26th Annual CO_2 Conference

Presented Both Live and Virtually

Illinois Basin ROZ Studies and Carper Formation Pilot Deployment

Nathan Webb, Nate Grigsby, Fang Yang, Dmytro Lukhtai, and Scott Frailey

Illinois State Geological Survey

University of Illinois at Urbana-Champaign

with Keith Tracy

Elysian Ventures

Presented at the 26th Annual CO_2 Conference

Tuesday - Thursday Dec 8th-10th, 2020

Bush Convention Center

Midland, Texas

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2020 CO_2 Conference
December 8-10

Acknowedgement

- Research herein supported by US Department of Energy contract number DE-FE0031700, FPM Andrea McNemar
- Steve Sargent (ISGS) provided instrumentation and remote monitoring capabilities
- Bi-Petro Inc. is the greenfield site operator; Projeo Corp. supported ISGS test plan implementation; Natural Gas Services Inc. assisted with site management and implementation of ISGS testing plan; MacCarb supplied CO_2
- Through a university grant, IHS Petra, Geovariances Isatis, and Landmark Software were used for the geologic, geocellular, and reservoir modeling, respectively
- For project information, including reports and presentations, please visit:

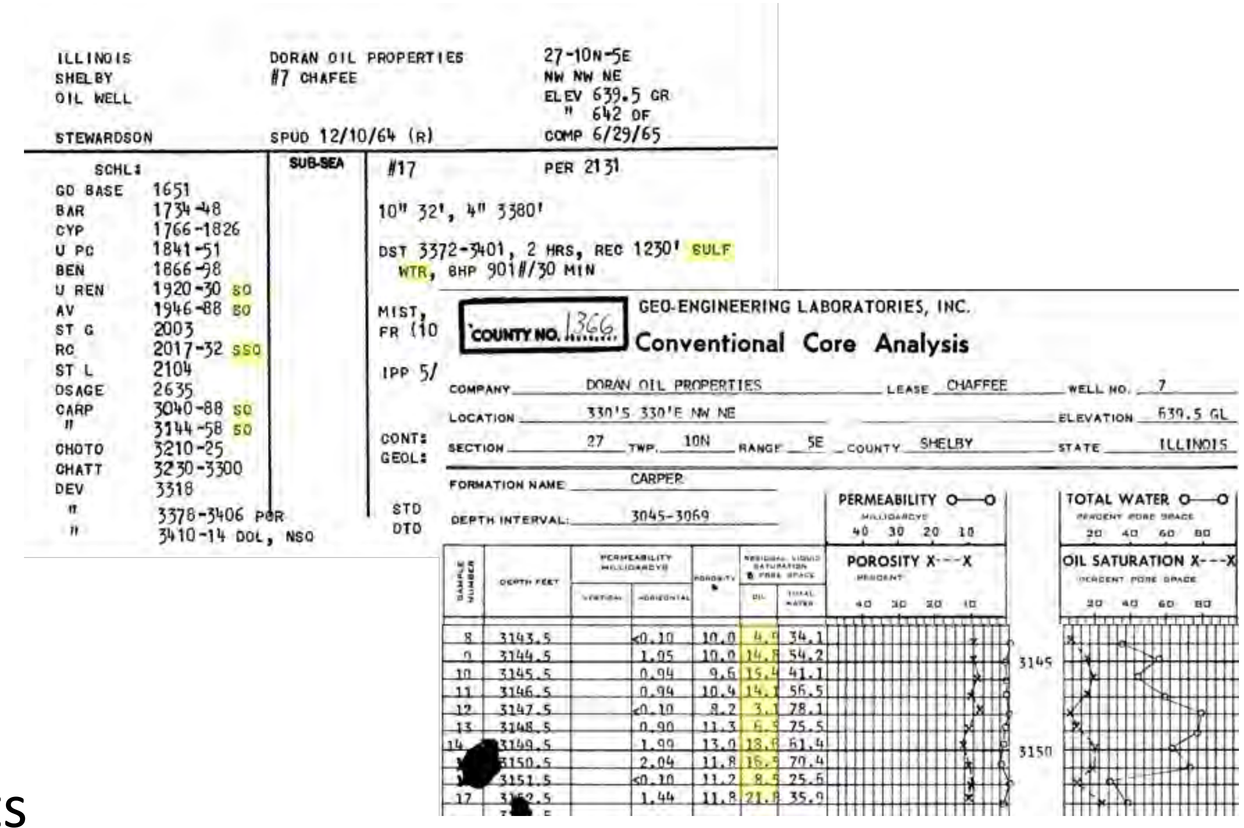
http://www.isgs.illinois.edu/research/ERD/NCO2EOR

Motivation

- DOE objectives
  - Develop specific subsurface engineering approaches leveraging CO_2 injection field tests and applied R&D, that address research needs critical for advancing CCS to commercial scale
- ISGS project objectives
  - Screen for ROZs using analysis of empirical data and basin evolution modeling
  - Characterize stacked brownfield/greenfield siliciclastic ROZs at field lab sites
  - Conduct injection tests and collect and analyze core and logs at field lab sites
  - Use calibrated simulation models and LCA to identify development strategies
- ISGS field pilot objectives
  - Characterize geology and fluids in ROZ
  - Demonstrate the efficacy of CO_2 EOR and storage in a siliciclastic ROZ

ILB ROZs: Identification Process

- Assess geologic properties of formations of interest
  - Porosity, permeability, thickness, fairway potential
- Document ROZ indicators in well data (e.g. *Trentham & Melzer 2016*)
  - Oil shows
  - Core with $S_o>0$
  - Low So indicated from log analysis
  - High water cut production attempts



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SHELBY
OIL WELL
STEWARDSON

DORAN OIL PROPERTIES
#7 CHAFEE
SPUD 12/10/64 (R)

27-10N-5E
NW NW NE
ELEV 639.5 GR
" 642 DF
COMP 6/29/65

SCHL:
GD BASE 1651
BAR 1734-48
CYP 1766-1826
U PC 1841-51
BEN 1866-98
U REN 1920-30 SO
AV 1946-88 SO
ST G 2003
RC 2017-32 SSO
ST L 2104
OSAGE 2635
CARP 3040-88 SO
" 3144-58 SO
CHOTO 3210-25
CHATT 3230-3300
DEV 3318
" 3378-3406 POR
" 3410-14 DOL, NSO

SUB-SEA

#17
PER 2131
10" 32', 4" 3380'
DST 3372-3401, 2 HRS, REC 1230' SULF WTR, BHP 901#/30 MIN
MIST,
FR (10
IPP 5/
CONT:
GEOL:
STD
DTD

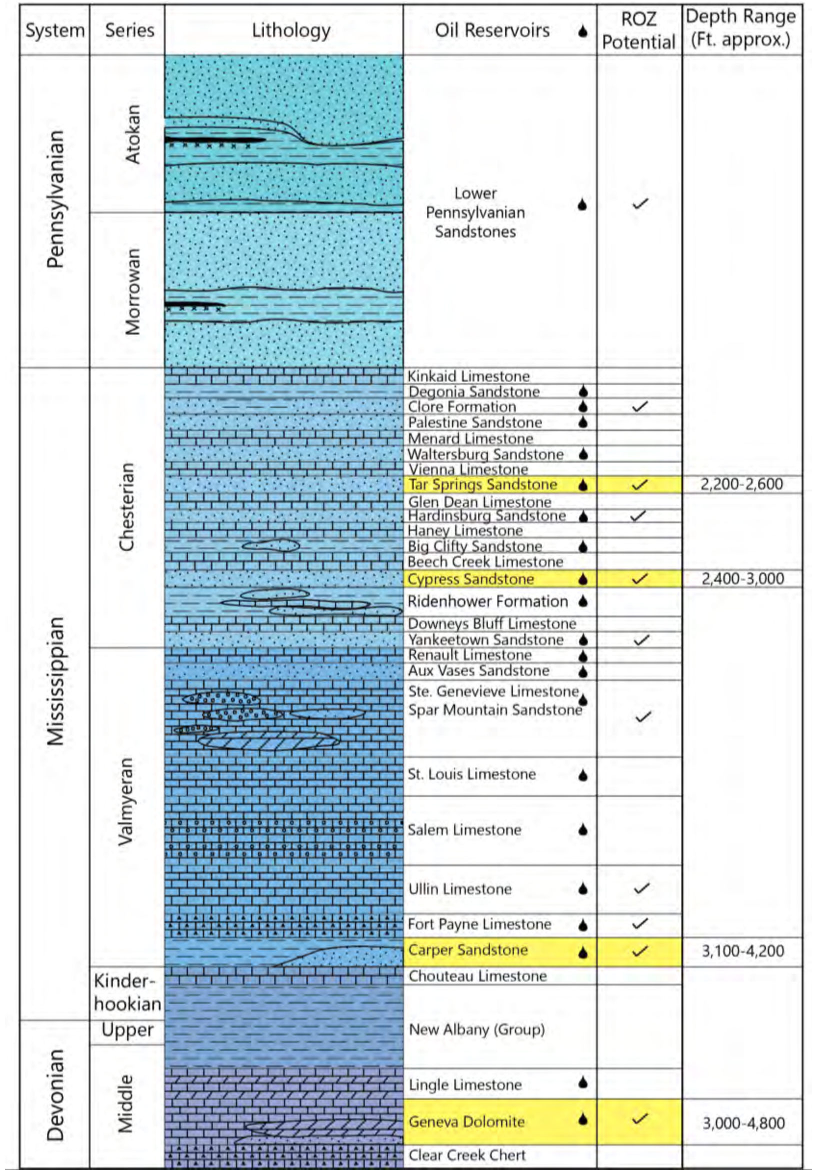
GEO-ENGINEERING LABORATORIES, INC.
COUNTY NO. 1366
Conventional Core Analysis

COMPANY DORAN OIL PROPERTIES LEASE CHAFFEE WELL NO. 7
LOCATION 330'S 330'E NW NE ELEVATION 639.5 GL
SECTION 27 TWP. 10N RANGE 5E COUNTY SHELBY STATE ILLINOIS
FORMATION NAME CARPER
DEPTH INTERVAL: 3045-3069

Sample Number	Depth Feet	Permeability Millidarcys: Vertical	Permeability Millidarcys: Horizontal	Porosity %	Residual Liquid Saturation % Pore Space: Oil	Residual Liquid Saturation % Pore Space: Total Water
8	3143.5		<0.10	10.0	4.9	34.1
9	3144.5		1.05	10.0	14.8	54.2
10	3145.5		0.94	9.6	15.4	41.1
11	3146.5		0.94	10.4	14.1	56.5
12	3147.5		<0.10	8.2	3.1	78.1
13	3148.5		0.90	11.3	6.5	75.5
14	3149.5		1.99	13.0	13.6	61.4
[illegible]	3150.5		2.04	11.8	16.5	70.4
[illegible]	3151.5		<0.10	11.2	8.5	25.6
17	[illegible]		1.44	11.8	21.8	35.9

