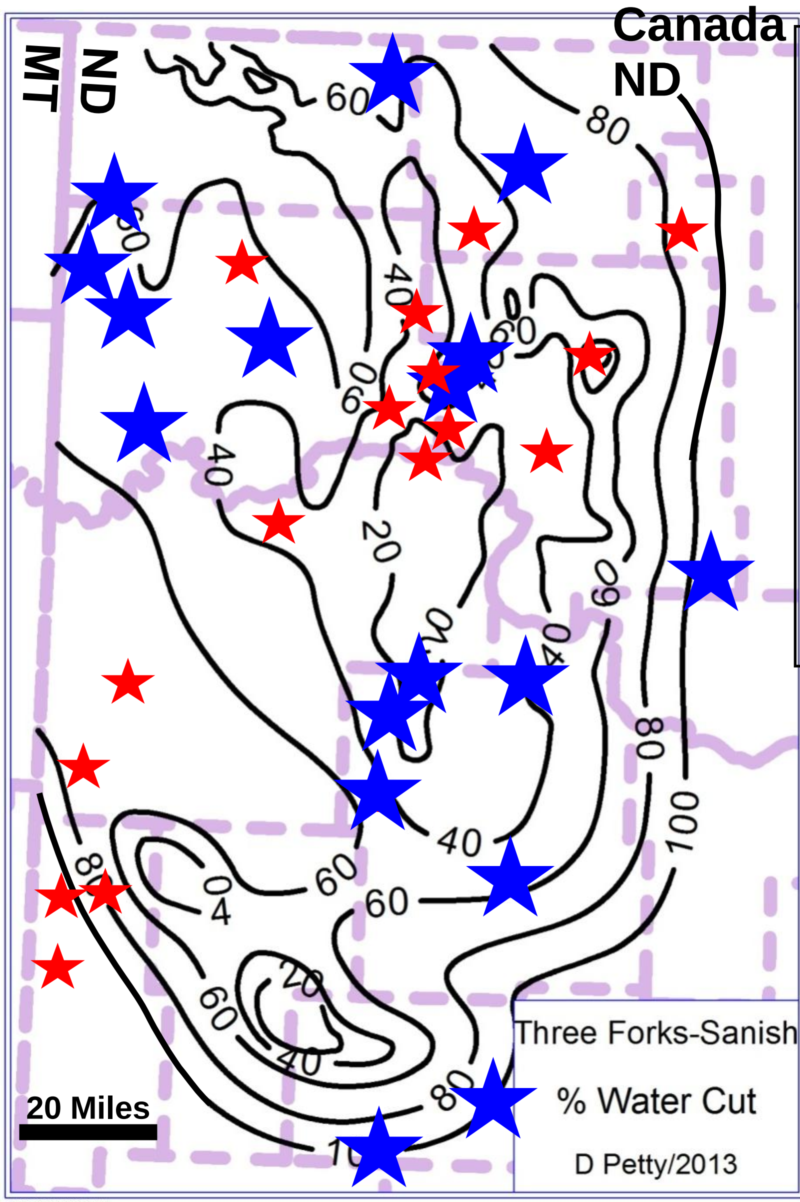
Objectives

- **Define reservoir rock types in the upper portion of the Three Forks Formation in the North Dakota portion of the Williston basin**
- **Discuss significance of saturation distributions for upper Three Forks rock types**

Stratigraphic Column



Upper Three Forks Data



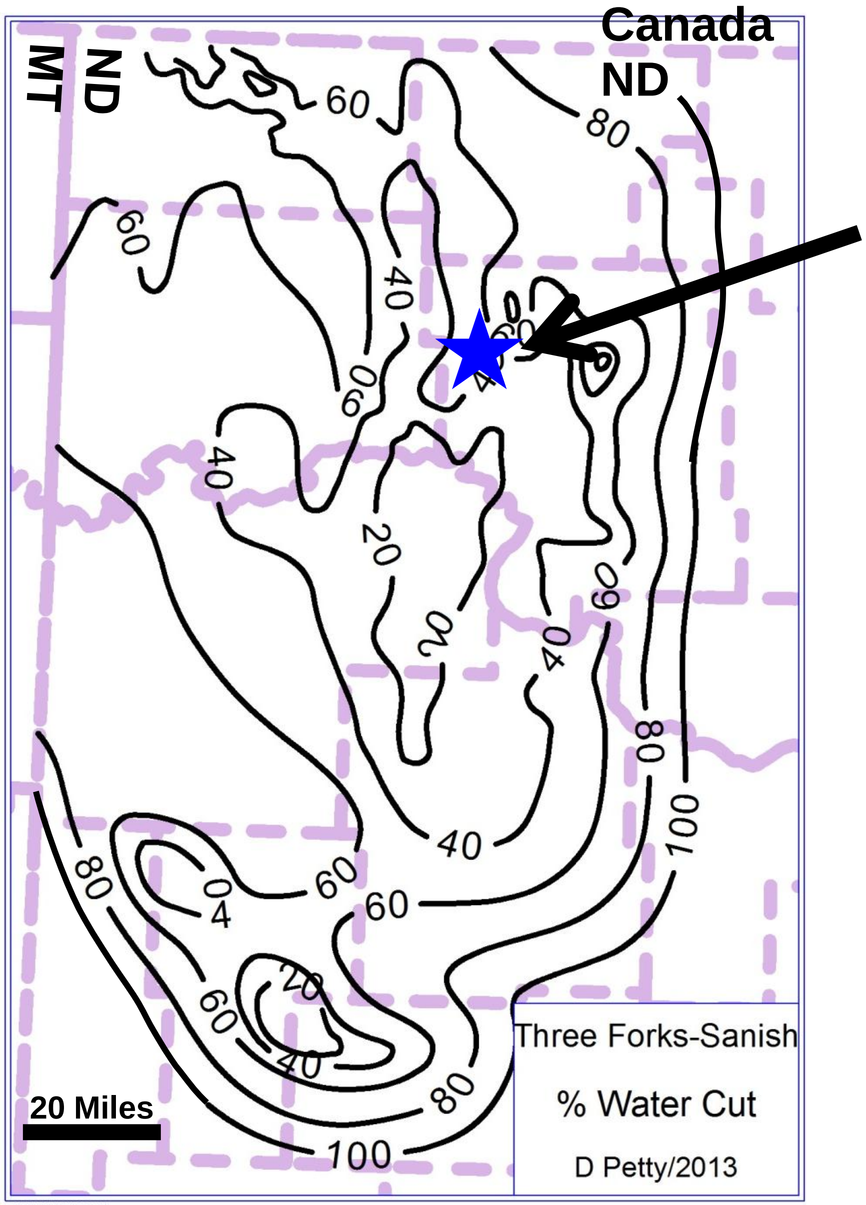
- Map shows contours for % water cut from the Three Forks-Sanish reservoir;
- Map broadly defines production quality with best production in low water-cut areas
- From 1320 horizontal wells with stabilized water cuts

Data For Rock Type Study

★ = Cores with XRD data for upper Three Forks.

★ = Cores examined; no XRD

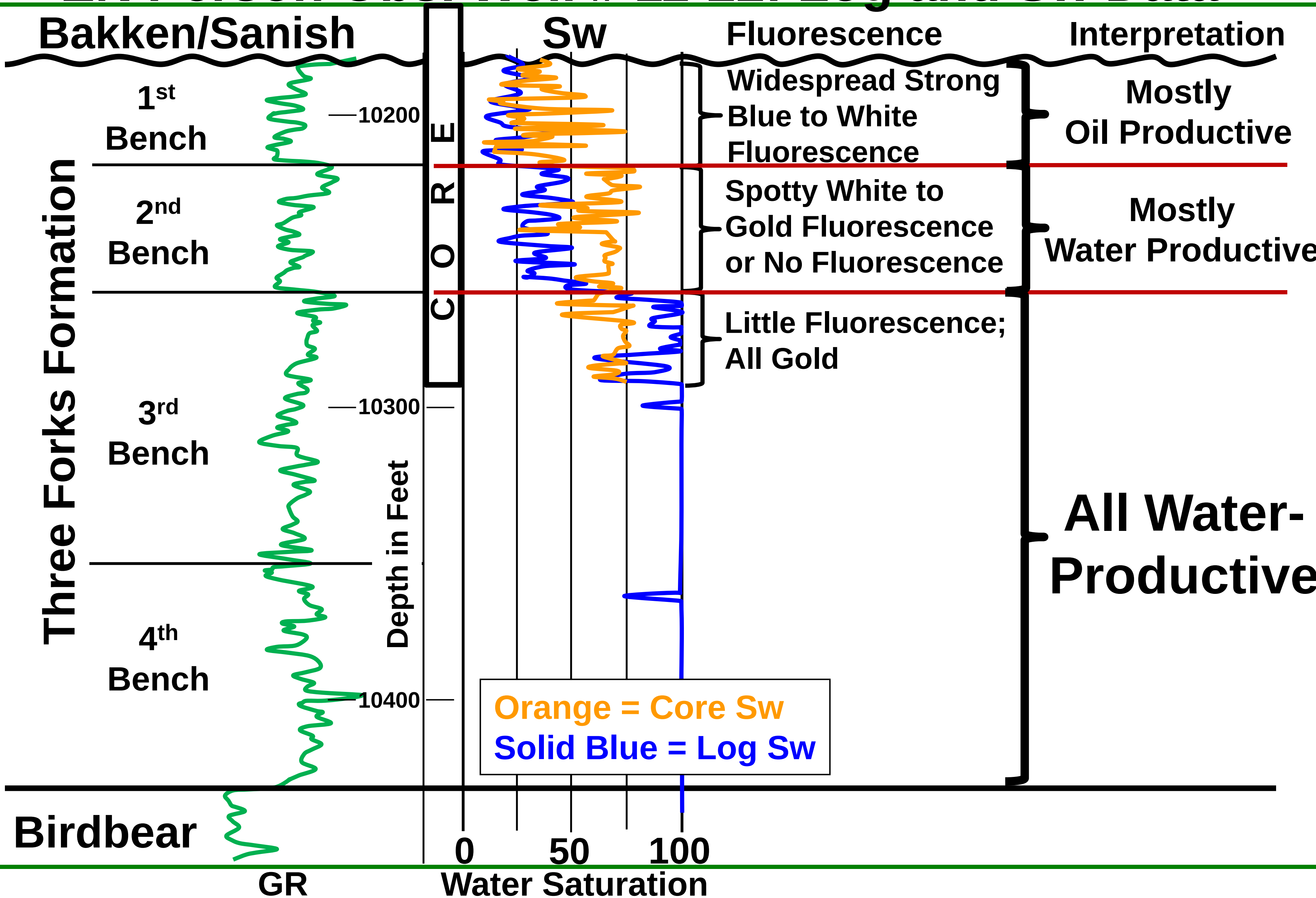
Type Log Location



<u>Type Log:</u> Hess Corporation EN Person Observation Well #11-22, 156-94-11; Mountrail County

