Department of Physics and Technology

CO_2 Foam EOR Field Pilots

East Seminole and Ft. Stockton

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Tore Føyen, Martin Fernø, and Arne Graue

CO_2 for EOR as CCUS Conference
Houston, Texas
October 4, 2017

University of Stavanger

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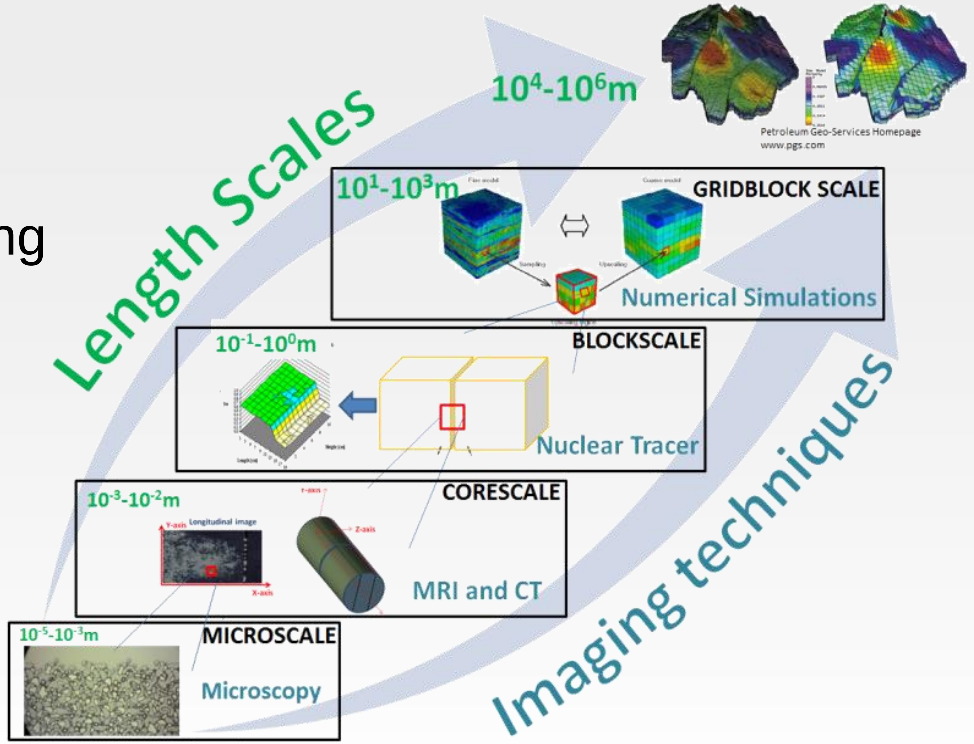
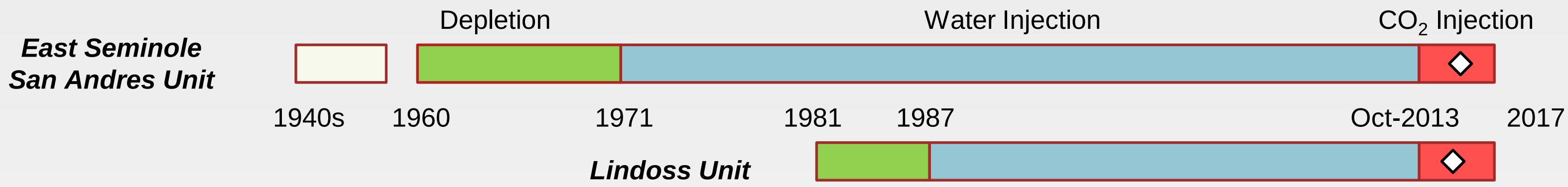
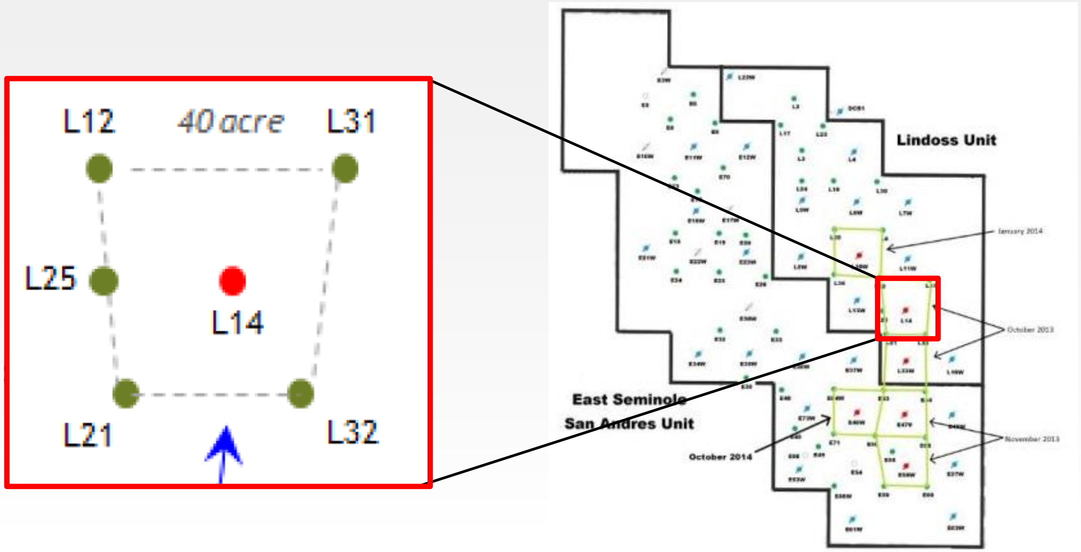


East Seminole Field

Development History





Reservoir Characteristic	Value
Depth	5200 ft
Permeability	1 – 300 mD Ave. 13 mD
Porosity	3 – 28 % Ave. 12- 15 %
Pay Thickness	110 ft
Reservoir Pressure	2500 psia
Temperature	105°F
Oil Gravity	31° API
Initial Oil Saturation	0.65
Initial Water Saturation	0.35
Oil viscosity (reservoir condition)	1.20 cP
Bubble Point Pressure	1805 psia
Formation Brine Salinity	70,000 ppm
S_{orw}	0.40 (Gray, 1989)
ROZ S_{orw}	0.25 (Honarpour et al. 2010)
ROZ ROS, waterflood	0.32 (Honarpour et al. 2010)
ROZ S_{orm}	0.12 (Honarpour et al. 2010)

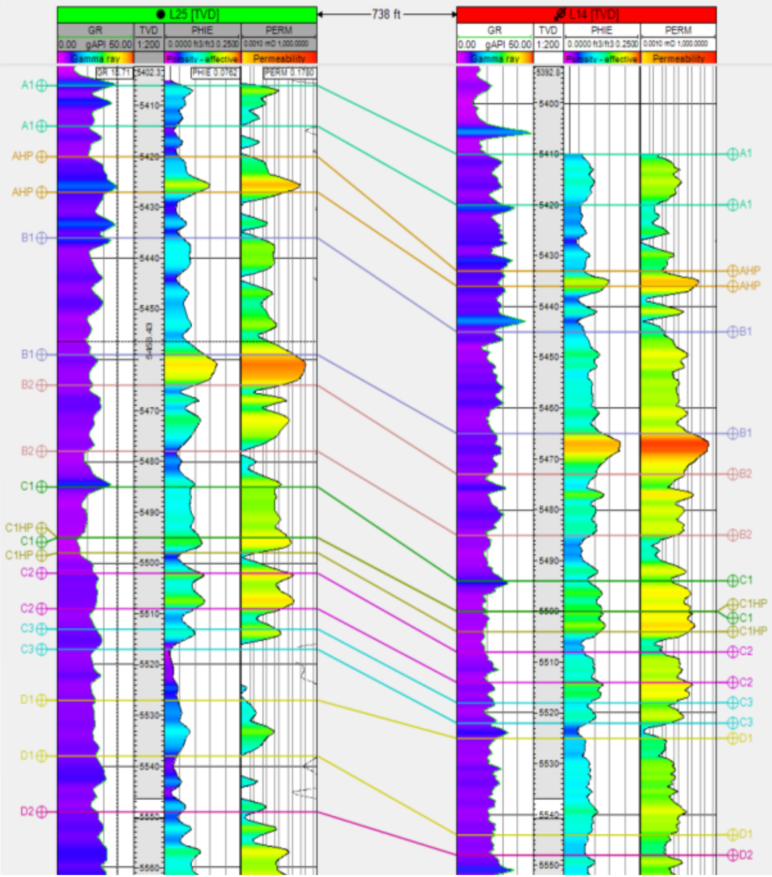
Geologic Modeling

Objectives

- Establish reservoir structure and framework
- Integrate petrophysical data with base geologic model
- **Develop a model with sufficient layering to represent the vertical and lateral heterogeneity at well and interwell distances without limiting flow simulation studies.**