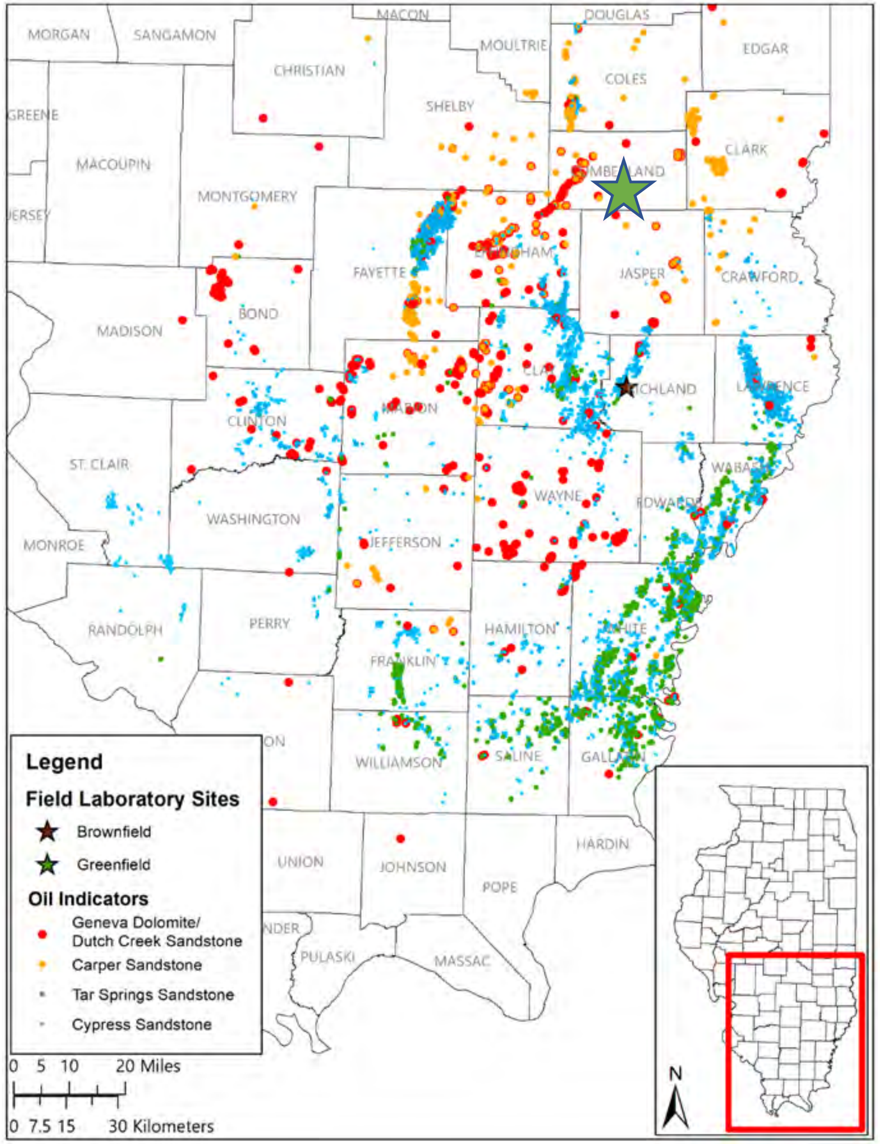
ILB ROZs: Stratigraphy

- Numerous Paleozoic formations with geologic properties favorable for ROZ development
  - Geologic setting conducive to widespread, well-connected, porous and permeable rock
- Current study focuses on regional characterization of four formations



ILB ROZs: Regional

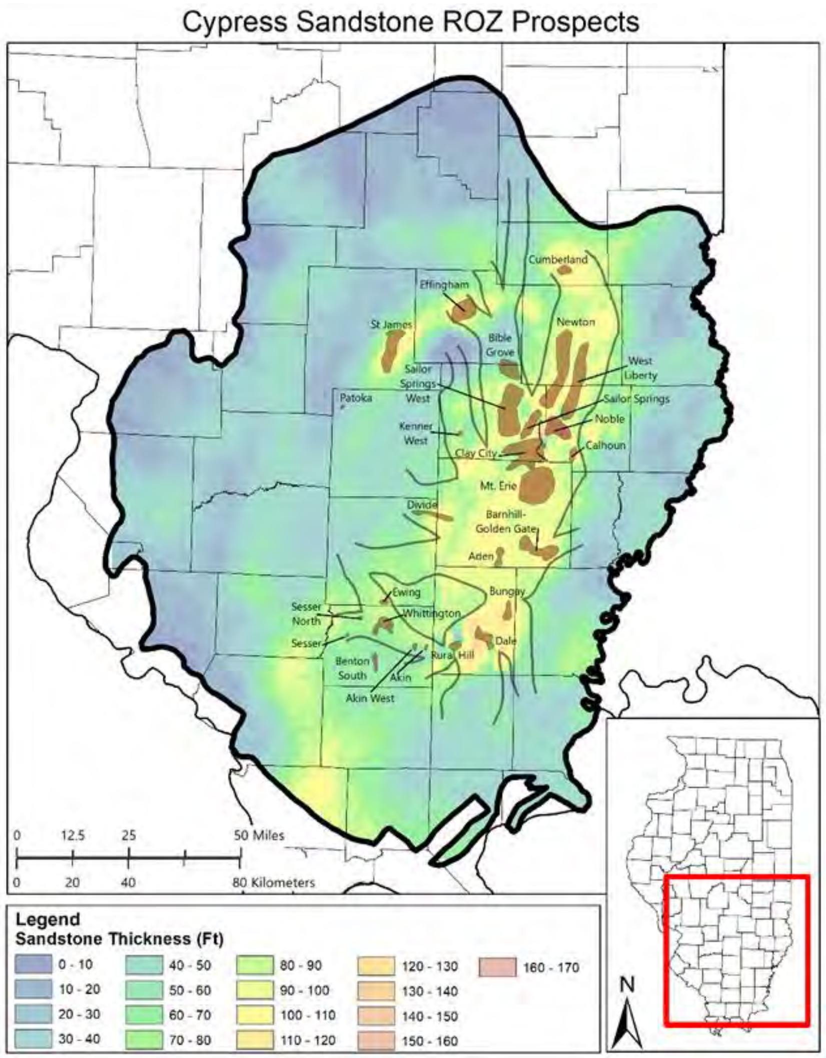
- Numerous Paleozoic formations with geologic properties favorable for ROZ development
- Current study focuses on regional characterization of four formations
  - Focus on siliciclastics
  - Greenfields and brownfields
  - CO_2 HnP demonstration in Carper sandstone



ILB ROZs: CO_2 EOR and Storage estimates

Example: Cypress Ss ROZ fairway

- ~1.9 million acre ROZ fairway
  - ~1 million acre-ft of pore volume
- ROZ estimated resource:
  - 1.8 billion barrels of oil in place[1]
  - 196 million barrels recoverable[2]
  - 10.4 billion tonnes associated CO_2 storage[3]

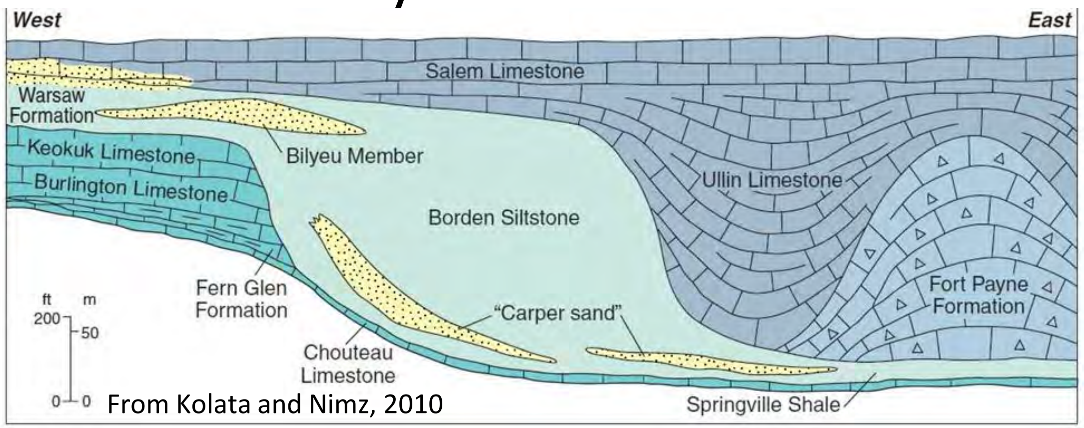


From Webb et al., 2019

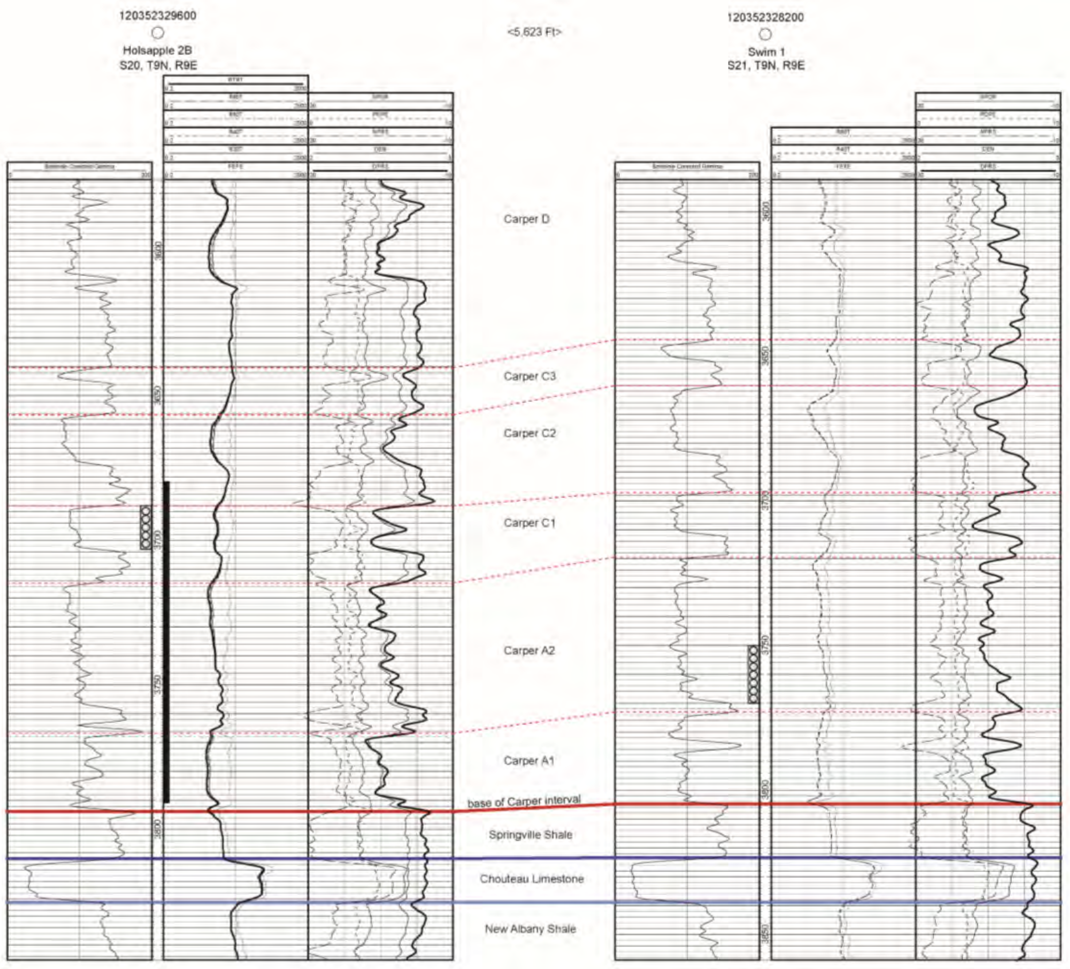
[1]23% median S_{OR}
[2]80-acre WAG flood EOR factor of 11.4% assuming miscible conditions
[3]Net utilization of 1,479 Mscf/stb

