Simulation and Experimental Investigations of CO_2 Injection in Both Conventional (Wellman Unit) and Unconventional Reservoirs

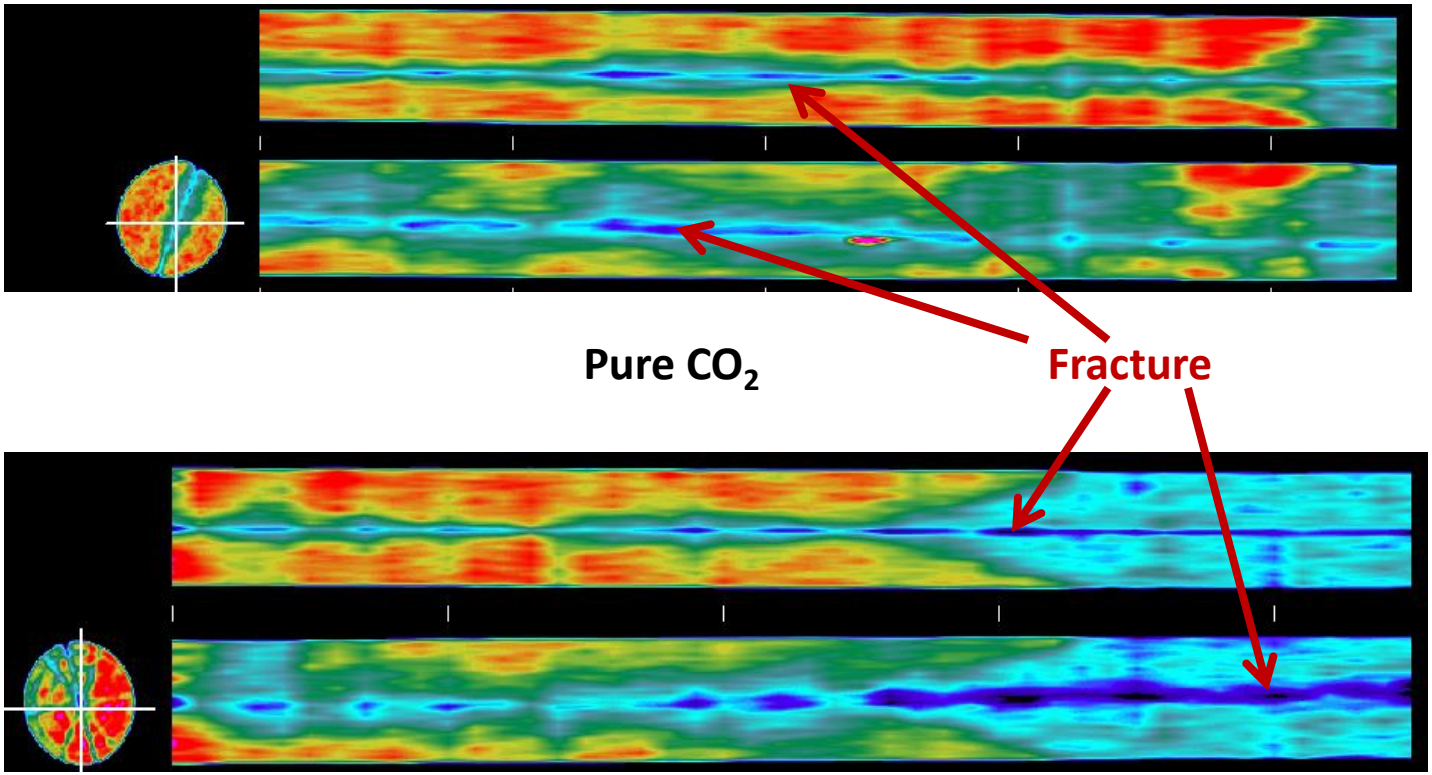
Department of Petroleum Engineering
Texas A&M University
Dr. David Schechter

19th Annual CO_2 Flooding Conference
Midland, TX
December 12th, 2013

Observations

- CO_2 EOR recovers oil very effectively
- It's limited by the ***availability*** of CO_2
- The laboratory and simulation research technology is aimed at improving the utilization of CO_2 (areal and vertical sweep efficiency) through ***mobility control***)
- Research into ***gravity stable floods*** (Wellman Unit)
- The research technology is improving prediction of processing rates (net utilization and gross utilization - Mscf CO_2/bbl EOR) with ***dimensionless curves for H_2O and CO_2***
- The big prize is utilizing CO_2 in the ***ROZ*** & countless "boom" wells in ***unconventional liquid reservoirs (ULR)***

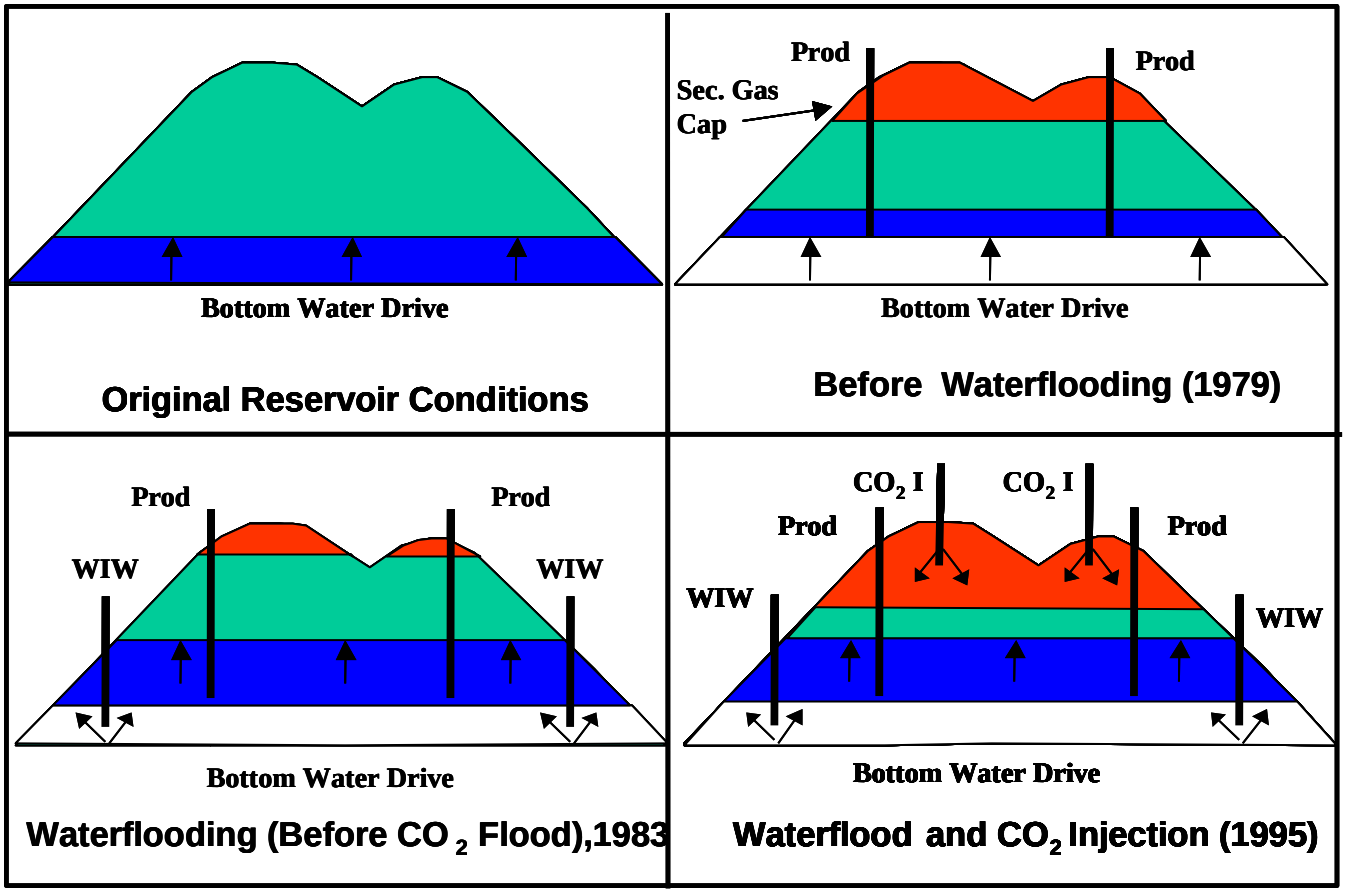
Mobility Control with Viscosifier Sweep Efficiency after 0.5 PV Injected



Dodecamethylpentasiloxane Viscosified CO_2 Flood

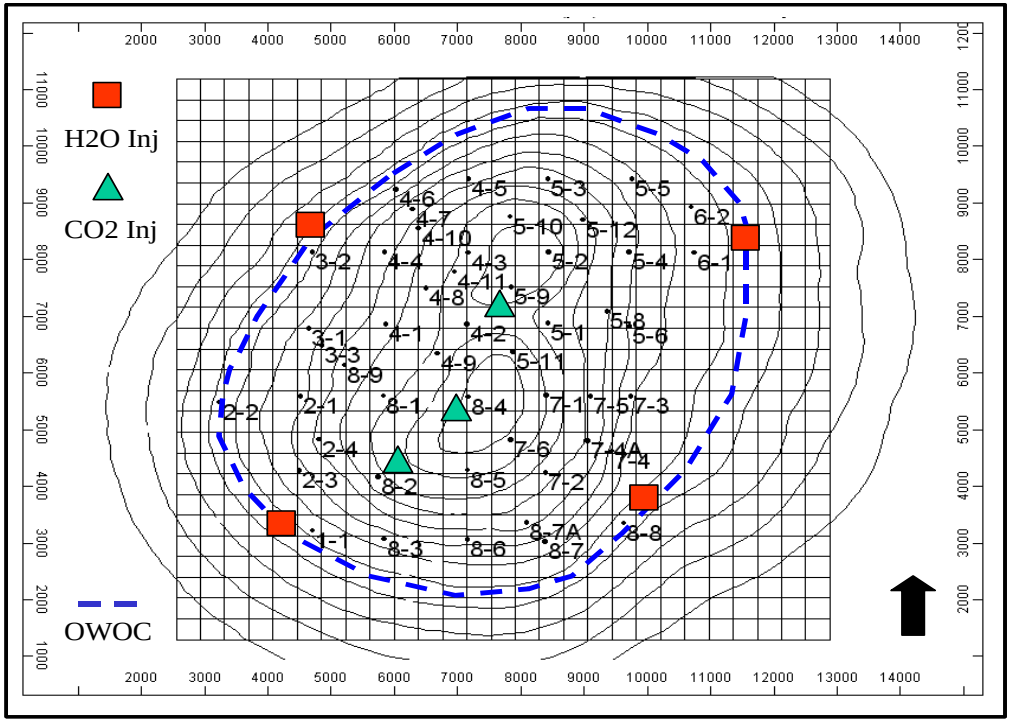
Shuzong Cai, 2011

Chronological Stages of Depletion



Simulation Model

Full field, 3-D black oil simulation
"Imex" – CMG

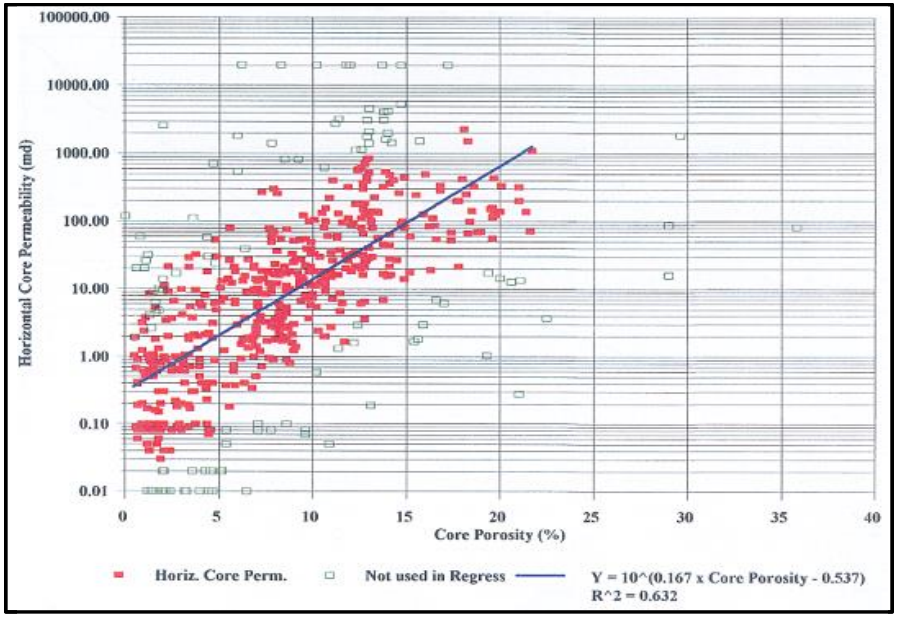


Grid System

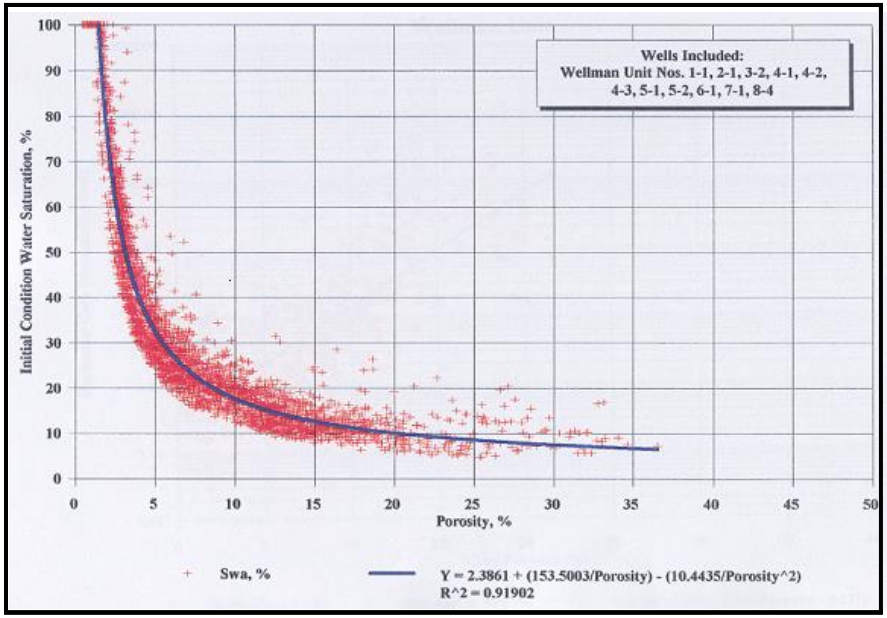
- Use of flexible grids: corner point, non - orthogonal geometry.
- 27 x 27 gridblocks I,J direction
- K, direction subdivided in 23 layers based on porosity correlations (geological description)
- Total 16,767 gridblocks

Simulation Model

Input Data



Permeability



Swc, aprox 20% for Φ = 8.5%

- Use previous estimations from correlations between open logs and core measurements

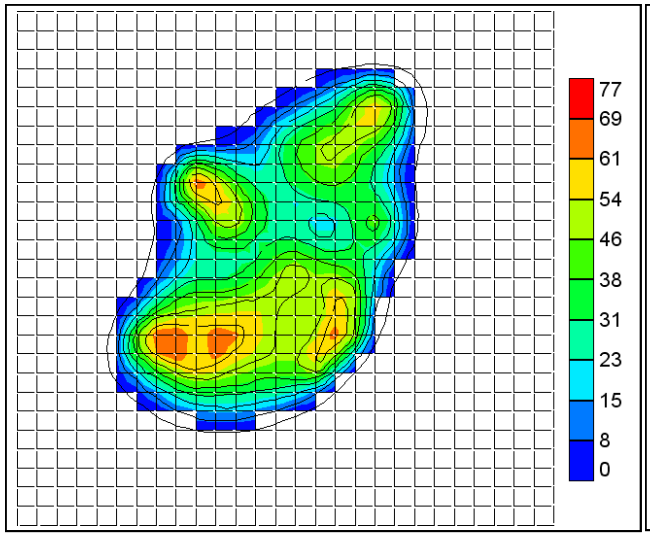
$$K = 10^{(0.167 * \text{Core porosity} - 0.537)}$$