- **Located in area with about 45% stabilized water cut**
- **30-day IP = 665 BOPD in offset well (EN Hein H4)**

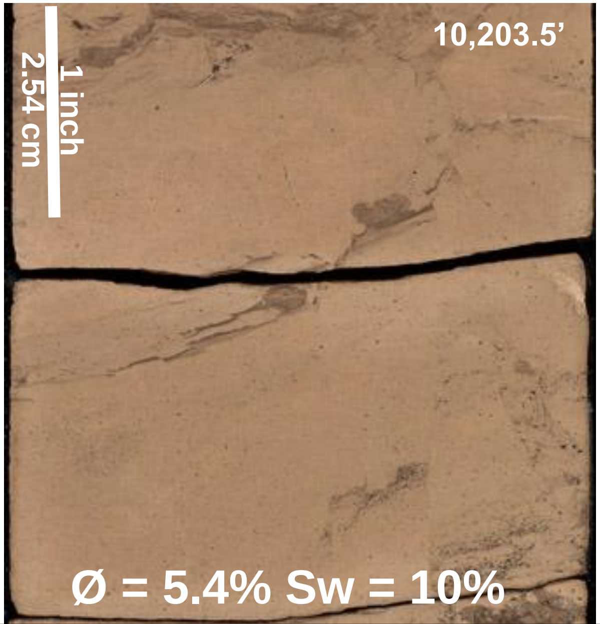
EN Person Obs. Well # 11-22: Log and Sw Data



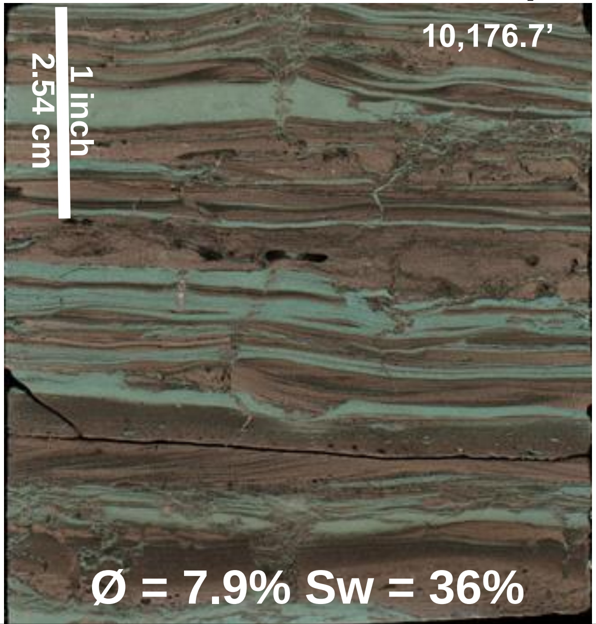
Reservoir Rock Types: Three Forks 1st Bench

- **Many sedimentological microfacies occur in the upper Three Forks**
- **Using the regional core data set, 3 main rock types can be defined based on mineralogy, capillary pressure characteristics and water saturation distributions:**
  - **2 rock types are end-member lithologies**
    - **Brown to tan, silty to sandy dolostone**
    - **Green silty mudstone**
    - **For this study, data is confined to pure, end-member samples**
  - **1 rock type consists of mixtures of brown dolostone and green mudstone**

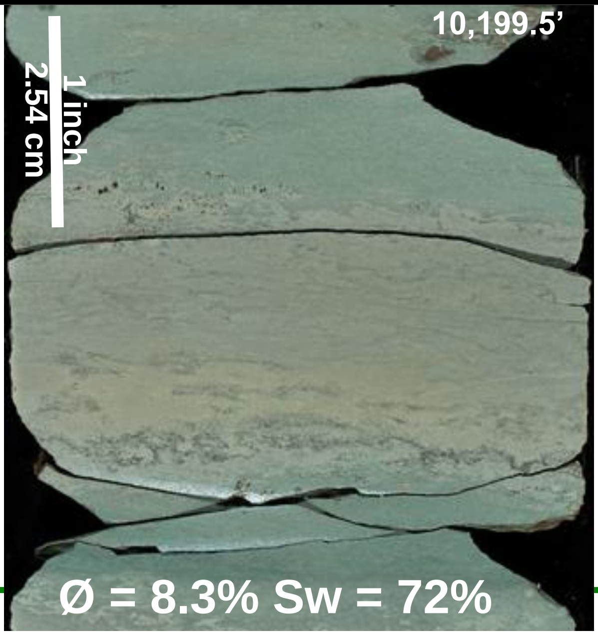
3 Reservoir Rock Types: Three Forks 1st Bench; EN Person



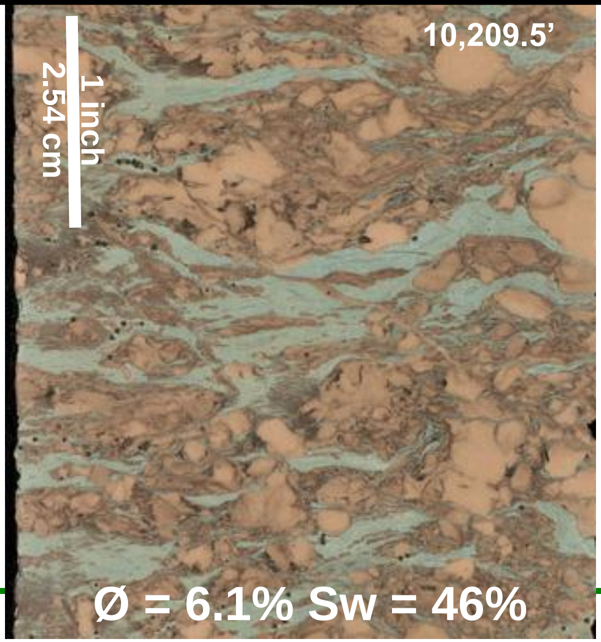
1) Brown to Tan, Silty to Sandy Dolostone End-Member



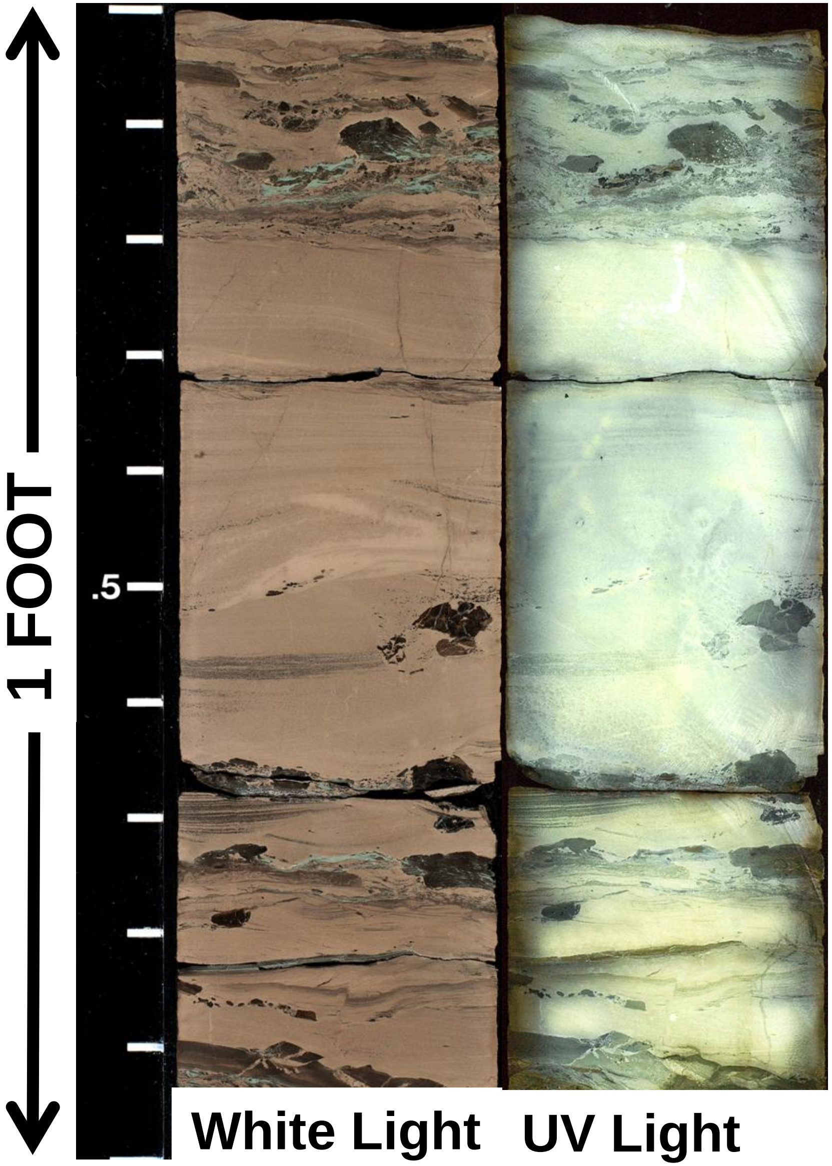
3) Mixed Green and Brown: Laminated



2) Green Silty Mudstone End-Member (marker-beds)