Carper and Borden (Caprock) ILB ROZ

- Mississippian (Osagean) deposits
- Carper sandstone encased in the basal Borden Siltstone
  - Overlain by middle-Miss limestones
  - Secondary seals in Chesterian shales

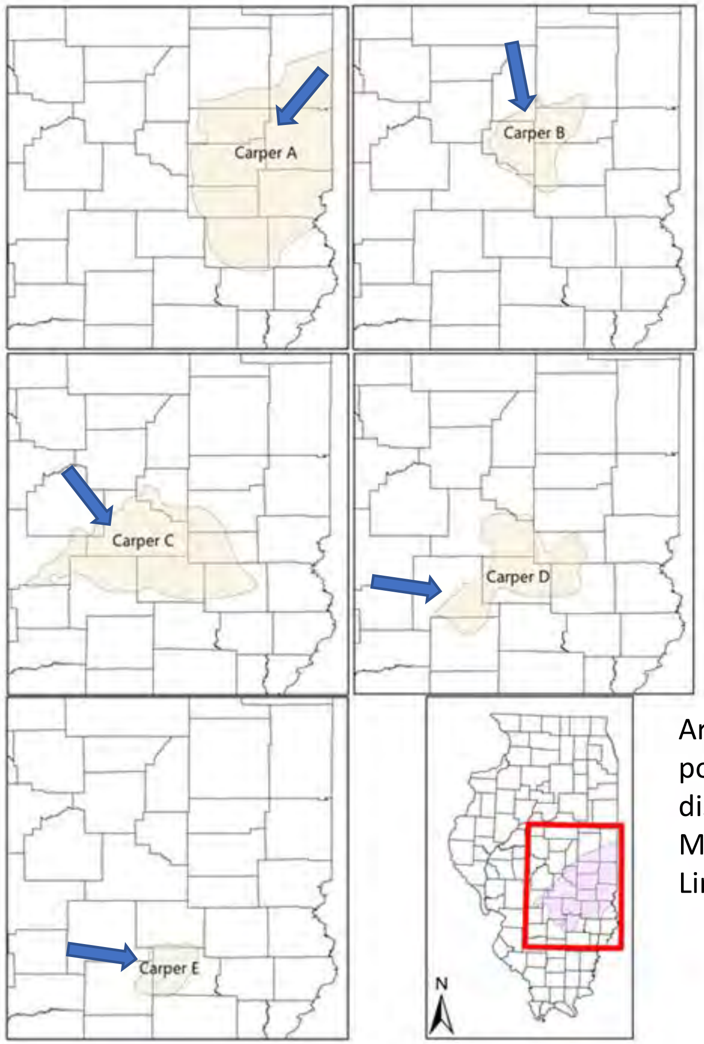


From Kolata and Nimz, 2010



Carper and Borden (Caprock) ILB ROZ: Geology

- Initially described as turbidite (gravity flow) beds off the foreset slopes of the low-angle Borden delta
- Five sandstone-lobes mapped and are named: Carper A – E
- Thickness varies up to 300 ft
  - Where lobes overlap, potential stratigraphic traps occur in otherwise structurally low areas

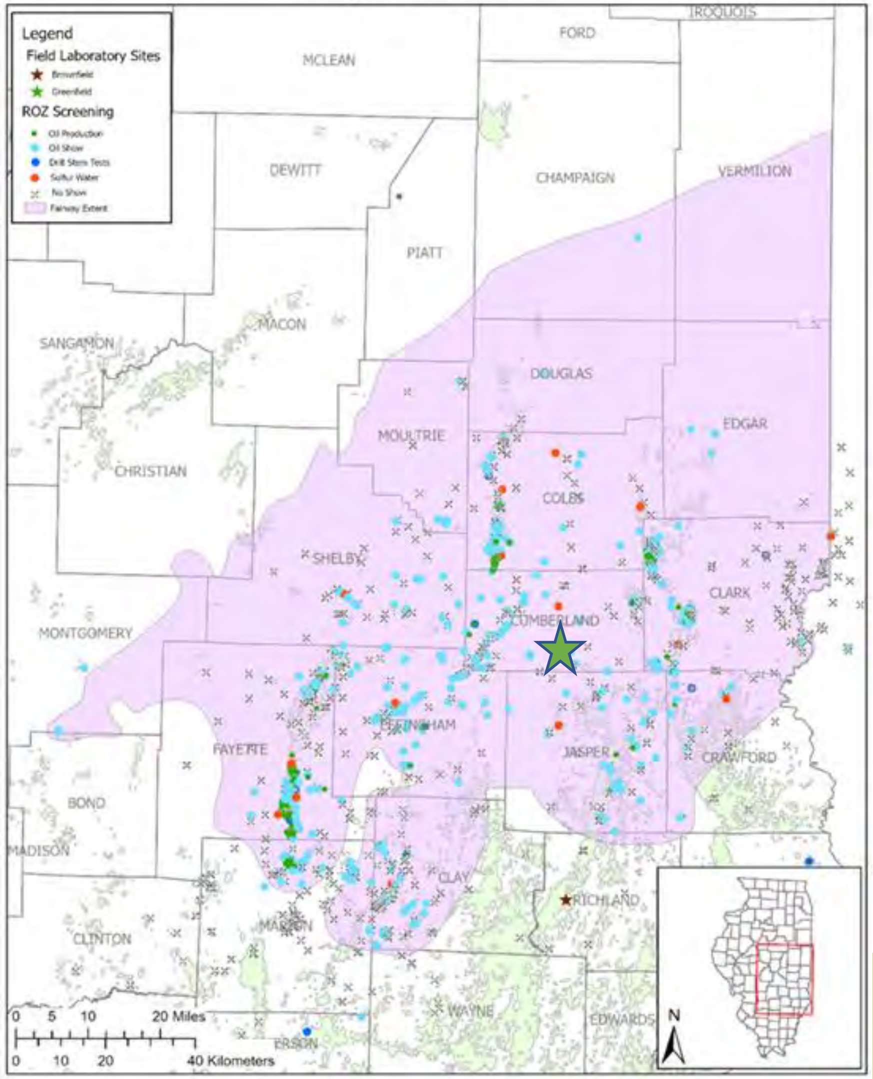


Arrows indicate position of major distributary outlets. Modified from Lineback, 1968.

Carper and Borden (Caprock) ILB ROZ: Regional

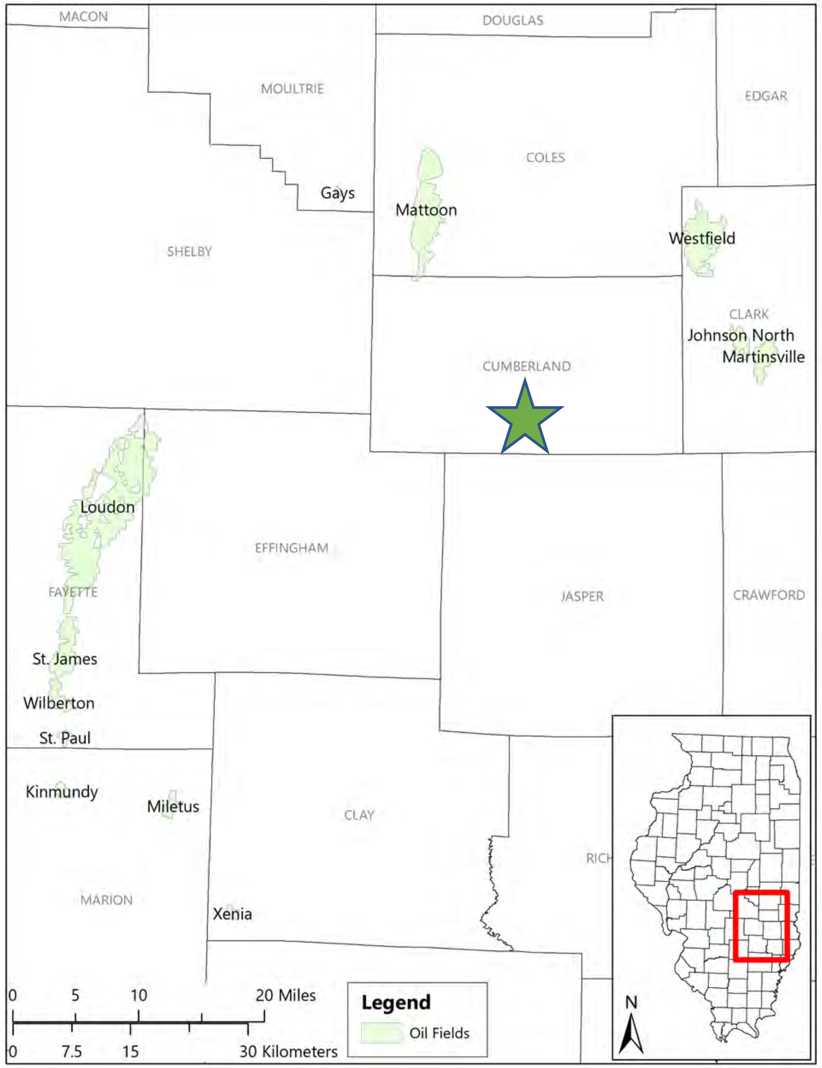
- Deposits extend into 18 counties in east central Illinois
- Oil produced from more than 10 oil fields – all on anticlines
- Evidence for regional greenfield based on oil shows w/ limited oil production at high-water cuts
  - Estimated S_{orw} of 25%

Carper Sandstone



Carper and Borden (Caprock) ILB ROZ: Historical Basin Oil Production

- Production on anticlines since 1920s
  - IP oil cuts of 70-80%; decrease to a consistent 1-5% after decades
    - All primary production
  - Best estimate of original S_o is 50%
  - Approx. 200 bbl of total daily fluid production common
  - 36-38°API; 5-8 cP oil



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Carper and Borden (Caprock) ILB ROZ: Unique Geologic Features

