
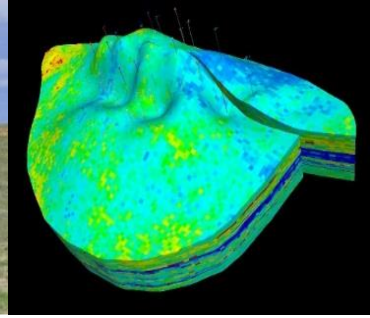

Developing CO_2-EOR and Associated Storage within the Residual Oil Zone Fairways of the Powder River Basin, Wyoming

DE-FE0031738

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Enhanced Oil Recovery Institute

Presentation Outline

- Project Overview
  - Project Objectives
  - What is a ROZ?
  - Salt Creek Field History and Geology
- Technical Status
  - Geologic Laboratory
  - Reservoir Modelling
  - Site Selection
- Accomplishments to Date
- Lessons Learned
- Synergy Opportunities
- Project Summary

Project Objectives

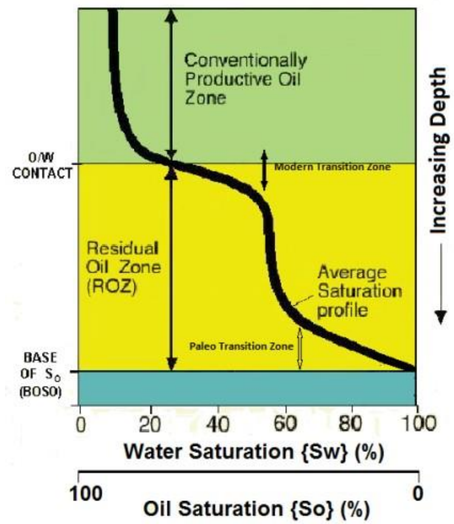
The project team has established four overall research objectives to assess the technical and economic viability of oil recovery associated CO_2 storage in a ROZ at the Salt Creek field

- Characterize the ROZ Fairway Resource Adjacent to the Salt Creek Oil Field, Powder River Basin
- Undertake Detailed Review of Mechanisms Influencing the Efficiency and Permanence of ROZ-Associated CO_2 Storage
- Examine Alternative CO_2 Injection and Storage Strategies for Optimizing Both Oil Recovery and CO_2 Storage
- Establish the Commercial Viability of Enhanced Oil Recovery and Associated CO_2 Storage for the ROZ Fairway at Salt Creek

What is a ROZ?

- Residual Oil Zone (ROZ)
- At the base of a typical oil column, a thin (10-50’) oil bearing transition zone occurs that uniformly grades from 85-90% oil saturation to 0%
- In an extensive ROZ, an anomalously thick transition zone (> 50’) occurs with oil saturations of ~ 30%
- In some cases, lower permeability rocks may provide a thicker transition zone that has locally trapped higher residual oil saturations
- CO_2-EOR flooding can commercially produce hydrocarbons within an extensive ROZ which generally represents stranded resource below the traditional productive limits of a field

Residual Oil Zones and Upper and Lower Transition



Melzer 2019

Types of ROZ Formation

Base Case - Static Aquifer Conditions

Type 1

- Local, regional or basin-wide tilt
- After tilting, oil-water contact re-equilibrates leaving a ROZ where oil has moved out

Type 2

- Leaky or breached seals
    - Seal breached by fractures or fault
    - As oil leaks off the oil-water contact moves up creating a ROZ
    - Seal heals before rest of oil leaks off

Type 3

- Laterally flushed by meteoric water

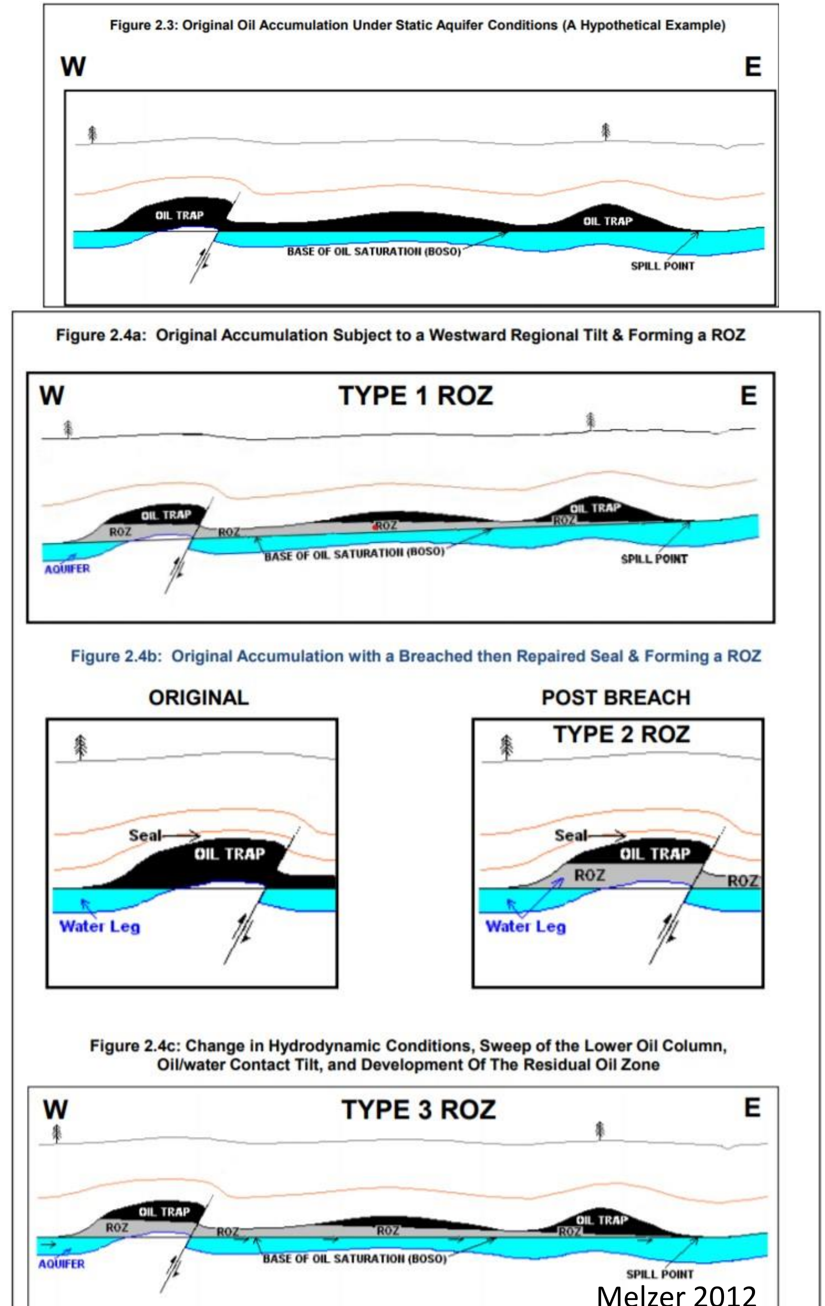


Figure 2.3: Original Oil Accumulation Under Static Aquifer Conditions (A Hypothetical Example)