3) Mixed Green and Brown: Breccia



Brown Dolostone with Uniform White Fluorescence ("Blue" or "Bluish-White" Fluorescence described by some researchers)

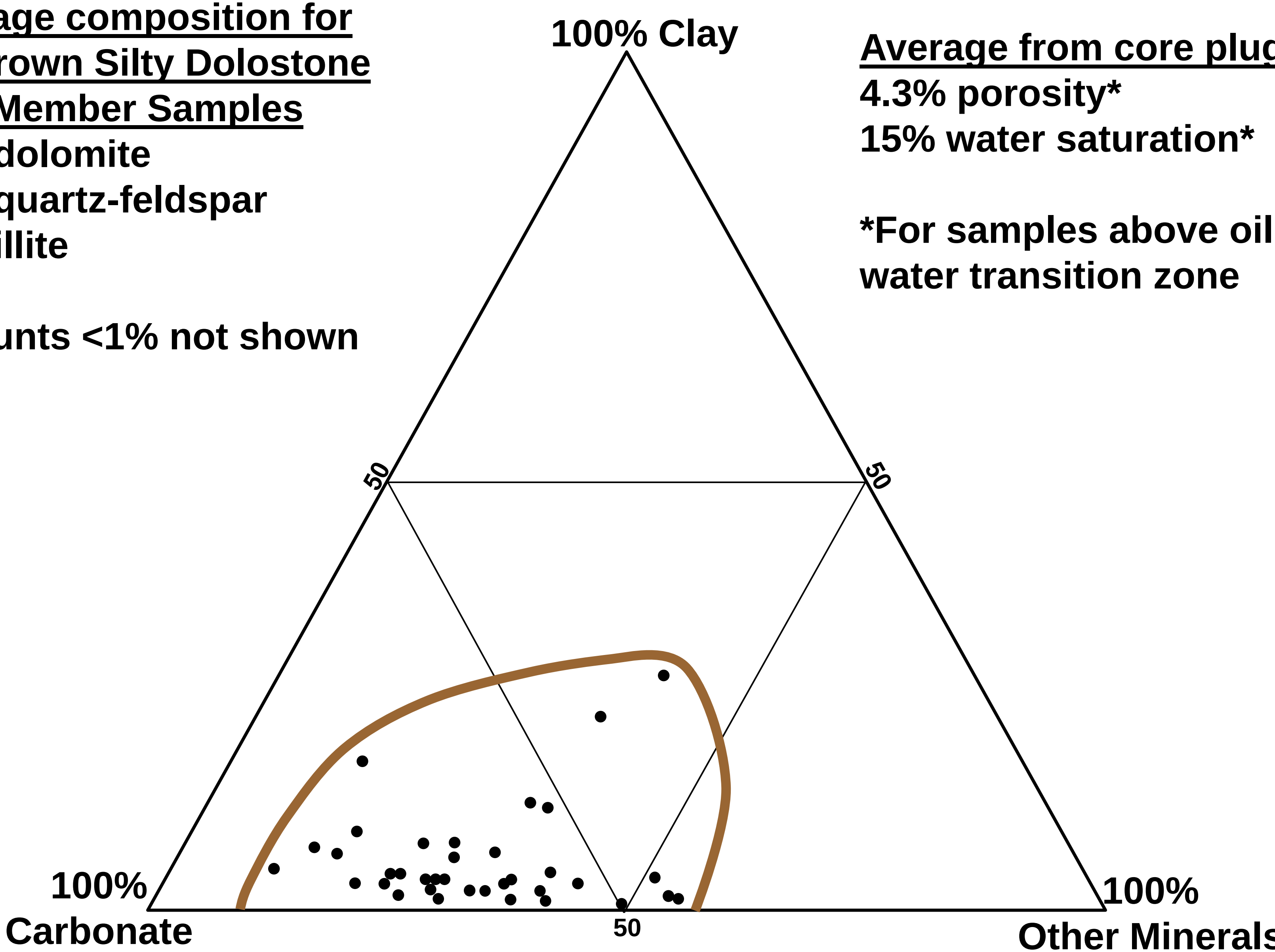
10189.45': **Dean-Stark Analysis**
Ø = 5.0% with confining stress
Core Water Saturation = 17%
Log Water Saturation = 15%

Brown Silty Dolostone End Member: Composition

<u>Average composition for All Brown Silty Dolostone End-Member Samples</u>

63% dolomite
30% quartz-feldspar
3% illite

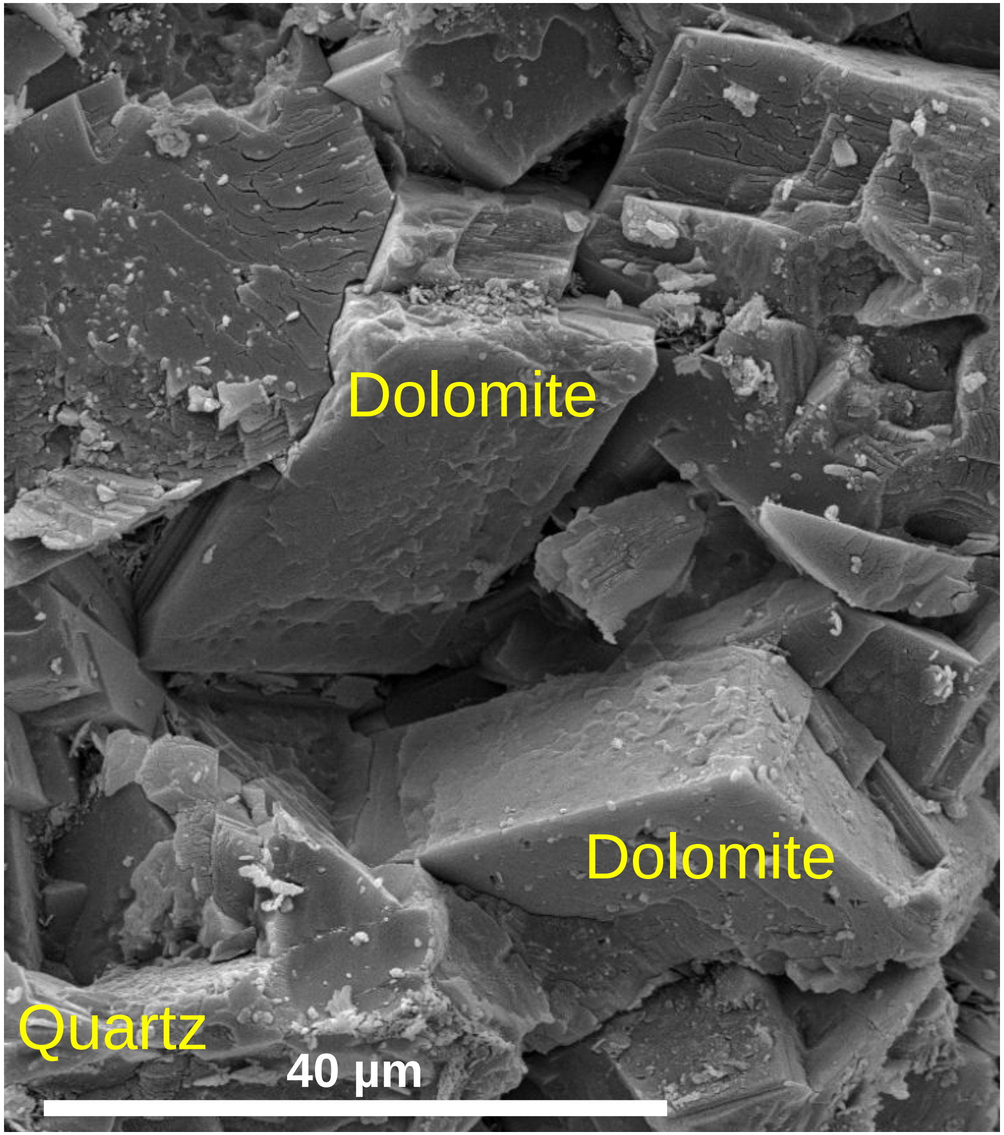
Amounts <1% not shown



<u>Average from core plugs:</u>
4.3% porosity*
15% water saturation*

***For samples above oil-water transition zone**

SEM View: Brown Silty-Sandy Dolostone



<u>**Hovden 15-1H (145-97-14)**</u>

11,256.40’