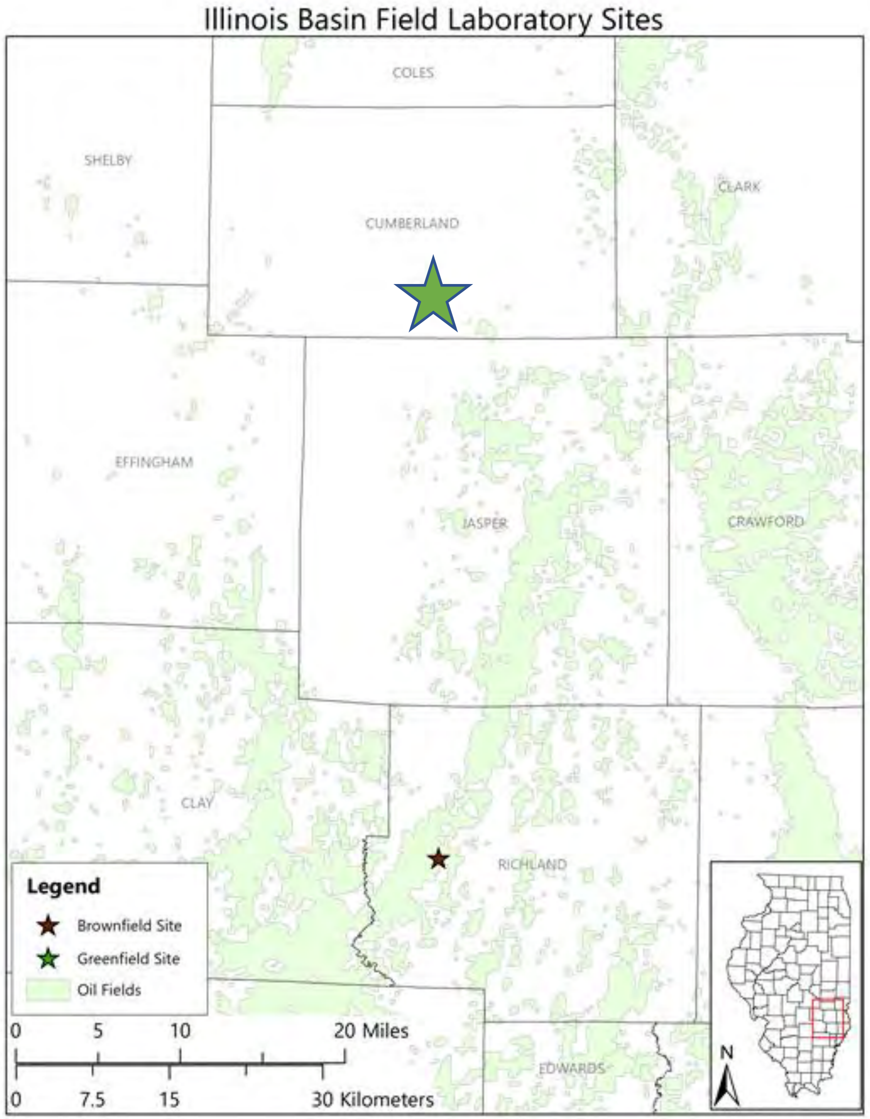
- Quartz sandstone (vf-grained) with clay and dolomite cements
  - Cementing minerals are oil wet vs. the water wet quartz matrix; likely intermediate wettability overall
  - Complex lithology; not ideal Archie rock
    - Difficult to establish 100% S_w baseline
    - Overestimate S_o
- Depositional environment (gravity flow)
  - Unique in Illinois Basin, individual units are generally thin, but have high lateral extent
- Natural Fractures and Reservoir Pressure
  - Fluid throughput during production not possible with 0.1-1.0 mD matrix permeability – inferred natural fractures
  - Operators report possible sub-normal pressure (deep fluid level) – formation is encased within massive siltstone in the subsurface and does not outcrop

Field Pilot Site Selection: Criteria

- Evidence of stacked greenfield ROZs
- Operator with existing well, completed in target formation within a greenfield
- Temperature and pressure suitable for miscible test
- Data availability
  - Well records, production history

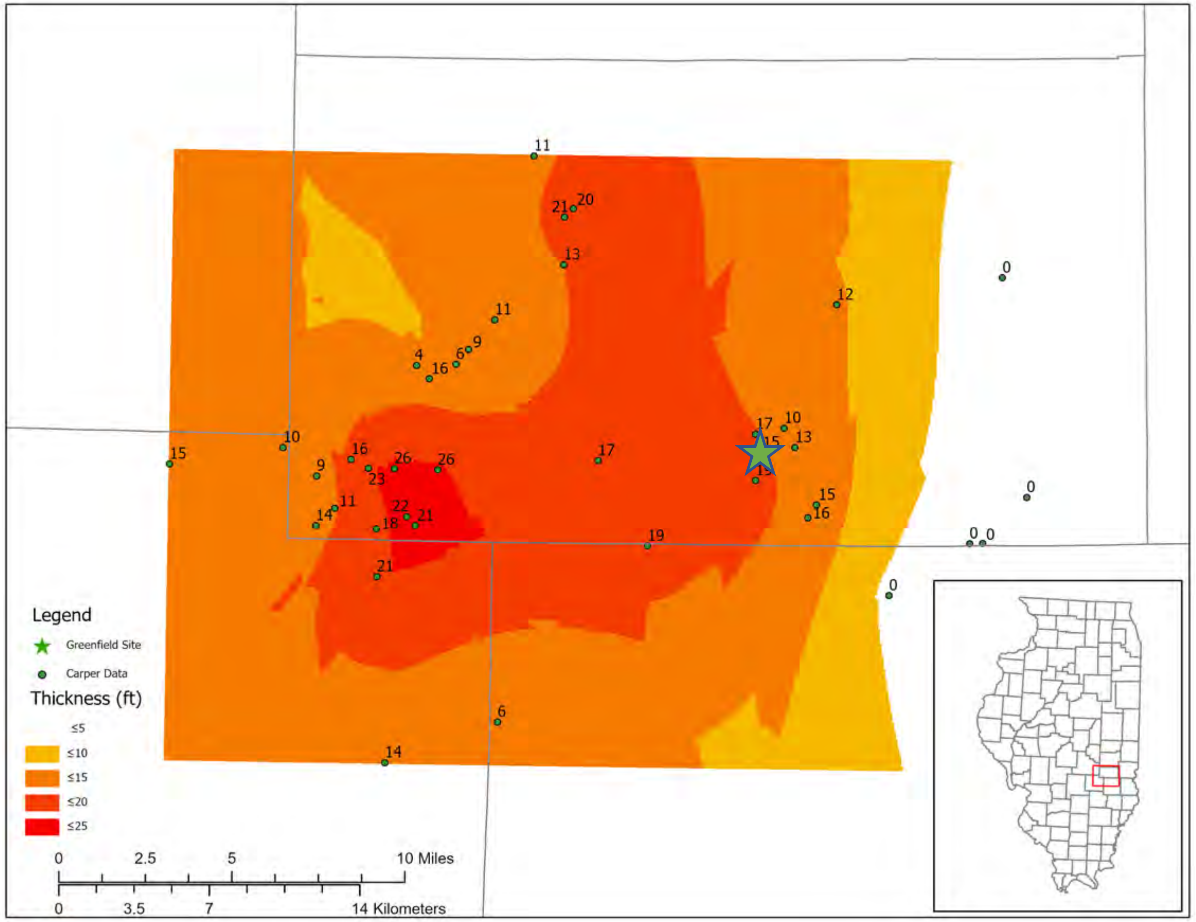
Field Pilot Site Selection: Geographic Location

- Greenfield
  - Cumberland County
  - South central Illinois
- Approximately 20 miles to nearest Carper oil fields on structures
- Within 70 miles of several significant CO_2 sources



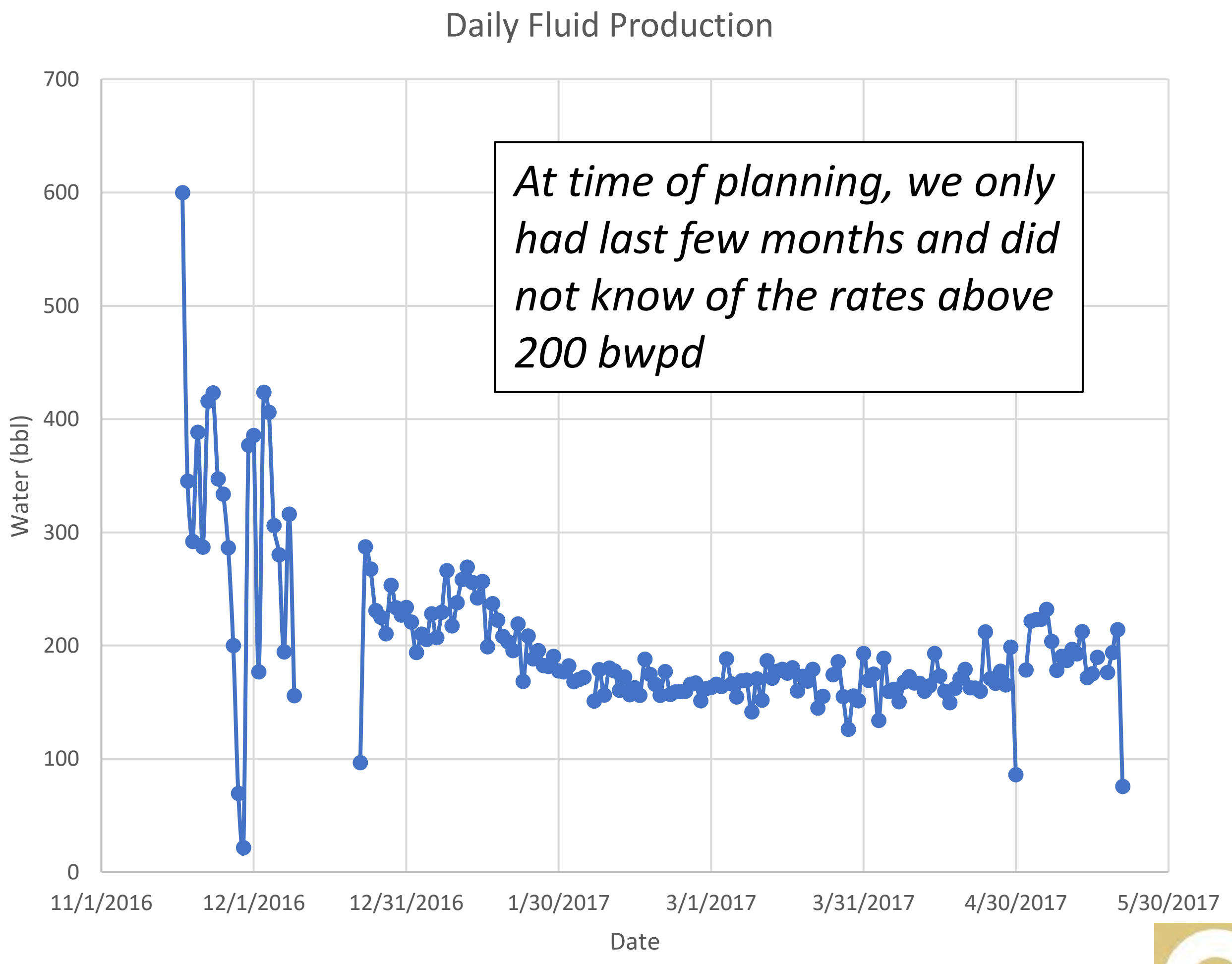
Field Pilot Site Selection: Site Geology