- Relationship may not be representative due to fractures and vugular porosity

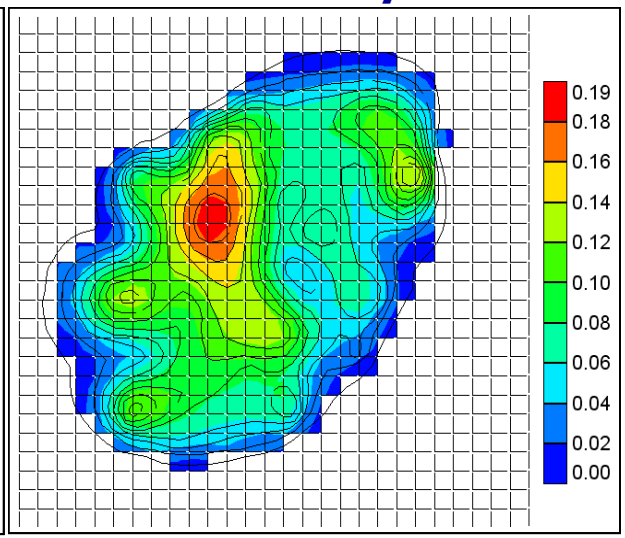
Simulation Model

Input Data

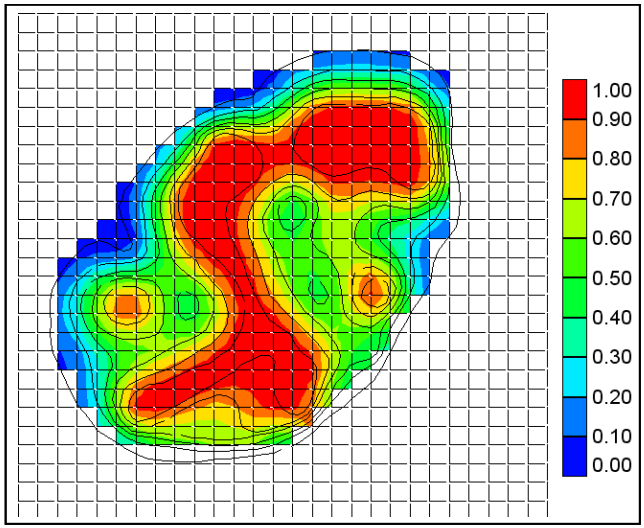
Gross Thickness

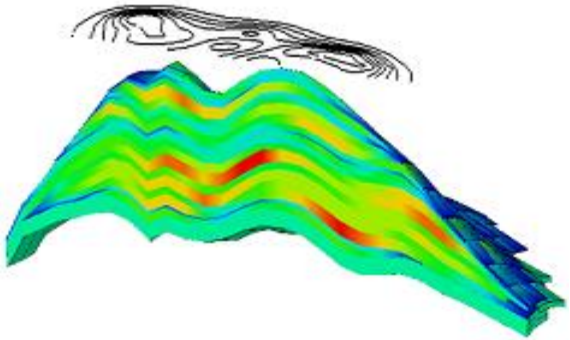


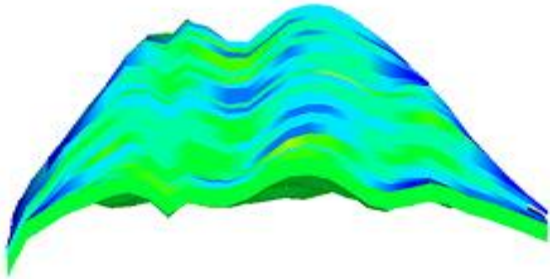
Porosity

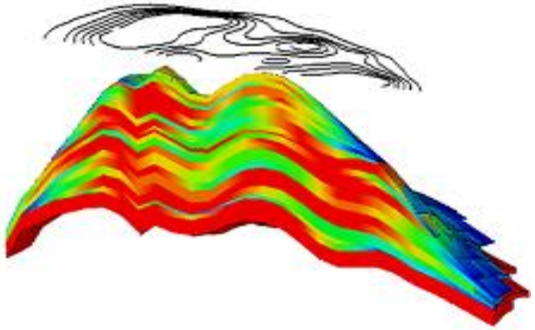


Net to Gross Ratio



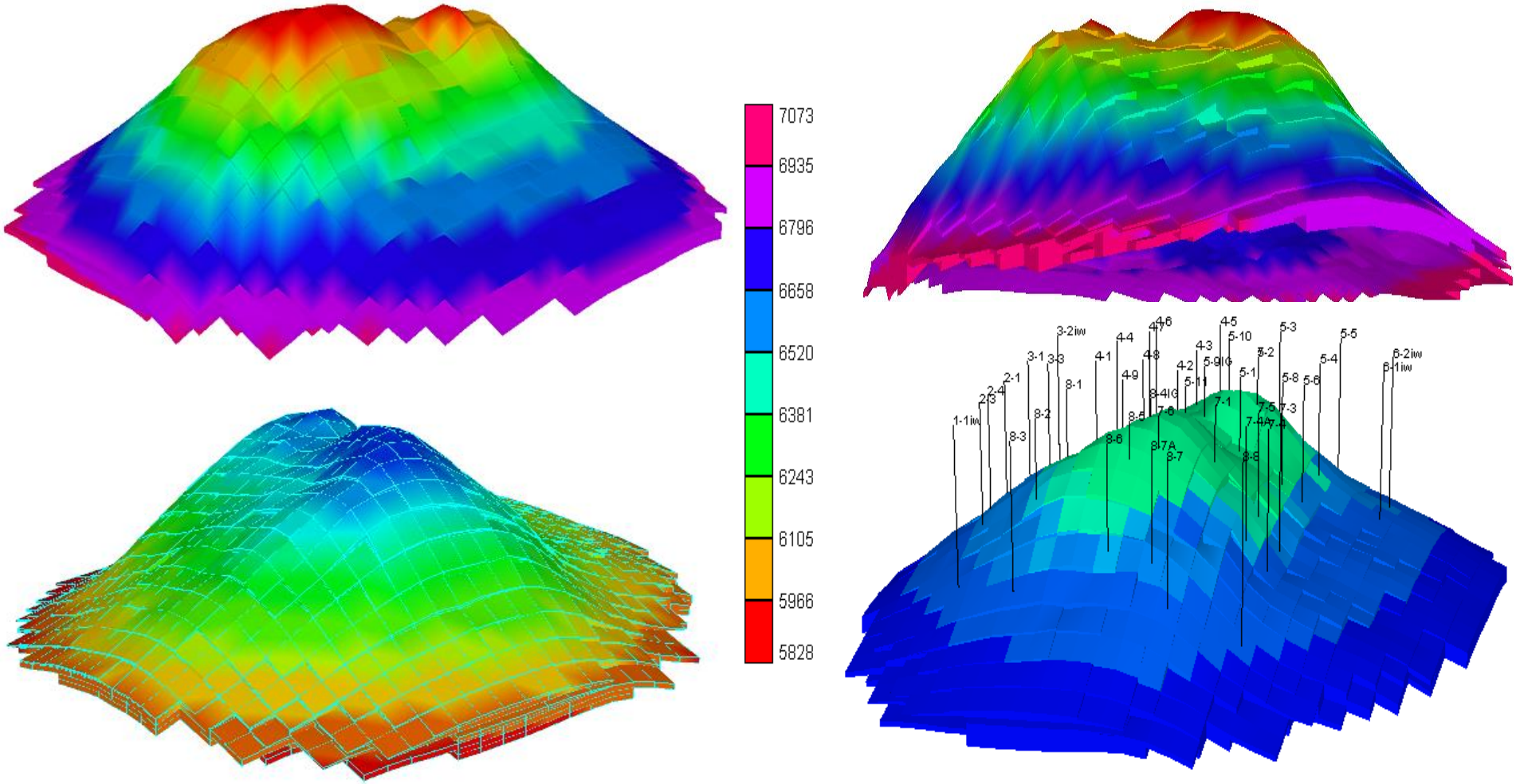






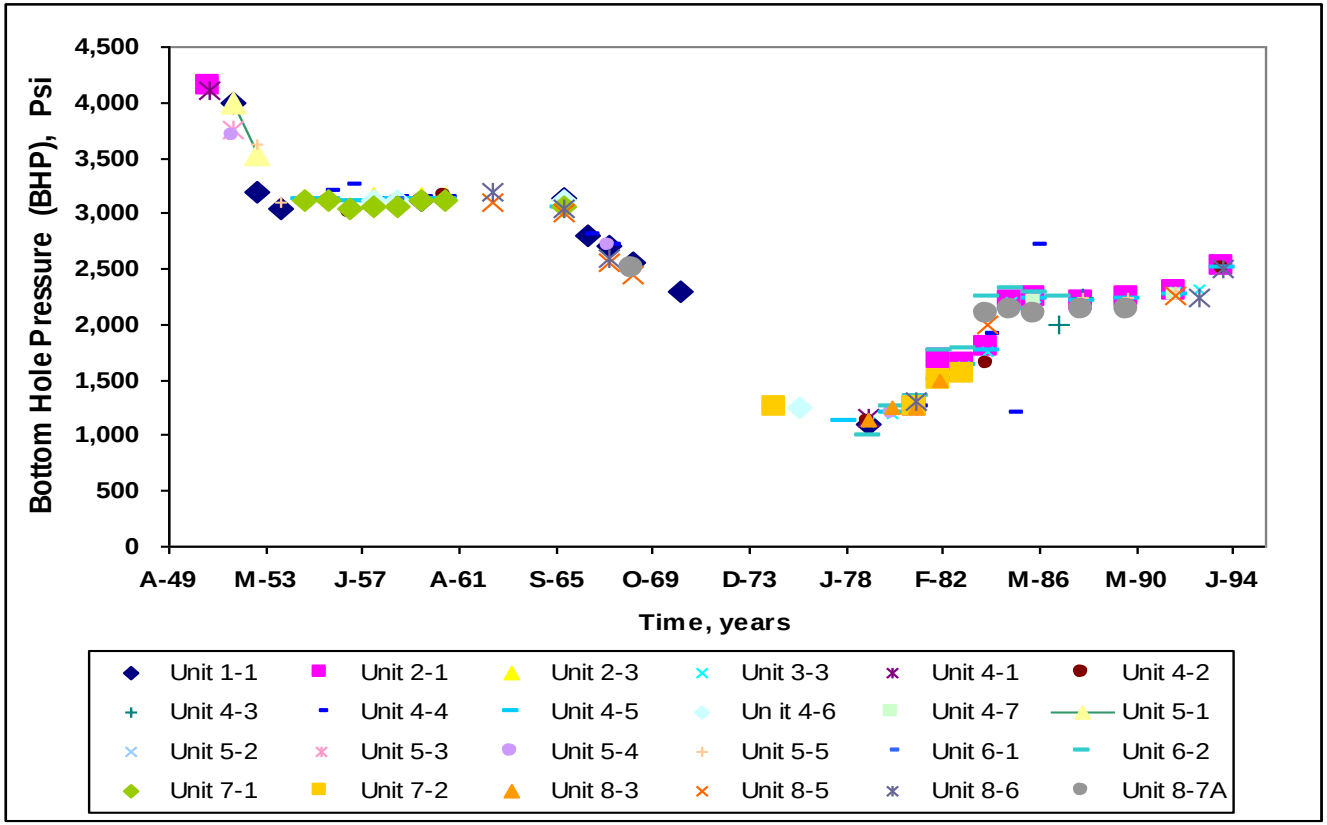
Simulation Model

3D – Structure Development

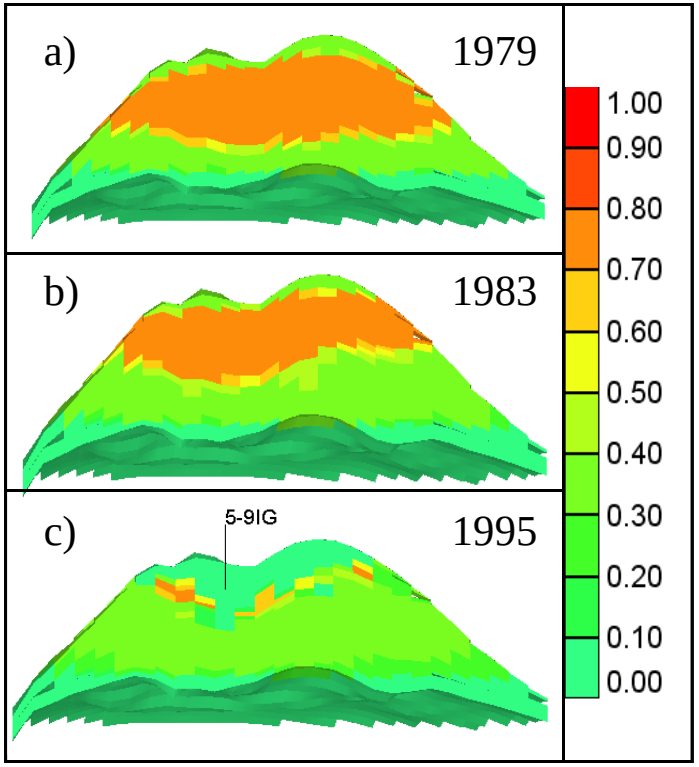


Measured BHP's for History Matching

Individual Static Bottom Hole Pressure



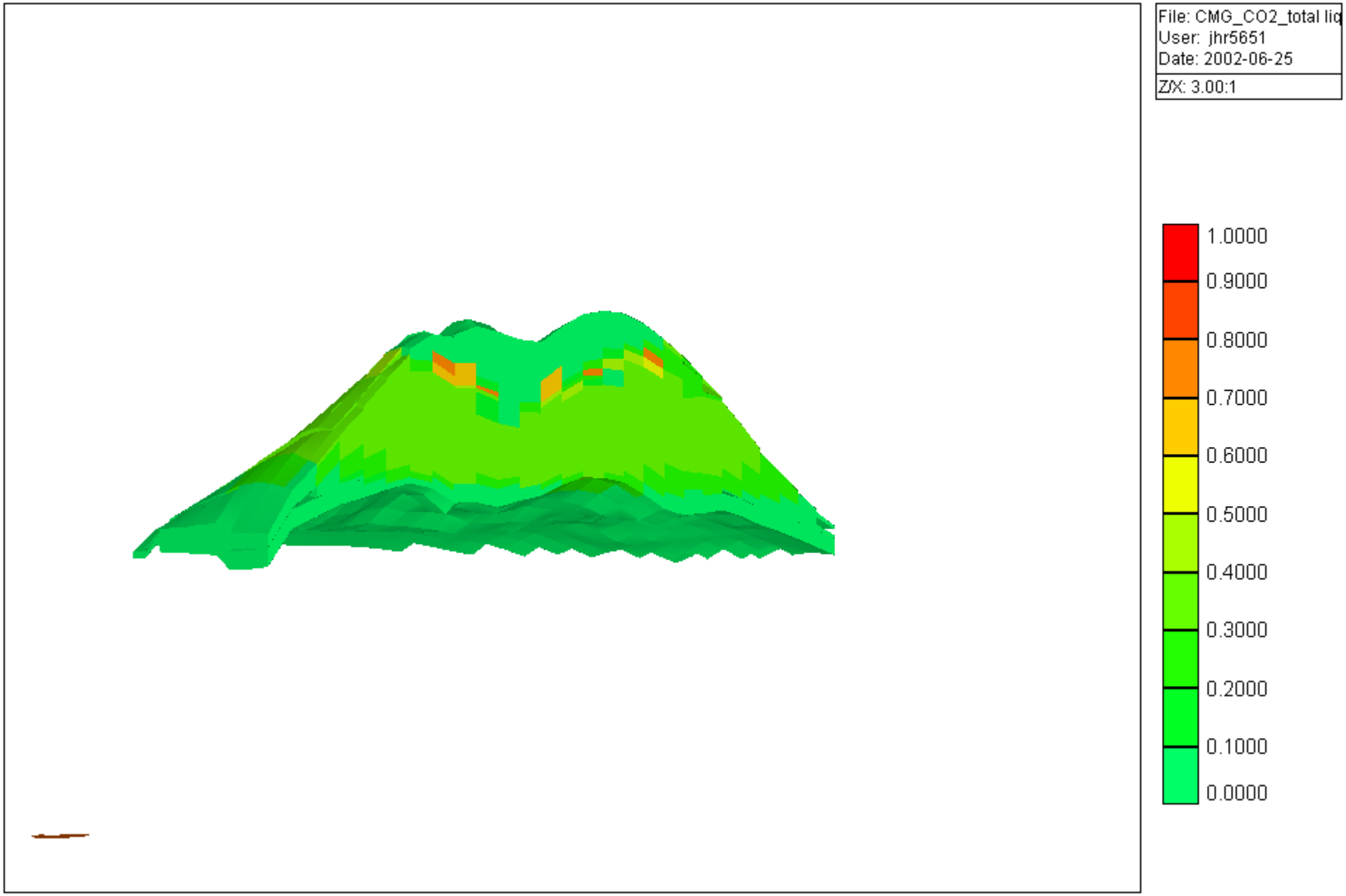
Chronological Oil Saturation Distribution



a) Primary depletion

b) Waterflooding

c) CO_2 miscible flooding
Oil saturation considered overestimated due to the excess of oil production


File: CMG_CO2_total liq
User: jhr5651
Date: 2002-06-25
Z/X: 3.00:1
1.0000
0.9000
0.8000
0.7000
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000