Figure 2.4a: Original Accumulation Subject to a Westward Regional Tilt & Forming a ROZ

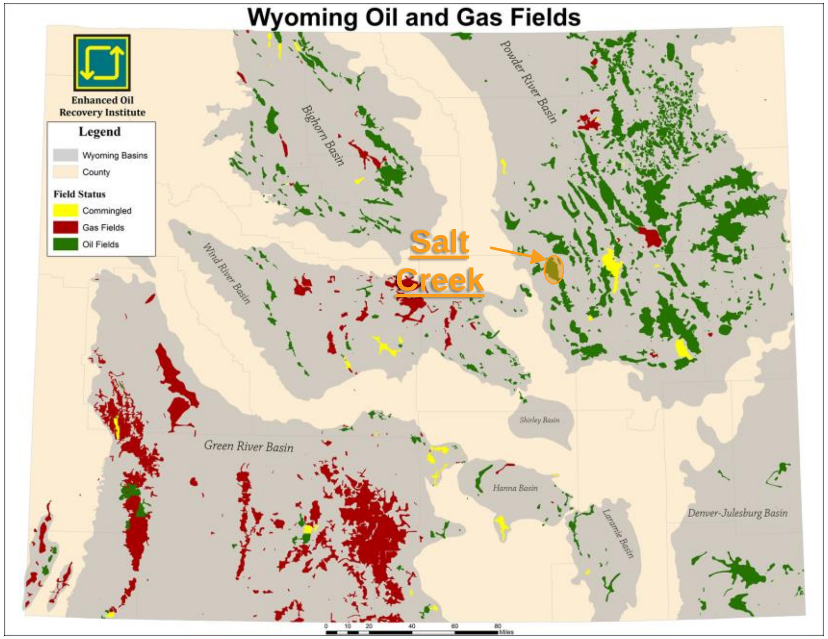
Figure 2.4b: Original Accumulation with a Breached then Repaired Seal & Forming a ROZ

Figure 2.4c: Change in Hydrodynamic Conditions, Sweep of the Lower Oil Column, Oil/water Contact Tilt, and Development Of The Residual Oil Zone

Melzer 2012

Salt Creek Field

- The Salt Creek oilfield, located along the western periphery of the Powder River Basin in Wyoming, is the largest conventional oilfield in the Rockies, with 1,680 MMbbl of original oil in place and 732 MMbbl cumulative production from over 4,000 wells
- The field has been undergoing CO_2-Enhanced Oil Recovery (CO_2-EOR) operations since 2003
- Salt Creek produces from eleven Mesozoic intervals with the <u>Cretaceous Frontier Formation</u> serving as one of the principal oil-producing units
- The Wall Creek 1 interval of the upper Frontier produces oil within the main historical development area and has been the target of a limited CO_2-EOR pilot program
- Down-dip of the main reservoir, Wall Creek 1 production tests indicate a potentially extensive Residual Oil Zone (ROZ)



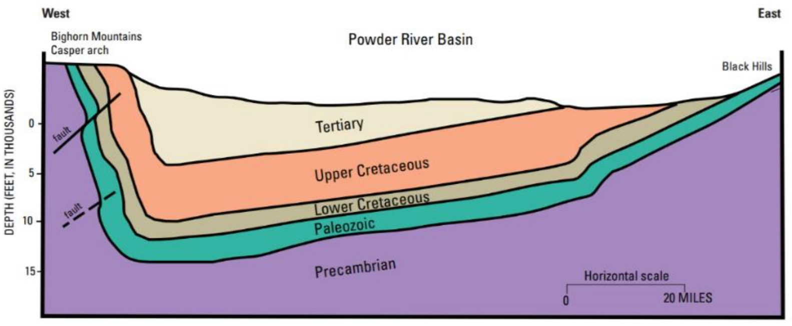
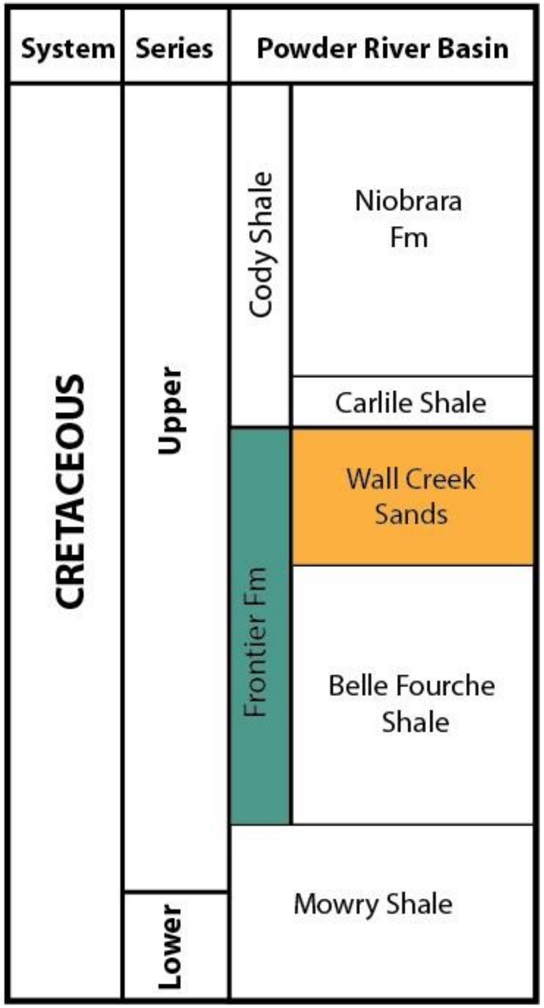


Figure 2. Generalized east-west cross section of Powder River Basin showing a west side basin axis. Black Hills monocline is shown in Cretaceous and Paleozoic rocks on east side of basin.

From Anna 2009

Geology

- The Wall Creek 1 interval is the uppermost sandstone member of the Frontier Formation and was deposited as a prograding sequence of deltaic deposits along the western margin of the Cretaceous Interior Seaway
- The Wall Creek 2 interval occurs below the Wall Creek 1 and is also hydrocarbon productive
- The Carlile shale immediately caps the Wall Creek 1 interval and is the primary confining unit
- The Wall Creek 1 ranges in depth from 1000-2200’ and has a gross thickness of 100-160’
- Average porosity: 18%, average permeability: 32 md
- Oil gravity ranges from 39-40^{o} API



Type Logs: Wall Creek 1 Productive vs. Wall Creek 1 ROZ

49025203800000

23WC1NE23
T40N R79W S23
KB 4,856’