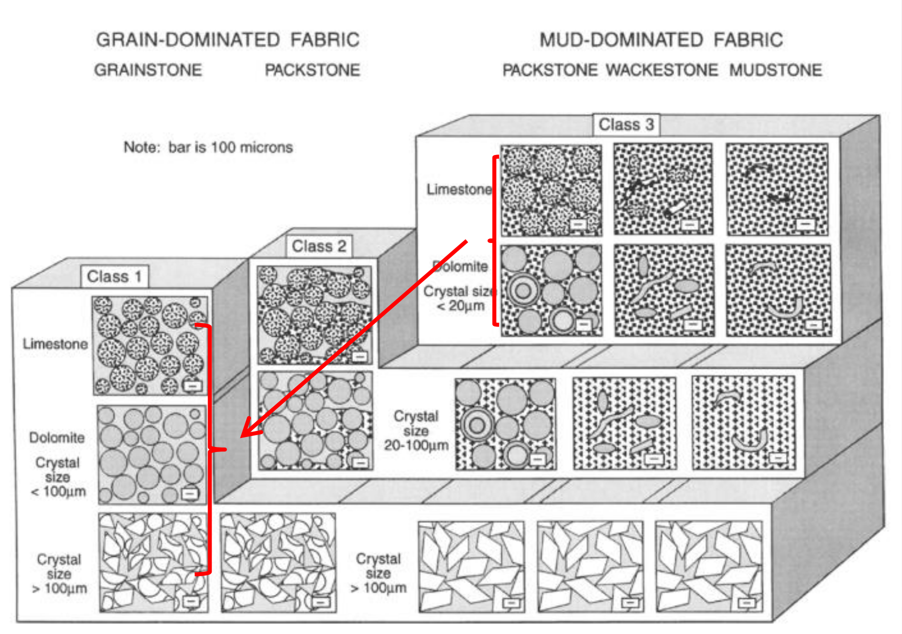
Available Data

- Petrophysical well logs
- RCA, Plug data (Lindoss #31, ESSAU #70)
  - Dean Stark, directional K, porosity, So, Sw, GD
- Production data
- Injection profiles
- Core photos



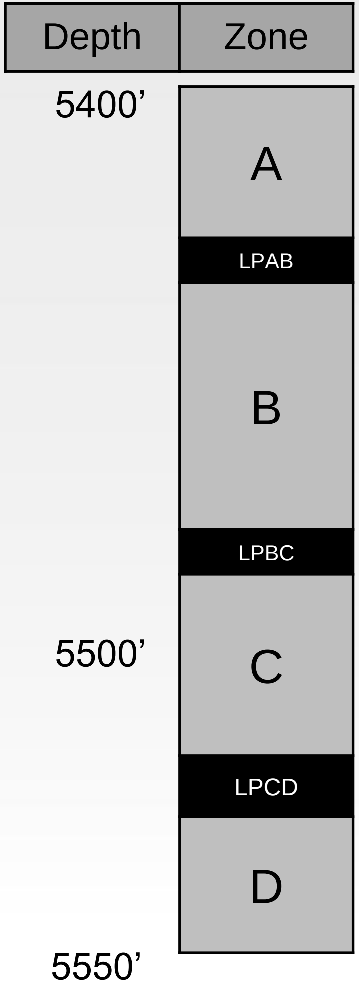
Geologic Framework

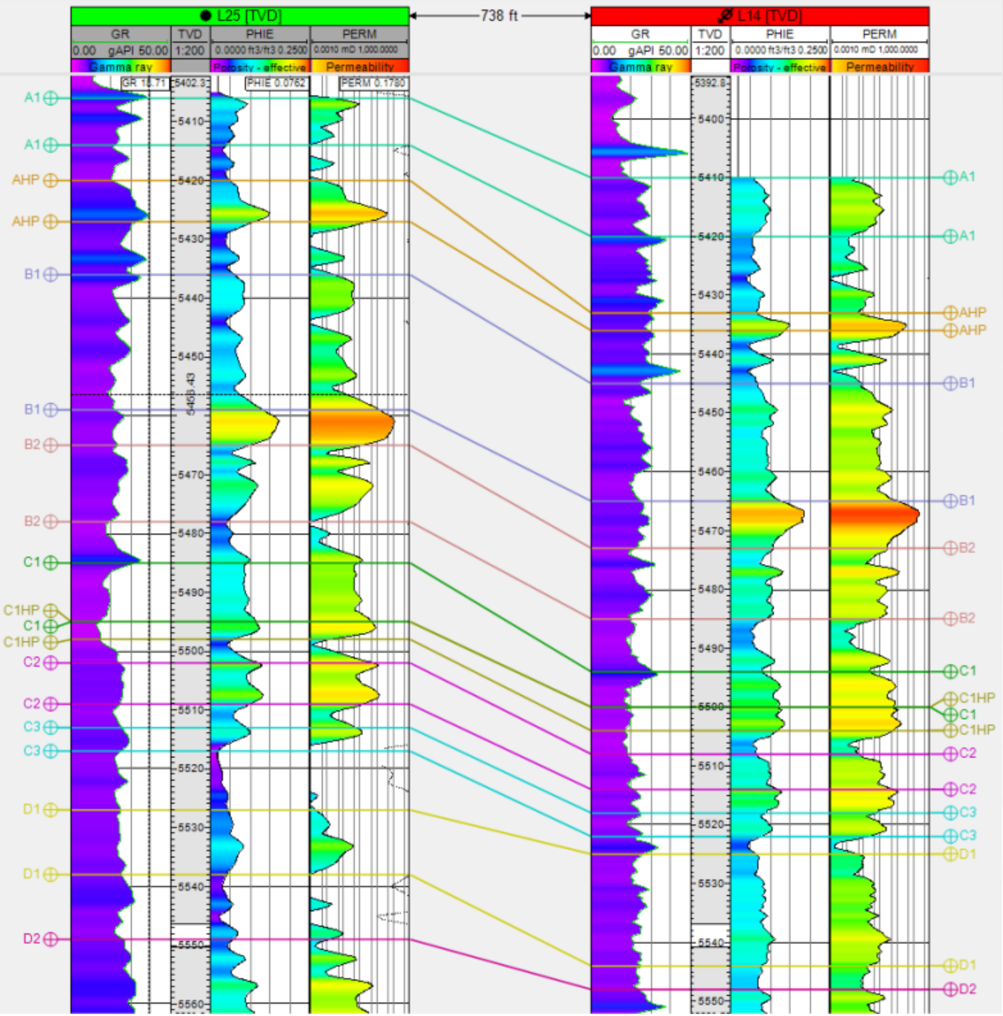
- Carbonate Ramp
  - cyclicity: critical scales
- HFCs are composed of systematically stacked rock fabrics
- Basal mudstones grade upward into grain dominated packstones and grainstones
- Shallowing upward sequences

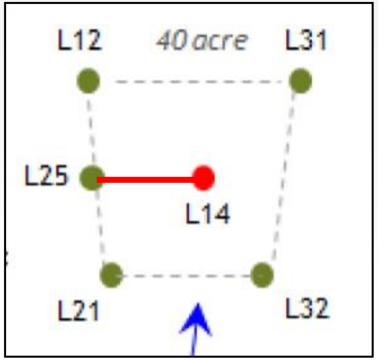


Modified from Lucia, 1995

EAST SEMINOLE

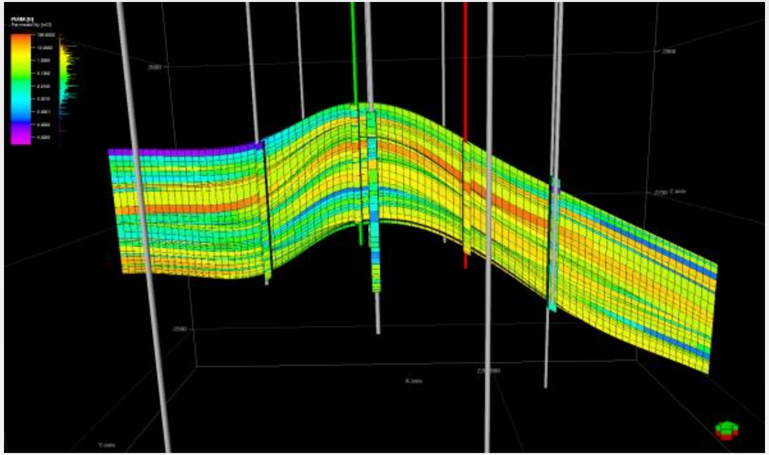

Depth
Zone
5400’
A
LPAB
B
LPBC
5500’
C
LPCD
D
5550’