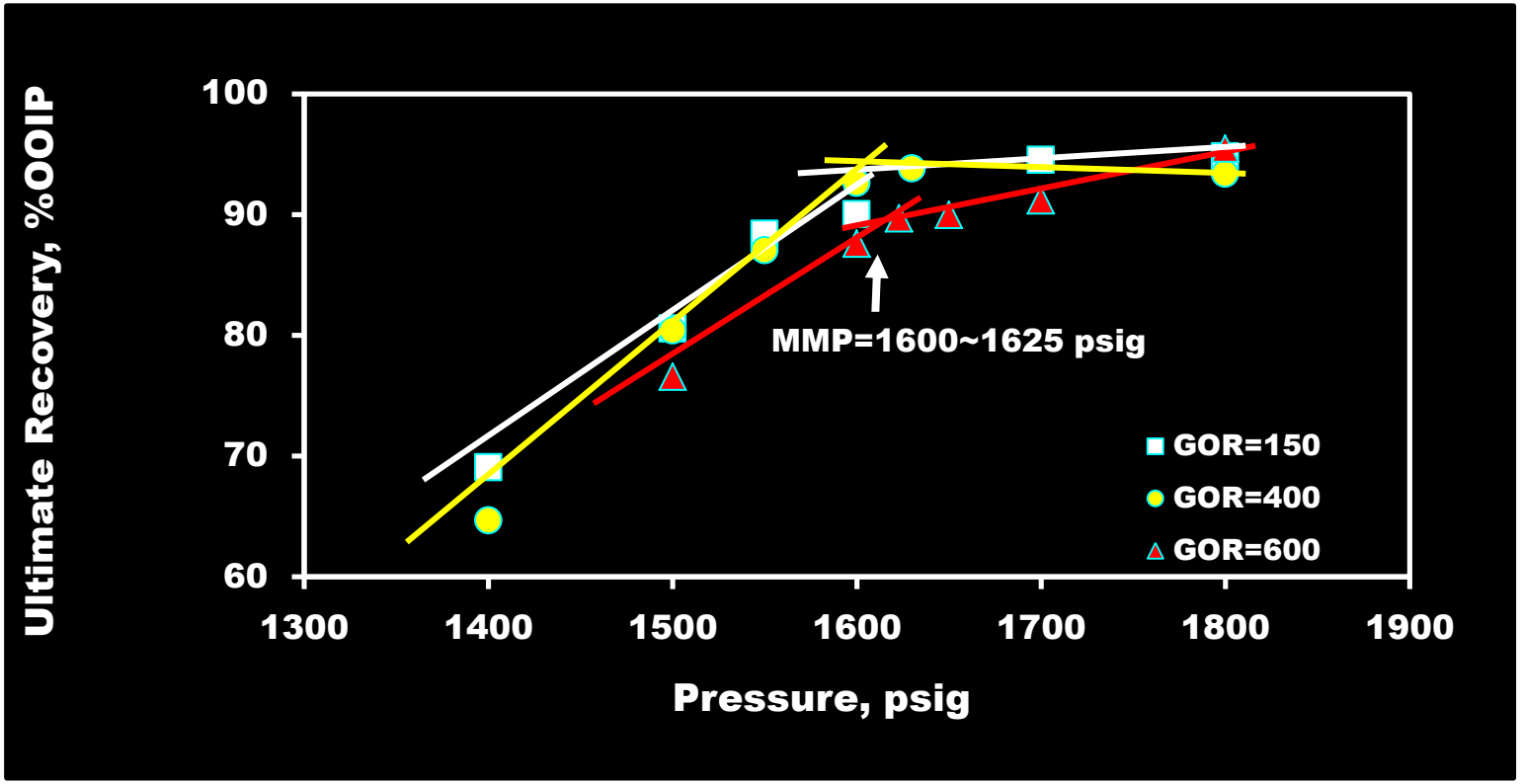
CO_2 Recovery Mechanism Gravity Drainage

- To examine the performance of recovery at or near the MMP with CO_2 in:
  - standard slim tube
  - vertically-oriented, bead-packed large diameter tubes
  - vertically-oriented reservoir cores at reservoir conditions
- To examine possibility that residual oil exists below the original water-oil contact that could be mobilized by continuation of CO_2 injection

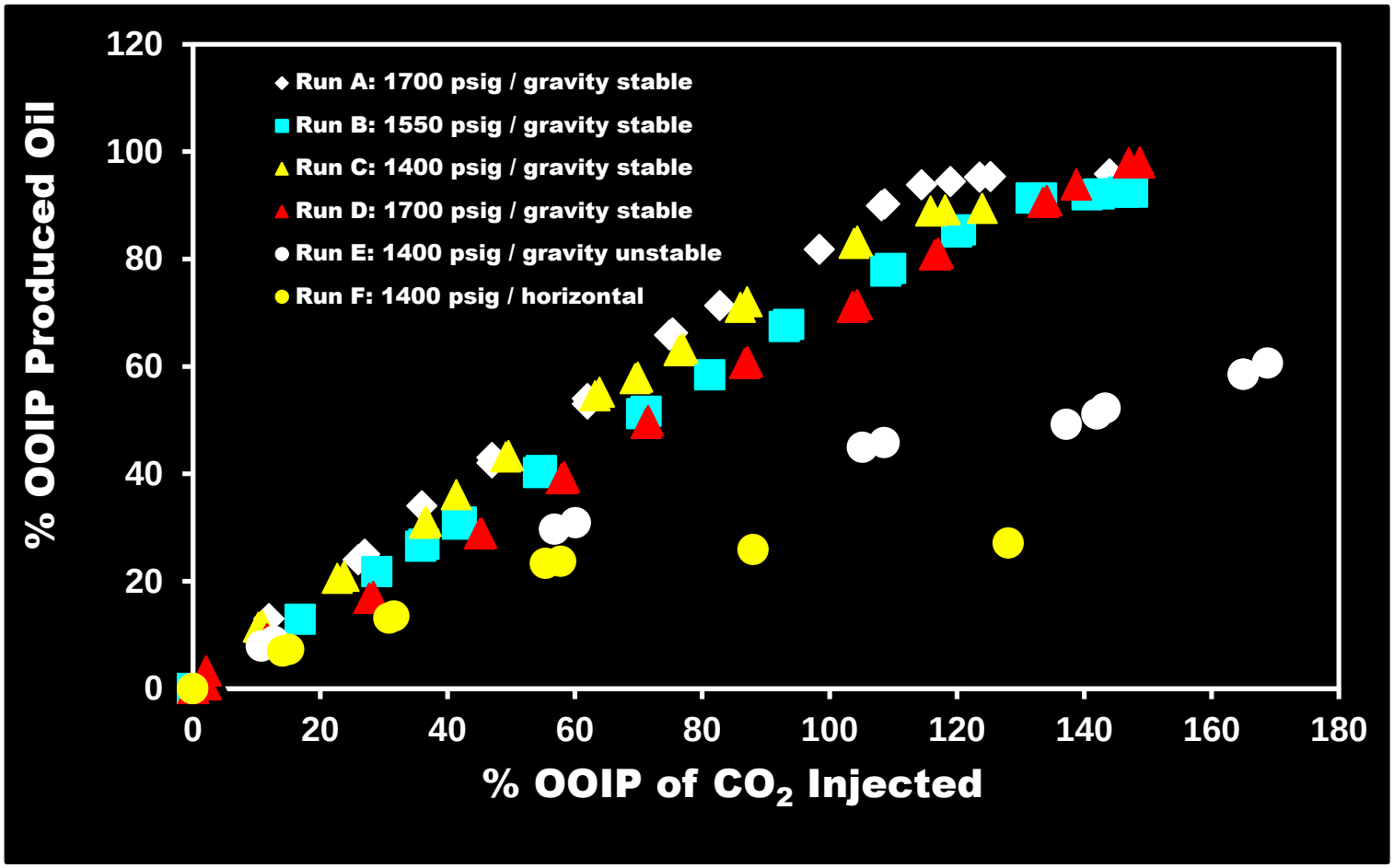
Wellman Unit Oil Characteristics

- Separator oil taken at 61 ^{o}F and 126 psig
- Average molecular weight: 147 g/mol
- GOR: 150 scf/bbl
- Density: 0.8329 g/cm^3 @ 100 ^{o}F and 1000 psig
- Viscosity: 2.956 cp

Recovery vs. Pressure for Different GOR's in Slim Tube



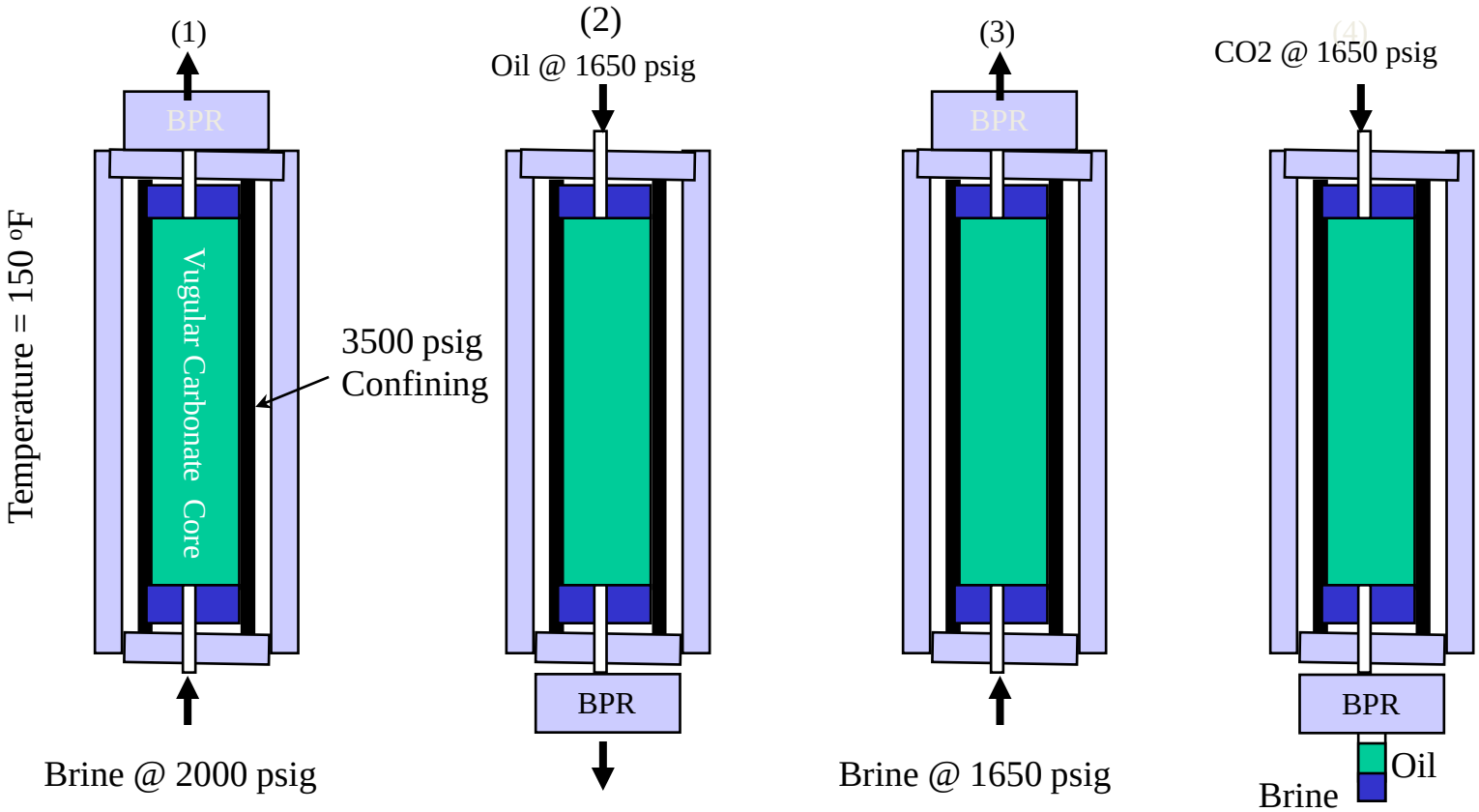
Recovery Curves for Each Large Diameter Tube Test



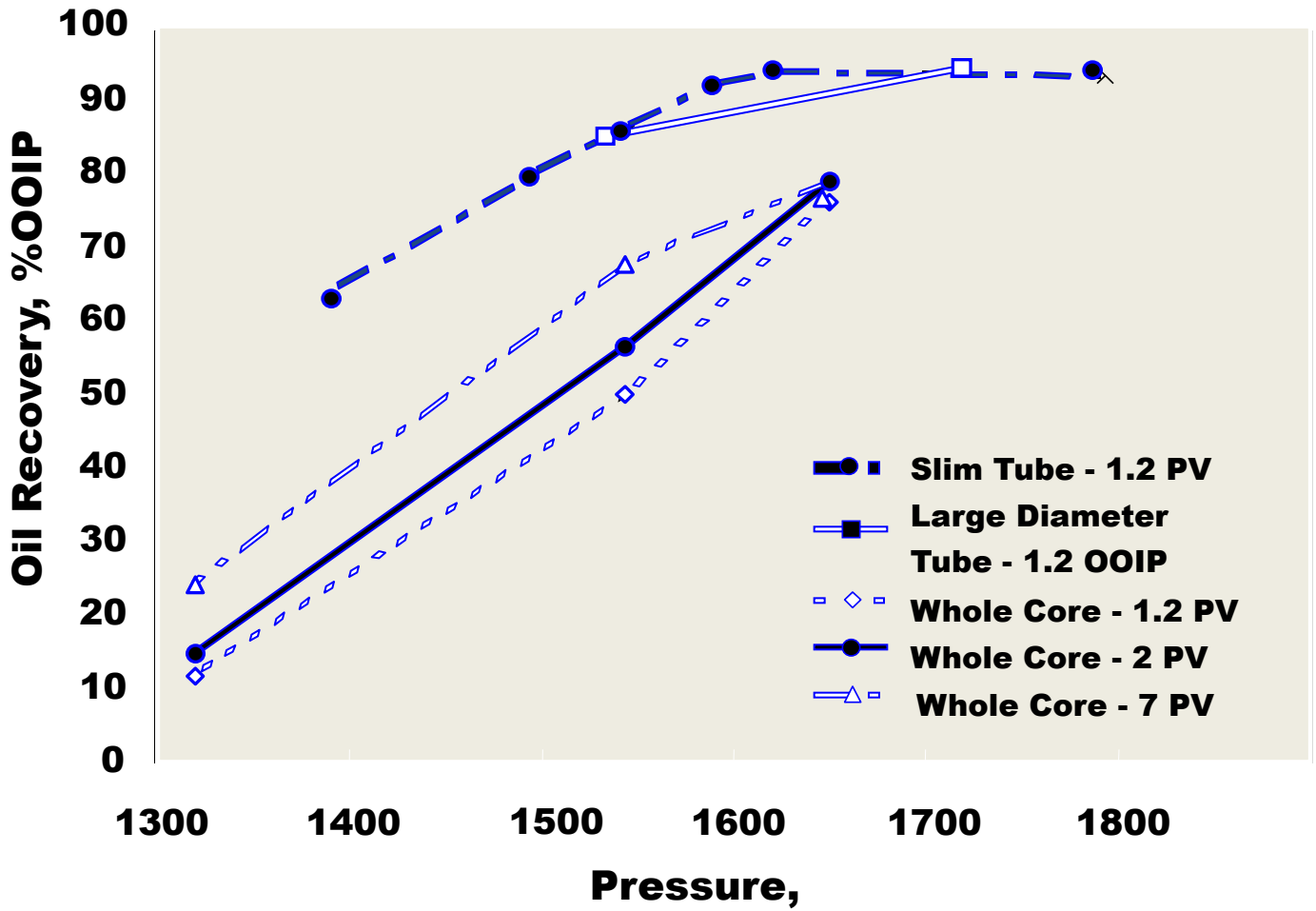
Cores From Wellman 5-10

- 30’ whole core from 9400’ to 9430’
- 26 samples for standard core analysis
- 3’ section for gravity stable CO_2 tests
- Helium porosities: 2.4% ~ 12.6%
- Average porosity: 5.8% for 26 samples
- Average water saturation: 42%

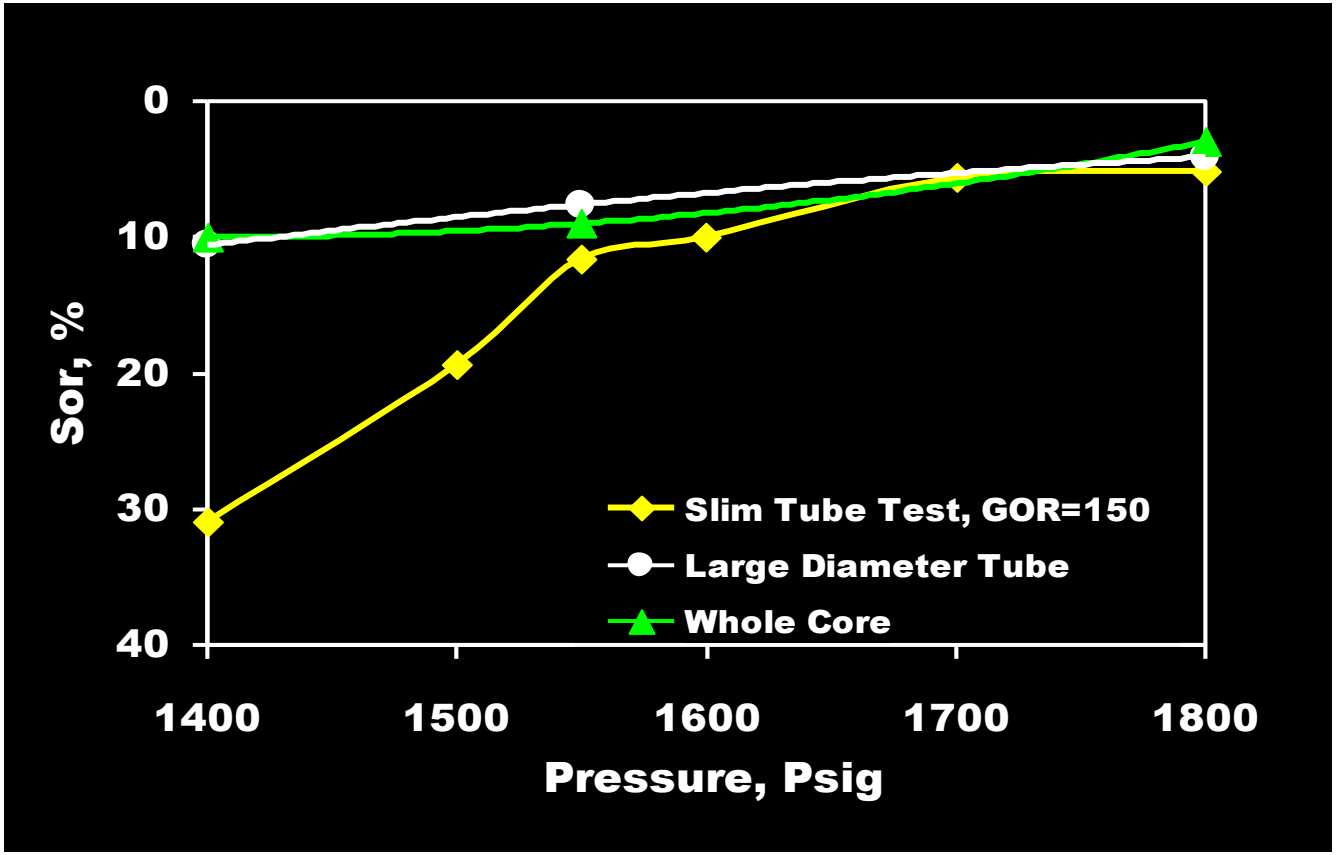
Schematic Diagram of the Core Holder and ROZ Procedure (Wellman Unit)