<10,952FT>

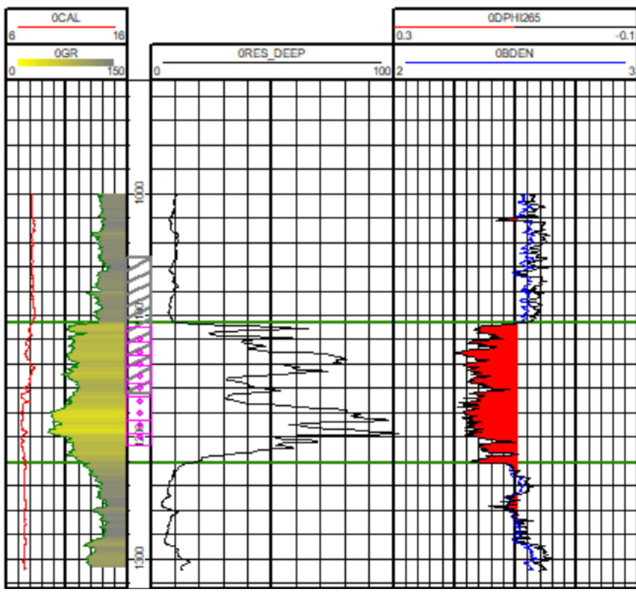
49025233470000

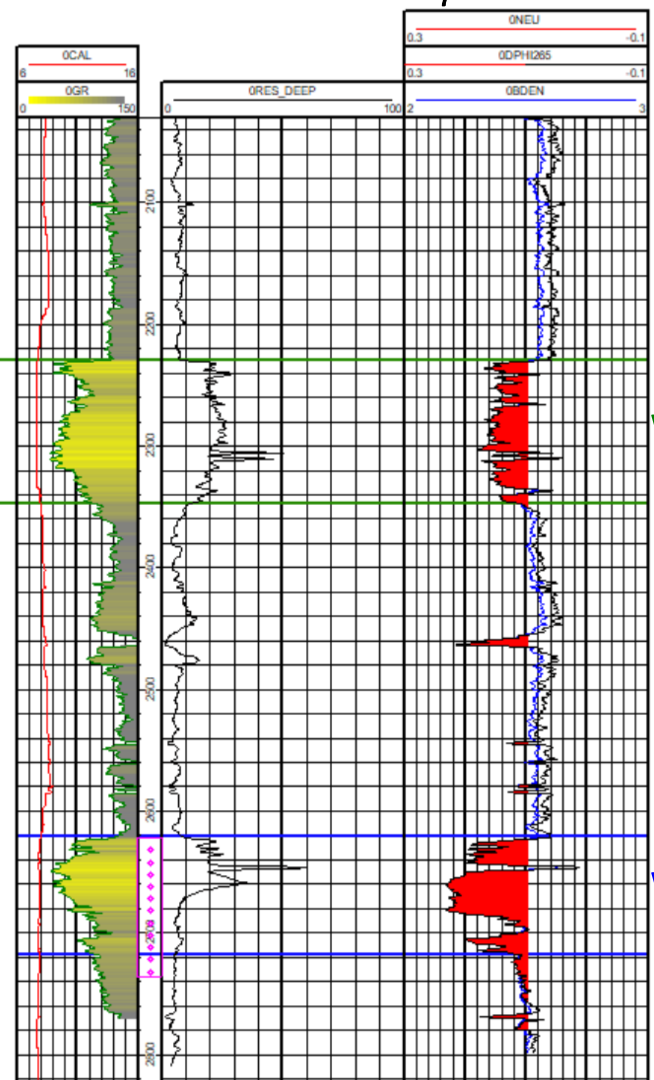
28WC2NE12
T40N R79W S12
KB 4,842’

Down-dip ROZ well

Productive well

Datum: Top of Wall Creek 1



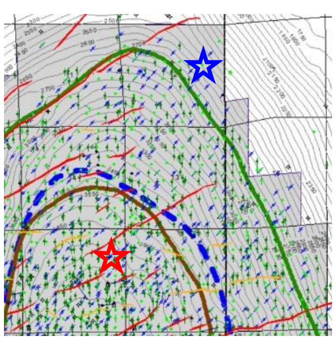


Wall Creek 1

Wall Creek 2

250-300’ separates WC1 and WC2

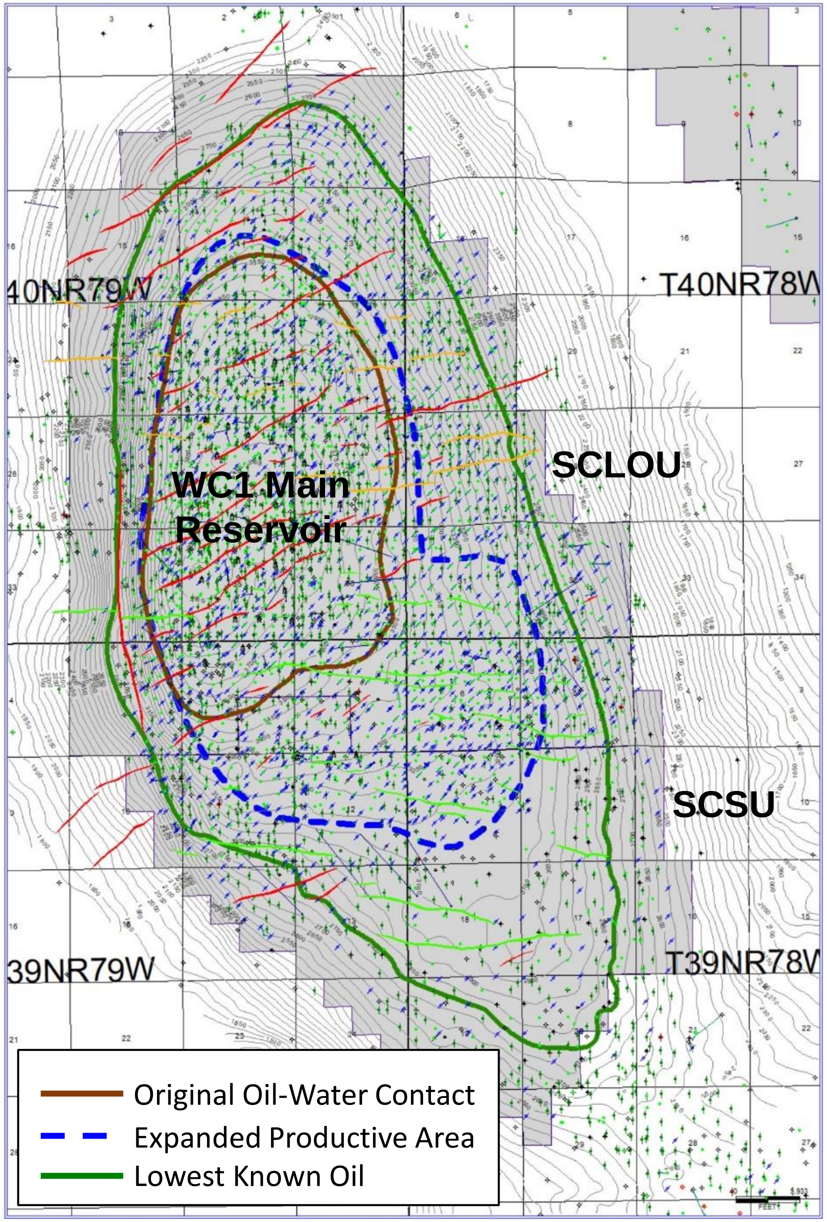
Oil: 280,281 Bbls
Gas: 3,014 MCF
Water: 1,819,904 Bbls