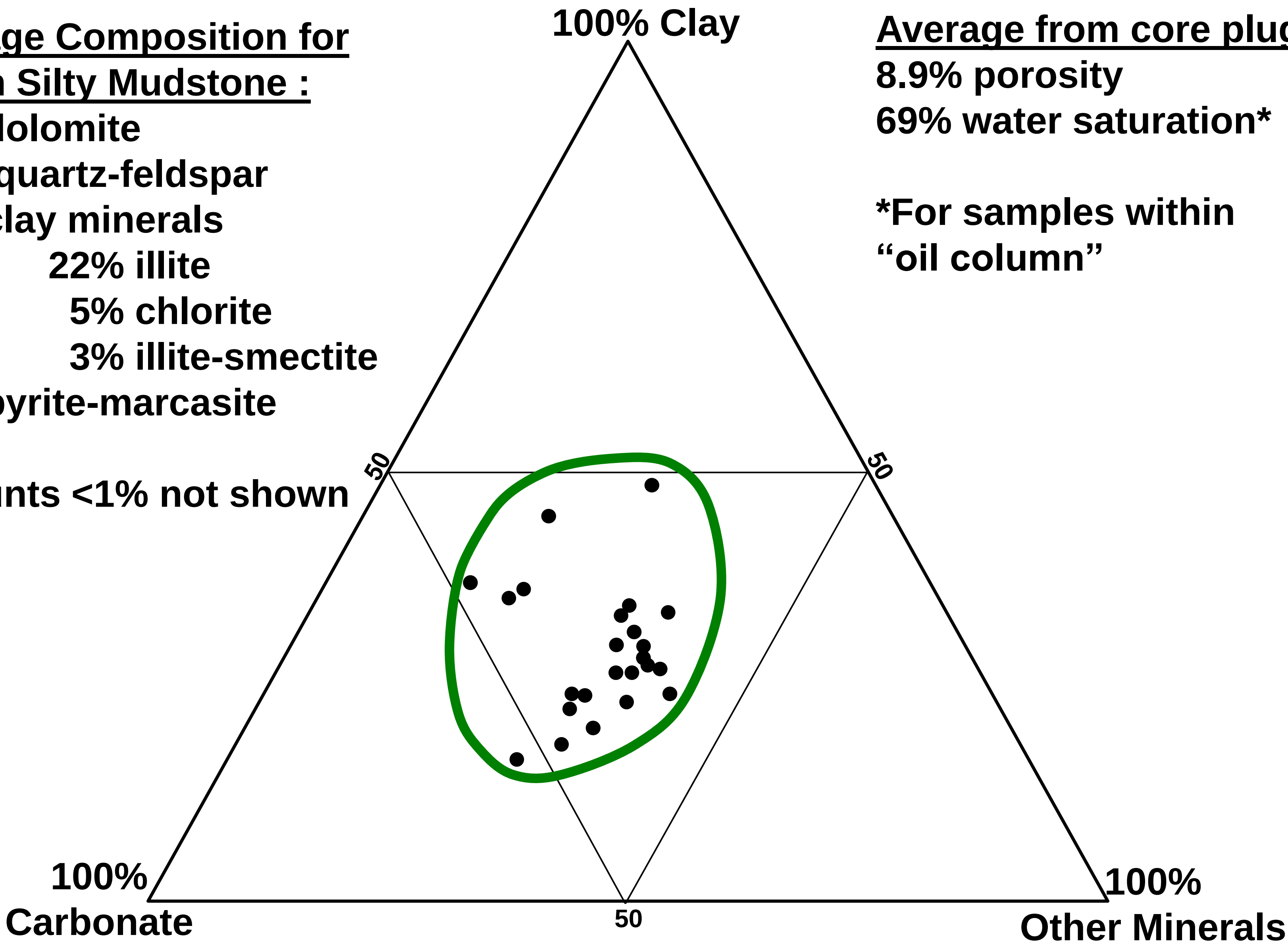
Ø = 4.9%,

Green Silty Mudstone End Member: Composition

<u>Average Composition for Green Silty Mudstone :</u>

36% dolomite
30 % quartz-feldspar
30% clay minerals
22% illite
5% chlorite
3% illite-smectite
2% pyrite-marcasite

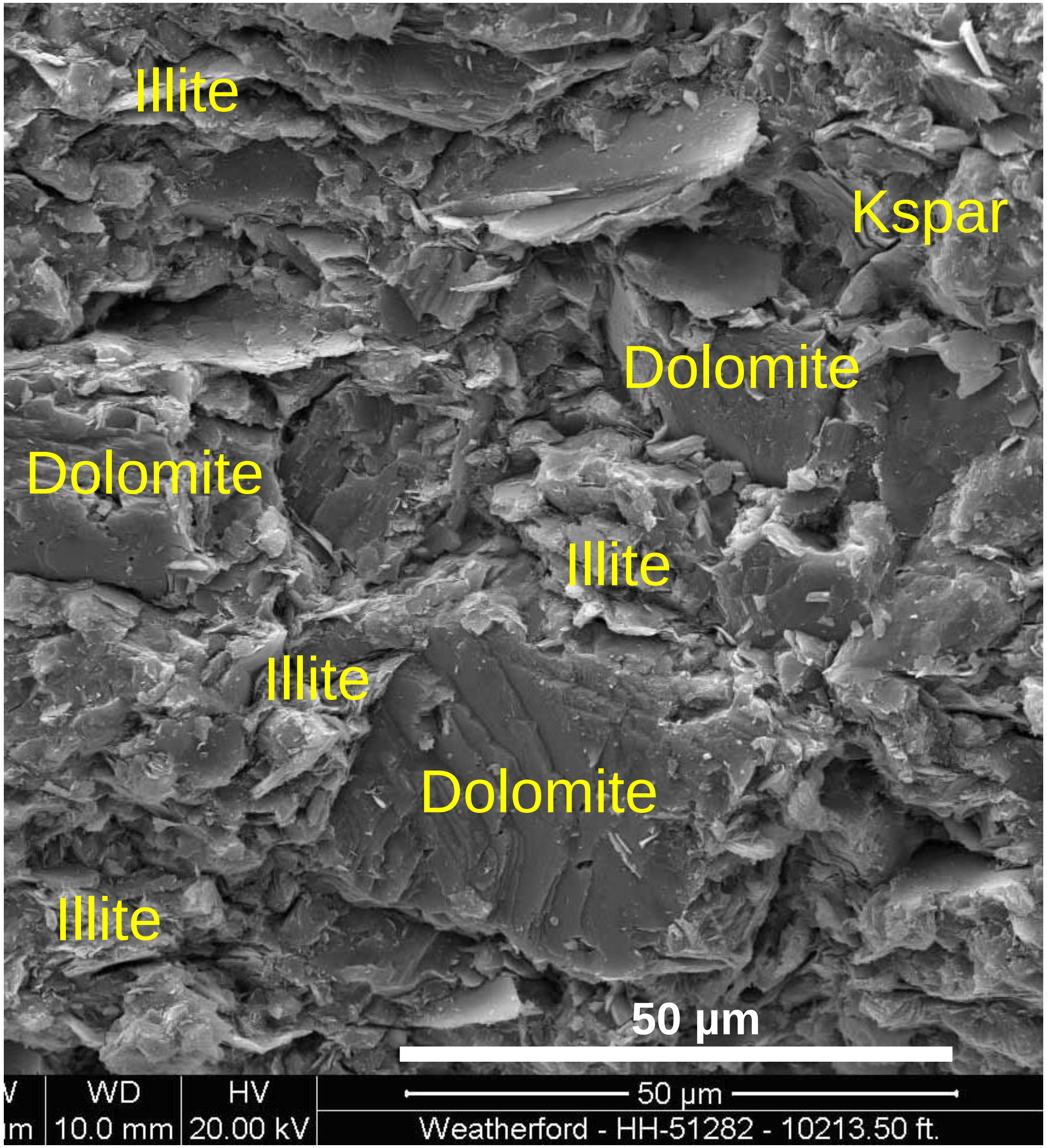
Amounts <1% not shown



<u>Average from core plugs:</u>
8.9% porosity
69% water saturation*

***For samples within "oil column"**

SEM View: Green Silty Mudstone

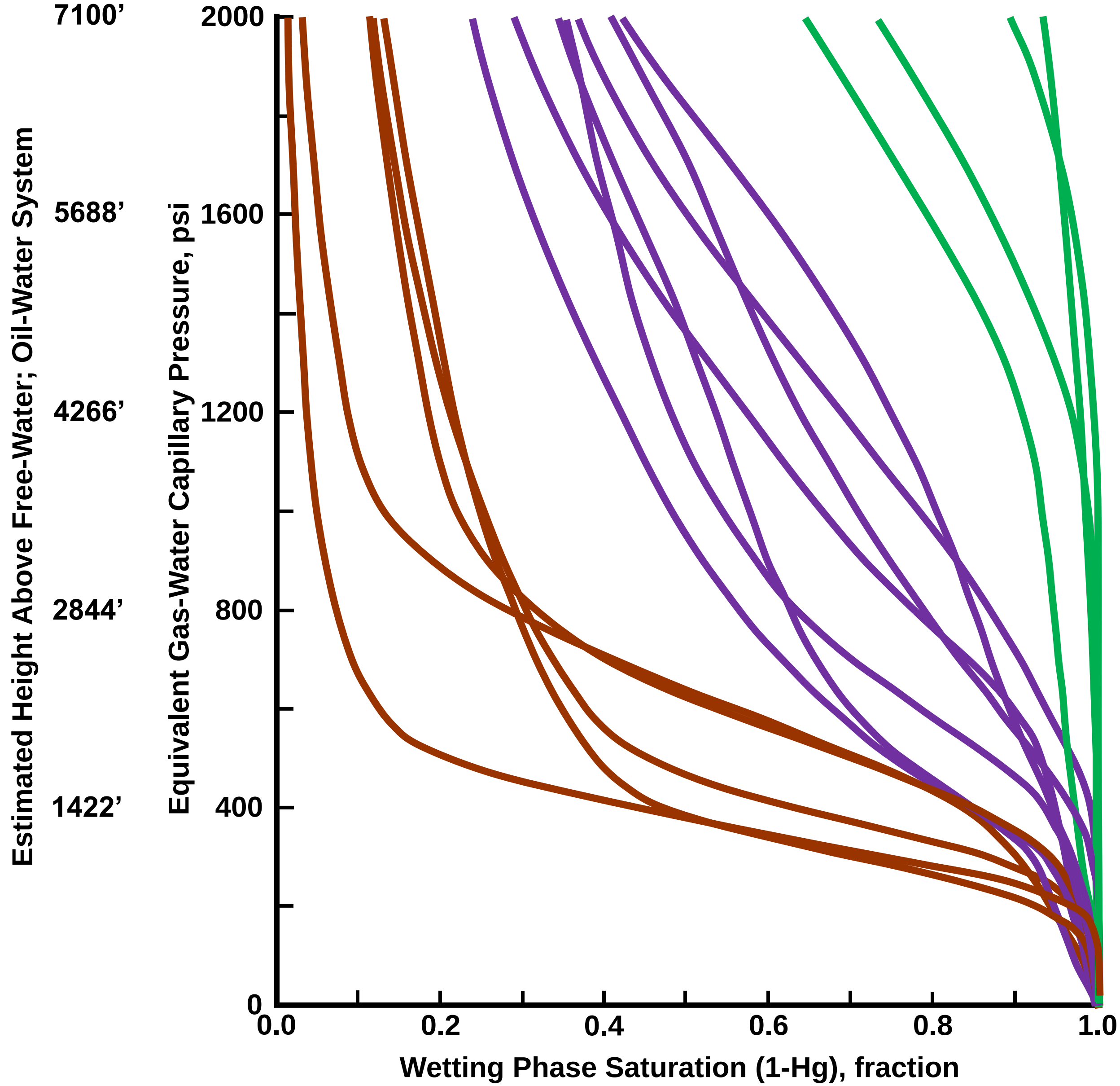


EN Person Obs. #11-22 (156-94-11)