- Carper sandstone net thickness 100+ ft in 5 distinct sandstone bodies
- Perforated interval
  - Highest calculated S_o (25%)
  - 15 ft thick, laterally extensive
  - 0.2 mD matrix perm (core)
  - Bounded above and below by 10-15 ft of shaley siltstone



Field Pilot Site Selection: Production History/Well Completion

- Drilled August 2016
  - Carper zone cored
- Casing set; 15 ft perforated
- Acid treatment
- Slickwater frac
  - 892 bbl water, 31,500 lb. sand
- Six months pumping
  - No measurable oil production
- Well shut-in May 2017



Field Pilot Site Selection: Simulation Scenarios

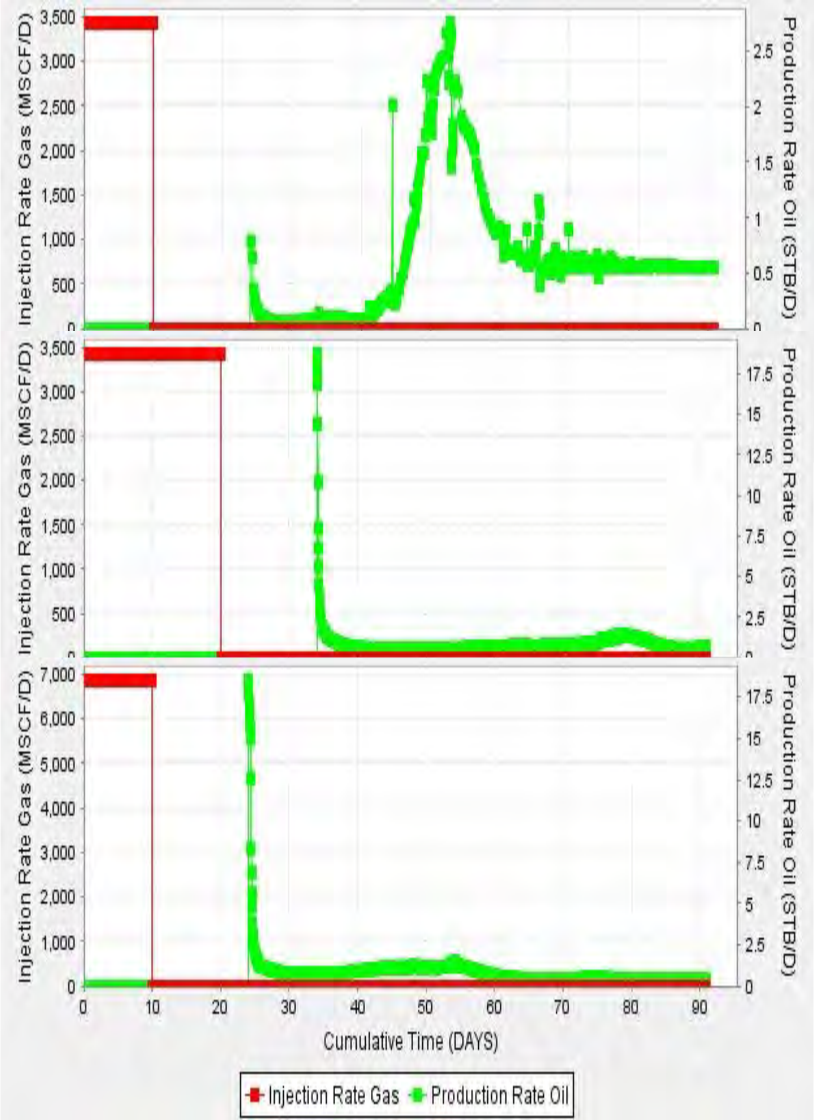
- Base model to match historical water production
  - Natural (vertical) fracture model
    - LY=3 ft, LX = 150 ft (orthogonal)
    - k_{xf}/k_{yf} =0.02
    - 10-20 md equivalent perm
  - Matrix: $S_{or} = S_{oi} = 25\%$
  - Fracture: $S_{or} = S_{oi} = 2\%$

- HnP sensitivity
  - Injection rate
  - Injection volume
  - Soak period
  - Injection scheme: continuous injection vs. discontinuous injection
  - Initial pressure: above MMP vs. below MMP
  - Prior water injection vs. No water injection

Field Pilot Site Selection: HnP Simulation Results: Pre-Water Tests

- Baseline: 0.0 stb/day
- Higher cumulative CO_2 inj
  - Higher peak oil rate and cumulative production
- Higher CO_2 injection rate (with same cumulative)
  - Similar peak oil rate but higher cumulative oil production

Comparison at 1 month production



200 ton/day for 10 days:
Peak oil = 3 stb/day
Cum oil at 1-month = 18 stb

200 ton/day for 20 days:
Peak oil = 19 stb/day
Cum oil at 1-month = 25 stb

400 ton/day for 10 days:
Peak oil = 19 stb/day
Cum oil at 1-month = 46 stb

200 tpd = 3.4 MMscf/d
400 tpd = 6.8 MMscf/d

Field Pilot Site Selection: HnP Simulation Results: Pre-Water Tests, Cont.

- Pump and delivery constrained: injection limit of 60 ton/d (1.0 MMscf/d)
  - Soak period has little impact on oil response
  - Shorter soak time, higher cumulative injection yielded slightly better cumulative oil

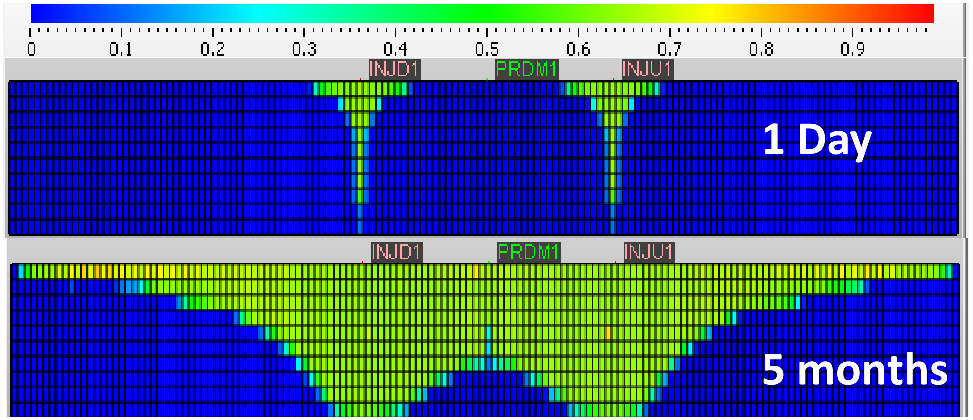
Scenarios	Injection time, day	Cumulative injection, ton	Peak oil rate, stb/day	Cumulative oil at 1-month production, stb
14-day soak	16	960	1.1	15
	8	480	1.1	13
	4	240	1.1	11
7-day soak	16	960	1.2	17
	8	480	1.2	14
	4	240	1.2	12

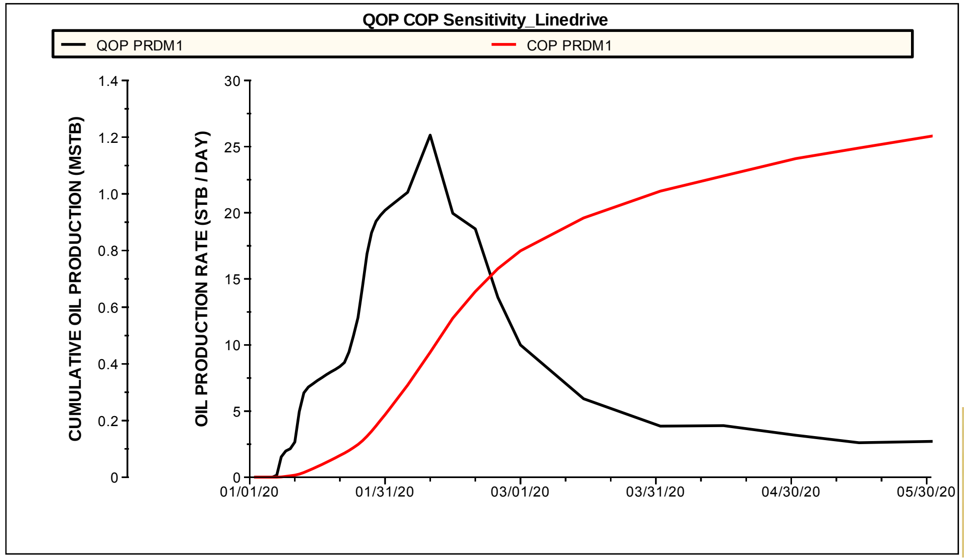
Field Pilot Site Selection: Line Drive Simulation Results: Pre-Water Tests

Direct line drive

- 20-acre pattern
- CO_2 inj rate: 200 ton/d (3.4 MMscf/day)
- Results:
  - Single pattern
    - Peak oil rate: 26 stb/day
    - 1,200-1,300 stb
  - Metrics after 5-months:
    - Oil recovery = 1.6% OOIP
    - Net utilization = 56 Mscf/stb (3.4 ton/stb)
    - Gross utilization = 428 Mscf/stb (25 ton/stb)

Gas saturation in fracture (side view of middle wells)