- 250-300’ between Wall Creek 1 and Wall Creek 2 reservoirs
- Note reduced resistivity in non-productive Wall Creek 1 ROZ
- Density Porosity >10% shaded in red

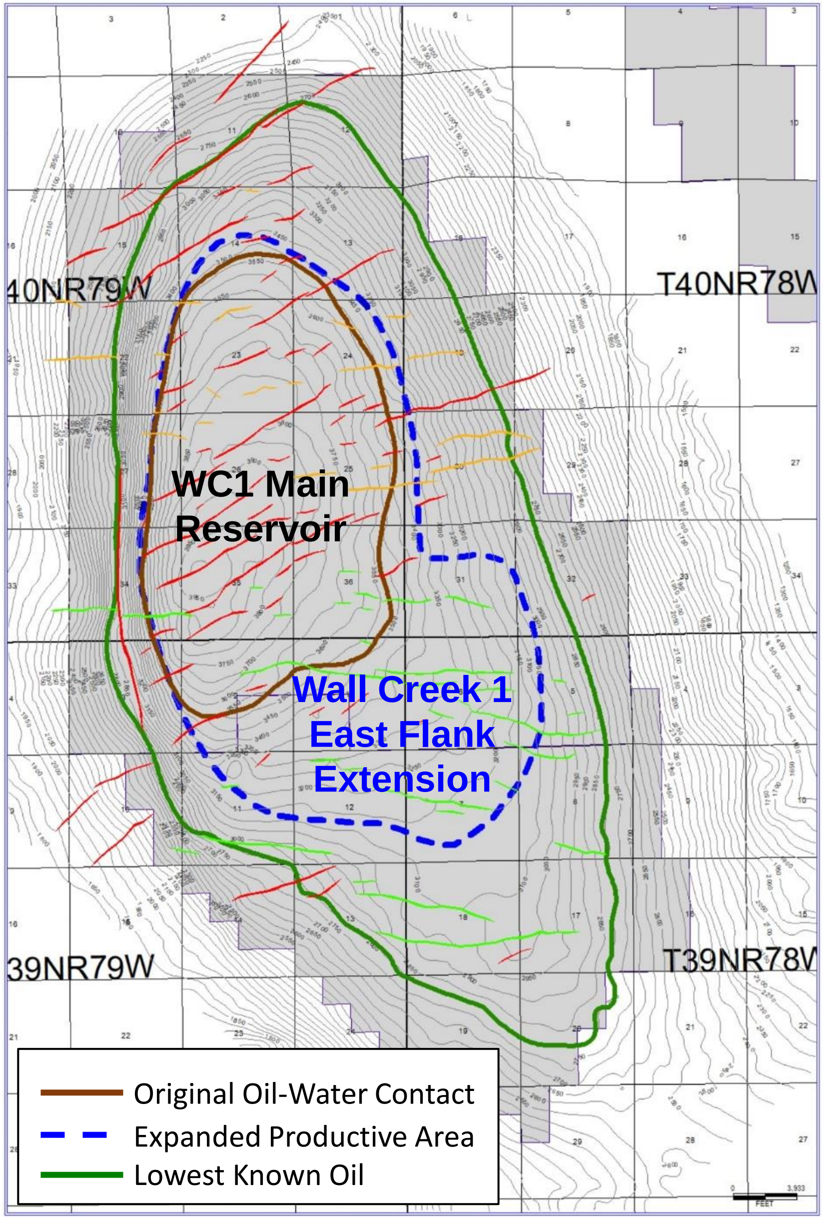
Salt Creek Field History

- Discovered in 1908 in section 23 at a depth of 1,050’ MD in Dutch No. 1 well; development commenced in 1911 after a pipeline to Casper was completed, production climbed to 125 wells making ~10,000 BOPD in 1918
- Development ceased until 1922 when production was brought back up to ~7,000 BOPD, subsequently decreasing to 500 BOPD in 1943 and was maintained at this rate through 1955
- A two-pattern water flood pilot was implemented in 1955 in section 25 and was deemed a success once expanded, full field waterflood above the oil water contact began in 1960
- Waterflood injection rates reached 160,000 BWPD while production climbed to 14,000 BOPD in 1967, at which time it began to decline
- Comprised of two units:
    - Salt Creek Light Oil Unit (SCLOU) - 1939
    - Salt Creek South Unit (SCSU) - 1962



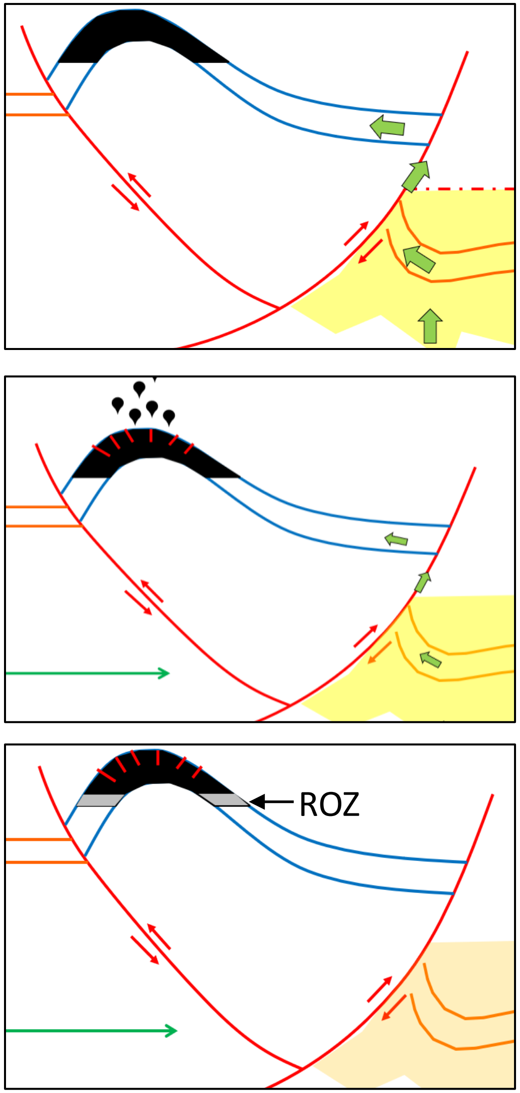
Salt Creek Field History

- Production of the Wall Creek 1 on the east flank began in 1963 through recompletes in Wall Creek 2 wells during expansion of the Wall Creek 2 flood and was commingled with the Wall Creek 2
- Development of the Salt Creek South Unit began in 1975 mostly commingled with Wall Creek 2 production
- In 2005 an immiscible pilot pattern in the Wall Creek 1 was deemed a success while a down dip miscible pilot drilled in 2006 gave inconclusive results
- After these successful tests, tertiary recovery via CO_2 flood began in 2009 on the east flank and in the Salt Creek South Unit with operations continuing through present day