Oil Recovery From the Wellman Unit Whole Core During CO_2-assisted Gravity Drainage at a Pressure of 1650 psig



S_{or} From the Wellman Unit Whole Core During CO_2-assisted Gravity Drainage at Three Pressures Above and Below the MMP



CO_2 Recovery Factors in Whole Core Wellman Unit Gravity Drainage

Experiment No.	1	2	3
Core porosity	0.0676	0.066	0.066
Core permeability, md	15.4	12.7	12.7
Initial oil saturation	0.47	0.102	0.191
Oil type	Reservoir Oil	Separator Oil	Separator Oil
Temperature, ^{o}F	150	150	150
Pressure, psig	1,650	1,543	1,320
CO_2 injection rate, cc/hr	20	10	2
Oil recovery after 1.2 PV CO_2 inj.	0.76	0.51	0.115
Oil recovery after 2 PV CO_2 inj.	0.78	0.57	0.148
Residual oil saturation	**0.09**	**0.03**	**0.10**

Conclusions

- The MMP of W.U. oil is 1600 +/- 50 psig over a range of GOR's 150 to 600 scf/bbl;

- Reservoir performance, slim tube, large diameter tube and gravity stable core floods in W.U. whole core at reservoir conditions demonstrate excellent displacement efficiency with S_{or} after CO_2 < 10% for a range of pressures;

Conclusions

- Gravity stable core flooding results from transition zone core taken from the W.U. demonstrates that oil not mobilized by water influx in the transition zone can be effectively mobilized with CO_2 over a range of injection pressures;

Conclusions

- Reducing pressure from above the MMP to near the MMP does not reduce efficiency in laboratory. BHP in the W.U. could be reduced to near the MMP with no reduction in displacement efficiency. The reduction in CO_2 purchases would be a positive benefit. The reduction in reservoir pressure is constrained by voidage replacement issues;

Conclusions

- CO_2 flooding in the W.U. has performed exceptionally well due to gravity stable displacement above MMP. This results in excellent sweep and displacement efficiency. Over 42 bcf of CO_2 has been injected and recovered 7.2 MMbbls of tertiary oil. The resulting utilization is 5.83 Mcf CO_2 injected per barrel of incremental oil as of the late 90's

TEXAS A&M UNIVERSITY

Enhanced Oil Recovery in ULR

CO_2 Injection

Objective

To observe the effect of CO_2 into ULR core and the effect that it may have on oil productivity.

Motivation

- Shale sidewall cores with negligible permeability
- Conventional CO_2 flooding was not possible
- Oil couldn't be recovered

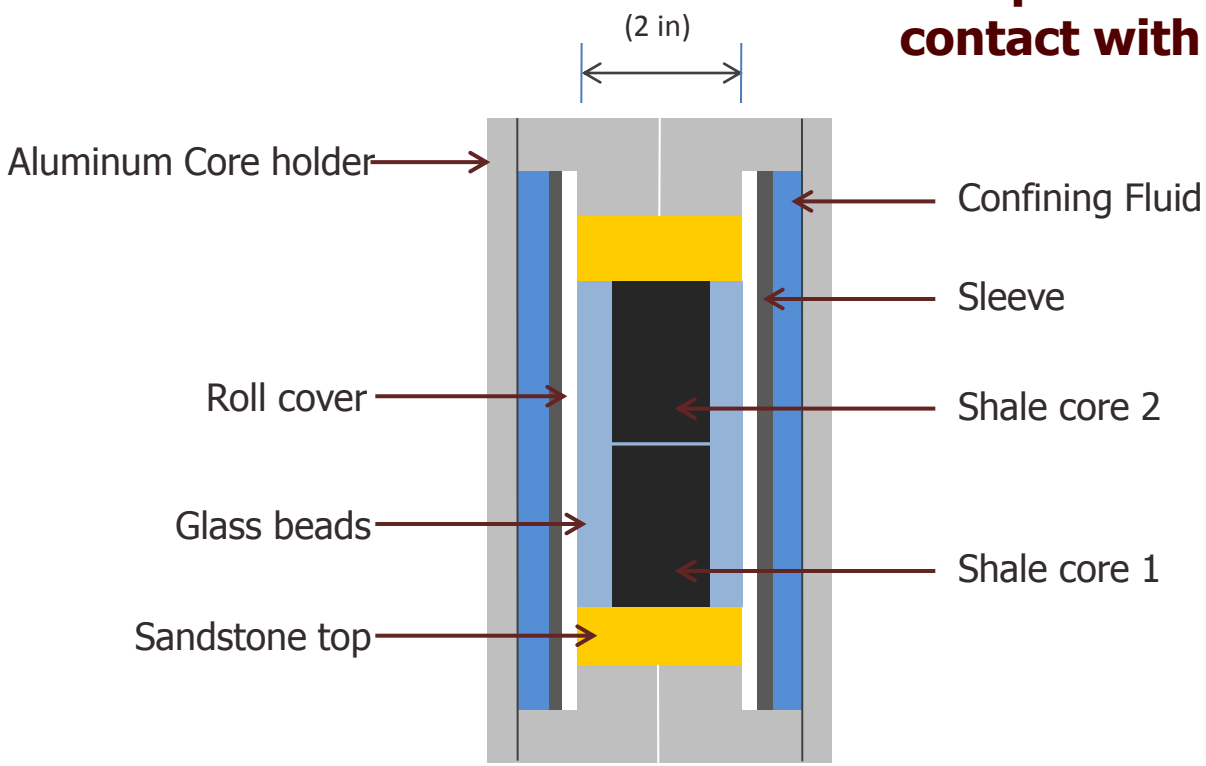
A totally different approach was required

Experimental Procedure

Shale cores were soaked in CO_2

Schematic of cores packing

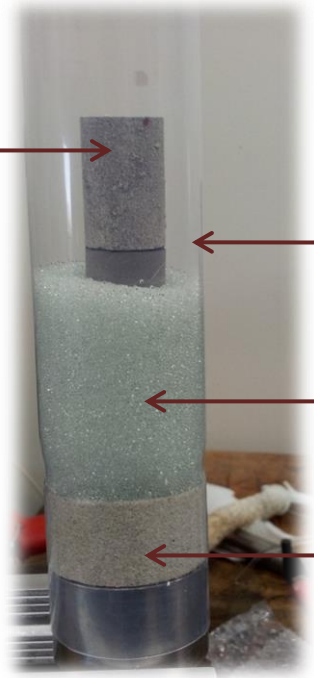
A high permeability media was provided to store CO_2 in contact with the shale cores



Core holder was placed horizontally

Experimental Procedure

CO_2 injection through the core is not intended

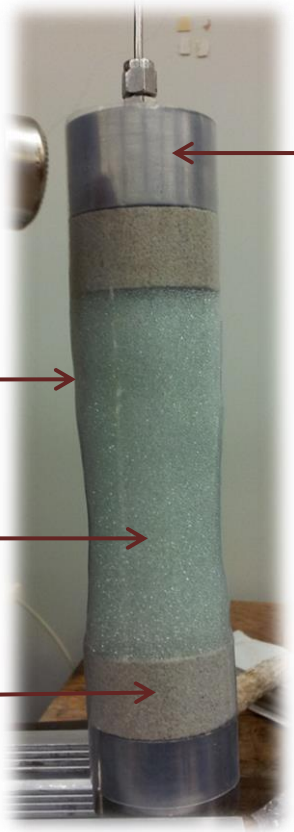


Shale core 2

Roll cover

Glass beads

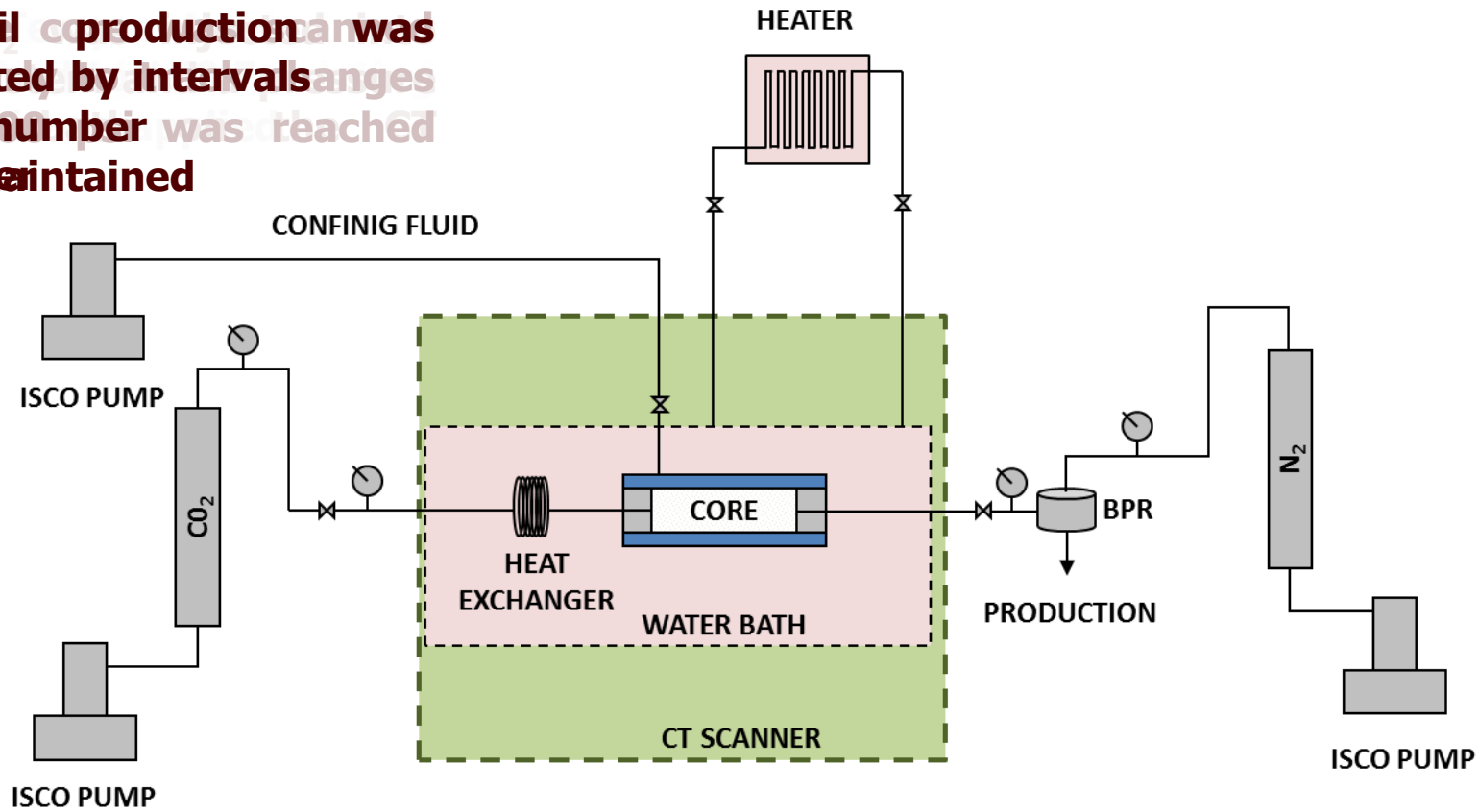
Sandstone top



Aluminum Core holder

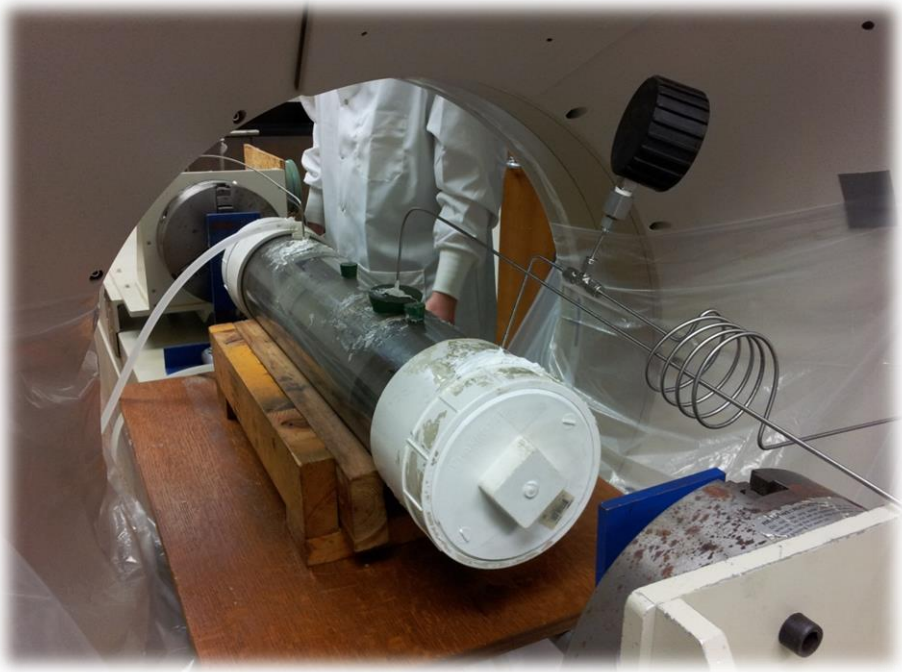
Experimental Procedure

6. Oil production was collected by intervals in CT number was reached and maintained

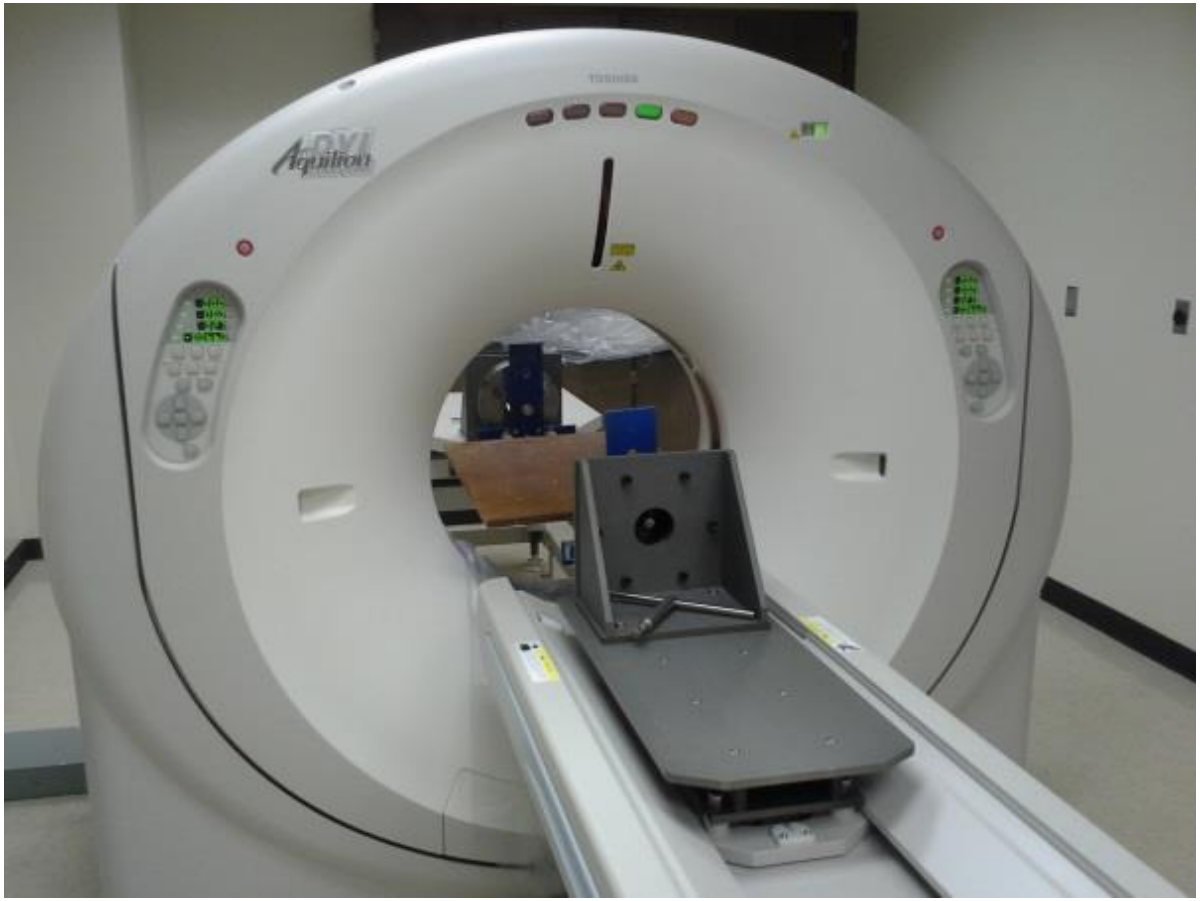


Displacement Equipment Schematic

Experimental Equipment



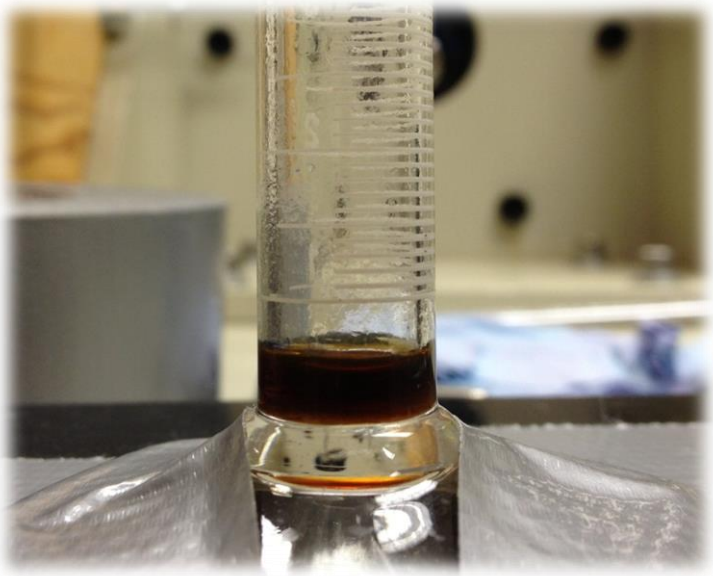
New CT Scanner at Texas A&M PE Department