10,213.5"

Ø = 4.9%,

EN Person 11-22; Three Forks Hg-Inj. Cap. Pressure



= Brown sandy-silty dolostone;
<u>Averages:</u>
Ø = 4.4%,
Ka = 0.0035 md*
Sw = 18%**

= Mixed brown & green lithologies;
<u>Averages:</u>
Ø = 7.0%,
Ka = 0.0010 md*
Sw = 43%**

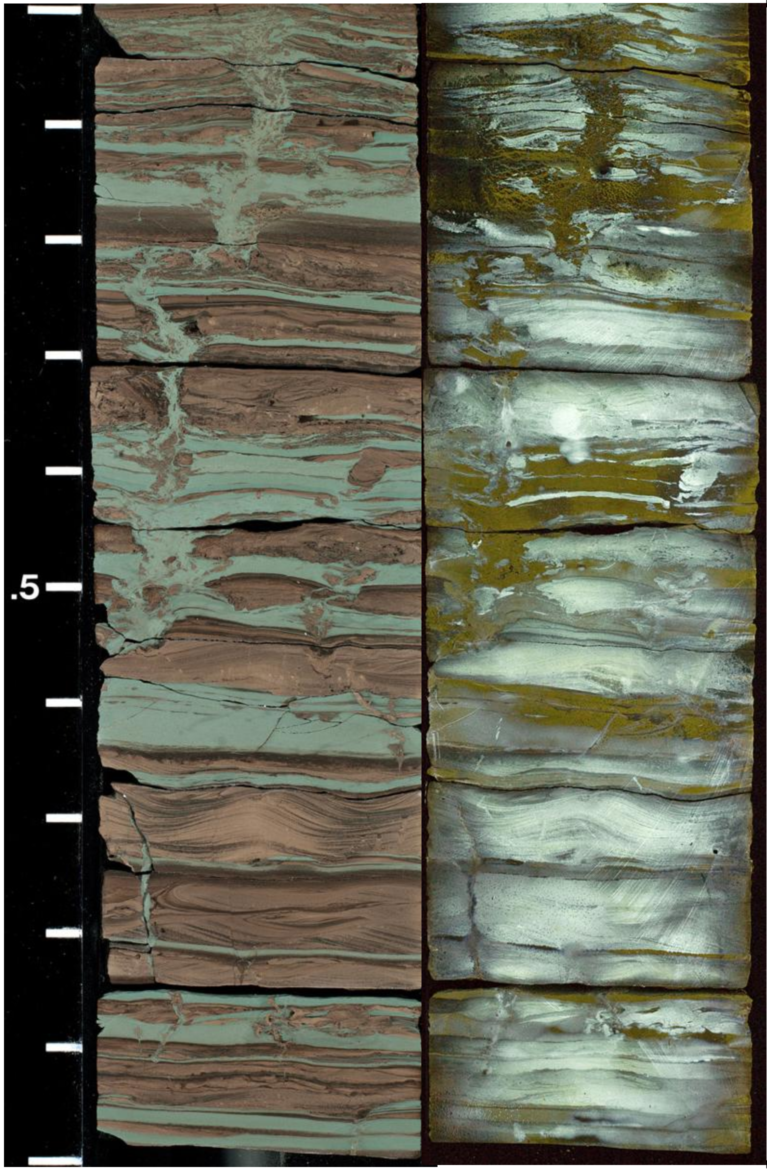
= Green mudstone;
<u>Averages:</u>
Ø = 7.0%,
Ka = 0.0003 md*
Sw = 73%**

*Calculated from Hg-injection
**For samples within oil column

EN Person Obs. #11-22:

White Light — UV Light

10,185’



10,186’

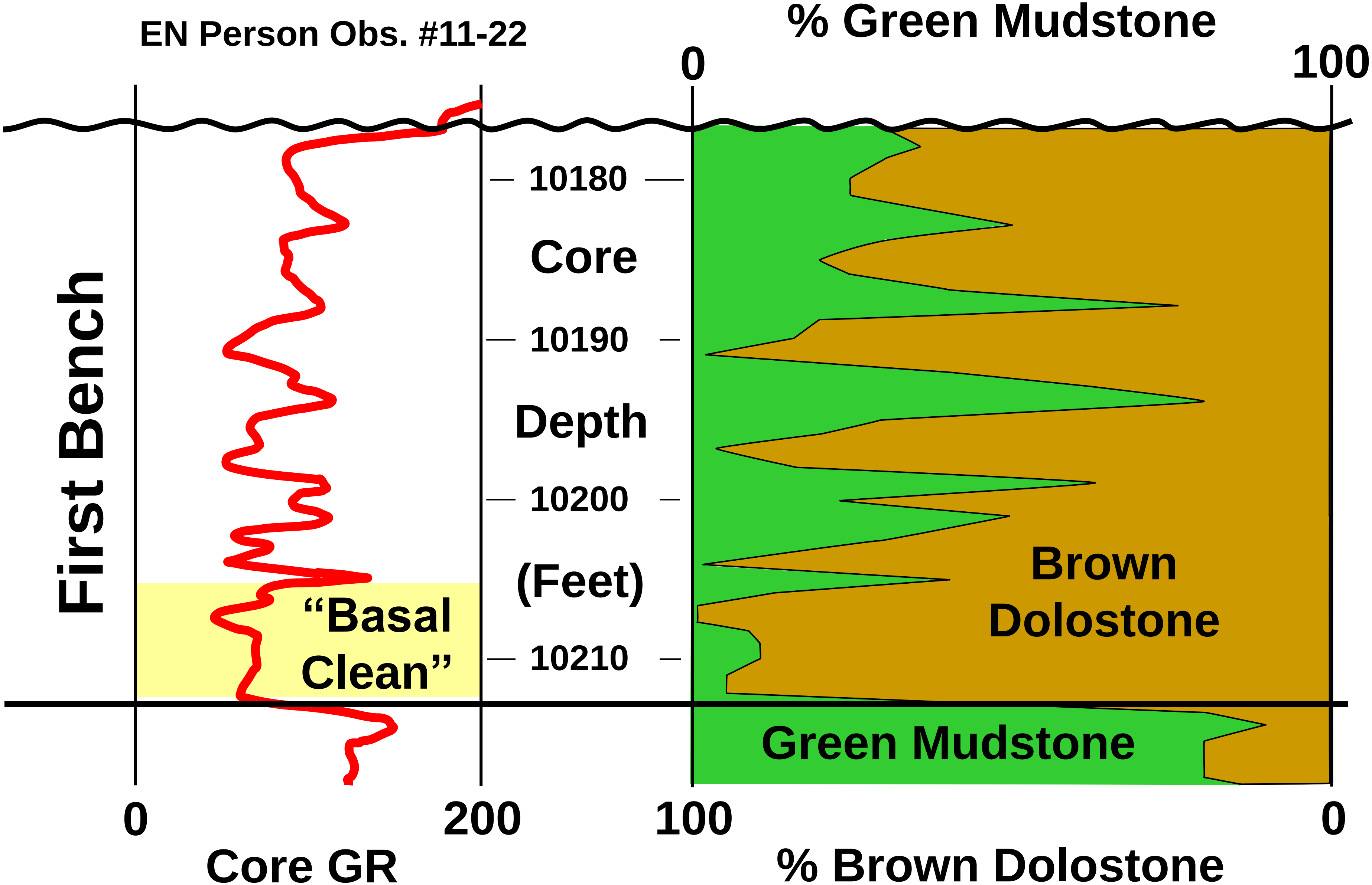
White Light — UV Light

This laminated sample illustrates one method for logging rock types in the upper Three Forks.