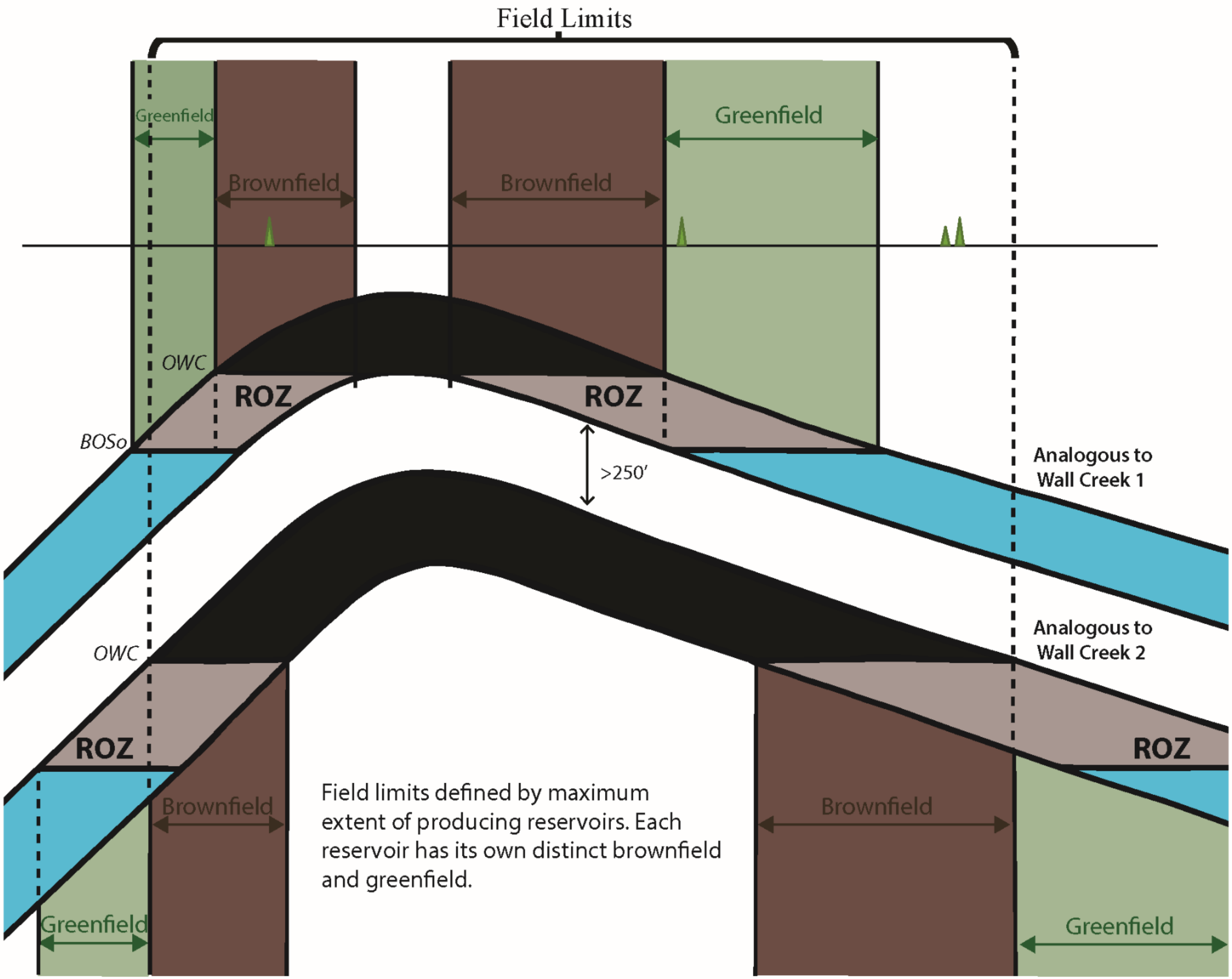


Origin of ROZ at Salt Creek

- Type 2 ROZ – breached seal
- Main thrust, back thrust, and Salt Creek structure develop during the Laramide Orogeny (75-40 mya)
- To the east in the Powder River Basin, the Mowry Formation generated hydrocarbons which migrated into the reservoirs on the Salt Creek structure, including the Wall Creek 1
- Renewed compression breached the overlying seal and allowed hydrocarbons to leak from the Wall Creek 1
- The oil/water contact adjusted after seal breach and an extensive ROZ is left behind in the Wall Creek 1 below the main crest of the field



Conceptual View of ROZ at Salt Creek

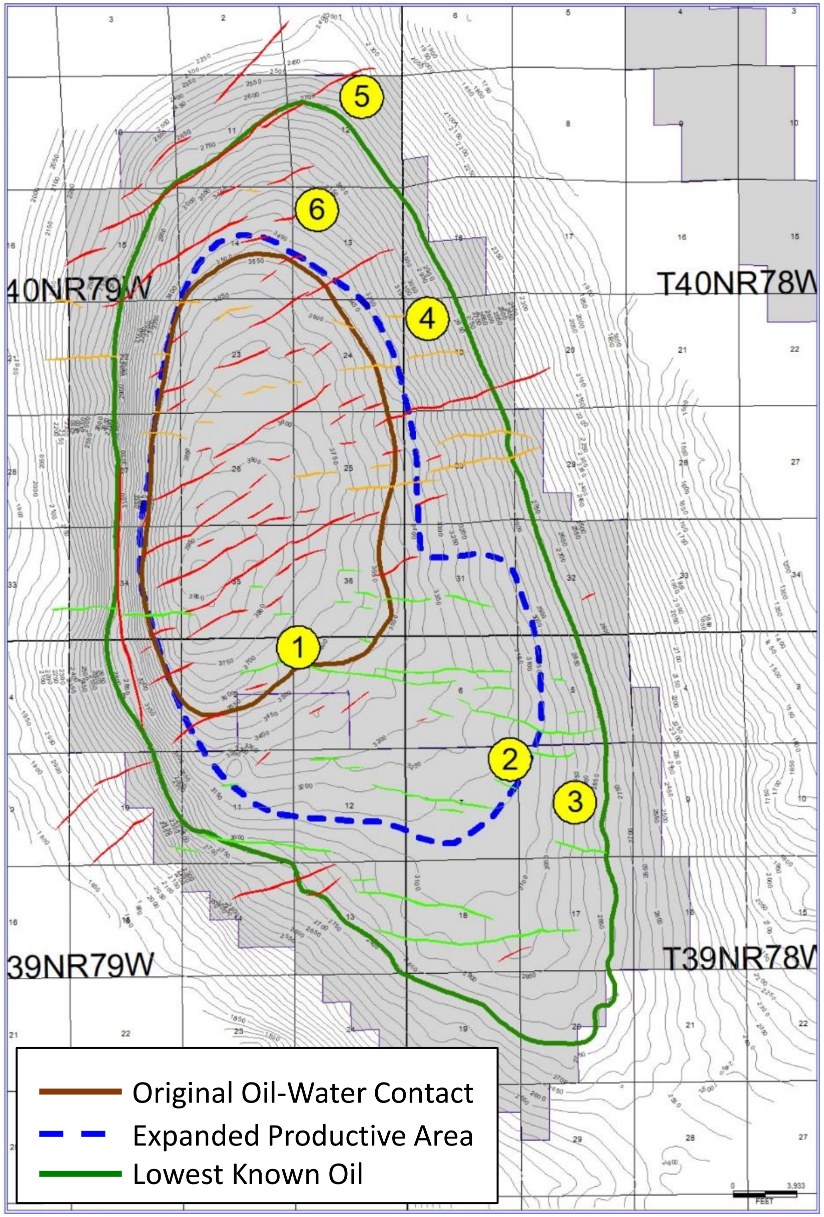


Geologic Laboratory (Geolab)