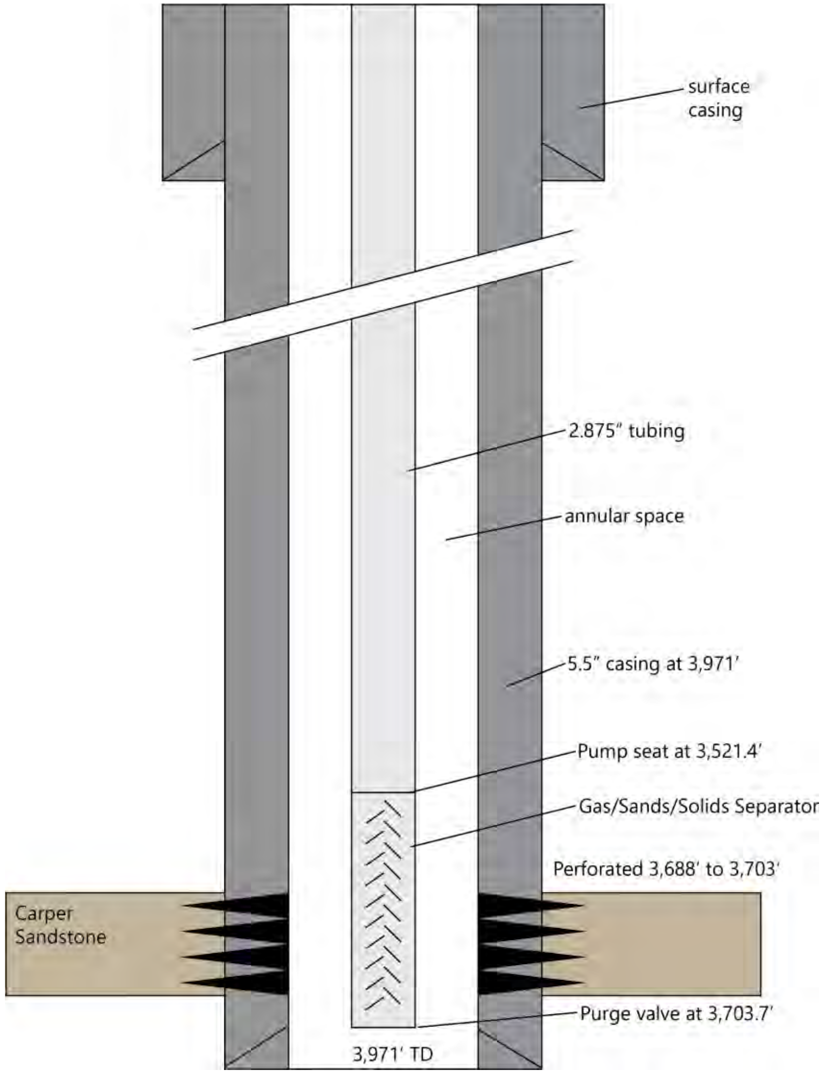
Pilot Design: Design Elements

- Goal: acquire HnP data to calibrate model to predict commercial scale CO_2 EOR and storage
- Initial HnP plan
  - Inject 1,000 tons (20-ton tank trucks)
  - Pump capacity (60 ton/day)
  - Soak for >7 days
  - Produce for 1-3 months
- Update plan after:
  - Water injection tests
  - Baseline production (1 month)

Frailey and Monson (in prep): Designing Small-Scale EOR/CO2 Storage Pilot Projects

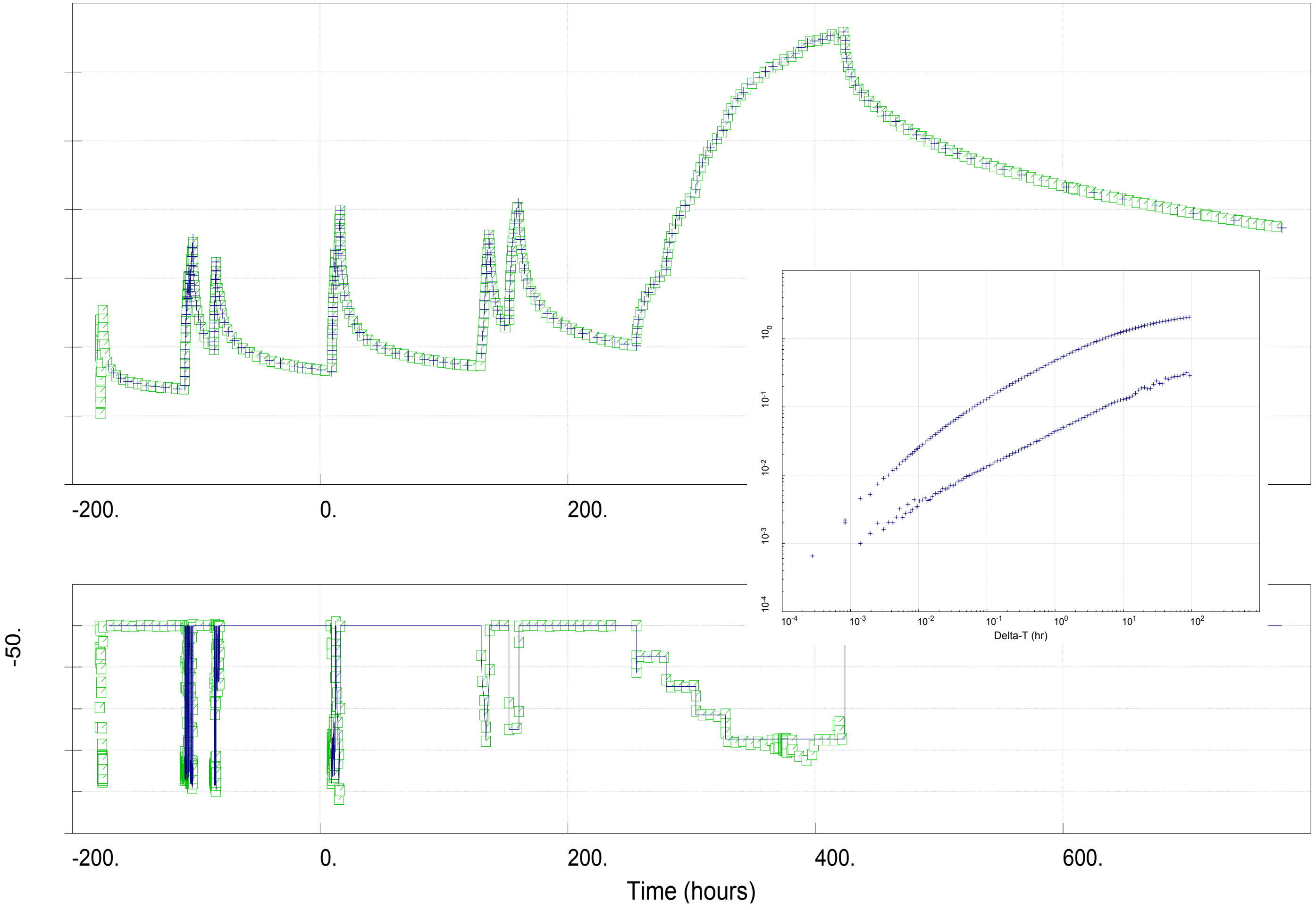
Pilot Design: Well

- Perforated interval: 3,688-3,703’
- Fill in bottom of well
  - Unable to remove
  - Suspected frac proppant
- Solid (sand)-gas-liquid separator added
- Pump depth: 3,524’
- Pump above perfs
  - Liquid CO_2 will engulf pump
  - Tubing full of brine



Pilot Design: Water Injection Tests

- Injection tests planned
  - Step rate tests
  - Pressure falloff tests
  - Designed for 20 mD
- Results
  - Expected 1,000s psi response
  - Found 10s psi response
  - Very slow pressure falloff
  - Hydraulic fracture dominated
  - MRT appears as SRT at <100 psi

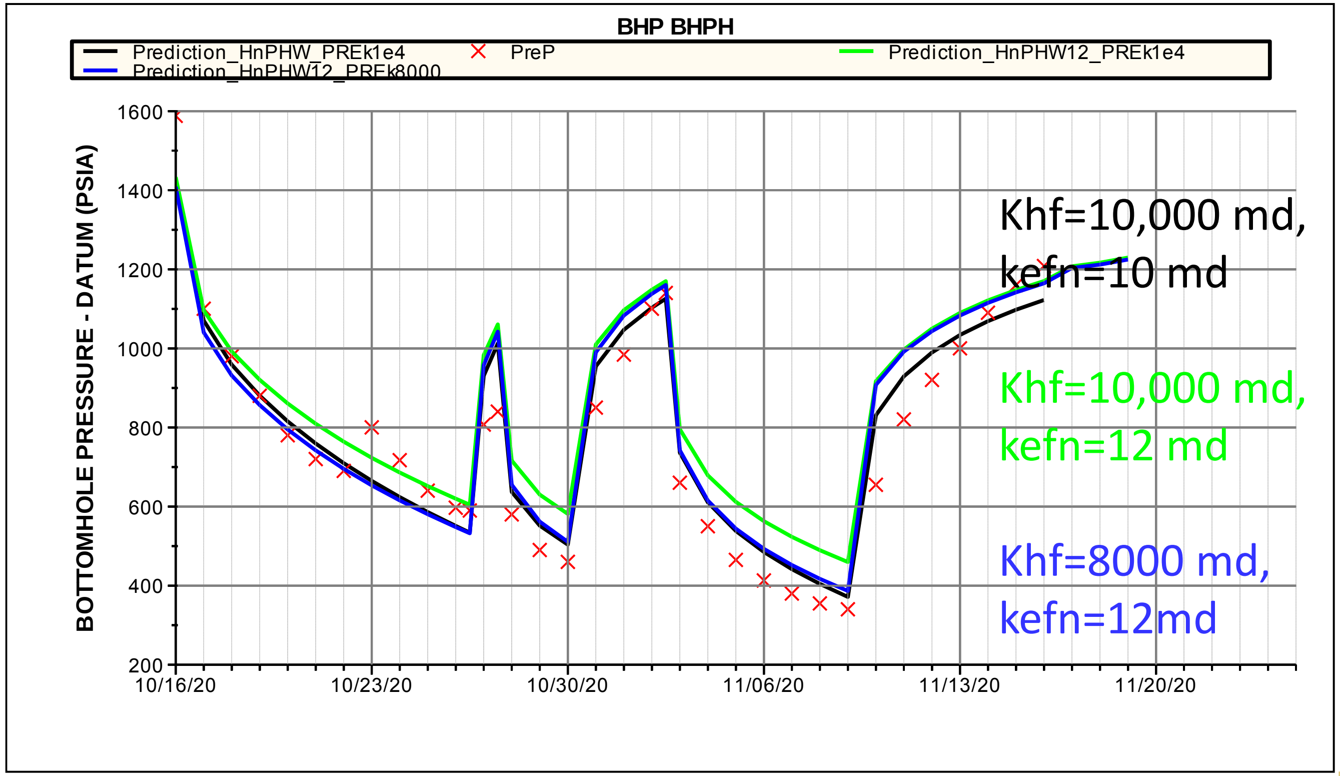


After discussing with operator, we learned of earlier water rates > 200 bwpd

Pilot Design: Simulation Results: Post-Water Injection Tests

- Use 1 ft wide cell to represent a hydraulic fracture
- Vary to match water injection tests
  - Hydraulic fracture half length (x_f)
  - Permeability (k_{hf})
  - Natural fracture spacing (LY)
  - Natural fracture effective perm (k_{efn})