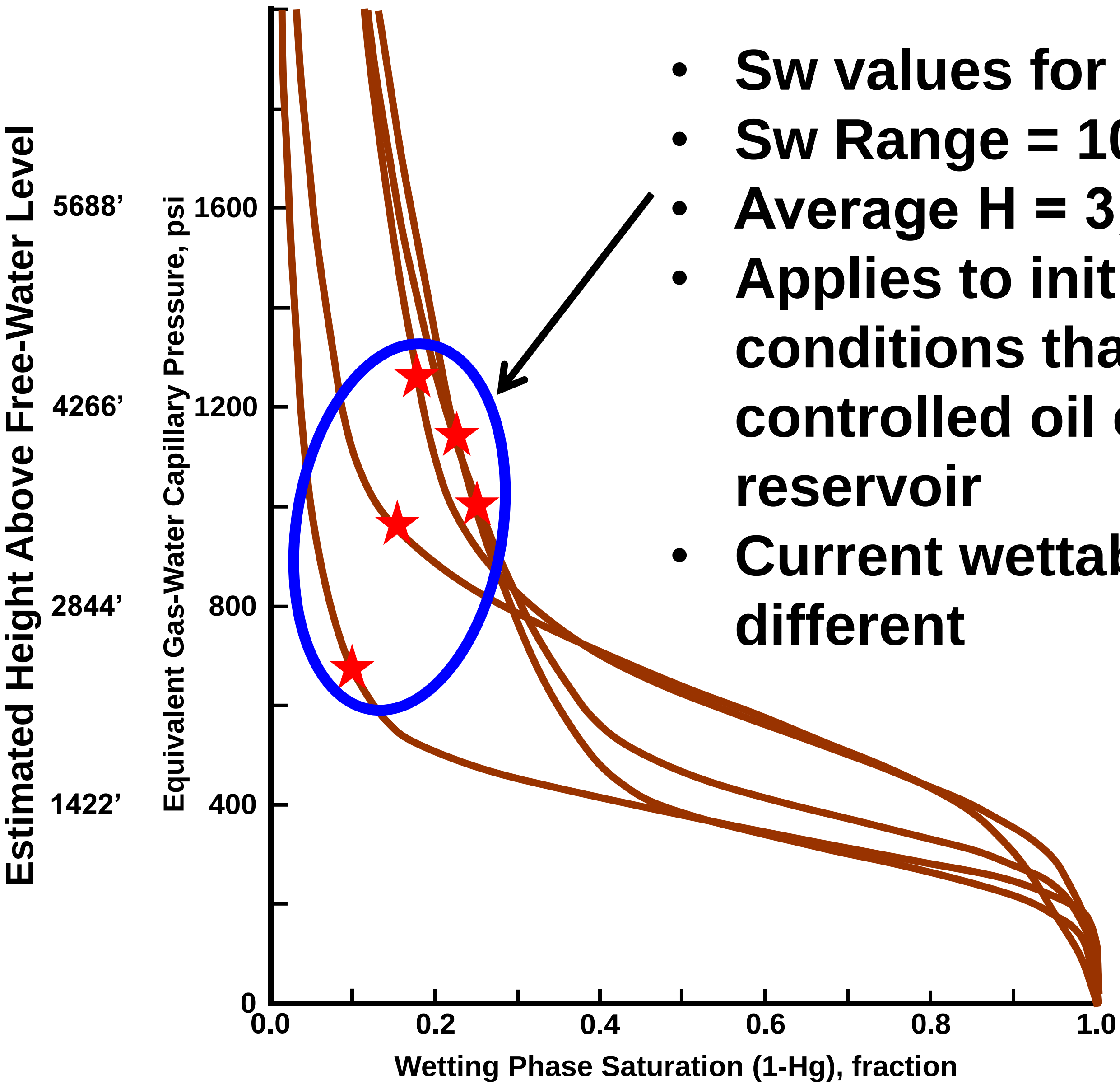
60% Sandy Brown Dolostone with White Fluorescence
40% Green Mudstone with Gold Fluorescence

End-member rock types are plotted relative to core gamma-ray log for 1st Bench in next slide.

Logging End-Member Rock Types in the Three Forks



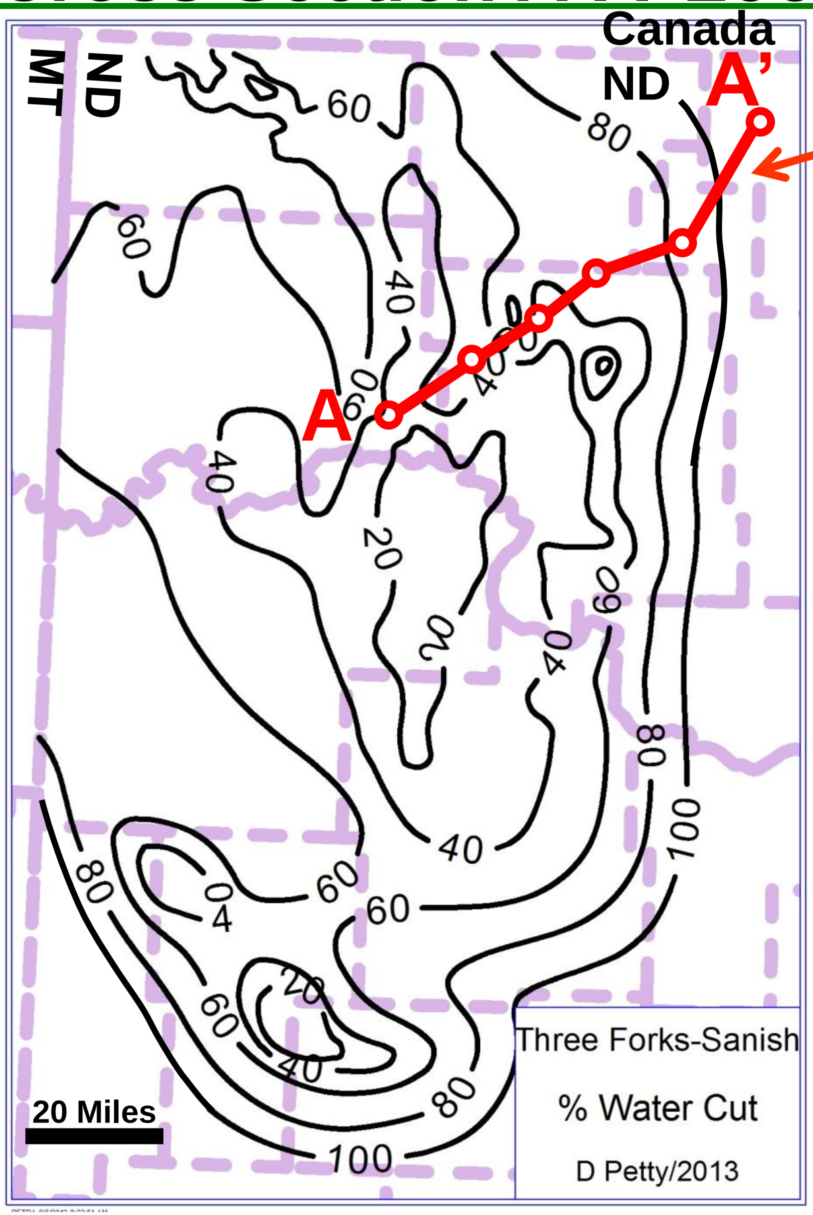
EN Person 11-22; Capillary Pressure for Brown Dolostone



- Sw values for brown dolostone
- Sw Range = 10-25%
- Average H = 3,540' above FWL
- Applies to initial water-wet conditions that would have controlled oil entry into reservoir
- Current wettability may be different