- The Geolab consists of:
    - Geologic model
    - Reservoir model
    - Well location to be chosen
        - New drill or re-entry(?)
            - Core
                - Routine core analysis and some special core analysis
            - Multi-phase core flooding experiments/reservoir testing
                - Supercritical CO_2
            - Geophysical well logs
            - Injection tests and monitoring
    - All data will be used to refine the geologic and reservoir models
    - Real world test

Reservoir Modelling

- Six potential drilling locations were selected across the Salt Creek field within the Wall Creek 1 leasehold for modeling
- The project team was developed single-well simulation models to ascertain production performance under a variety of scenarios
- Reservoir properties (depth, thickness, permeability, porosity) were developed from pre-existing Anadarko and Fleur de Lis geologic analyses originating from detailed well log, core, and facies analyses
- Using well logs, a field wide map of water saturation using the Indonesia Equation was also constructed as an input for reservoir simulations and to assess oil saturations within the ROZ
- ¼ pattern, 20-acre (5 spot) dynamic reservoir simulation models were developed to study each potential site
- The models considered pressure depletion (primary), waterflood (secondary), and CO_2-EOR (tertiary) performance



Site Selection

Location 1

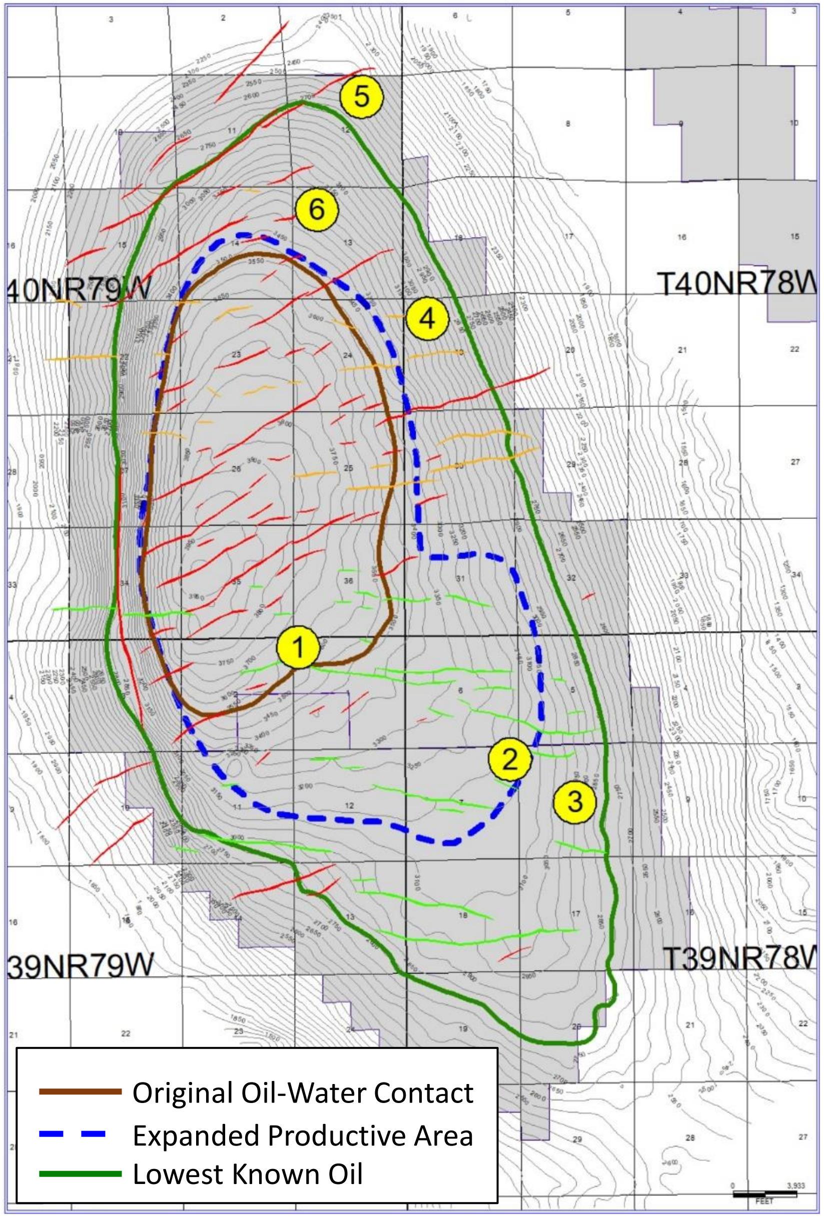
- Located in the Wall Creek 1 Main Pay Zone – brownfield area and not in a residual oil zone

Location 2

- Located in a productive Wall Creek 1 area – brownfield
- Modeled to serve as analog to Location 3 due to lack of Wall Creek 1 data

Location 3

- Located outside Wall Creek 1 field development – greenfield ROZ
- Model resulted in relatively good oil recovery
- Higher pressure & closer to miscibility than Locations 1 & 2
- Heterogeneous facies
- Harder to predict oil saturations and fluid pathways
- Tests large “open” area in SE part of field