Results

Oil Recovery

First Experiment
Test conditions : 3000 psi, 150 F



- **0.4 cm^3 of oil were recovered**

$$\text{OOIP} = \text{Core Volume} * \phi * (1 - \text{Swi})$$

- **Different scenarios for <u>recovery factor</u>**

		Porosity (ø), %	
		3	***6***
S_{wi}, %	***0***	36	18
	30	51	25

Results

Core weight

First Experiment
Test conditions : 3000 psi, 150 F

- **Mass of Core 1 increased by 0.07 g**
- **Mass of Core 2 increased by 0.06 g**

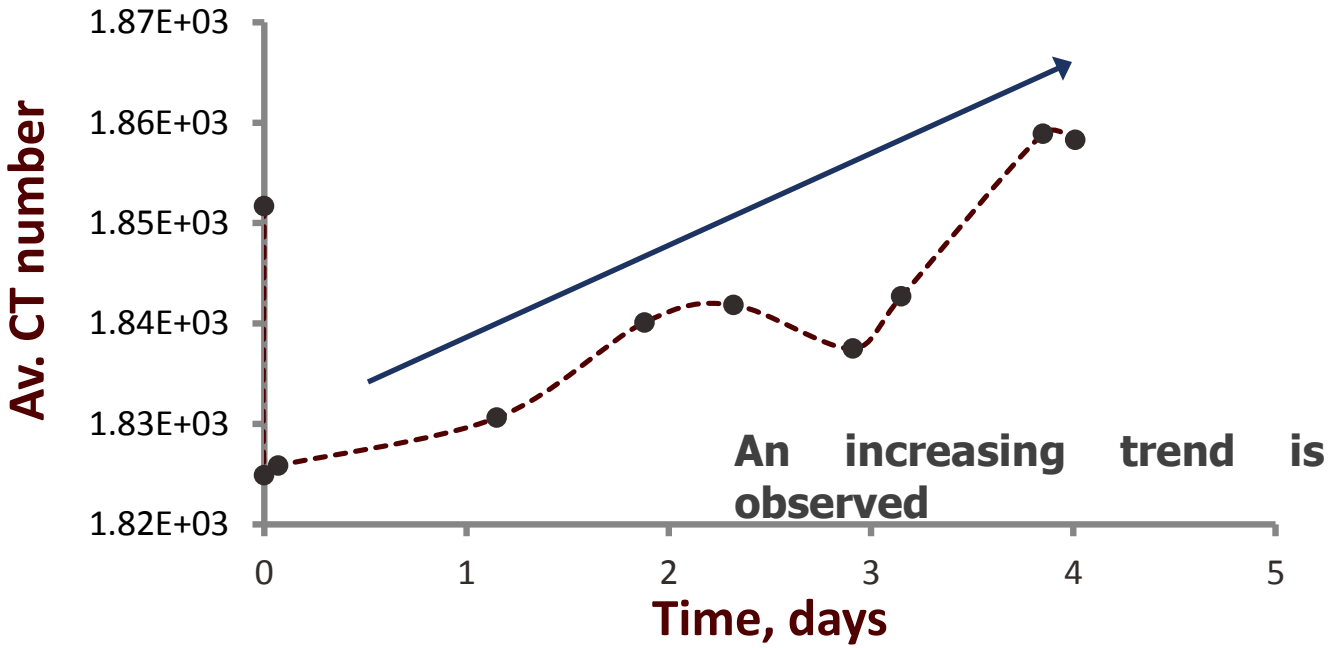
	Sample 1	Sample 2
Weight before experiment, g	50.48	45.39
Weight after experiment, g	50.55	45.45
Diameter, cm	2.53	2.53
Length, cm	3.97	3.48
Bulk volume, cm^3	19.94	17.50

Results

CT Number behavior

Average CT number for both cores

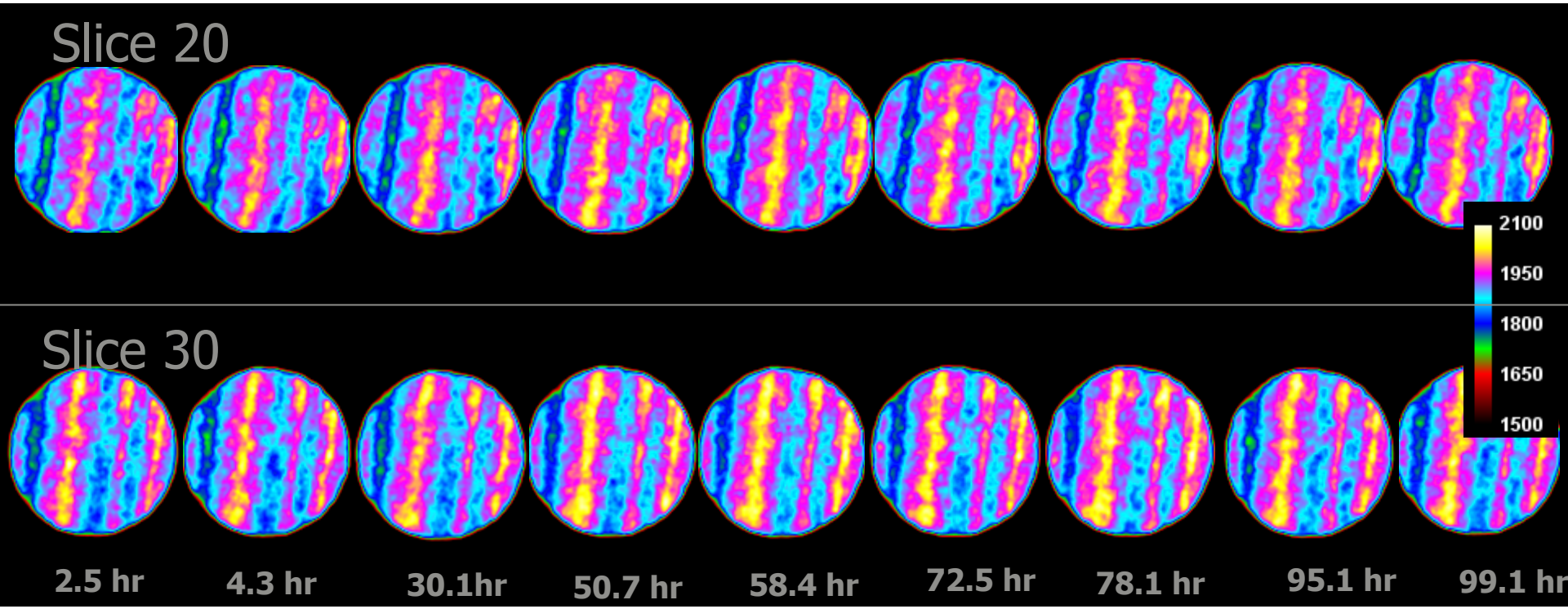
First Experiment
Test conditions : 3000 psi, 150 F



Results

CT Images
Shale sidewall core 1

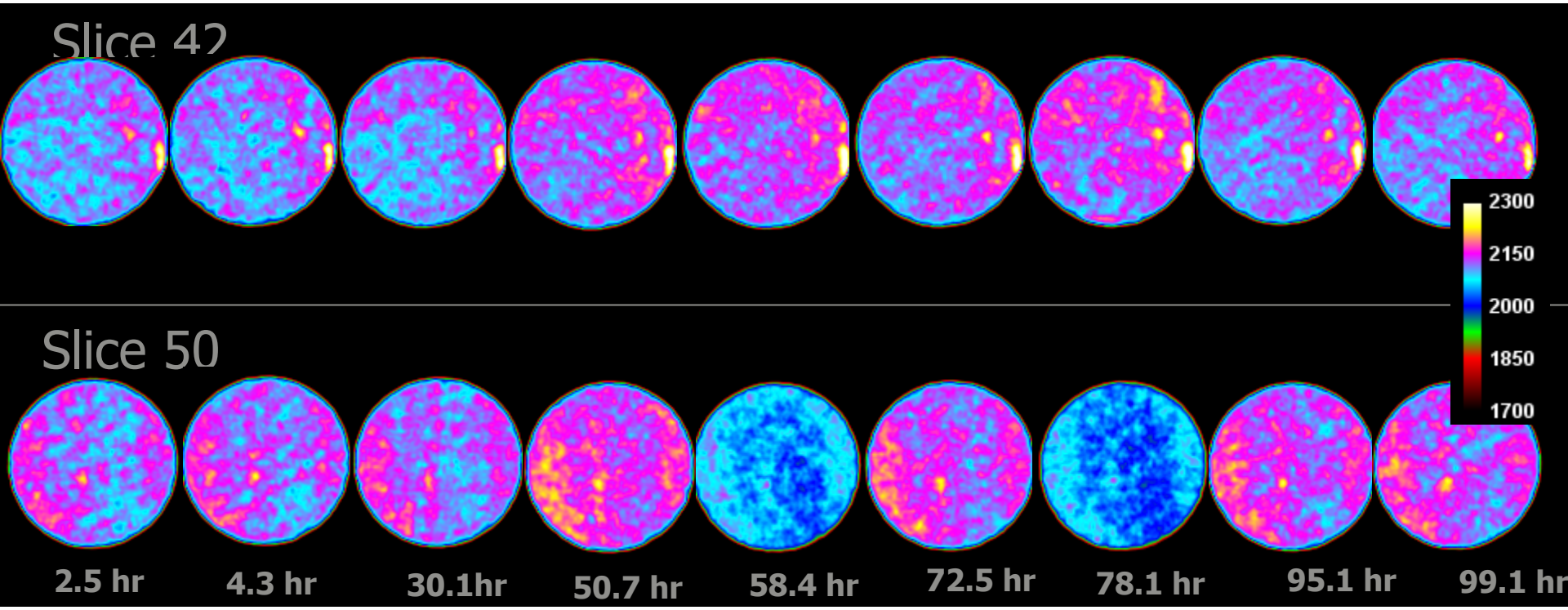
First Experiment
Test conditions : 3000 psi, 150 F



Results

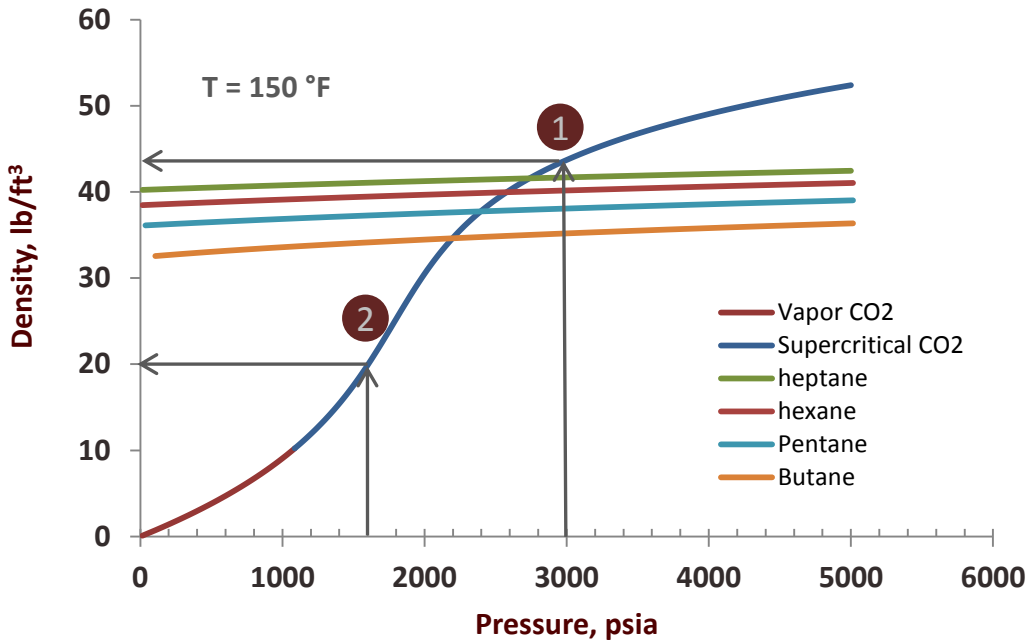
CT Images
Shale sidewall core 2

First Experiment
Test conditions : 3000 psi, 150 F



Results

Since CT number correlates to density

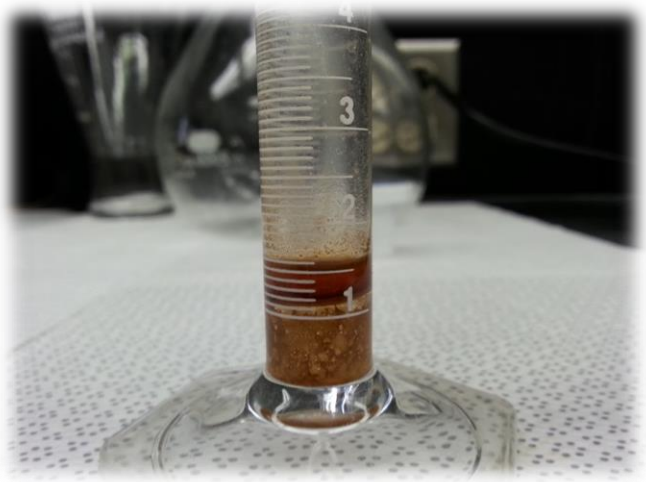


The experiment was repeated at 1600 psi, where a higher density difference exists

Results

Oil Recovery

Second Experiment
Test conditions : 1600 psi, 150 F



This test was prematurely terminated because of a water leak

- **0.4 cm^3 of oil were recovered**

$$OOIP = \text{Core Volume} * \phi * (1 - Swi)$$

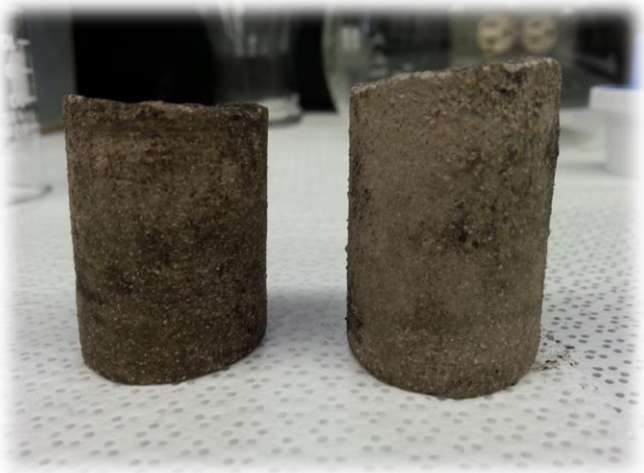
- **Different scenarios for <u>recovery factor</u>**

		Porosity (ø), %	
		3	***6***
S_{wi}, %	***0***	39	19
	30	55	28

Results

Core weight

Second Experiment
Test conditions : 1600 psi, 150 F



- **Mass of Core 1 increased by 0.95 g**
- **Mass of Core 2 increased by 0.86 g**

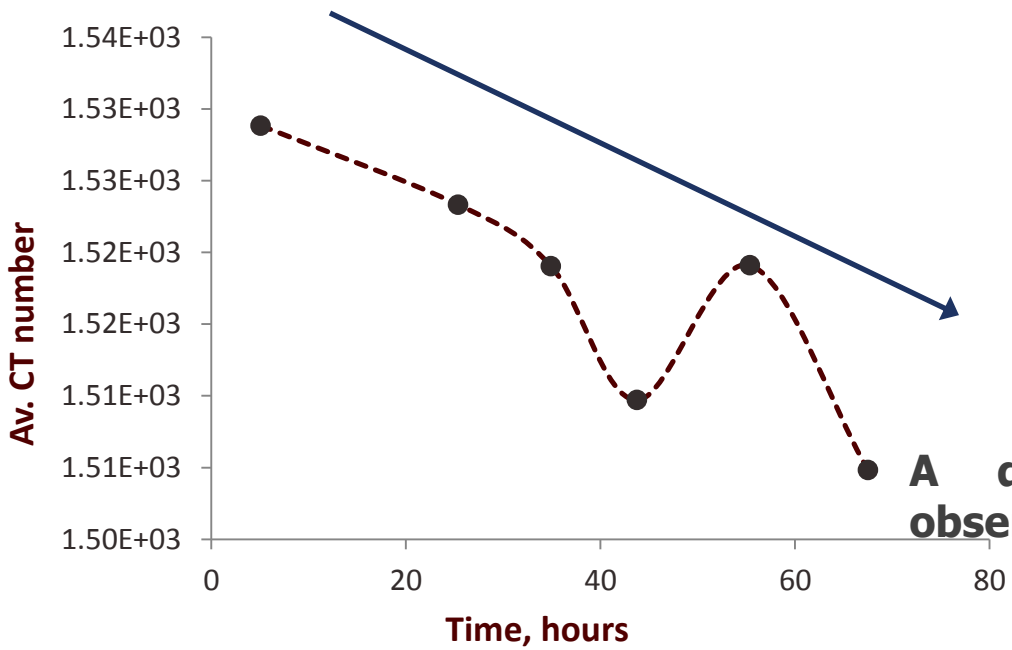
	Sample 1	Sample 2
Weight before experiment, g	40.09	36.04
Weight after experiment, g	41.04	36.90
Diameter, cm	2.53	2.52
Length, cm	3.62	3.29
Bulk volume, cm^3	18.20	16.42