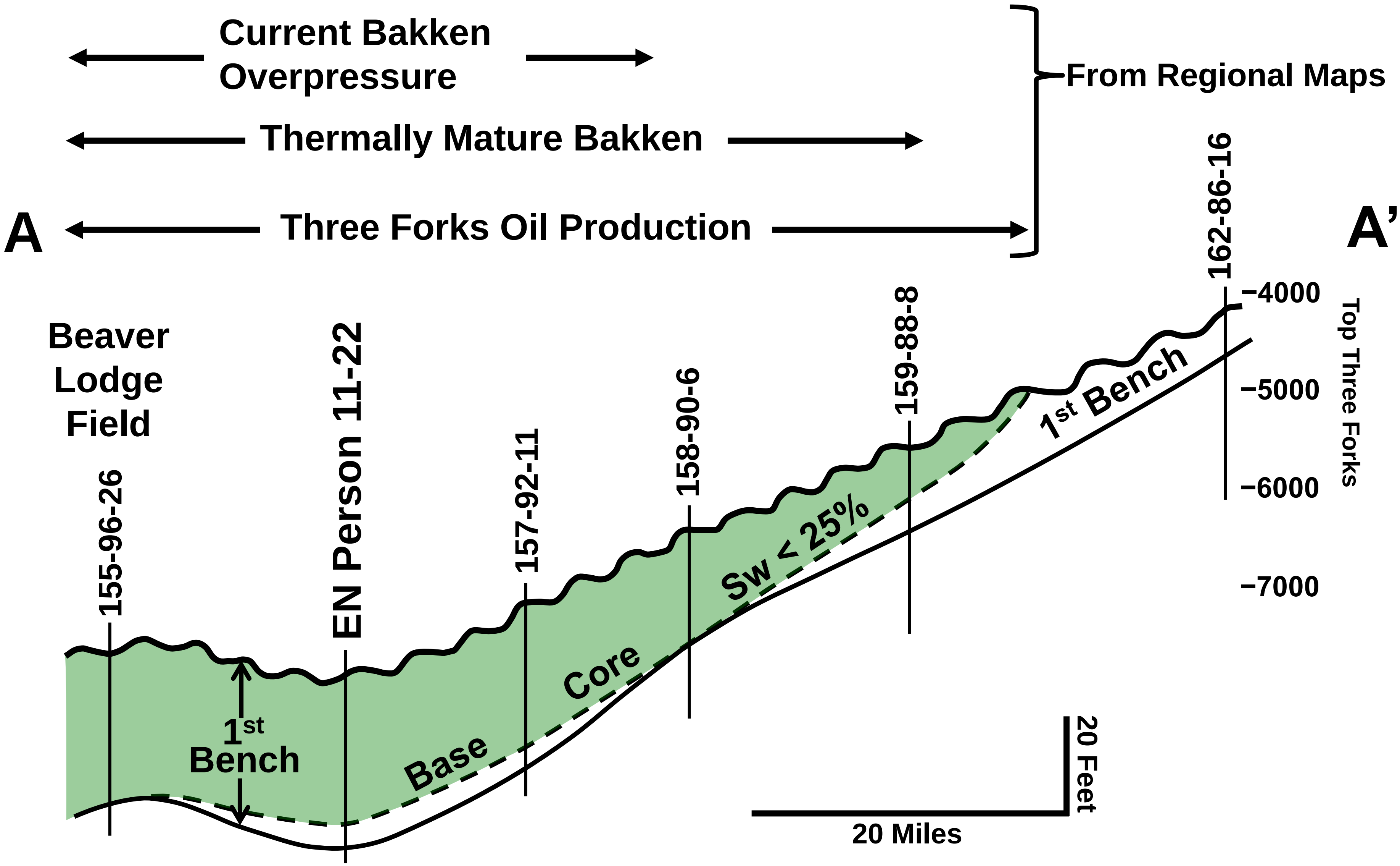
Oil-Water System
Contact Angle = 30°

Cross Section A-A' Location: 1st Bench



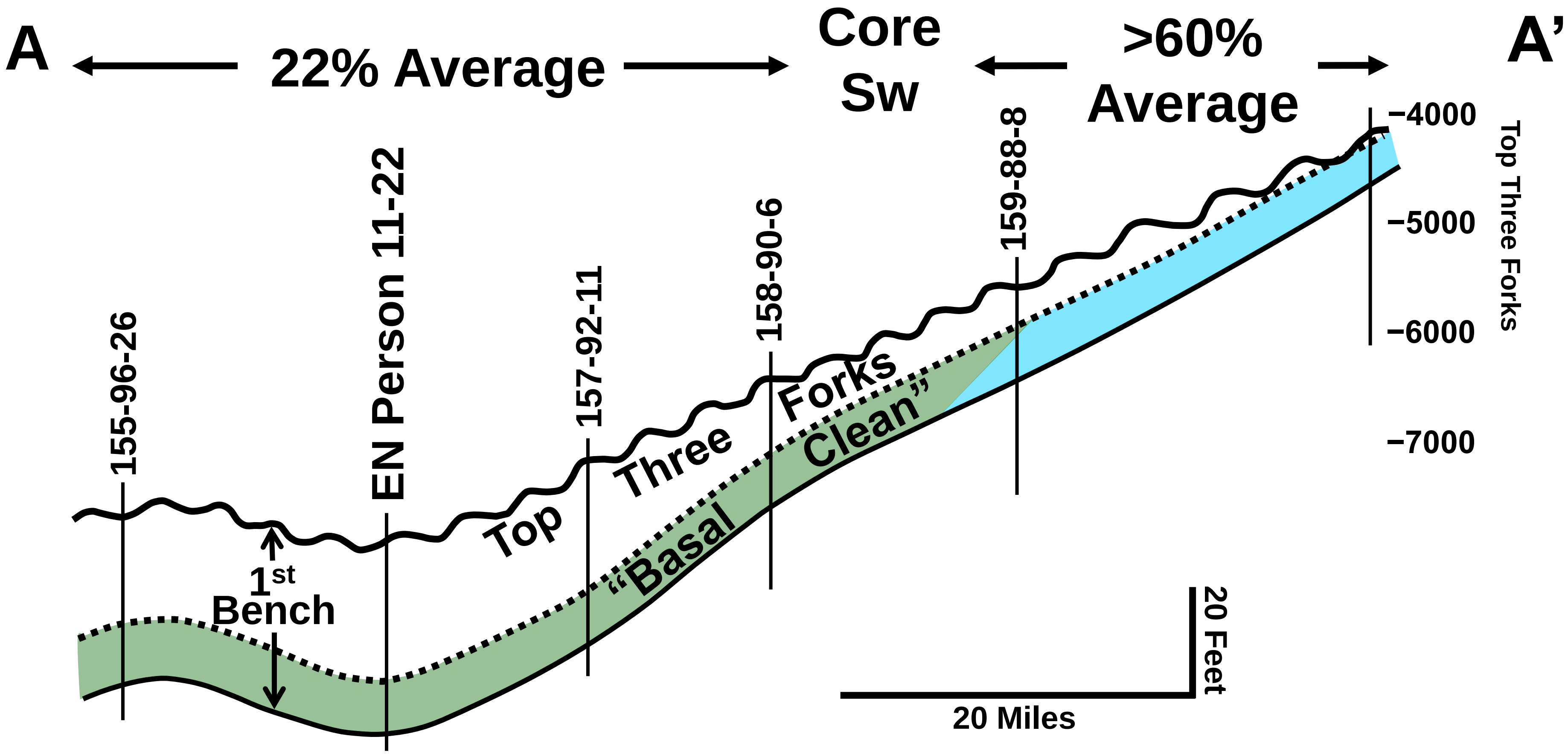
Location Cross Section A-A' Next 2 Slides: Relative to Three Forks water cut contours

Regional Structure and Saturation for 1st Bench



“Basal Clean” Saturations

The “Basal Clean” unit of the Three Forks is the horizontal target in most productive areas. This unit is laterally continuous and transitions from oil-bearing downdip to water-bearing updip

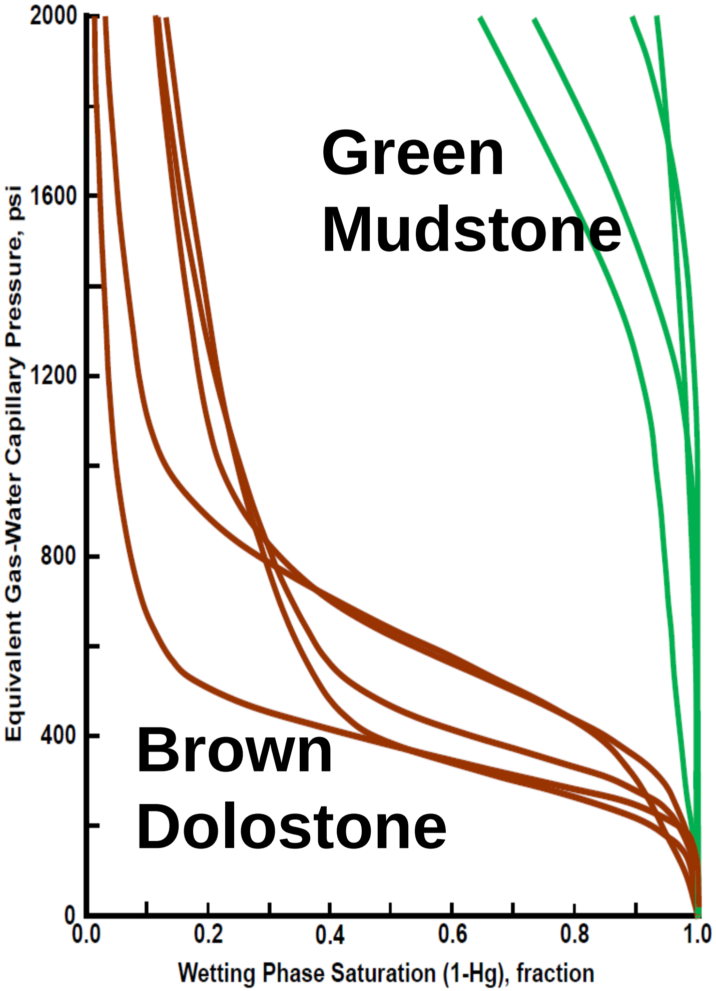


Discussion

- **There is no evidence for a lateral barrier within the upper Three Forks on the eastern and southern edge of the Three Forks accumulation, as illustrated by Cross Section A-A'. *In these areas, the brown dolostone acts as a reservoir in basinal areas and a baffle or capillary barrier in flank areas.***
- **Water saturations that require a 3,540' oil column cannot be explained by simple buoyancy-driven emplacement in a water-wet system.**
- **Research on tight gas accumulations suggests that overpressure due to hydrocarbon maturation is a mechanism to saturate very low permeability rock under water-wet conditions (e.g., Fall et al., 2012). Most oil-bearing reservoirs are believed to be water-wet initially, (Anderson, 1986).**