Site Selection

Location 4

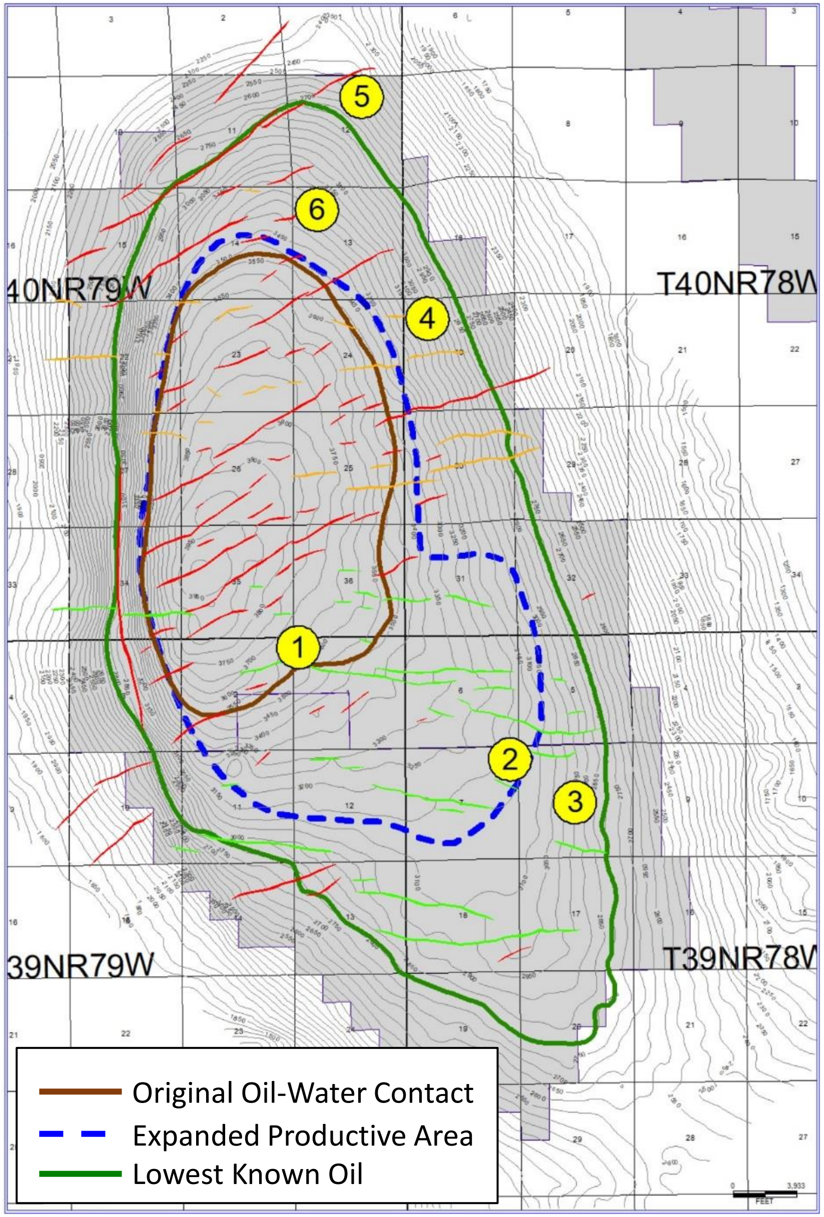
- Located in a down dip Wall Creek 1 area, but is brownfield due localized production
- Leads to a possible future test outside the unit to the east

Location 5

- Location suggested by DOE
- Beyond lowest known oil boundary
- Lowest oil saturation of all the models, therefore least oil recovered in simulation

Location 6

- Location preferred by Project Team and supported by FDL
- Homogenous marine facies is dominant
- Oil more likely to leak off where homogenous = i.e. most likely to be a ROZ
- Modelling suggests the best oil recovery with good CO_2 storage of the greenfield ROZ locations



Site Selection

- Reservoir parameters were collected from various sources
  - Wall Creek 1 geologic assessment (Anadarko Petroleum) that defined the depositional environments across the Salt Creek field played a key role in determining the reservoir property distribution within the reservoir.
  - Core and geophysical well logs

Location	1	2	3	4	5	6
Reservoir	Wall Creek 1	Wall Creek 1	Wall Creek 1	Wall Creek 1	Wall Creek 1	Wall Creek 1
Depth (ft)	1,201	1,815	2,207	1,816	2,343	1,570
Elevation (subsea)	3,650	3,200	2,900	3,100	2,525	3,275
Thickness (ft)	144	102	100	117	100	128
Permeability (mD)	20	20	13	12	28	28
Porosity	0.18	0.17	0.16	0.14	0.16	0.16
Water Saturation	0.53	0.63	0.65	0.54	0.70	0.64
Reservoir Pressure (psia)	566	823	992	827	1,051	728
Min Miscibility Pressure (psia)	1,292	1,292	1,292	1,292	1,292	1,292
Facies	Estuarine Sand Sheet	Tidal Shoal/Estuarine	Tidal Shoal/Estuarine	Tidal Shoal/Estuarine	Distributary Complex	Distributary Complex
Sequence	Constant	Constant	Fining Upward	Fining Upward	Coarsening/fining/coarsening	Coarsening/fining/coarsening

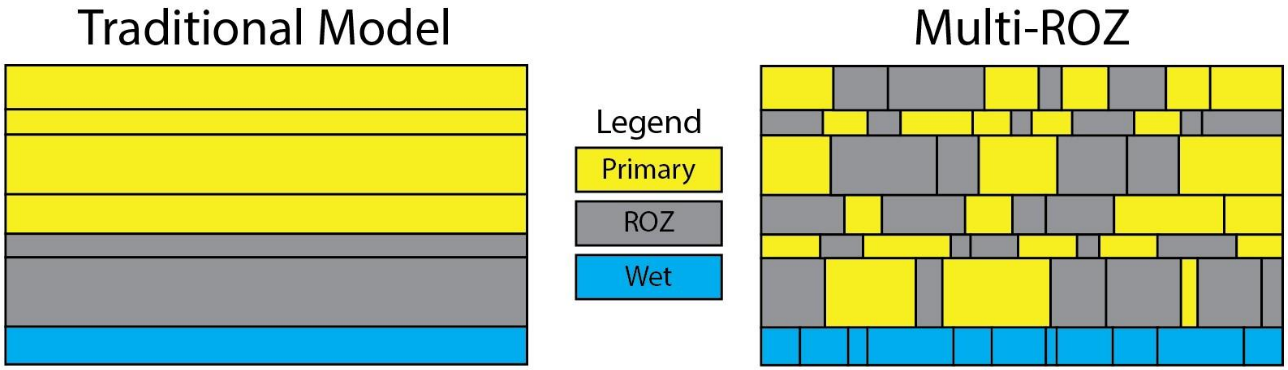
Site Selection

- Simulated recovery factors are based on the current oil in place (OIP) in the numerical model, each shown below, with the WAG CO_2 demand for the ¼ 20-acre pattern
- The project team has suggested location 6 as the site for the geo-lab for the DOE's consideration
- This suggestion is currently under review by the DOE

Location	OIP (MSTB)	Recovery (% of OIP)	Gross CO2 Injected (MMscf)
1	462	32	318
2	244	16	244
3	210	18	327
4	286	39	534
5	178	7	1095
5-conformance	178	12	823
6	273	20	800

Multi-ROZ Concept

- Evidence at Salt Creek suggests that a ROZ can be discontinuous laterally in a reservoir but can also by discontinuous vertically, even down to the wellbore scale.
- Given the stacked-sand nature of the reservoir (i.e., heterogeneity), the team believes it is possible that individual sand beds within the reservoir interval leaked at different rates
- What's left consists of intermingled ROZs and higher saturation sand beds.



- "Primary" refers to reservoir that has close to original pressure and oil saturation
- In a homogeneous reservoir, the reservoir is less compartmentalized OR the compartments act more like each other, leading to a more consistent ROZ (traditional model)
- In a heterogeneous reservoir, the ROZ forms in the relatively high permeability rocks (oil can leak off) while the tighter reservoir is less likely to flow oil, thus leaving it at near original conditions (multi-ROZ model)

Accomplishments to Date

- Successfully competed:
  - Geologic Model
  - Reservoir Modelling
    - To be iterated with geolab data
  - Site Selection Report
    - Delivered to DOE
  - Upon approval of site from DOE, we will move from Task 3: Geo-Laboratory Design and Site Selection to Task 4: Field Deployment and Data Collection

Lessons Learned

- Research gaps/challenges:
  - Major challenges in determining water saturation (Sw) in the Upper Cretaceous reservoirs of the Powder River Basin
    - Clays in reservoir (bound water)
    - Geophysical well log vintage – 100+ year old field – every generation of log represented
    - Disconnect between water resistivity data (Rw), a key variable in Sw calculation, and well logs
      - There is robust set of Wall Creek 1 Rw data from the 1920's and 1940's, but…
      - The field was already under waterflood prior to modern logs
        - Any log data used in Sw calculations would measure the saturation of the reservoir at a specific moment in time, not at original reservoir conditions

Lessons Learned

- Unanticipated research difficulties:
  - Difficulty in nailing down a site for the geolab
    - Original geolab location proposed on unleased acreage
    - Had to move into the existing unit to be able to provide a drillable (leased) location
    - This decision differed with the original stated goal for the project
      - Worked with DOE to come up with a suitable location
  - COVID-19 and Associated Drop In Oil Price
    - Eroded operator's financial ability to drill a well during 2020
- Technical disappointments:
  - The biggest disappointment is the delay of project
    - 1 year no-cost technical extension approved
    - Additional 6 month no-cost technical extension pending
- Changes that should be made next time:
  - No COVID!