Results

CT Number behavior

Average CT number for sidewall core 1

Second Experiment
Test conditions : 1600 psi, 150 F

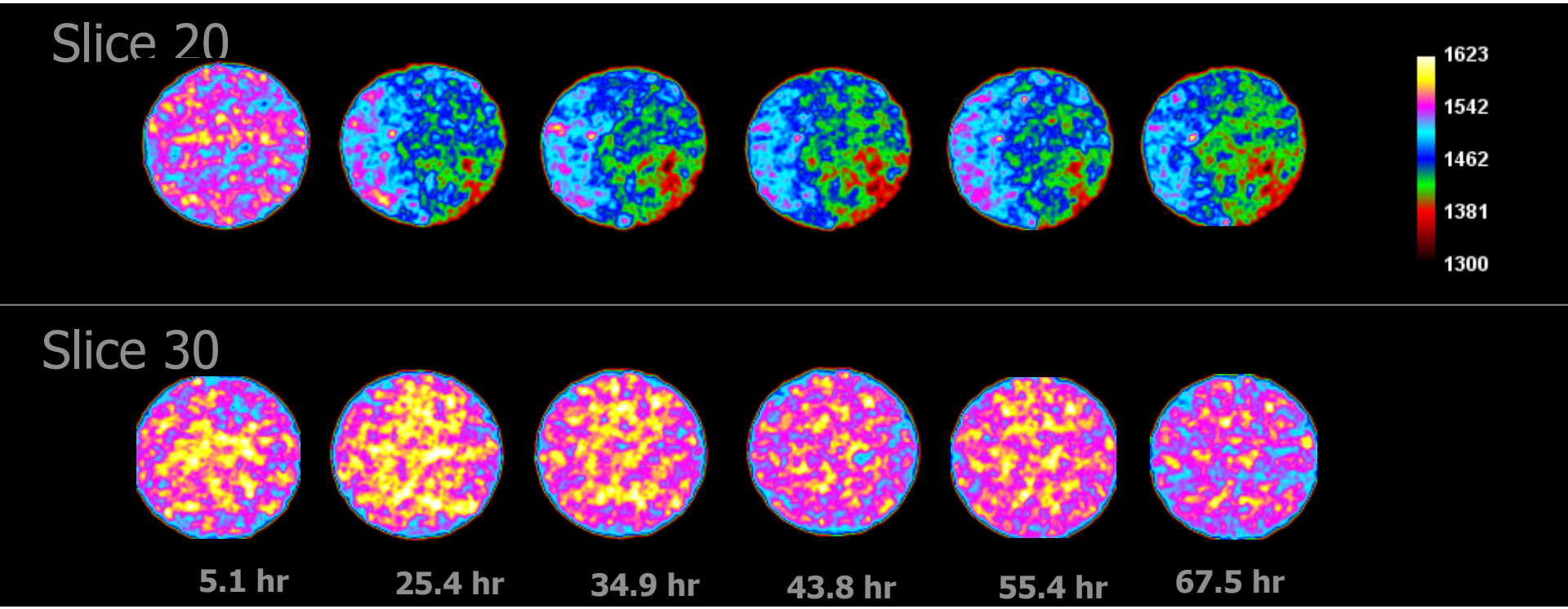


A decreasing trend is observed

Results

CT Images
Shale sidewall core 1

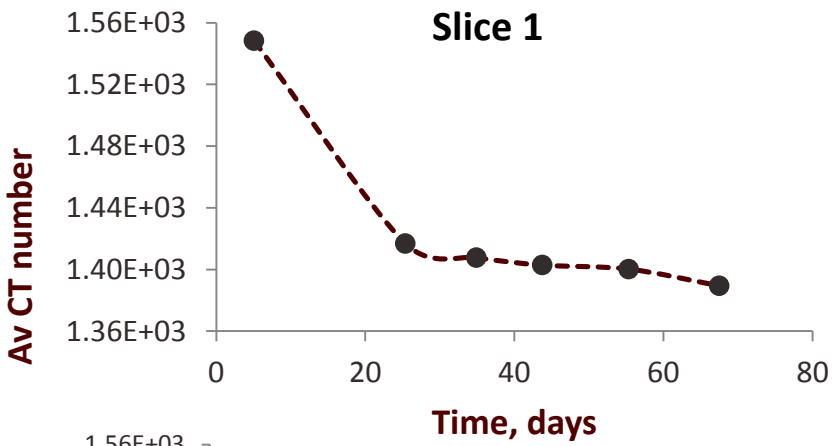
Second Experiment
Test conditions : 1600 psi, 150 F

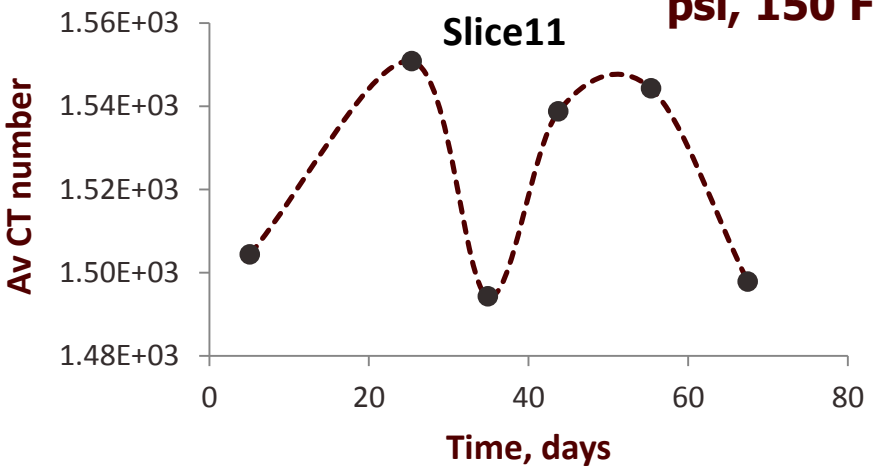


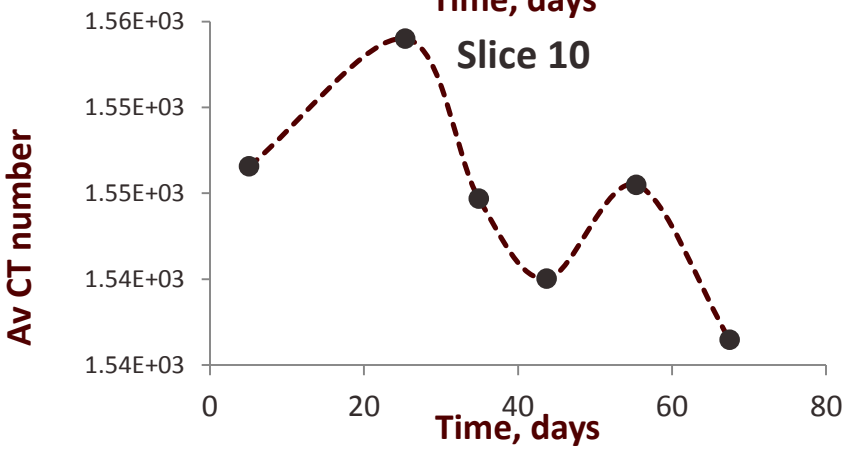
Results with CT Number

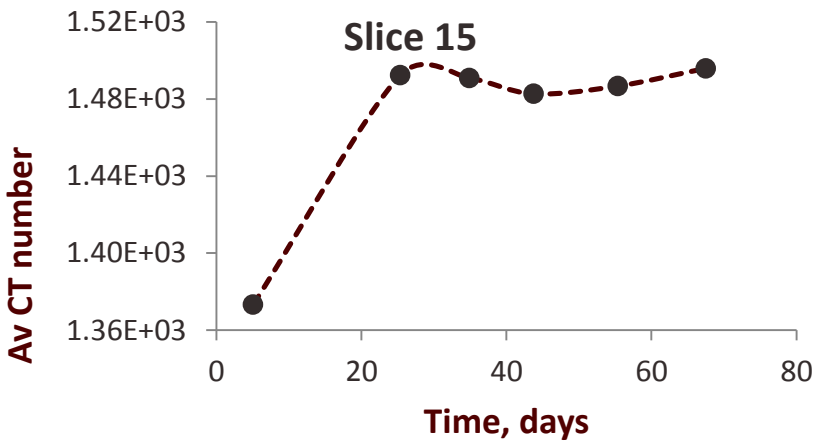
Average CT number for sidewall core 2

Second Experiment
Test conditions : 1600 psi, 150 F







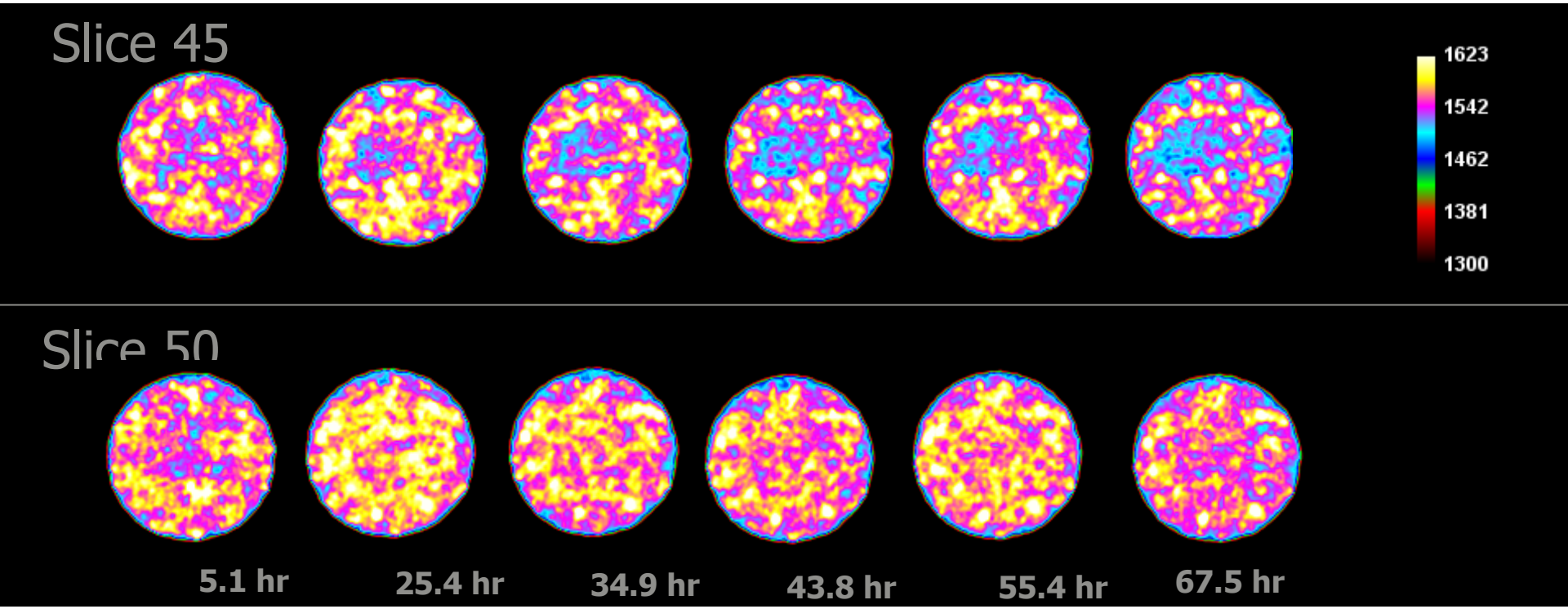


Different trends are observed

Results

CT Images
Shale sidewall core 1

Second Experiment
Test conditions : 1600 psi, 150 F



What is next ?

3rd Experiment

- Production Vs. time data
- Produced oil composition

Numerical Model

- Sensitivity analysis to understand influence of parameters

Conclusions

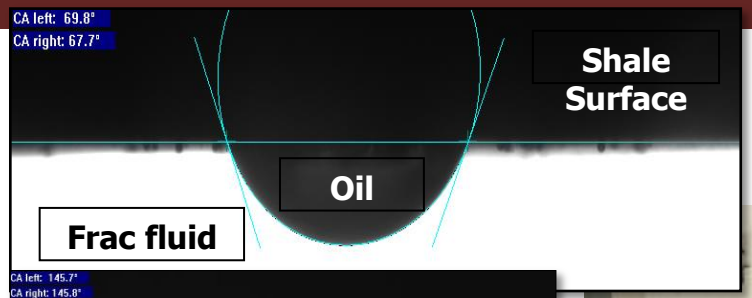
- **Oil production was accomplished by soaking shale cores with CO_2 at 3000 psi and 1600 psi. Recovery in both cases is estimated to be from 18 to 55 % of OOIP. The permeability of the cores does not allow for conventional CO_2 flooding.**

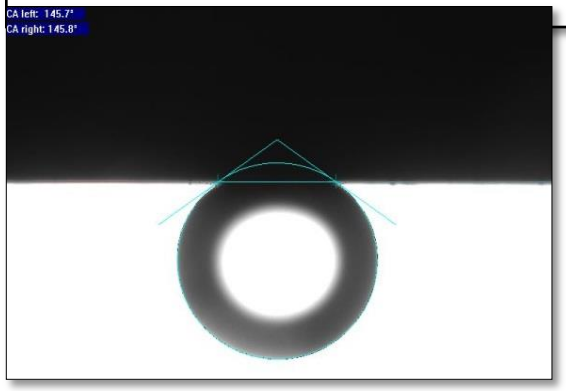
- **CT imaging was done during the course of the experiment revealing changes inside the sidewall cores.**

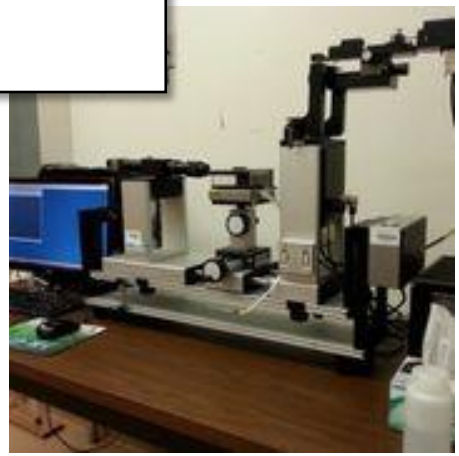
- **Changing the pressure of the test influenced the behavior of CT number, this could be related to the different densities of CO_2 at the two experimental conditions.**

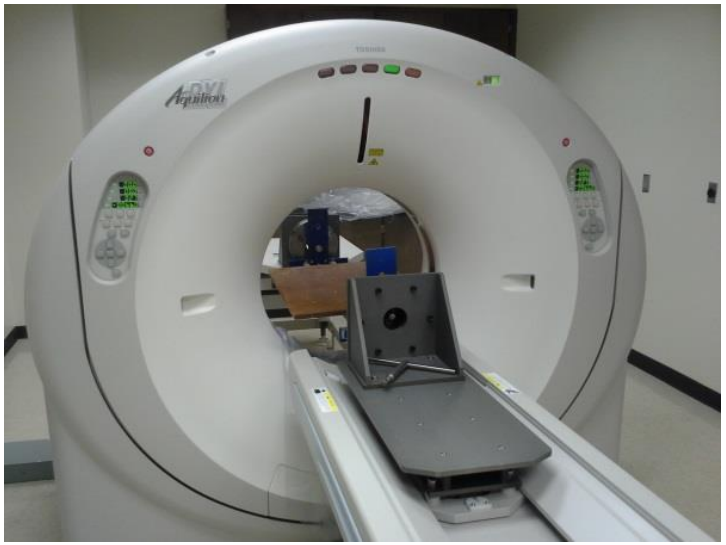
- **More work is required to better understand the mechanisms causing oil production during these tests.**

New Equipment - Chevron Imaging Lab and Chaparral CO_2 EOR Lab









CO_2 and Enhanced Oil Recovery in Unconventional Liquid Reservoirs

Department of Petroleum Engineering
Texas A&M University
Dr. David Schechter

Please Join Our Newly Established JIP

TEXAS A&M UNIVERSITY

Dimensionless Curves

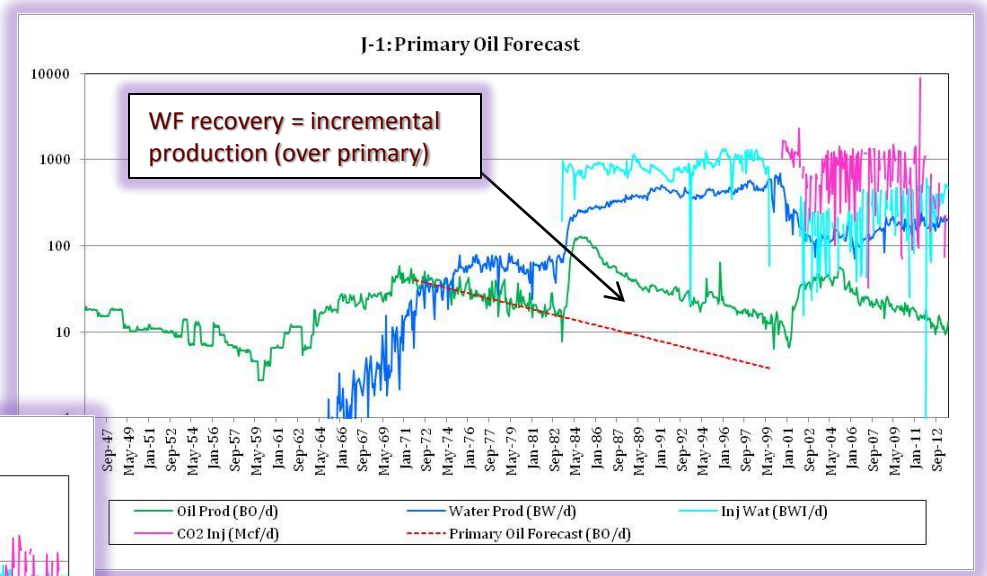
Improving Prediction of CO_2 Injection in Conventional Reservoirs