LY = 6 ft, x_f = 510 ft, k_{hf} = 8000 mD, k_{efn} = 12 mD



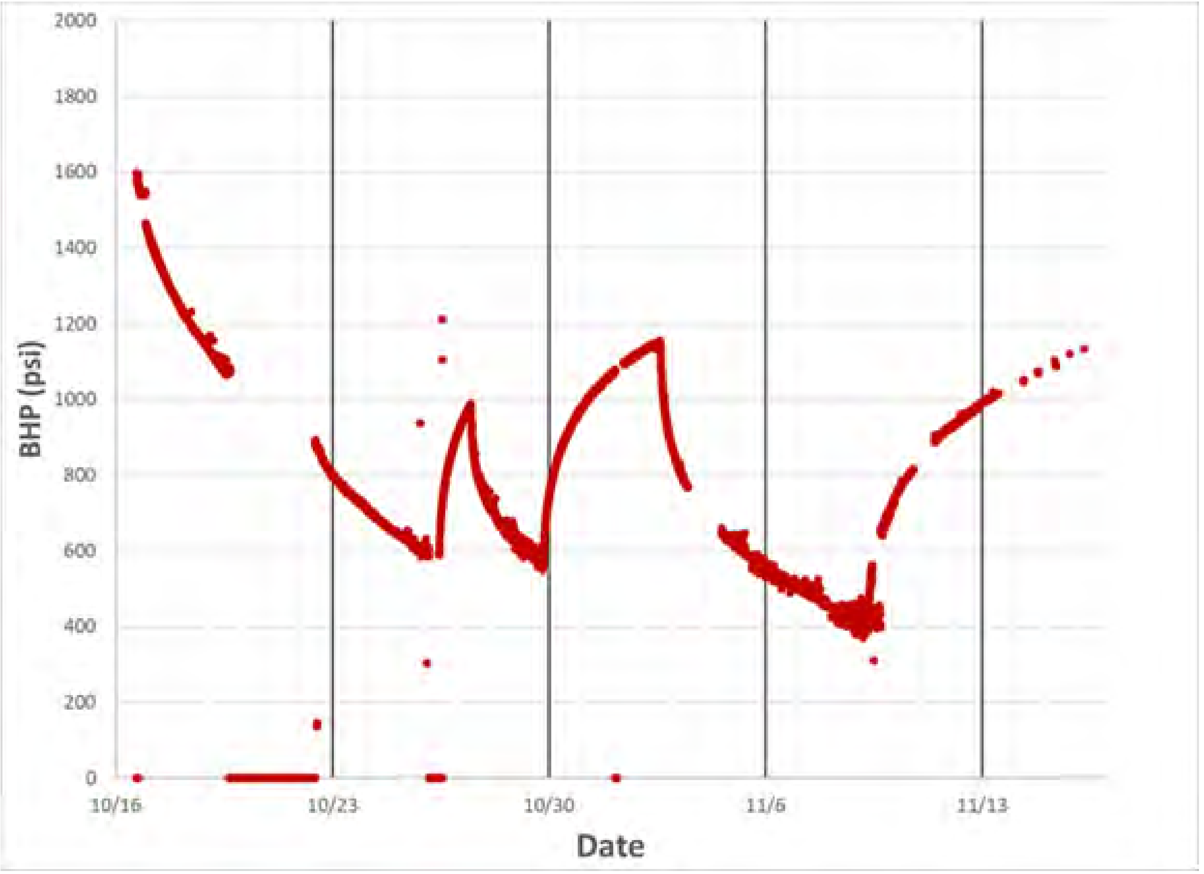
Pilot Design: HnP Simulation Results: Post-Water Injection Tests

- Inject: 40 ton/day for 25 days (1,000 tons)
- Soak: 7 or 14 days
- Produce: 1 month

Soak period, days	Cumulative oil at 1-month, stb	Peak oil rate, stb/day
7	13	1.6
14	12	1.5

Pilot Design: Baseline Production Test

- Verify water production from 2017
  - One month
  - Rod pump; 280 bbl/day
  - BHP (Echometer)
- Pressure
  - Readily drawdown well
  - Slow pressure buildup
  - Similar to injection tests
    - Flowing vs. shut-in well response



Pilot Design: Equipment and Data Acquisition

Injection

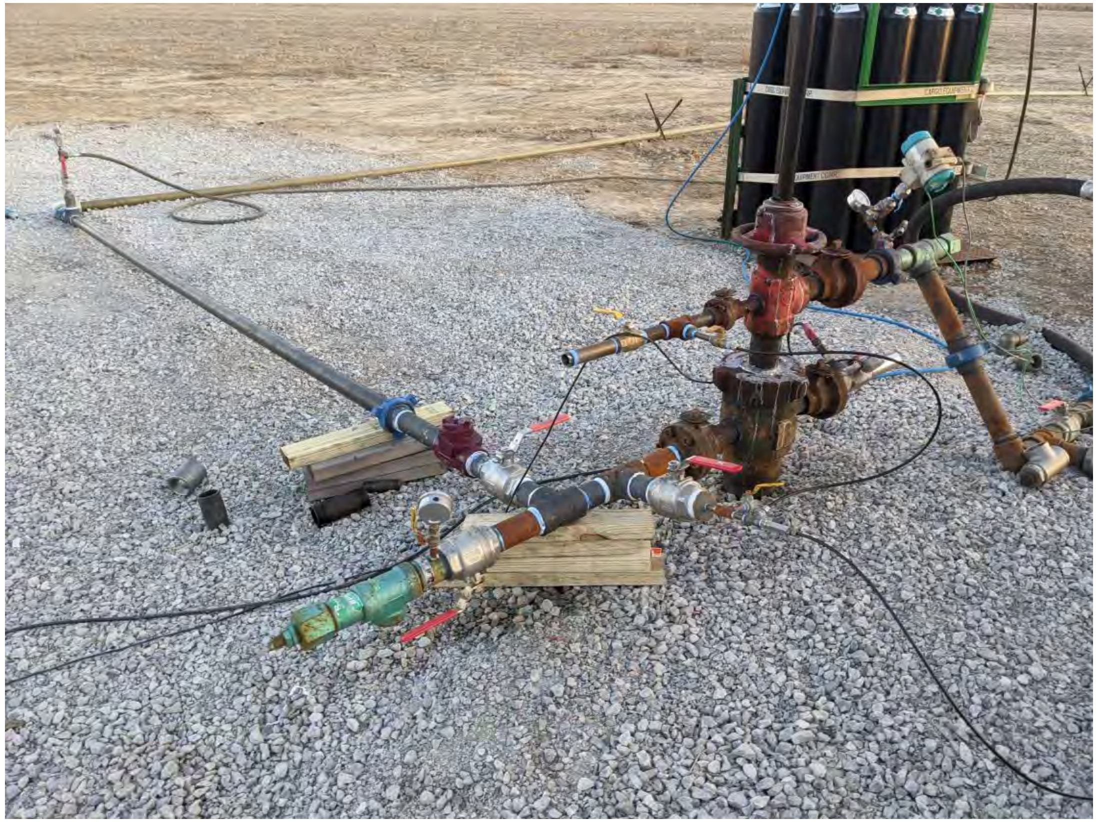
- 50-ton CO_2 storage tank on site
- ISGS CO_2 pump skid (prev. DOE project)
  - Booster and triplex pumps capable of injecting up to 60 tons/day
  - In-line propane heater

Production

  - Corrosion treatment at wellhead
  - Gas-liquid separator

Pilot Design: Equipment and Data Acquisition

- Quantity of CO_2 injected into annulus
  - Turbine meter at triplex pump
  - Mass sold
  - Delivered mass
- Pump skid gauges linked to data logger and viewed remotely
  - Echometer monitoring annulus pressure
- Production
  - Meter oil, water, CO_2 produced
    - Flexim ultrasonic unit motoring oil and water production, gas provers for CO_2
  - Echometer tracking fluid level and BHP
  - Water disposal well on location

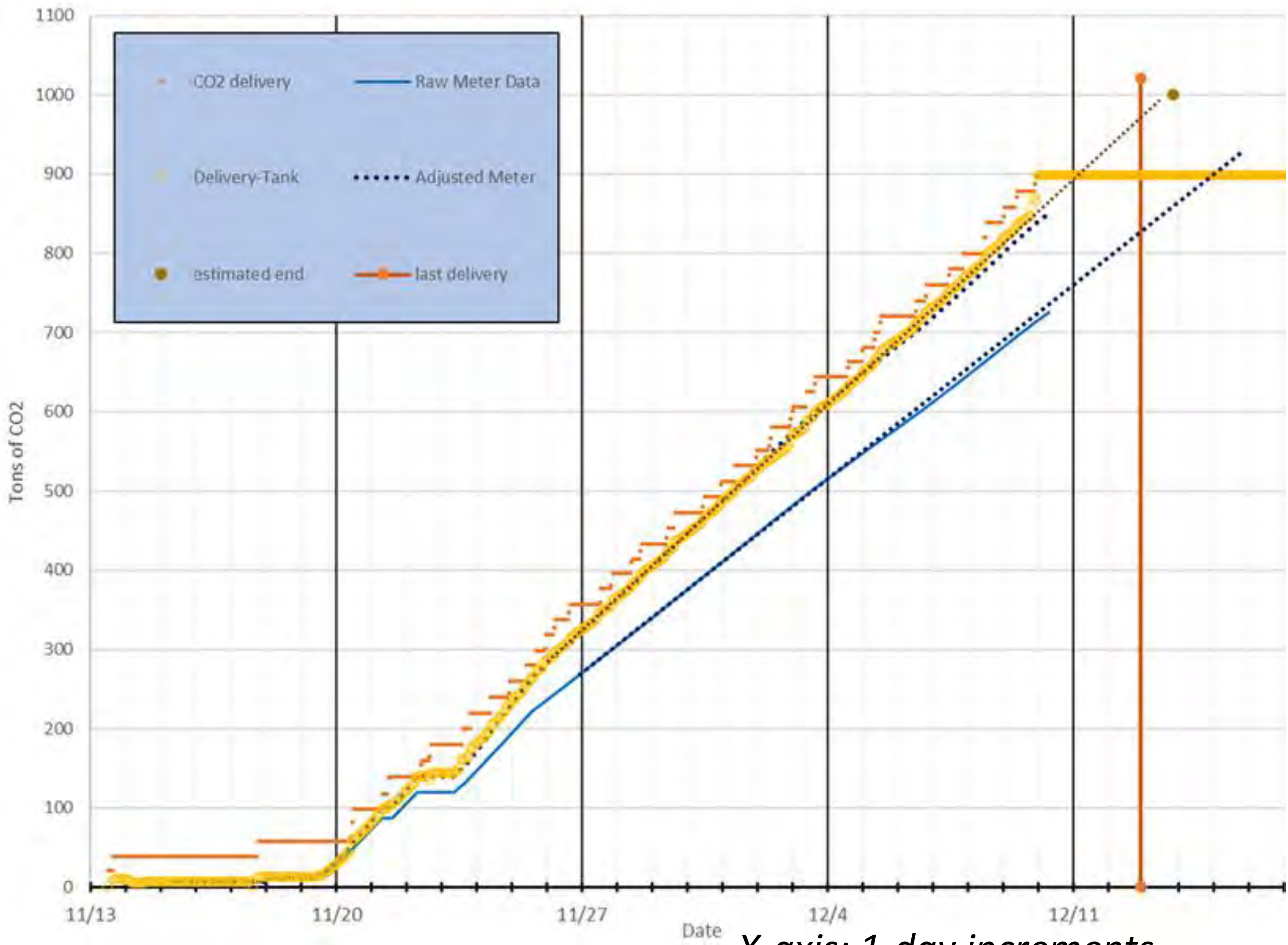


Pilot Design: Deployment Challenges

- Budgetary
  - No infrastructure remaining at site
    - Costly and time consuming to set up
- Operational
  - Booster pump issues
  - Tank <15% full, caused shut down
  - Differences between metered and delivered CO_2
  - Connectivity issues
  - Winter road restrictions
  - Road surface degradation