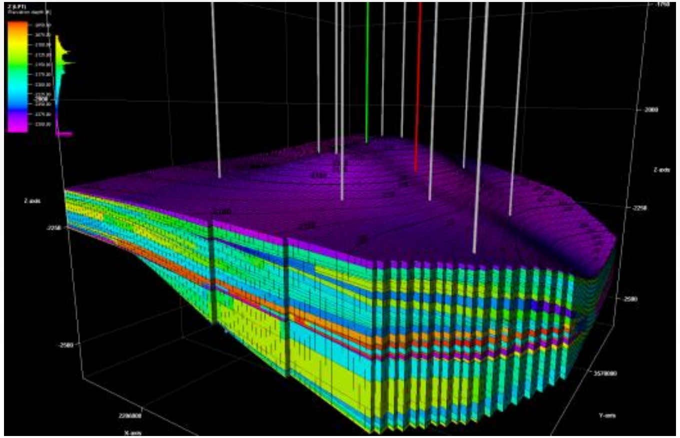

L25 [TVD]
738 ft
L14 [TVD]
GR
TVD
PHIE
PERM
0.00 gAPI 50.00
1:200
0.0000 ft3/ft3 0.2500
0.0010 mD 1,000.0000
Gamma ray
Porosity - effective
Permeability
A1
AHP
B1
B2
C1
C1HP
C2
C3
D1
D2


L12
40 acre
L31
L25
L14
L21
L32

Reservoir Modeling

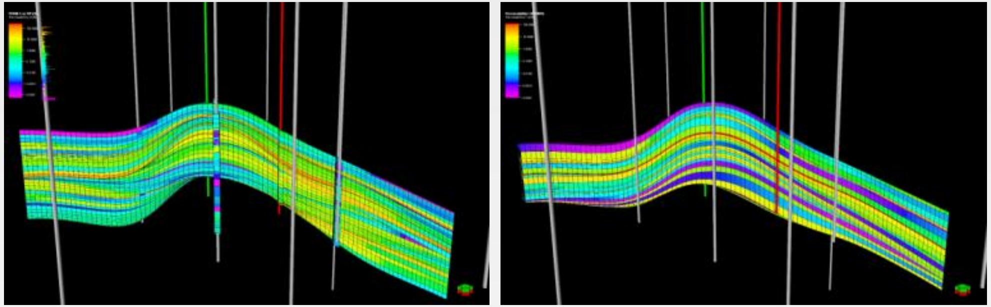
- Condition petrophysical properties to HFC/flow zones
- HFCs mapped as tops
- Upscaled well logs
- Stochastic simulation with stratigraphic constraints





Layering Updates

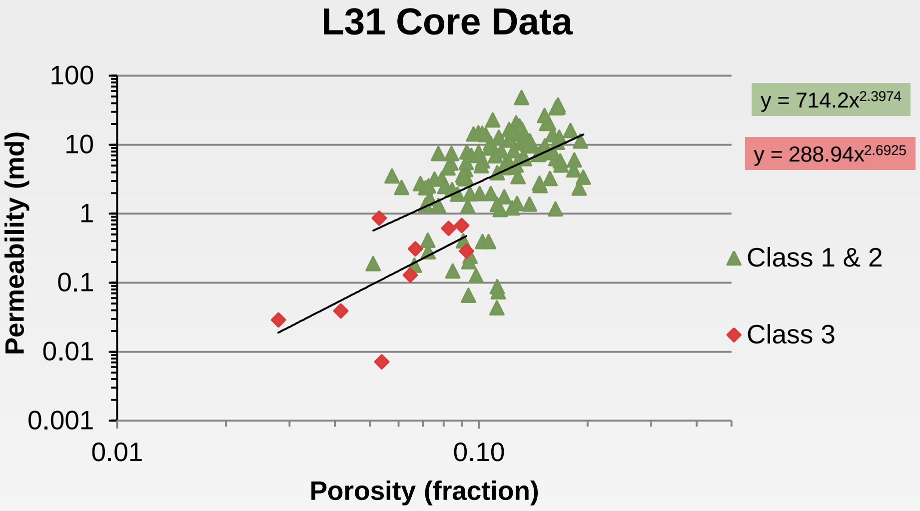
- Maintains cycle tops, no flow boundaries
- Respects porosity from well logs and production well Kh
- Layers merged
  - revised porosity/perm transform
  - reservoir zones/rock type
  - core Kvh

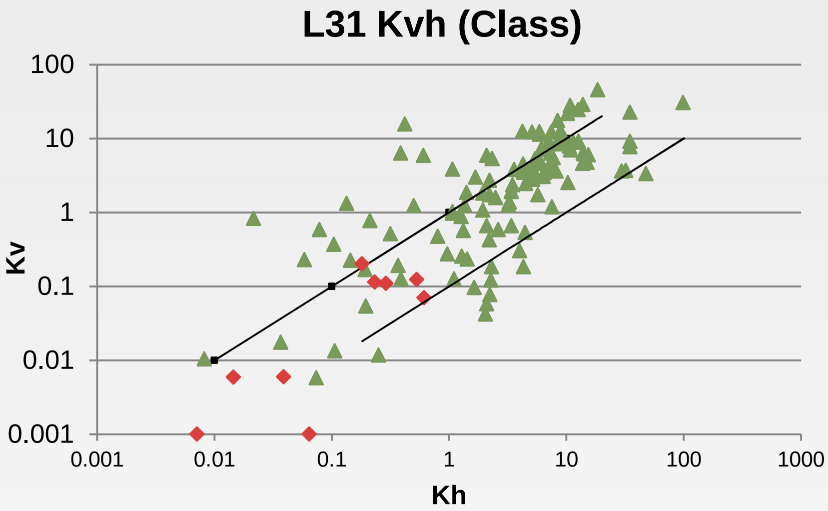


Cross section of initial model (left) with 57 layers in the Z-direction, compared to updated model with 28 layers (right).

Parameter	Initial Model	Updated Model
Layers (z-direction)	57	28
Dimensions (x, y, z)	89 x 96 x 57	89 x 96 x 28
Cell Thickness	0.5-44 ft (4 ft avg)	2-31 ft (6 ft avg)
Cell size (ft)	50 x 50	50 x 50
Total Grid Areal Extent (acres)	371	371
Global Grid cells	487,008	239,232

Rock Fabric and Petrophysical Class



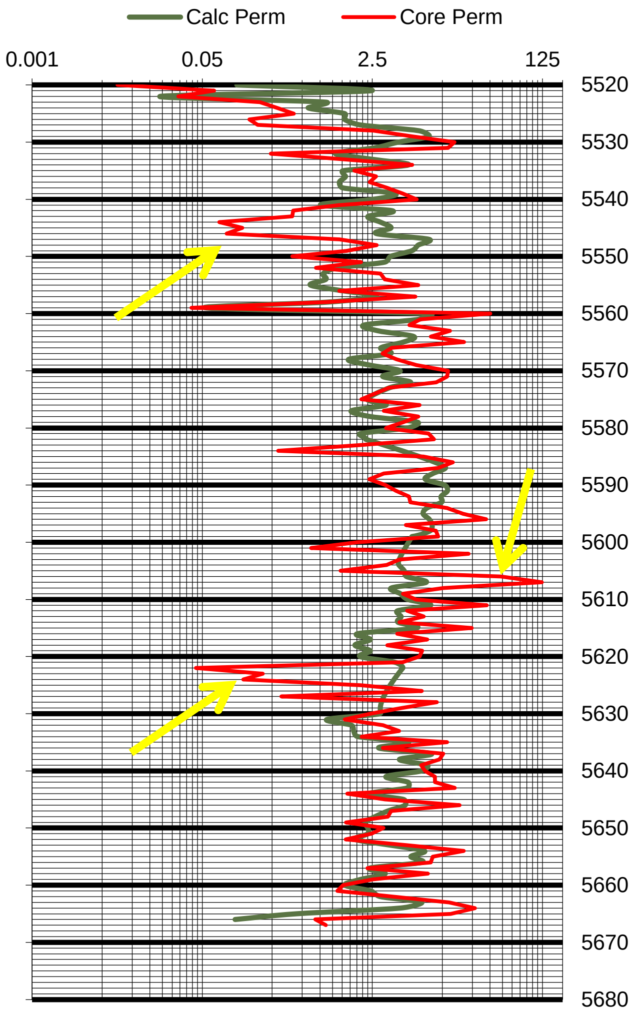


Class	Rock Fabric	Particle Size
1	Large crystalline dolostones and grainstones	>100μm
2	Grain dominated packstones; fine to medium crystalline grain dominated dolopackstones	20-100μm
3	Mud dominated dolostones and limestones	<20μm