Methodology

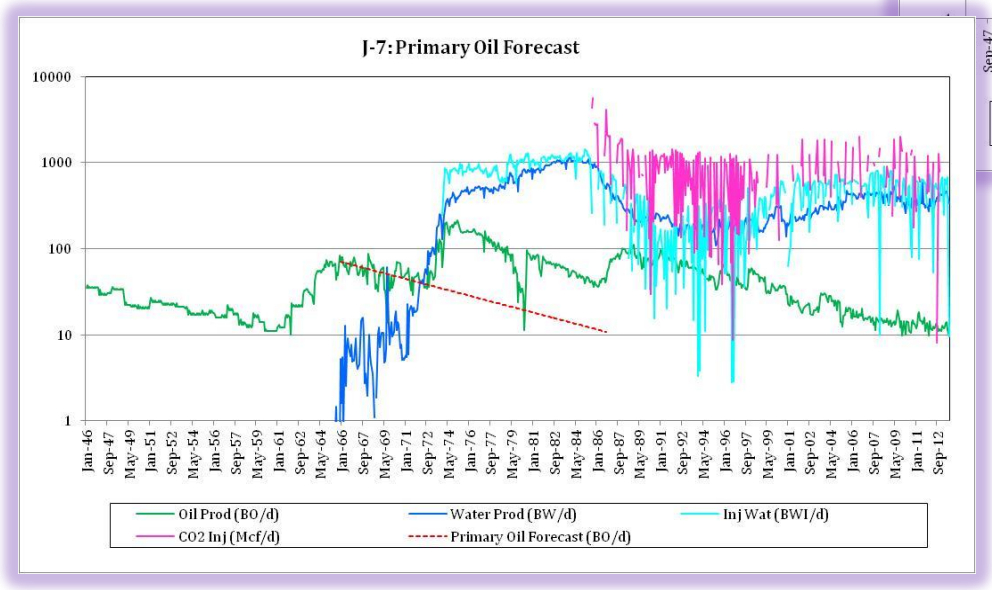
Evaluation of Water-Flood Recovery

- Cumulative dimensionless WF calculated for each pattern

$$DimRecovery(\%) = \frac{Oil\ (after\ WF\ start) - Primary\ Oil\ Fcst}{OOIP}$$

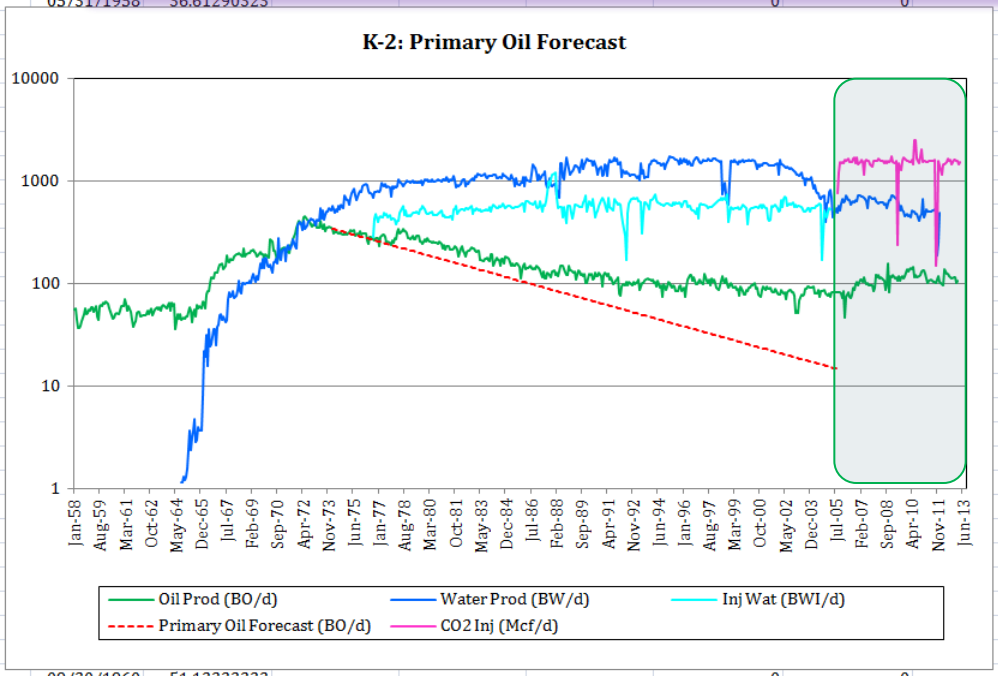


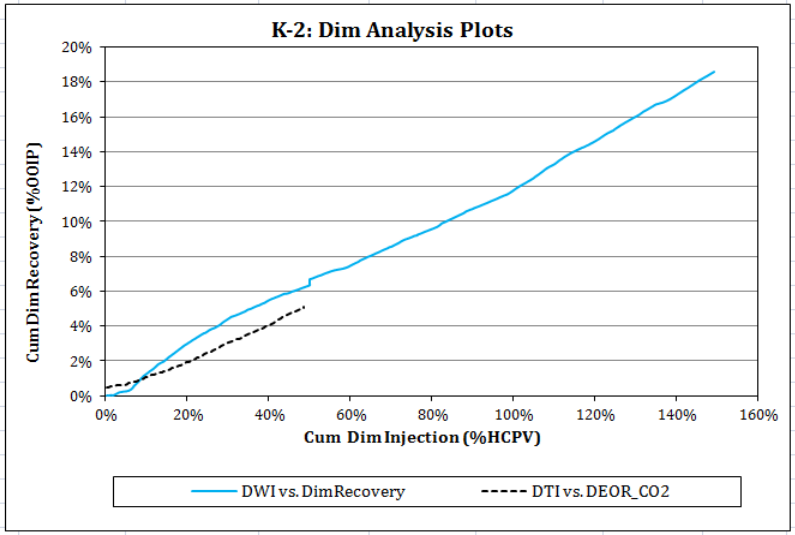
Primary Production DCA Sample: **Pattern J-1 (8.5%/yr)**



Primary Production DCA Sample: **Pattern J-7 (9%/yr)**

Anino Adokpaye 2013





Methodology

Dimensionless Recovery Curves – WF & CO_2 Comparisons

Input Cells =

Calc Data =

Selected Pattern: K-2

HCPV: 3,872,739

OOIP: 3,153,696

Begin Primary Fcst Date: 02/28/1974

Oil Prod @ Primary Decline Start Date: 340.6 BO/d

WF Start Date: 09/30/1976

Oil Prod @ WF Start Date: 265.9 BO/d

Primary Exp Decline Rate: 10.0% nominal (%)

Pattern Comments: Centre-pattern in K-Lease, supports 6 Producers, high GWR. Similar WF & CO2 recovery slopes

Return to Pattern List

PATTERN DATA - FROM OFM (ODS DATABASE)										CALCULATED DATA - WF Recovery			
Date	Oil Prod (BO/d)	Water Prod (BW/d)	Inj Wat (BWI/d)	CO2 Inj (Mcf/d)	Dim_DCI	Dim_DTI	Dim_DEOR	DIM_DCP	DIM_DWI_WF	Primary Oil Forecast (BO/d)	WF Recovery (BO/d)	Cum WF Recovery (STB)*	Cum DimRec (% OOIP)
01/31/1958	54.67741935				0	0		0.0000	0.00000000	0.0	0.0	0	0.0000
02/28/1958	56.67857143				0	0		0.0000	0.00000000	0.0	0.0	0	0.0000
03/31									0.00000000	0.0	0.0	0	0.0000
04/30									0.00000000	0.0	0.0	0	0.0000
05/31/1958	36.61290323				0	0		0.0000	0.00000000	0.0	0.0	0	0.0000
								0.0000	0.00000000	0.0	0.0	0	0.0000
								0.0000	0.00000000	0.0	0.0	0	0.0000
								0.0000	0.00000000	0.0	0.0	0	0.0000
								0.0000	0.00000000	0.0	0.0	0	0.0000
								0.0000	0.00000000	0.0	0.0	0	0.0000
09/30/1960	51.13333333				0	0		0.0000	0.00000000	0.0	0.0	0	0.0000
10/31/1960	49.70967742				0	0		0.0000	0.00000000	0.0	0.0	0	0.0000

While a pattern is under the initial pure CO_2 slug (prior to WAG), DTI = DCI

K-2: Primary Oil Forecast

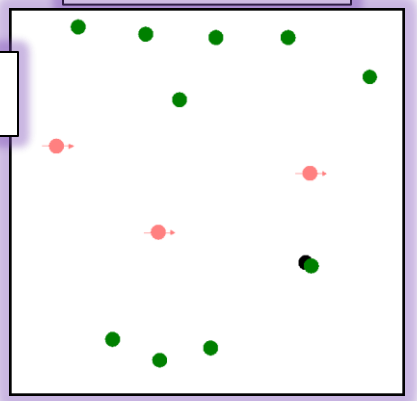
K-2: Dim Analysis Plots

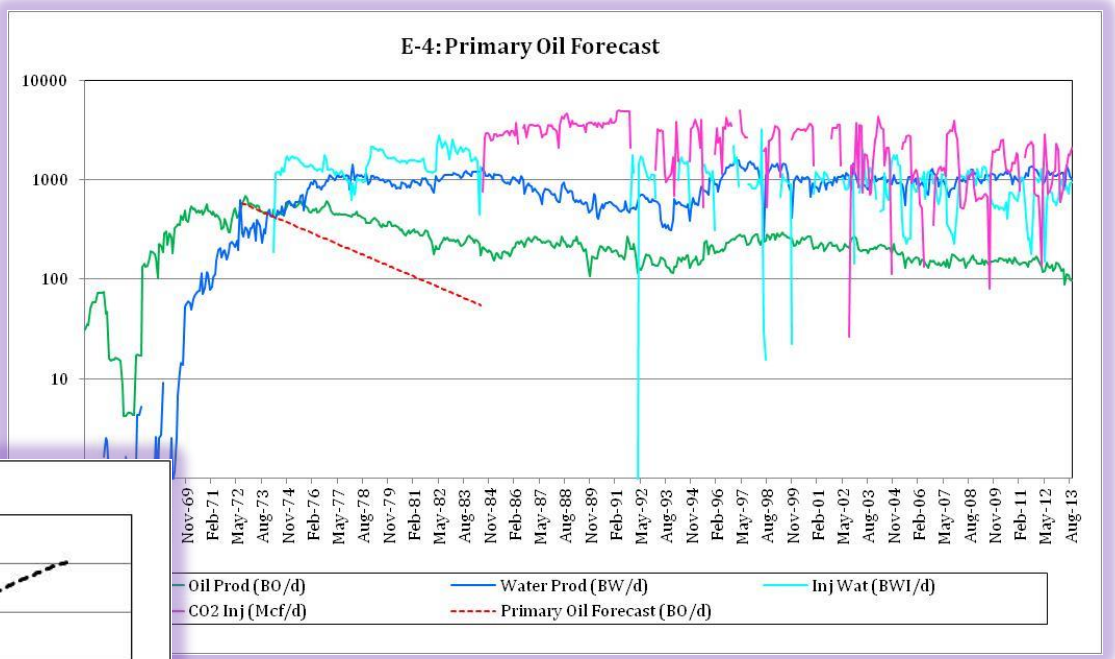
Results & Observations

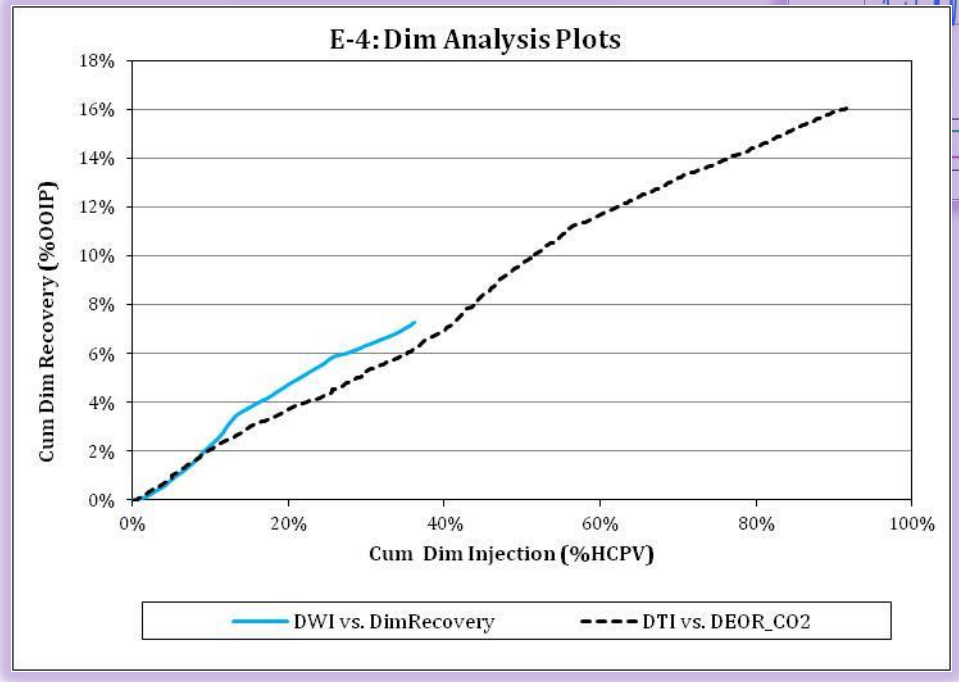
Strong WF & CO_2 Correlations

PATTERN E-4

Multiple (3) injector pattern



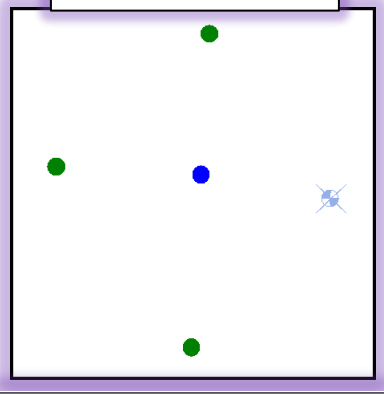


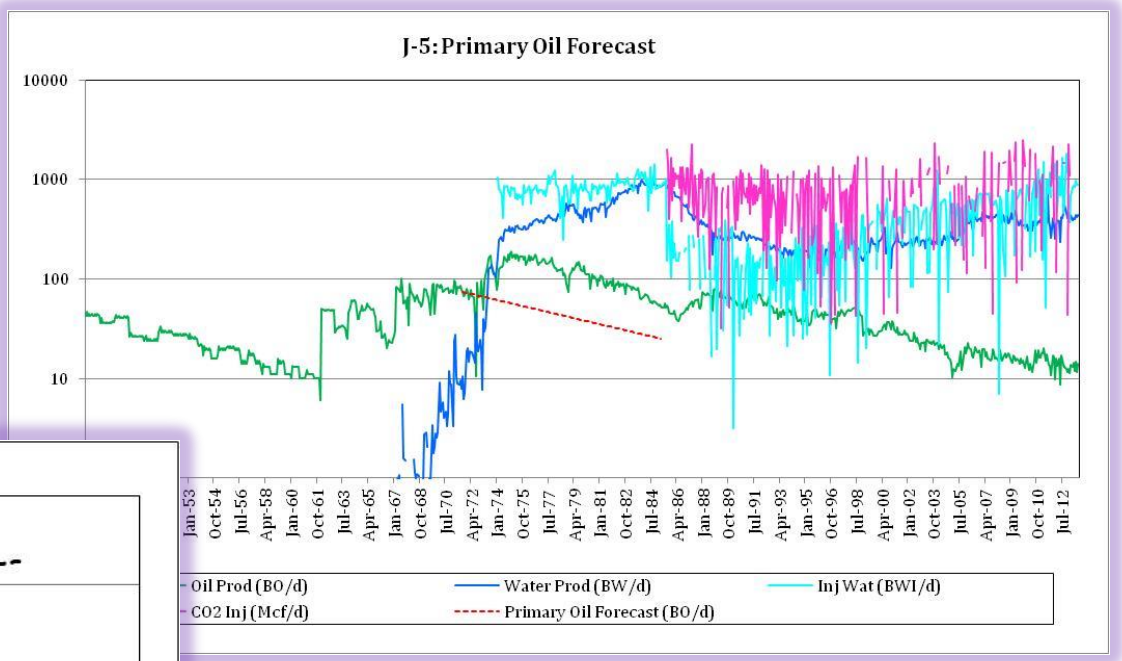


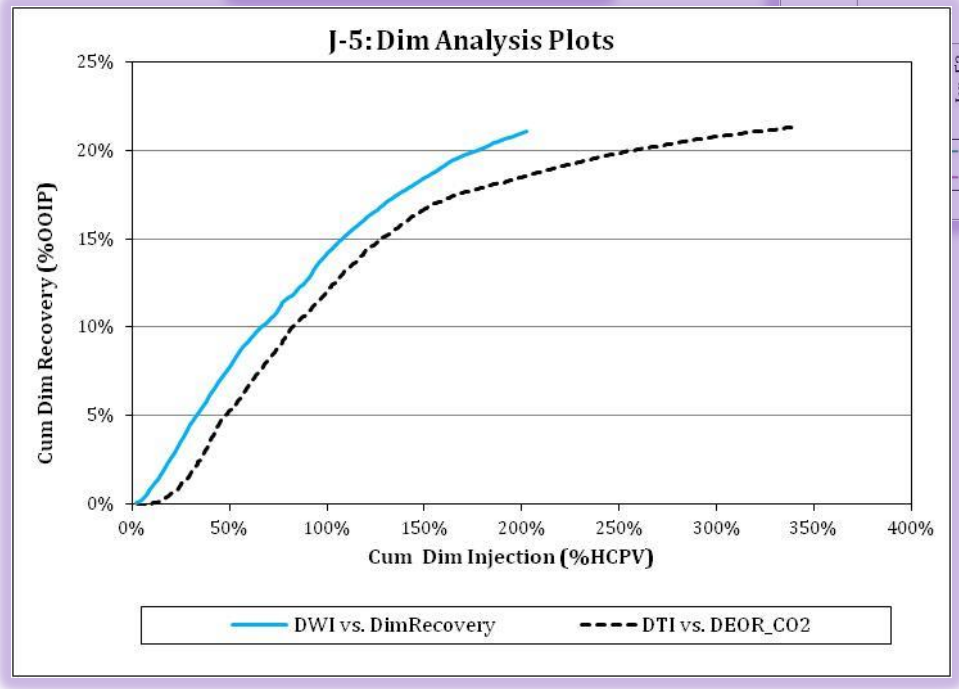
Initial overlay (perfect correlation) of WF & CO_2 recovery - diverge at ≈10% dim injection.
Short-lived waterflood (only 36% DWI-WF) - although, enough to trend for comparison

Results & Observations

Strong WF & CO_2 Correlations







WF & CO_2 recovery curves remain parallel through 200% dimensionless injection!