Conclusions

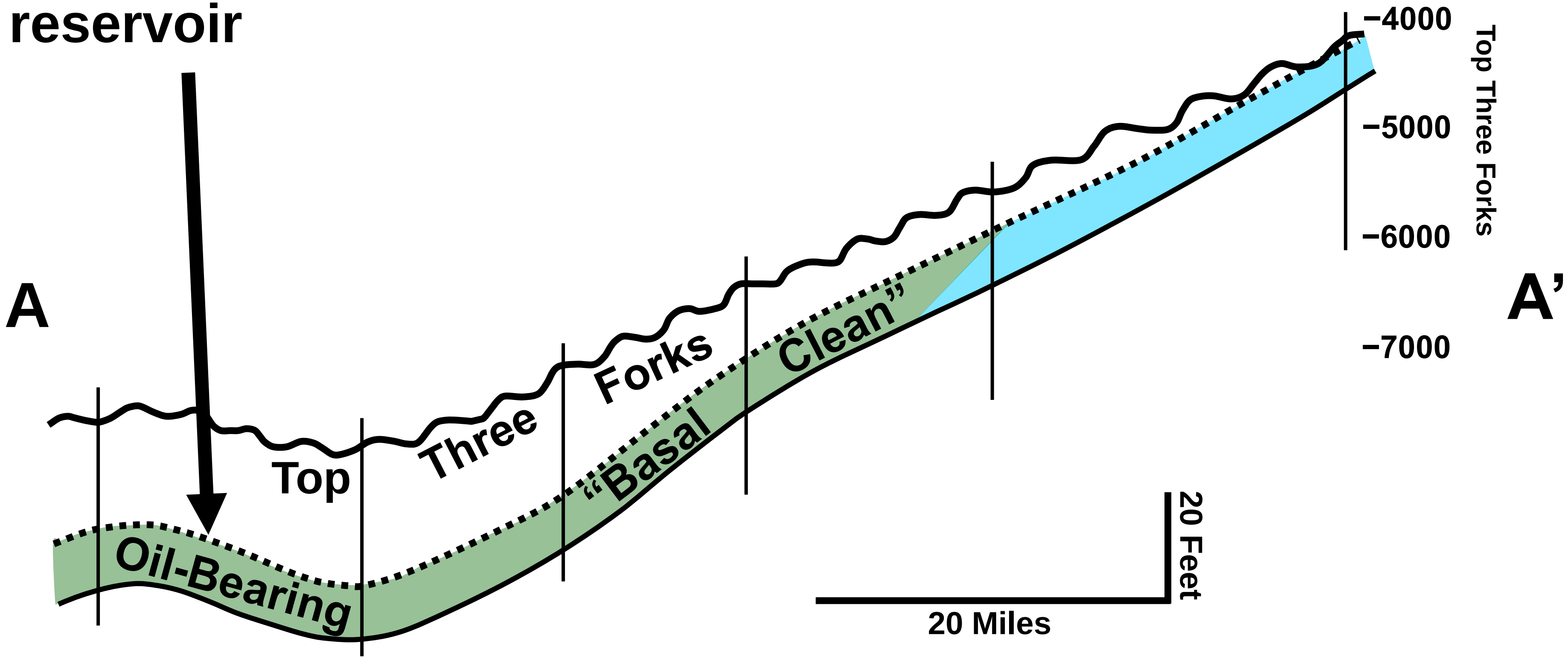
Three Forks Hg-Inj. Capillary Pressure



- **Capillarity characteristics control saturation distributions within the reservoir**
- **Low water saturations are generally confined to the brown dolostone because this rock type has the largest pore throats and best permeabilities**

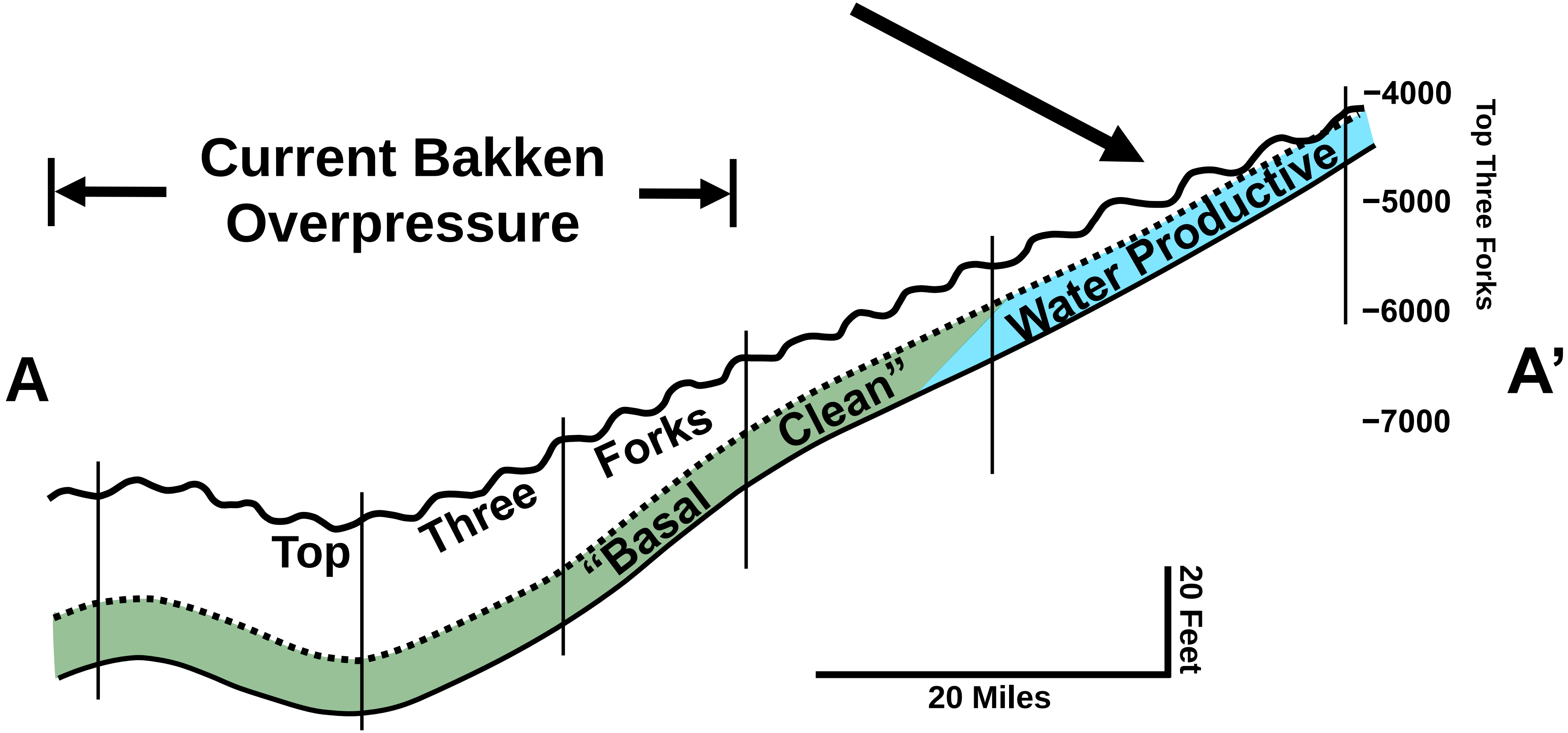
Conclusions

- Capillarity characteristics also control oil entry into the reservoir
- Overpressure (current or ancient) is the most likely cause for low water saturations in the very low-permeability rocks typical for the upper Three Forks reservoir



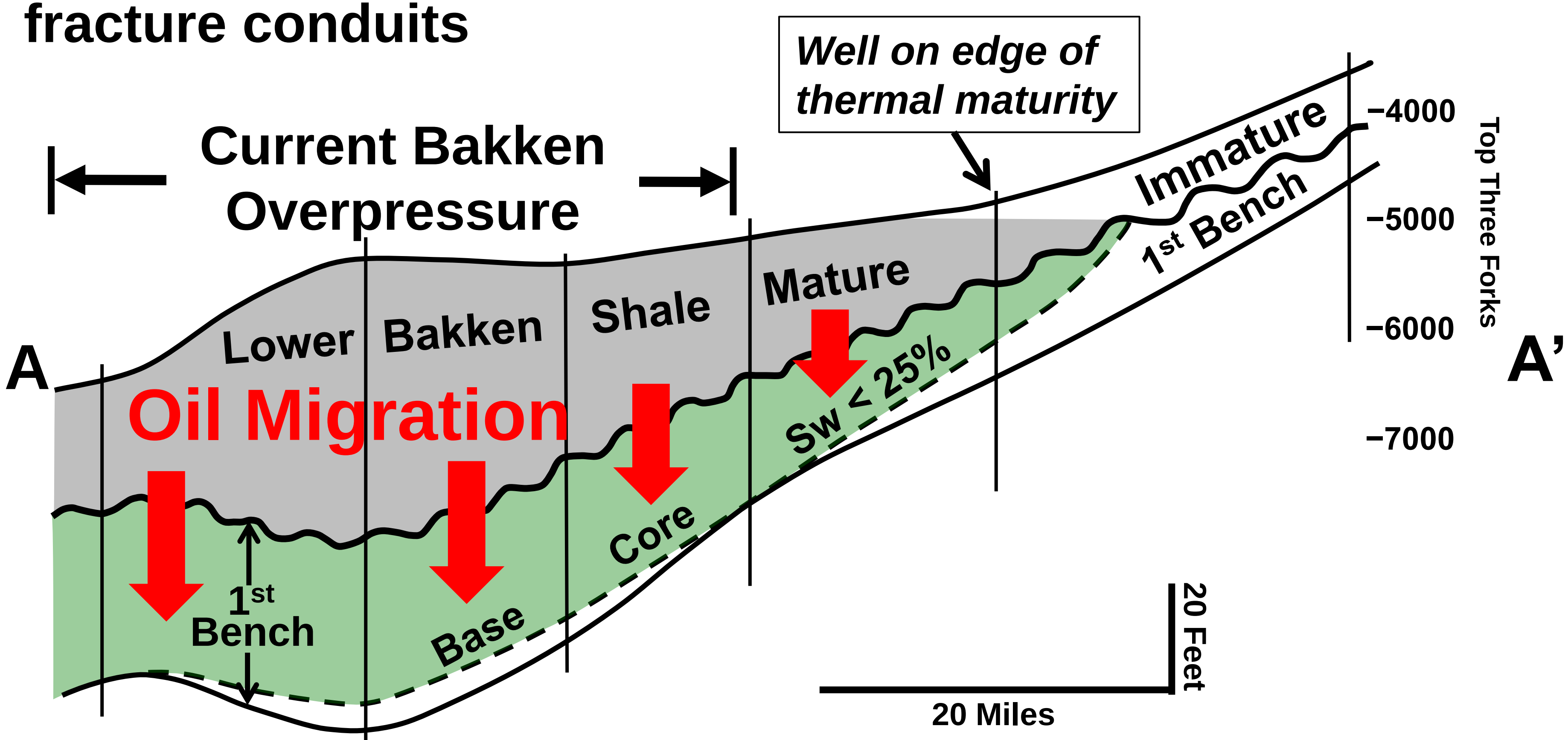
Conclusions

- Capillarity characteristics also control oil migration out of the reservoir
- High entry pressures in the brown dolostone act as a baffle to oil migration in normal-pressure areas



Conclusions

- **On a regional scale, hydrocarbon migration was primarily vertical; oil was forced downward under pressure from overlying Bakken shales and there was limited oil migration outside of overpressure areas or areas with regional fracture conduits**



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Petty, D.M., 2006, Stratigraphic development of the Madison paleokarst in the southern Williston basin area: The Mountain Geologist, v. 43, no. 4, p. 263-281

End