Class 1 Avg	Class 2 Avg	Class 3 Avg
0,62	0,60	0,16

Lucia, 1995; Wang et al. 1998; Jennings and Lucia, 2003

Log Porosity
Lab Porosity
0
0,25



Calc Perm
Core Perm
0.001
0.05
2.5
125
5520
5530
5540
5550
5560
5570
5580
5590
5600
5610
5620
5630
5640
5650
5660
5670
5680

Enhanced Permeability Zones

- Input deterministically after initial global property realizations were generated.

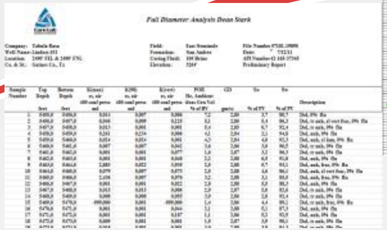
- Grain dominated facies of Petrophysical Class 1

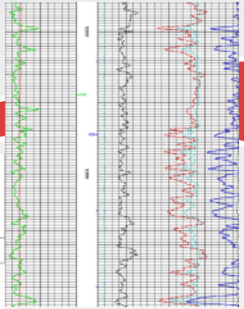
- Modeled as thin, continuous layers when sufficient permeability was calculated from wellbore data.

	Zone	Top	Bottom	High Perm Layer		Avg. Perm (md)	L14	L25	L31	L32	L12	L21
MPZ	A	2	5	4	AHP	22	✓	✓	✓	✓		✓
	B	7	13	8	B1HP	115	✓	✓	✓			
				10	B2HP	8	✓	✓				✓
	C	15	20	16	C1HP	14	✓	✓	✓	✓	✓	✓
ROZ				19	C2HP	13	✓	✓	✓	✓	✓	✓
	D	22	24	24	D2HP	5	✓	✓	✓	✓	✓	✓

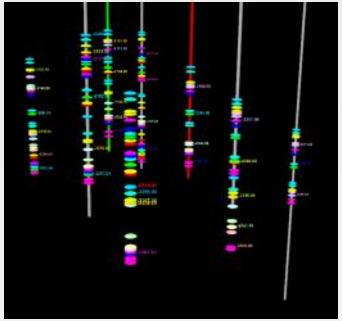
Modeling Workflow

Identify HFC/flow zones

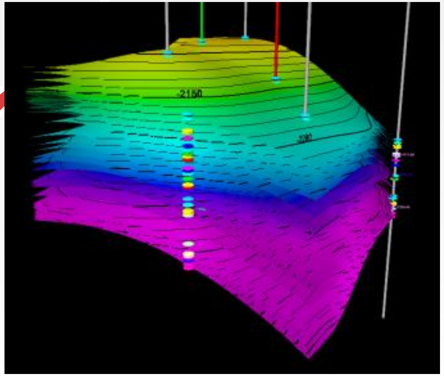


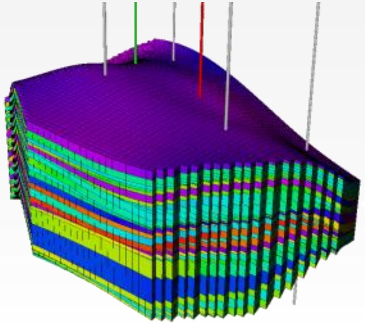


Formation Structure



Petrophysical props and geologic structure

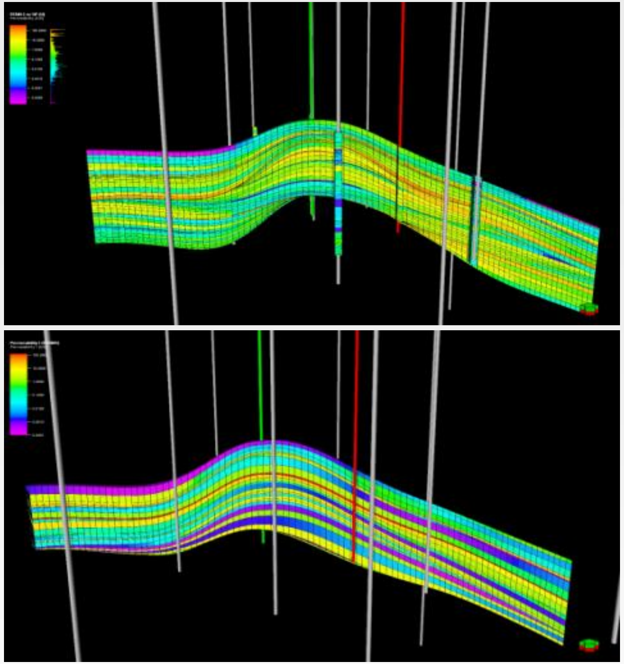




Model petrophysical props

Ongoing Work

- Update directional permeability values between injector and individual producers
- Sensitivity after HM for Kvh
- Local PV
- Updates from tracer test



Cross section of initial model (top) with 57 layers in the Z-direction, compared to updated model with 28 layers (bottom). Layers were merged based upon petrophysical class and reservoir quality within each zone.

Laboratory Work

Foam Quality and Rate Scans

CO_2 Foam EOR

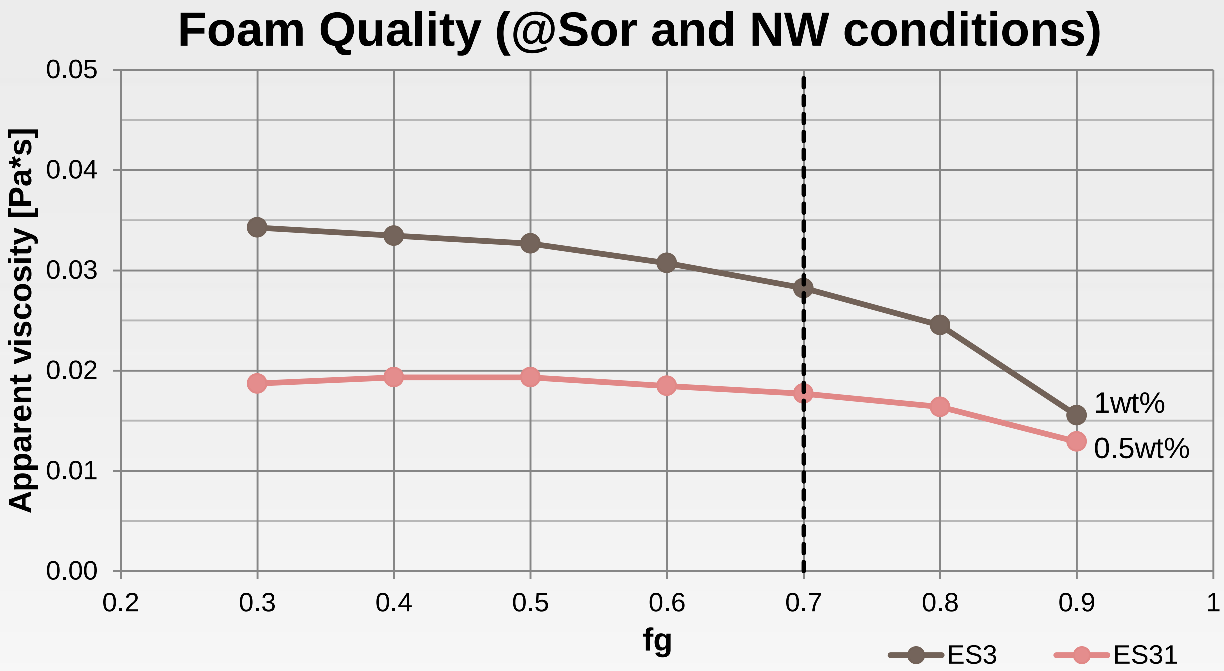
Foam Quality/Rate Scans

Objectives

- Determine optimal fg and parameters for tuning of foam model.
  - run foam quality scans at 1ft/day for various fg (0.3 to 1.0)
- Measure foam strength at different flood rates at optimal fg.