Curves tend to diverge at ≈20% DEOR

Conclusions

- **Results from dimensionless analysis of well-established vintage water and CO_2 injection patterns show the usefulness of dimensionless water-flood curves as a basis for prediction of performance under CO_2 injection**

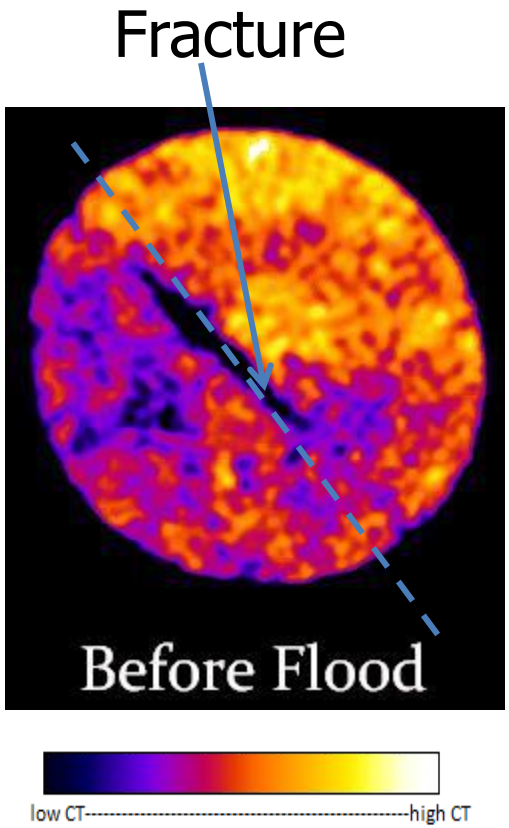
TEXAS A&M UNIVERSITY

Surfactant Studies in ULR

CO_2 Injection in Conventional and Unconventional Liquid Reservoirs

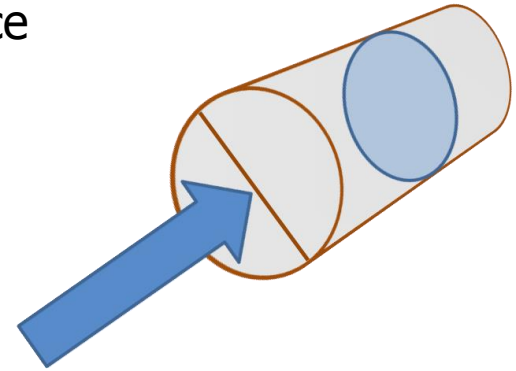
Department of Petroleum Engineering
Texas A&M University
Dr. David Schechter

Barnett Shale



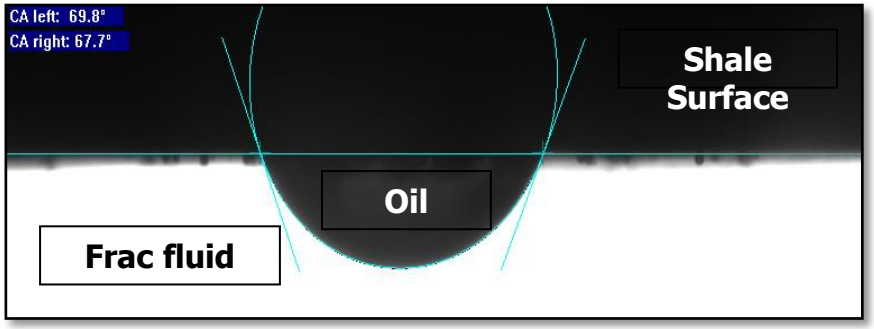
The penetration of anionic surfactant in this particular siliceous shale core is shown in this sequence of fluid in seven cross sectional views of the core before flooding, 0 hours, 30 minutes, 1 hour, 2 hours, 4 hours and 20 hours after flooding.

This slice is one of the 18 slices used to create the horizontal view in the previous slice

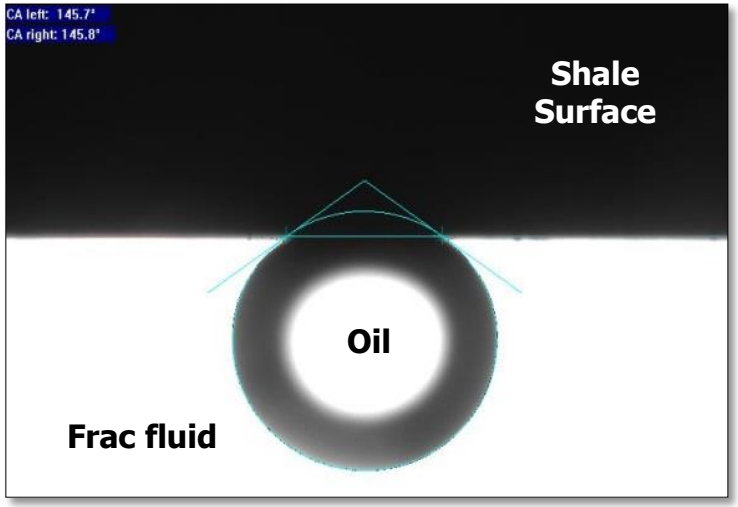


Changing Contact Angles

Frac Water w/o surfactant: 110°

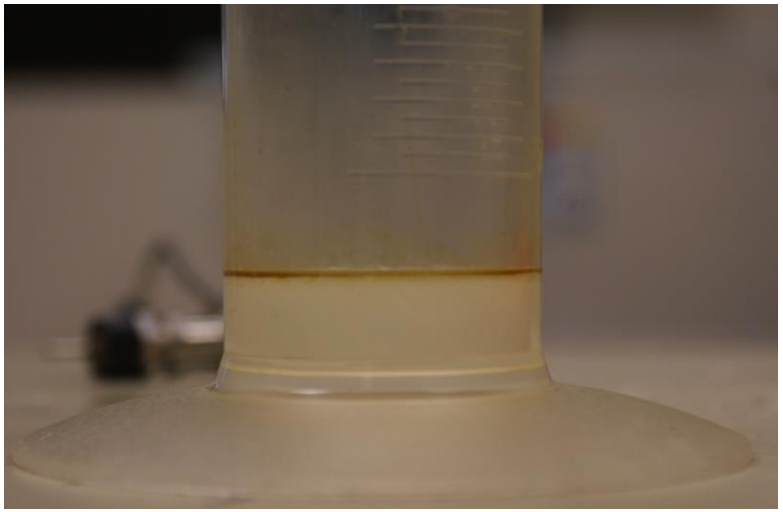


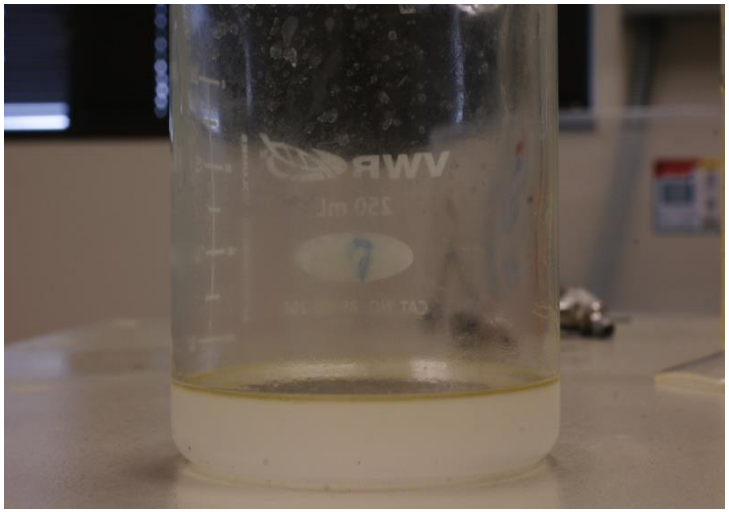
Frac Water with



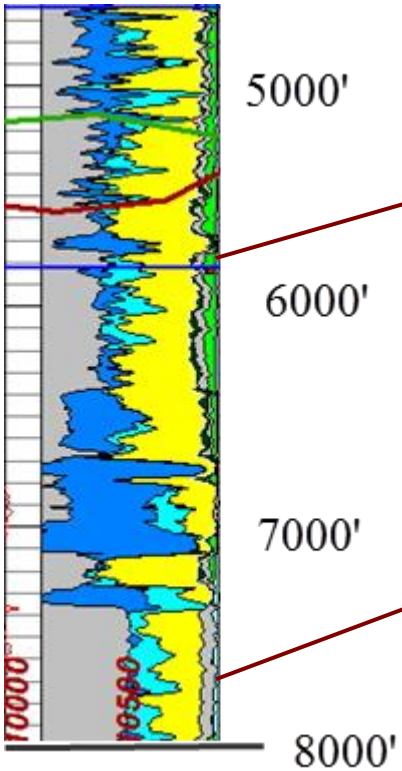
Barnett Shale

- Anionic surfactant
  - Superior penetration magnitude
  - Better matrix penetration – spontaneous imbibition
  - Best oil recovery
  - Low ‘contact angle’ with oil-saturated shale surface

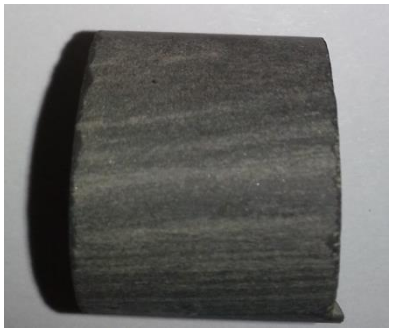


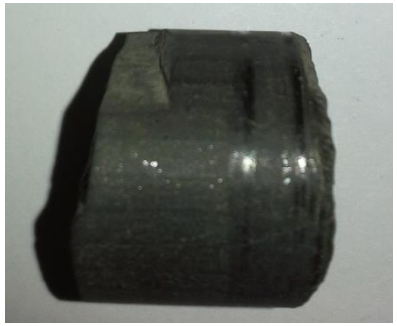


Barnett Shale



Grey - clay
Blue - carbonate
Yellow - silica

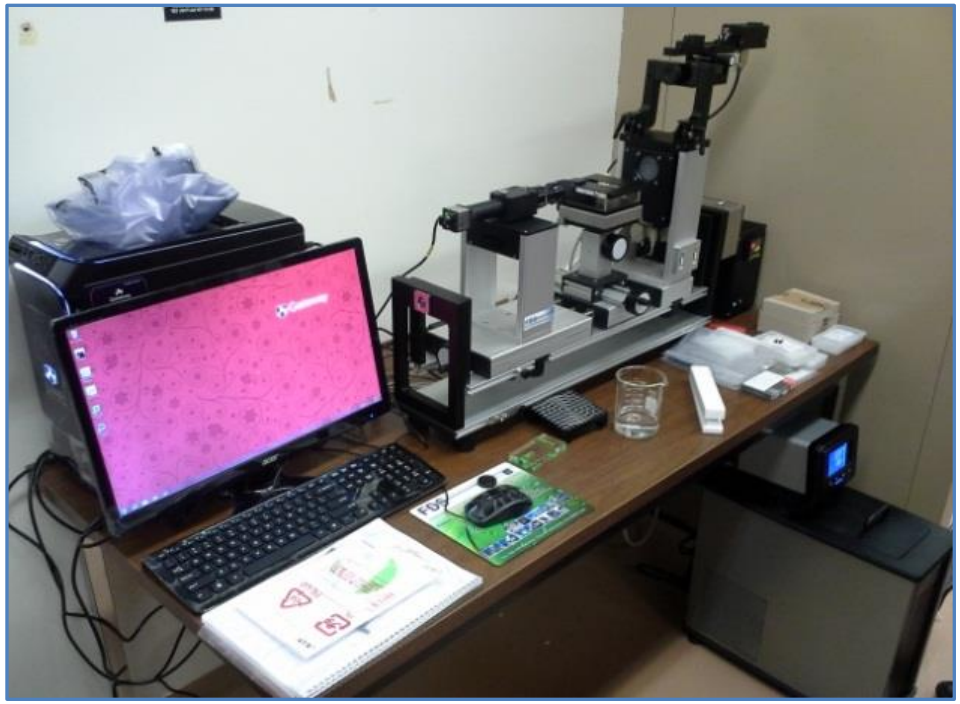




8700′

Contact Angle & IFT Measuring Capabilities

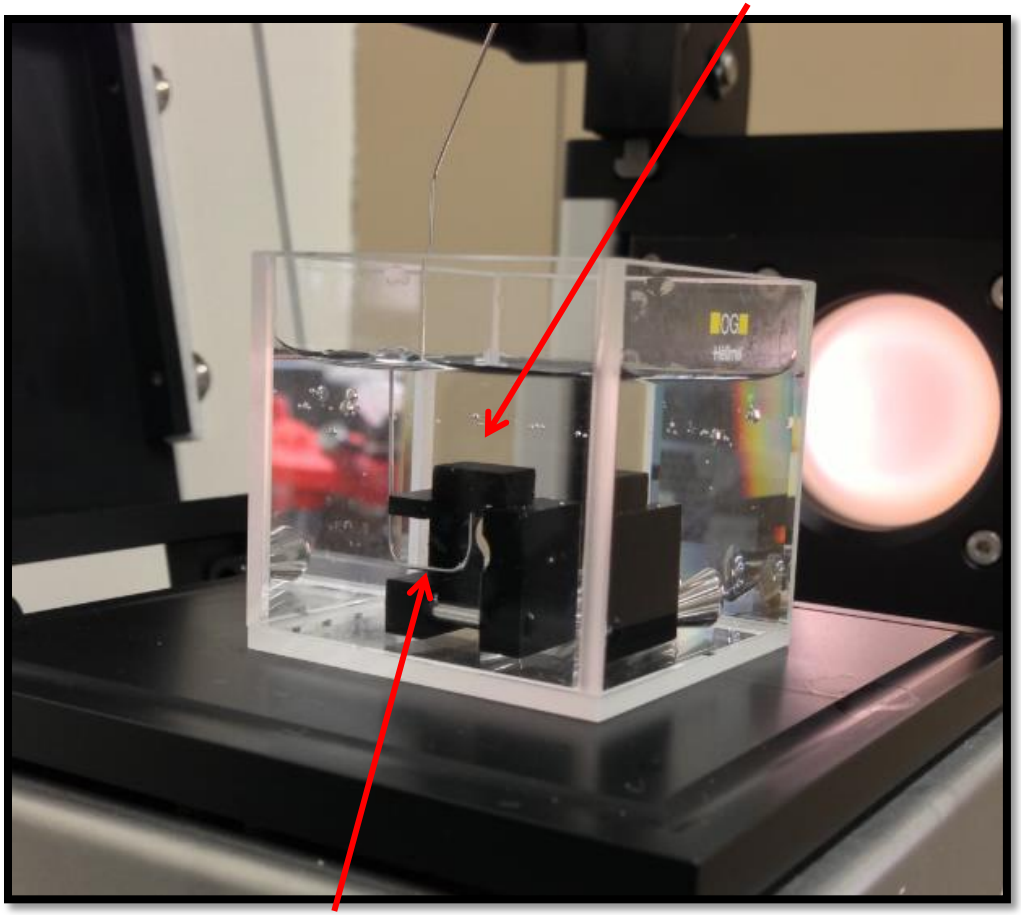
- Static and dynamic contact angles
- Surface and interfacial tension
- Surface free energy of solids and their components
- Temperature control unit to maintain reservoir temperature



Dataphysics OCA 15 Pro

Experiment Design- Contact Angle

Shale sample



Capillary Needle

Captive bubble method