CO_2 Injection: Current Status

- Injection rate into annulus
  - Initially 50-60 ton/day
  - Stabilized at 40 ton/day
- Surface injection:
  - 500-600 psi
    - Highly temperature dependent
    - CO_2 density
  - 40-50°F
- 900 tons injected to date



X-axis: 1-day increments

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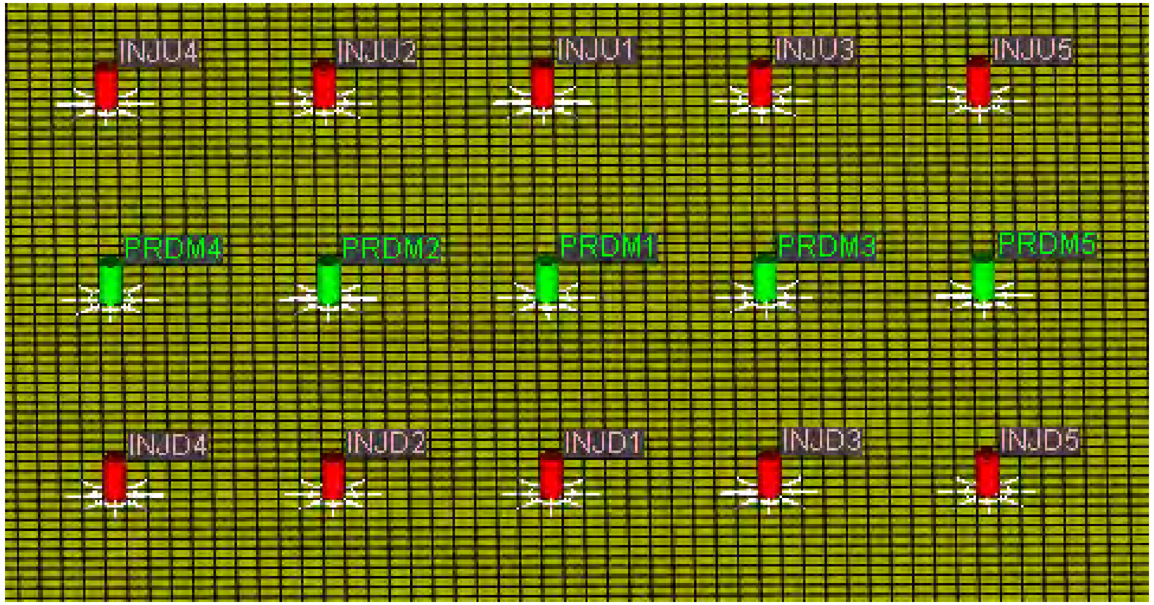
CO_2 Injection: Current Plan

- Another week of injection
- Soak 1-2 weeks
- Produce CO_2 from annulus until water/oil is in the wellbore
  - Echometer: Monitor brine/oil fluid level
- May require pumping brine into the annulus to initiate rod pump
- Calibrate model to full-field pattern injection



Commercial Deployment Example Assessment: 45Q Application

- Assumptions:
  - Minimum CO_2 injection rate of 325 ton/day
    - ~5.6 MMscf/d or ~107,000 metric ton/year
    - CO_2 is captured from industrial facility
  - 12 consecutive years of injection for EOR
    - Starting January 1, 2022
  - Carbon capture equipment owner elects to transfer 45Q credit to “credit claimant” (EOR operator)
  - EPA approval of MRV plan for field or area of injection, or satisfaction of CSA/ANSI ISO 27916:19 standard
- 45Q Tax Credit:
  - Minimum amount of tax credits is $2.5 to $4.25 million per year
  - Cumulative 45Q credits for the Project is $44 million (year 2022-2033)
- 45Q Tax Equity Partnership
  - Assume tax equity investor’s return is fixed at 14% (cumulative of $38 million investment)
  - Tax equity investor would make an up-front investment of at least $7.6 million (Rev Proc 2020-12 requires this 20% minimum investment)

Commercial Deployment Example Assessment: 45Q Monitoring, Reporting & Verification (MRV) Plan

- Assume project elects to "opt in" to Subpart RR of the EPA Greenhouse Gas Reporting Program
- "General Technical Support Document for Injection and Geologic Sequestration of Carbon Dioxide: Subparts RR and UU" (EPA - Nov 2010)
  - Provides examples for complying with MRV Plan requirements
  - Explains mass balance calculations
  - Describes MRV Plan approval process
  - Identifies annual reporting requirements

- MRV Plan will:
  - Delineate the areas of review
  - Describe the geology and historical use of the area
  - Identify anticipated lifetime of project and amount of CO_2 to be injected
  - Describe injection process
  - Include mass balance equations
  - Provide a schedule for implementation of plan
  - Assess or evaluate risks of potential leakage
  - Explain monitoring techniques and methods

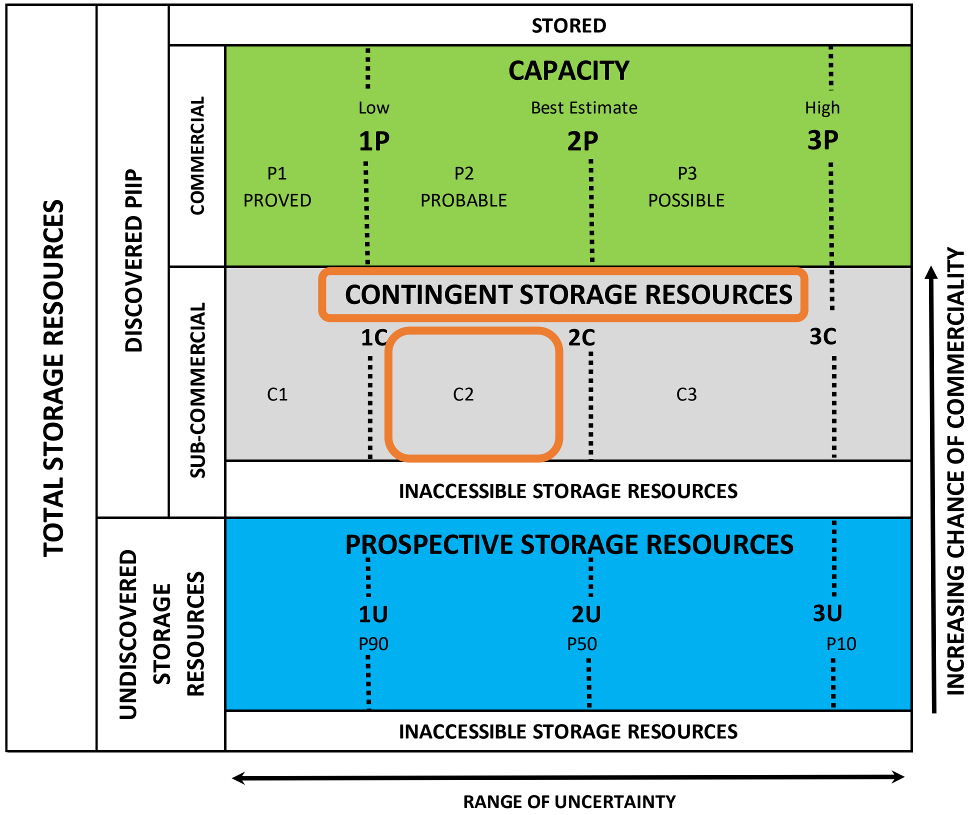
Commercial Deployment Example Assessment: Carper Sandstone

- Caprock/containment
  - Borden siltstone
    - Lateral extensive
    - 50-100 ft
- Leakage Pathways
  - Geologic
    - Tectonically quiet area
    - No known faults
  - Wellbores
    - Greenfield so very few existing
    - Relative deeper with fewer penetrations

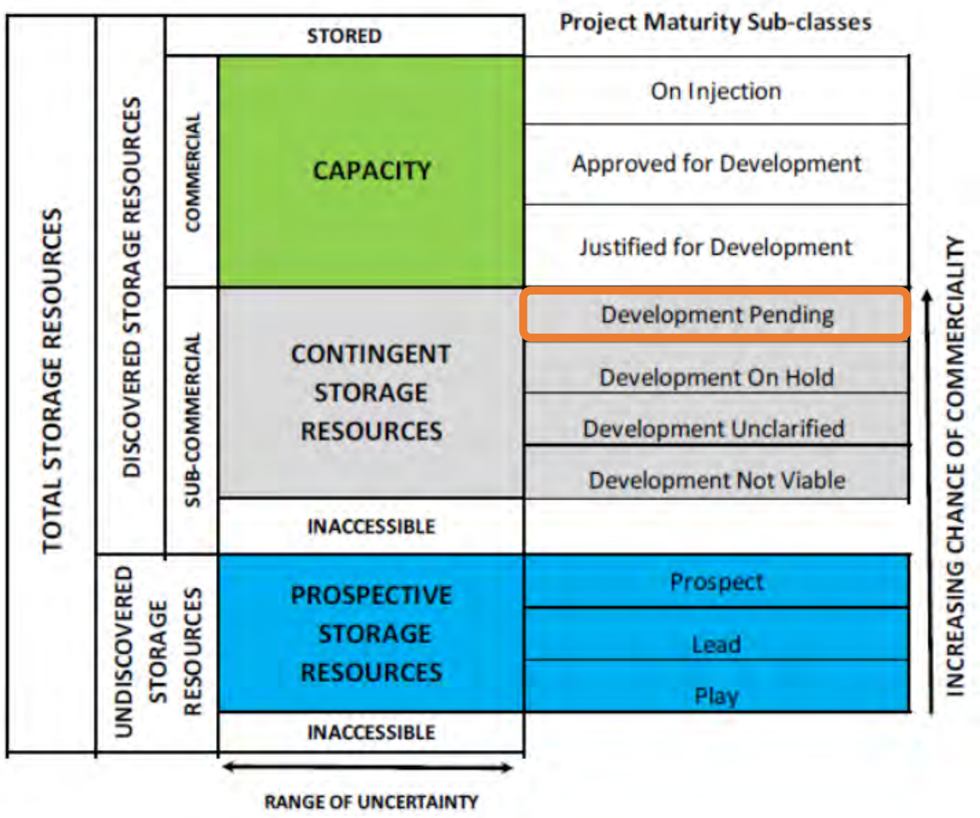
- Minimum storage rate (325 ton/day)
  - 5-10 patterns
- Produced CO_2 must be recycled
  - Breakthrough occurs in 2-5 months
  - Build-out additional patterns to keep up with minimum storage rate
  - Start large, so that minimum storage rate is the long-term difference between injected and recycled

Commercial Deployment Example Assessment: SPE Resource Classification and Categorization

Categorization: storable quantities certainty



Classification: project maturation



Summary

- HnP Pilot
  - Another few days of injection
  - Soak >7 days
  - Production
- Calibrate model to HnP results
  - Identify greenfield development strategies for storage and EOR
  - Economics
    - Pilot
    - Commercial scale

Greenfield ROZ Challenges:

- CO_2 EOR
  - Low oil saturation
  - High utilization factors
  - High water production rates
- CO_2 Storage
  - 45Q MRV Plan
    - Economic monitoring
    - Monetizing credits

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