Materials and Conditions

- 100% brine saturated East Seminole core
- 40°C and 172bar (near the hydrostatic pressure ~2500psi)



Core ID	Porosity [ϕ]	Permeability [mD]	Length [cm]	PV [ml]	Surf Conc. [wt %]
ES_31	0.15	15	5.6	15.2	0.5
ES_3	0.17	11	5.9	18.7	1.0

Gas fraction of 0.7 is recommended for field testing based upon the highest apparent viscosity at economically feasible fg (most CO_2, low surfactant fraction)

CO_2 Foam EOR Corefloods

Optimal f_g and injection rate

Objectives

- Determine optimal surfactant concentration for field implementation
- Investigate sensitivities on CO_2 foam performance

Core and Fluid Properties

- ES reservoir crude oil and Permian Basin brine
- Nonionic surfactant (Huntsman L24-22): 0.5 wt% and 1 wt% surfactant solution

Core ID	Porosity [ϕ]	Permeability [mD]	Length [cm]	PV [ml]	Surf Conc. [wt %]	Pressure (bar)
ES_27	0.14	27	5.7	15	0.5	171
ES_31	0.15	15	5.6	15.2	0.5	171
ES_23	0.11	8	5.4	9.4	1.0	176
ES_30	0.11	32	5.7	11.9	1.0	174

Experimental Procedure

- 42^oC and 2500 psi (~172 bar)

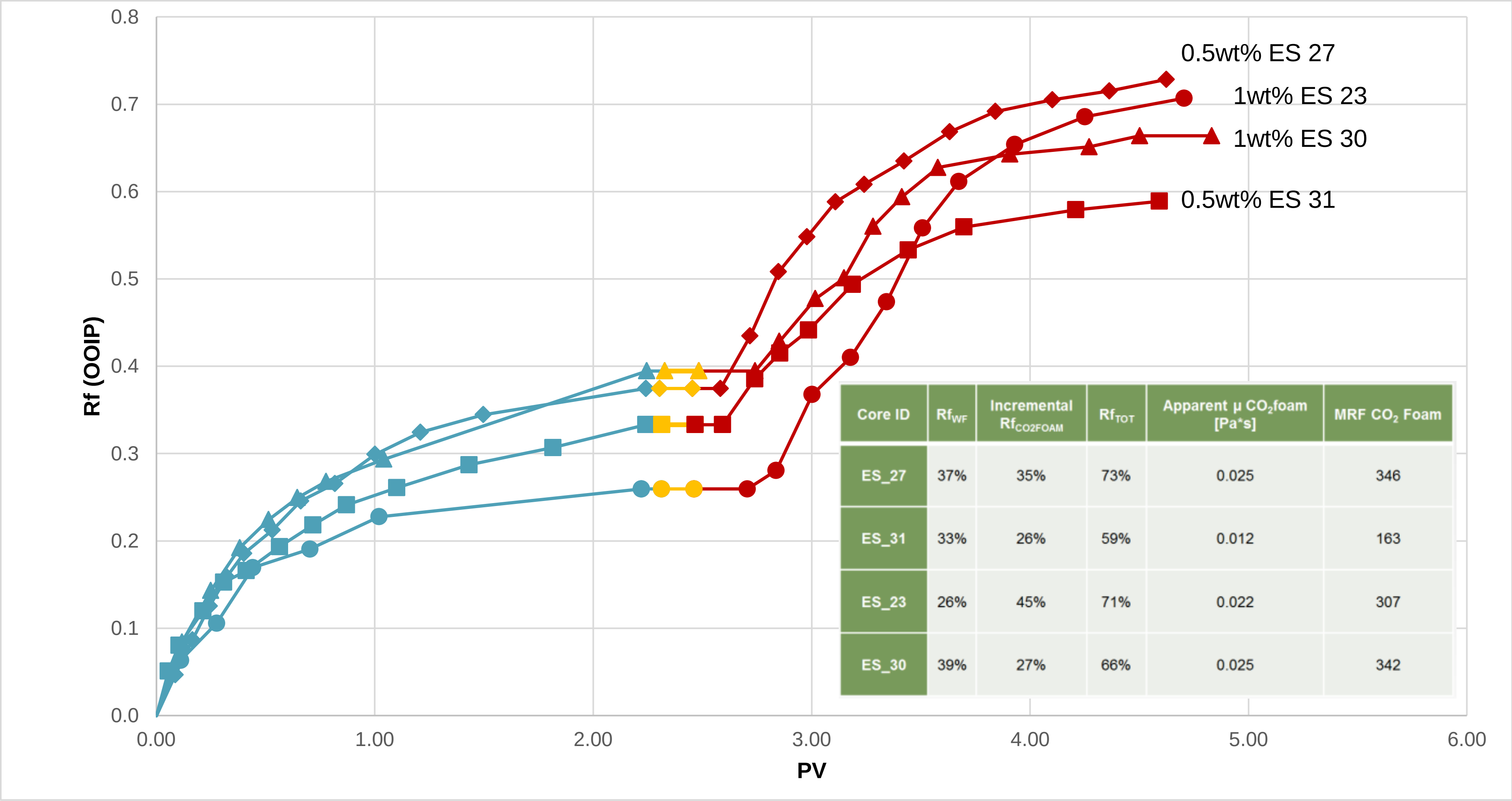
- **Aged and oil saturated core**

- **Secondary waterflooding** at superficial velocity of 1 ft/day (~23ml/h).

- **Surfactant pre-flush** (0.15PV) at superficial velocity of 1 ft/day (~23ml/h).

- **Tertiary CO_2 foam injection**, co-injecting surfactant solution and CO_2 gas at a foam quality of 70%.

    - The total rate during co-injection was kept equal to waterflooding (i.e. 16ml/h CO_2 and 7ml/h surfactant solution)



Core ID	Rf_{WF}	Incremental $Rf_{CO2FOAM}$	Rf_{TOT}	Apparent μ CO_2foam [Pa*s]	MRF CO_2 Foam
ES_27	37%	35%	73%	0.025	346
ES_31	33%	26%	59%	0.012	163
ES_23	26%	45%	71%	0.022	307
ES_30	39%	27%	66%	0.025	342

Conclusions

- Negligible difference in overall Rf and MRF between 0.5wt% and 1wt% surfactant solution
- Does not justify the use a more expensive 1wt% surfactant solution
- Recommend 0.5wt% surfactant solution for field testing

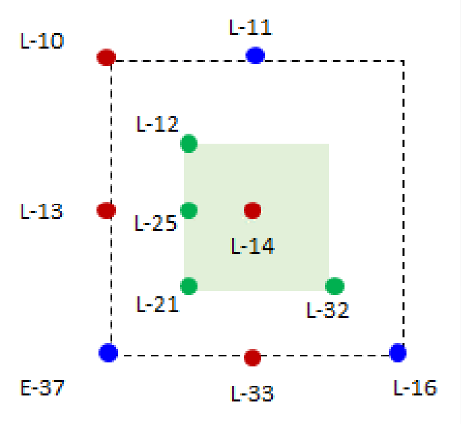
Core ID	Surfactant Conc.	Rf_{WF}	Incremental $Rf_{CO2FOAM}$	Rf_{TOT}	Apparent μ CO_2foam [Pa*s]	MRF CO_2 Foam
ES_27	0.5	37%	35%	73%	0.025	346
ES_31	0.5	33%	26%	59%	0.012	163
ES_23	1.0	26%	45%	71%	0.022	307
ES_30	1.0	39%	27%	66%	0.025	342

Data Collection Program and Pilot Monitoring

Data Collection Program

Objectives:

- Establish interwell connectivity (L14/L25, L13/L25) and allocate produced CO_2
- Demonstrate creation of stable foam in reservoir
- Monitor the propagation of CO_2, water, and surfactant
- Reduce the producing GOR of L25 while maintaining injectivity
- Increase oil production and improve sweep efficiency