Project Summary

- Key Findings:
    - Project team believes there is a ROZ in the Wall Creek 1 within the confines of the existing Salt Creek Unit.
    - Project team is expanding the idea of ROZ to include the concept of Multi-ROZ
- Next Steps:
    - Site selection – report submitted, approval pending
    - Take core
    - Update geologic model and reservoir simulation
        - Includes updating CO_2 storage volumes

Thank You!

Questions?

NATIONAL ENERGY TECHNOLOGY LABORATORY

Fleur de Lis ENERGY, LLC

UW | School of Energy Resources

Enhanced Oil Recovery Institute

Advanced Resources International, Inc.



Appendix

Accomplishments to Date

Requested

Completed

Success Criteria	Criteria to Define Success
Negotiation/Implementation of PMP Criterion #1	EORI will revise the PMP by including details from the negotiation process. The PMP will be updated to incorporate any changes in project management, schedule, and/or budget. DOE/NETL's approval of this plan and its implementation is necessary to carry out the stated goals of the project and budget objectives.
Candidate Well(s) Selection Criterion #2	The Project Team will ensure the selected test well(s) are well-suited for use in the project. Key selection criteria will include potential ROZ and reservoir characterization data to be collected when the well is drilled, as well as operational and technical risks.
Completion of Test Well(s) Criterion #3	Success will be determined by the completion of the well, collection of data and core to be analyzed.
Completion of Geo-Laboratory Final Report Criterion #4	Success will be determined by the use of this information for completing the techno-economic and lifecycle analysis of ROZ development in the PRB

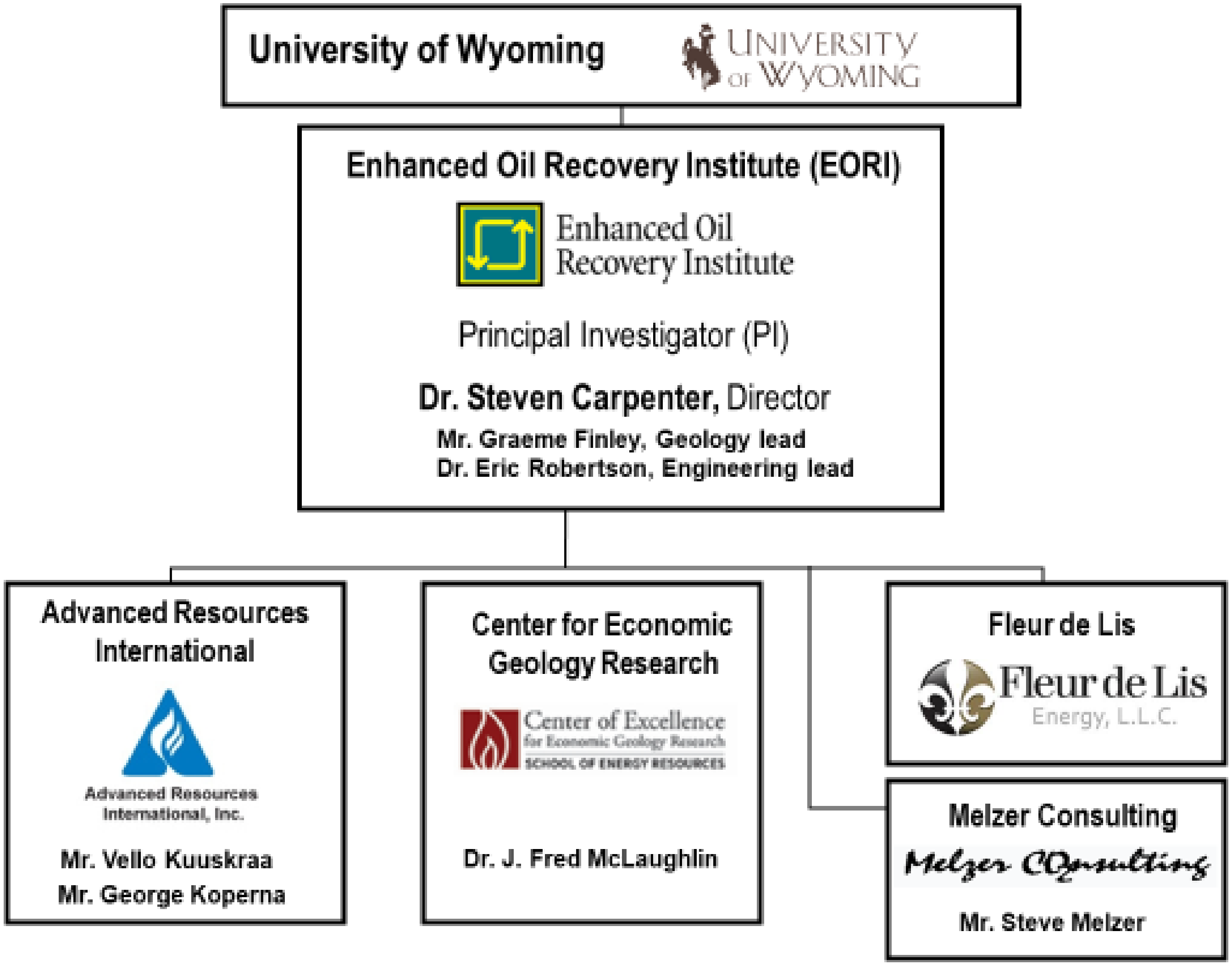
Benefit to the Program

- Identify the program goals being addressed.
    - Investigating CO_2 storage and associated oil recovery (which makes CO_2 storage economical and more appealing to industry)

Project Overview

- Describe the project goals and objectives in the Statement of Project Objectives.
  - How the project goals and objectives relate to the program goals and objectives:
    - Project seeks to prove that a ROZ is a viable target for CO_2 storage
  - Identify the success criteria for determining if a goal or objective has been met. These generally are discrete metrics to assess the progress of the project and used as decision points throughout the project:
    - Success will be determined upon injection of CO_2 in the Wall Creek 1 ROZ
    - This project is a proof of concept that, if successful, can be applied to other mature oil fields throughout the United States

Organization Chart



Organization Chart