Baseline and Pilot Monitoring

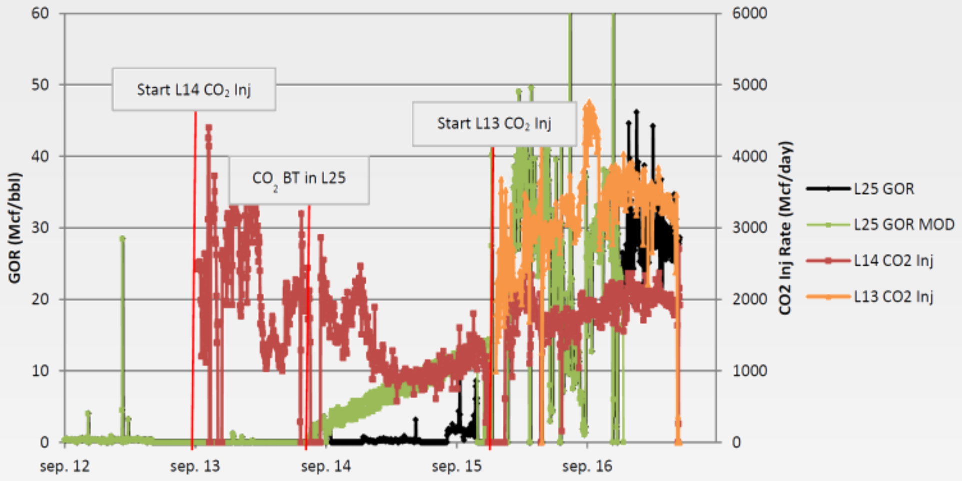
- **Interwell Connectivity**
- Reservoir Characterization and Fluid Monitoring
- Recovery and Production Monitoring
- Injection Profiling
- Corrosion

Stage	**Pre SAG (baseline)**	**Pilot Phase (3 SAG cycles)**						**Post SAG**
Slug	Ongoing CO_2 Injection	Surfactant	CO_2	Surfactant	CO_2	Surfactant	CO_2	
Tracers	CO_2 (L14 & L13)	Water	CO_2					
Injection Profiles (L14)	✓		✓					✓
Fall off test	✓		✓					✓
Crosswell Seismic (L14/L25)	✓							✓

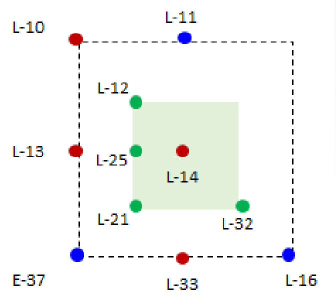
Characterizing Interwell Connectivity - Tracers

- Describe baseline interwell connectivity and sweep efficiency between L13/25 and L14/L25
  - two separate nonradioactive tracers

- Different tracers will be injected during the first cycle of SAG in the CO_2 and water phase

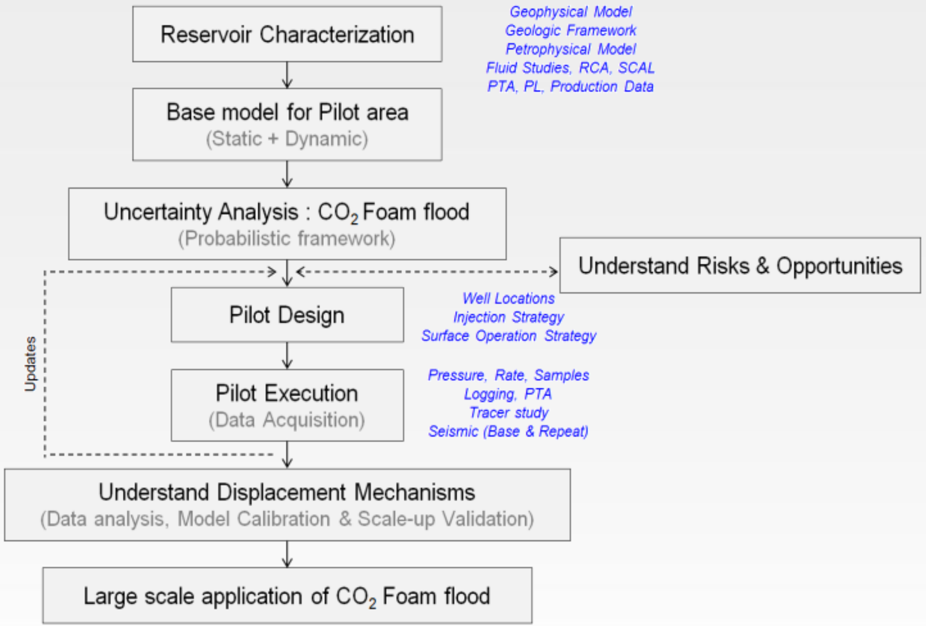


Plot of historical CO_2 injection for Lindoss 14 and 13 and producing GOR for Lindoss 25. Recorded GOR (black curve) is plotted along with linearly extrapolated GOR (green curve) after BT.



Way Forward

- Baseline data gathering and modeling updates
- Laboratory Work
  - CO_2/brine rel perm analysis
  - Foam rate scan analysis
  - EOR sensitivities
- Foam simulation cases
- SAG schedule



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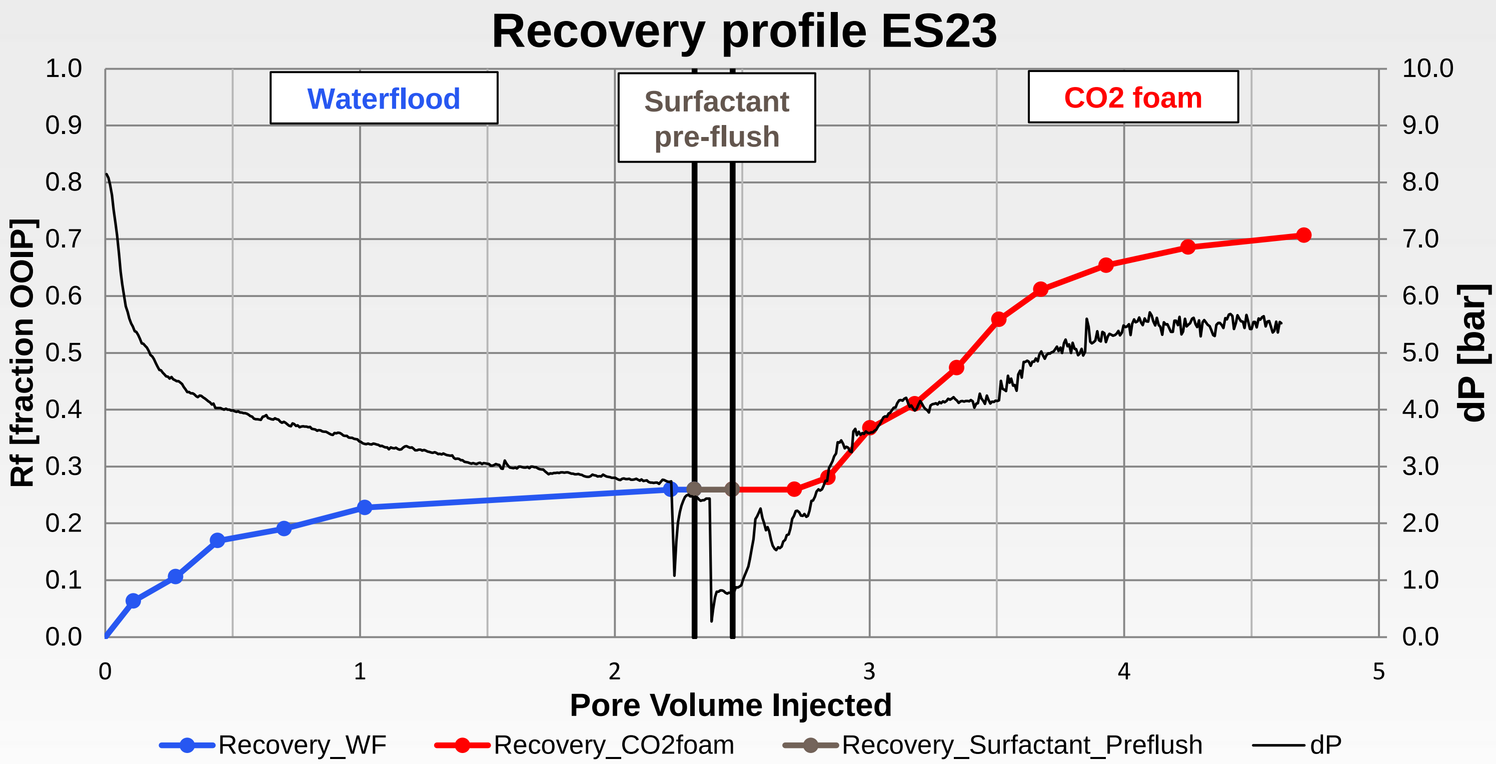
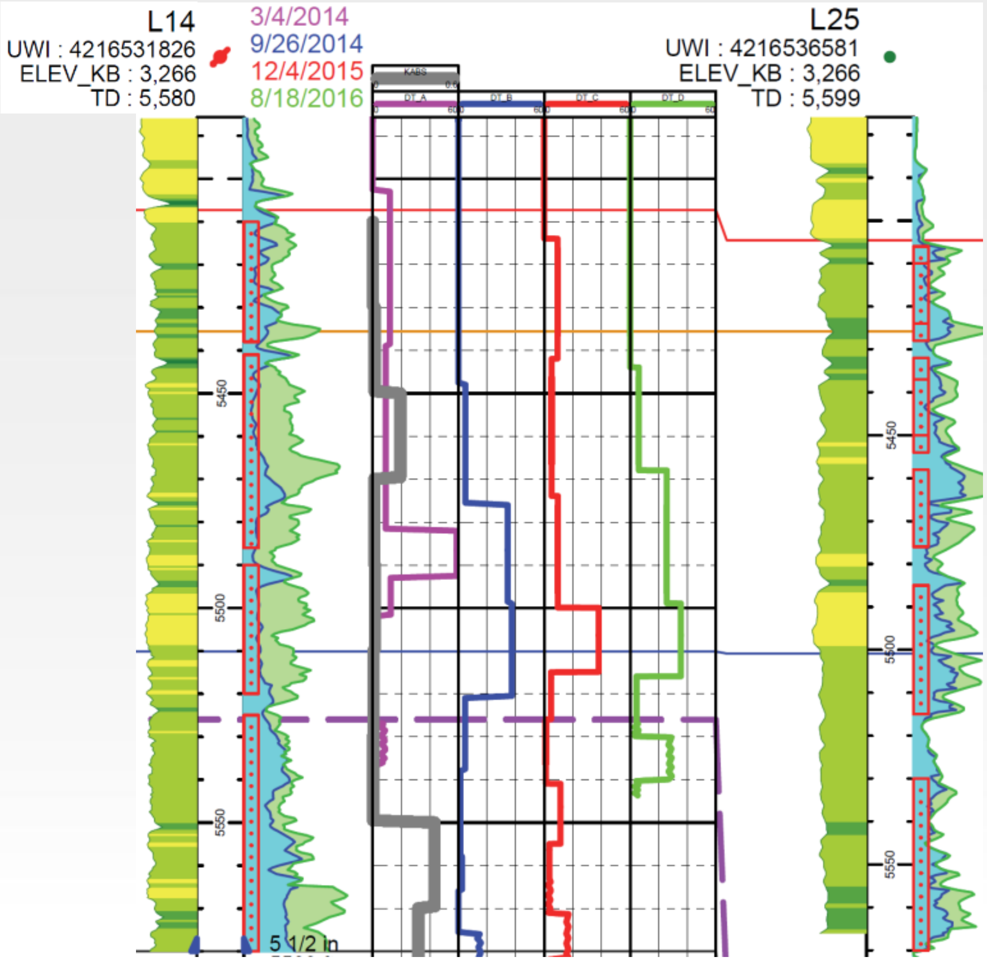


Recovery profile ES23
Waterflood
Surfactant pre-flush
CO2 foam
Rf [fraction OOIP]
dP [bar]
Pore Volume Injected
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
0
1
2
3
4
5
Recovery_WF
Recovery_CO2foam
Recovery_Surfactant_Preflush
dP


L14
UWI : 4216531826
ELEV_KB : 3,266
TD : 5,580
3/4/2014
9/26/2014
12/4/2015
8/18/2016
L25
UWI : 4216536581
ELEV_KB : 3,266
TD : 5,599
5450
5500
5550
5 1/2 in

Ft. Stockton Field

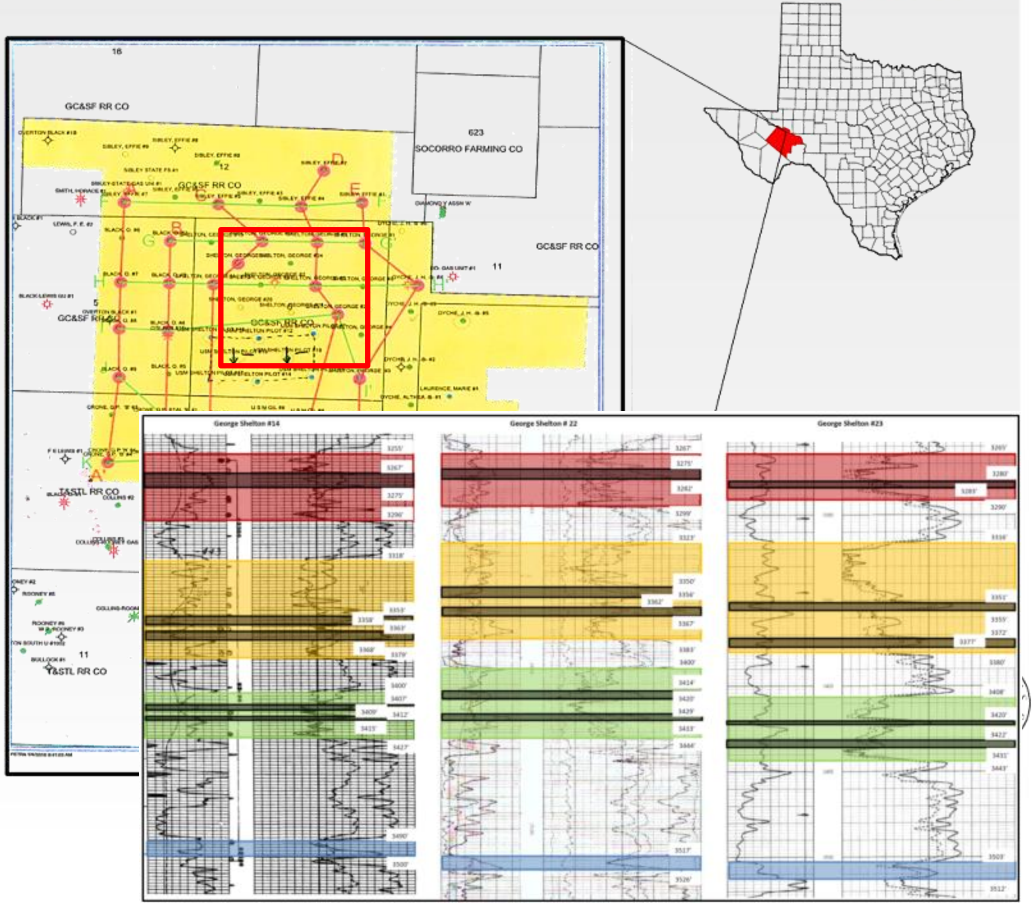
Ft. Stockton Field Queen Formation

- Field Production Size – 3,000 acres
- Cyclical sequence of mixed siliciclastics and carbonates with lesser amounts of evaporites.
- Reservoir rock composed of arkosic sandstone interbedded with variable amounts of dolomite and anhydrite.

Reservoir Characteristic	Value
Depth	3300 ft
Permeability	1 – 30 mD Ave. 16 mD
Porosity	3 – 35 % Ave. 20 %
Pay Thickness	120 ft
Reservoir Pressure	350 psia
Temperature	95°F
Oil Gravity	36° API
Initial Oil Saturation	0.56
Initial Water Saturation	0.44
Oil viscosity (reservoir condition)	2.50 cP
Formation Brine Salinity	40,000 ppm

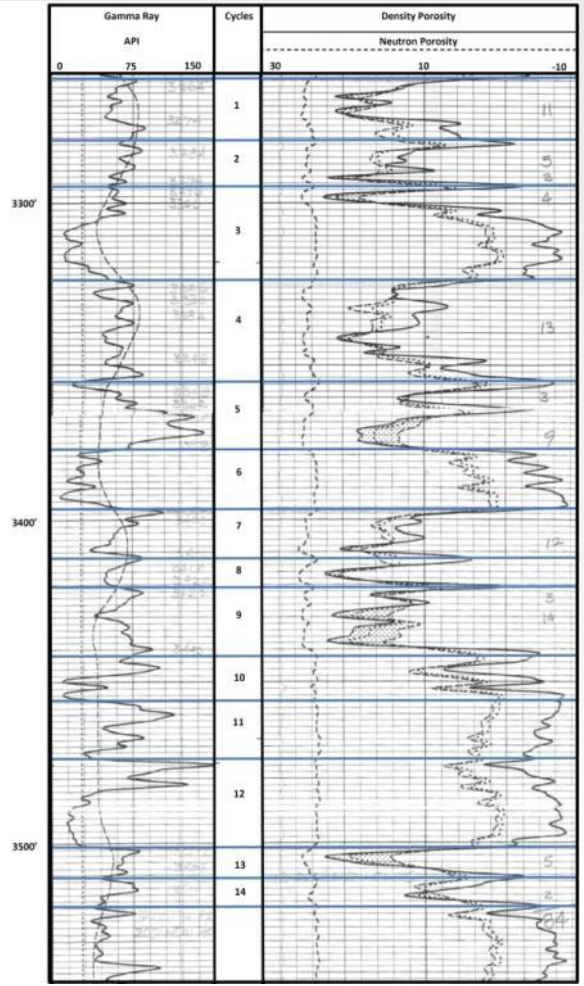
Selection of Field Pilot Location Area

- Data: historical production data, well logs, RCA, thin sections, XRD, four newly drilled wells
- Inverted 5-spot pattern
- Representative geology
- Continuous flow zones with average permeabilities and porosities of 16 md and 20%, respectively.



Cyclicity

- 14 depositional cycles
- Basal fine grained sandstone, carbonate facies at tops
- Cycles range in thickness from 10-25ft



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Phase 1 Laboratory Work

CO_2 Foam EOR Corefloods

Foam Stability

Objectives

- Test CO_2 foam systems for mobility control to optimize EOR potential
- Determine effects of reservoir pressure on CO_2 foam performance for field implementation.
- Optimize experimental procedure for field material

Core and Fluid Properties

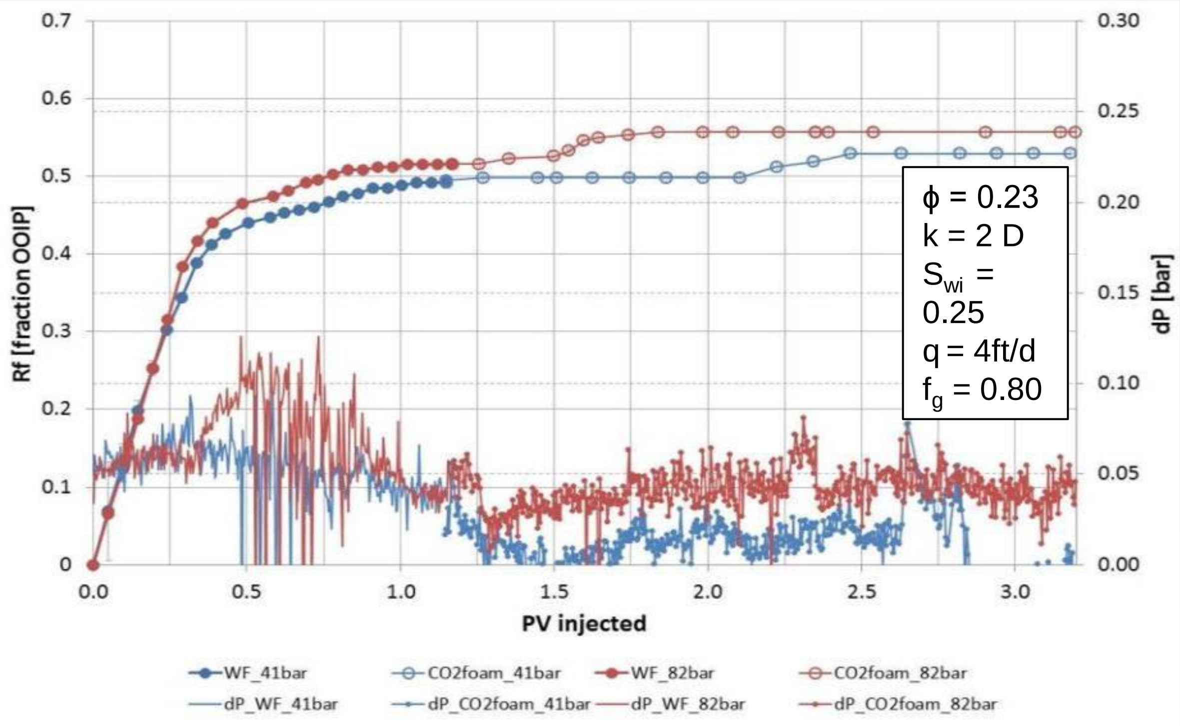
- 1.5" diameter Bentheimer Sandstone
- Reservoir crude oil and Permian Basin brine
- Anionic surfactant: 1 wt% surfactant solution

Core ID	Porosity [ϕ]	Permeability [D]	Length [cm]	PV	Exp.
FT_S1	0.23 ±1.18E-03	1.9 ±0.1	15.2 ± 2.0E-05	39.3 ±0.2	Foam Stability
FT_S2	0.23 ±1.18E-03	2.2 ±0.1	15.3 ± 2.0E-05	39.4 ±0.2	EOR
FT_S3	0.23 ±1.16E-03	2.3 ±0.1	15.3 ± 2.0E-05	38.6 ±0.2	EOR

Experimental Procedure

- Two CO_2-foam injections performed at 35ºC
  - 600 psi (~41bar) 1200 psi (~82bar)
- **Oil drainage**
  - Five PVs of oil were injected until an irreducible water saturation of ~0.25.
- **Secondary waterflooding** (1PV) with a superficial velocity of 4 ft/day (~56ml/h).
- **Tertiary CO_2 foam injection**, co-injecting surfactant solution and CO_2 gas at a foam quality of 80%.
  - The total rate during co-injection was kept equal to waterflooding (i.e. 45ml/h CO_2 and 11ml/h surfactant solution)

Dynamic Recovery Profiles



41 bar: CO_2 mobility was reduced by a factor of 17.6

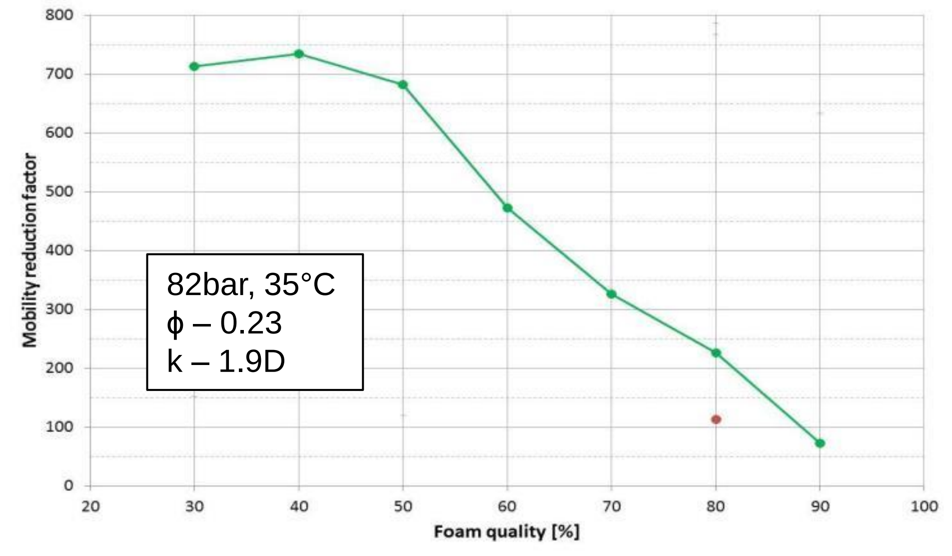
-apparent viscosity of the foam 17 times greater than CO_2 gas at same conditions.

82 bar: MRF was 113, five times greater than the foam generated at 41bar.

Foam Stability

Objective: isolate the parameters that may affect the behavior and generation of CO_2 foam (i.e. effect of oil on foam)

- 100% saturated with surfactant solution
- Co-injection of CO_2 and surfactant solution using foam qualities from high-to-low gas fractions
- The MRF at a foam quality of 80% was 227, approximately double the observed MRF during the co-injection for EOR at 82 bar (red circle on graph).



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